Final Report

STATUS AND PERSPECTIVES OF LIQUID ENERGY SOURCES IN THE ENERGY TRANSITION

A Study by Prognos AG, the Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT and the German Biomass Research Centre DBFZ

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MEW Mittelständische Energiewirtschaft Deutschland e.V.
UNITI Bundesverband mittelständischer Mineralölunternehmen e. V.

Date Completed
May 2018

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Legal Form
Joint-stock company (Aktiengesellschaft) under Swiss law

Year Founded
1959

Activity
Prognos AG advises decision-makers from the worlds of politics, business and society throughout Europe.

On the basis of neutral analyses and well-founded forecasts, we develop practical solutions and future strategies for companies, public clients and international organisations.

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ABBREVIATIONS AND GLOSSARY

ASTM	International Organization for Standardization (originally the American Society for Testing and Materials)
BEV	Battery-electric vehicle
GDP	Gross domestic product
BtL	Biomass-to-liquid
BtX	Conversion of biomass to gaseous or liquid secondary energy sources (Biomass-to-X)
GVA	Gross added value
CAPEX	Capital expenditure
CCS	CO_2 capture and long-term storage (carbon capture and storage)
CNG	Compressed natural gas
DAC	CO_2 capture from air (direct air capture)
DBFZ	Deutsches Biomasseforschungszentrum (German Biomass Research Centre)
RE	Renewable energy
EEG	German Renewable Energy Sources Act
FEC	Final energy consumption
FCV	Fuel cell vehicle
FTS	Fischer-Tropsch synthesis
FT syncrude	Fischer-Tropsch syncrude: Hydrocarbon mixture as a product of FTS
CTS, HH, IND, TRA	Commerce/trade/services, household, industry and transport consumption sectors
Hi	Lower calorific value (i for inferior)
Hs	Upper calorific value (s for superior)
HV, MV, LV	Power grid network levels: High, medium and low-voltage grid
ICEV	Internal combustion engine vehicle
IMO	International Maritime Organization
KBA	German Federal Motor Transport Authority

CHP	Combined heat and power
LCV	Light commercial vehicle
LPG	Liquefied petroleum gas
MENA	Middle East North Africa region
MeOH	Methanol
MIT	Motorised individual transport
SWDS	Seawater desalination
NEC	Non-energy-related consumption
OME	Oxymethylenether
OPEX	Operational expenditure
PBtL	Power-biomass-to-liquid
PEM	Polymer electrolyte membrane
PEC	Primary energy consumption
PHEV	Plug-in hybrid electric vehicle
pkm	Passenger kilometre
POME	Polyoxymethylene ether
PBtX	Conversion of biomass and electricity into gaseous or liquid secondary energy sources (power and biomass-to-X)
PtG	Conversion of electricity to gaseous secondary energy sources (power-to-gas)
PtH_2	Conversion of electricity to hydrogen (power-to-hydrogen)
PtL	Conversion of electricity to liquid secondary energy sources (power-to-liquids)
PtL syncrude	Hydrocarbon mixture as a product of PtL
PtX	Conversion of electricity to liquid or gaseous secondary energy sources (power-to-X)
RED	EU Renewable Energy Directive
RWGS	Reverse water-gas shift reaction
HCV	Heavy commercial vehicle
SOEC	Solid oxide electrolyser cell

GHG	Greenhouse gases
tkm	Tonne kilometre
TRL	Technological readiness level
UMSICHT	Fraunhofer Institute for Environment, Safety and Energy Technology
fuh	Full utilisation hours
WACC	Weighted average cost of capital
WGS	Water-gas shift reaction
η	Efficiency

PRELIMINARY REMARK

Prognos AG, Berlin/Basel, the Deutsche Biomasse Forschungszentrum DBFZ and the Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT were commissioned by the German mineral oil industry associations in April 2017 to draw up a study on the **prospects of liquid energy sources in the energy transition**.

The study was carried out in two **phases:** first, the **technological principles** were worked out and the costs and potential for PtL production, biomass and other renewable energies were examined in more detail. After phase I (in September 2017), an interim report was published.

In phase II, Prognos created **scenarios** to assess how the energy transition could be shaped, with a special emphasis on PtX. The study focuses on liquid energy sources, but many of the statements also apply to synthetic gases (PtG). Therefore, gases were treated in the same way as liquid energy sources in the scenarios.

Despite repeated, careful quality controls, Prognos, DBFZ and UMSICHT do not assume any guarantee for the statements and results in this report.

Any liability is hereby expressly excluded.

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SUMMARY

Liquid energy sources and raw materials are of considerable importance today

- Liquid energy sources and raw materials are easy to store and transport. Their chemical properties make them very versatile. As a result, they form the basis for important industrial value added chains in Germany.
- Approx. 98 % of the propulsion energy in the transport sector and 22 % of heating energy currently comes from liquid energy sources.
- Germany has around 5.6 million oil-fired heaters. Approx. 20 million people live in oil-heated buildings.
- 16 % of the mineral oil produced is used in the chemicals industry, covering 75 % of its organic raw material requirements.
- Close networking and the exchange of energy and products in the important industrial sectors of refining, petrochemicals, chemicals and plastics processing in Germany lead to synergies and contribute to the international competitiveness of these sectors.

In the future, it will be possible to produce GHG-neutral liquid energy sources from renewable electricity or biomass

- Electricity from renewable energies can be converted into **liquid energy sources** with the help of electrolysis hydrogen and synthesis with carbon.
- If the carbon required to do so is obtained from the air or from biomass, a practically **greenhouse gas-neutral** fuel is produced: **PtL** (power-to-liquid) or BtL (biomass-to-liquid). Unavoidable concentrated exhaust gas flows can also be utilised.
- **Biomass**-based energy sources and raw materials have many uses and can play an important supplementary role in reducing GHG emissions. They can also be combined with PtL technology (PBtL).

Important economic sectors and consumers will continue to need liquid energy sources in the future

- Especially in parts of the **transport sector** (e.g. air traffic, shipping, long-distance road haulage) and in the **chemicals industry**, liquid energy sources and raw materials are **difficult or impossible to replace**.
- In other areas that are currently largely supplied with liquid energy sources, including passenger car traffic and the heating sector, **competition** will arise between GHG-neutral liquid energy sources and other systems (for example, electricity-based systems).
- Since liquid energy sources continue to be needed, the development of the power-to-liquid technology path is a **no-regret measure** from a climate protection perspective **and is therefore highly recommended**.

Infrastructure and application technologies for liquid energy sources can be further utilised

- GHG-neutral liquid energy sources and raw materials can technically be used in all consumption sectors; time-consuming retrofits are no longer necessary.
- PtL energy sources and raw materials can be processed, stored, transported and used in the same way as today's liquid energy sources.
- German refinery sites can process PtL "crude oil" into end products after certain adaptation investments. As is the case today, they are in competition with locations in producer countries.
- The domestic infrastructure requirements are significantly lower than in scenarios with higher degrees of electrification. Such scenarios require considerable investment abroad.

Consumers apply a variety of criteria in their investment decisions

- This study compares electricity solutions with liquid energy sources (with increasing proportions of PtL) from the **consumer**'s point of view. The criteria used are economic efficiency, usage and environmental aspects.

- The **economic efficiency** criterion provides a varied picture. In the short and medium term (2030), liquid energy sources will in most cases provide economic advantages while PtL proportions are still low. In the long term, our analyses show the advantages for electricity solutions in the higher price path for PtL and with end-consumer electricity prices remaining at around 2015 levels. However, depending on the PtL and electricity cost levels and usage constellation, there may also be long-term advantages for liquid energy sources. As a basic principle, from the consumer's point of view, the assessment of economic efficiency also depends on the level of the tax burden. Today, liquid energy sources in mobility are subject to higher taxes per energy unit than electricity.

- In terms of **use**, the primary differences are in mobility. Due to the improved storability of liquid energy sources, we see long-term advantages in the use of liquid energy sources.

- From **an environmental perspective**, electrical solutions in heating and mobility have advantages over liquid energy sources, especially in the short and medium term. Among other things, the electricity solutions produce fewer air pollutants and GHG emissions. It should be noted that a life cycle analysis to investigate upstream emissions was not carried out in this study. PtL fuels can cause less air pollutants than fossil fuels. With regard to greenhouse gases, the result of the evaluation in the long-term is neutral – if both the proportion of renewable energies in the electricity mix and the proportion of PtL blending converge towards 100 %.

PtX complements other solution options such as renewable energy and efficiency. Ambitious GHG reduction can be achieved more robustly through the use of PtL

- The PtX 80 and PtX 95 scenarios in this study show that it is possible to achieve the GHG reduction targets even if energy efficiency only increases as before and the development of renewable energies in Germany and the increasing electrification of applications for consumers reach their limits.

- This could be due to insufficient remediation speeds or delays in the expansion of the power grid.

In our scenarios, the PtL requirement in 2050 is between 555 and 2,000 PJ

- With ambitious climate protection (95 % GHG reduction), the **minimum PtL requirement** here is 555 PJ, equivalent to that of air and sea traffic. If the electrification of motorways in Germany is to be dispensed with, the minimum PtL demand will be approx. **985 PJ** (in 2050, see fig. 1 and fig. 2).

- If PtL is used proportionately as a solution strategy in all sectors, the PtL demand will be around **1,700 PJ** (corresponding to 39.5 million tonnes in the PtX 80 scenario; see figure 1) or around **2,000 PJ** (46.5 million tonnes in the PtX 95 scenario; see figure 2) in 2050. Depending on the scenario, around 1,000 PJ (26 billion m^3) and around 1,600 PJ (41 billion m^3) of PtG and PtH_2 are added to this. For comparison: Germany's current oil demand is around 104 million tonnes.

- It was assumed that carbon dioxide capture/storage with **CCS** will be used in parts of industry and in waste incineration in the PtX 95 scenario. To reduce the **use of CCS**, fossil resources could also be partially **replaced by PtL** in the petrochemicals industry. In this case, the PtL requirement would be about 470 PJ higher (see figure 2).

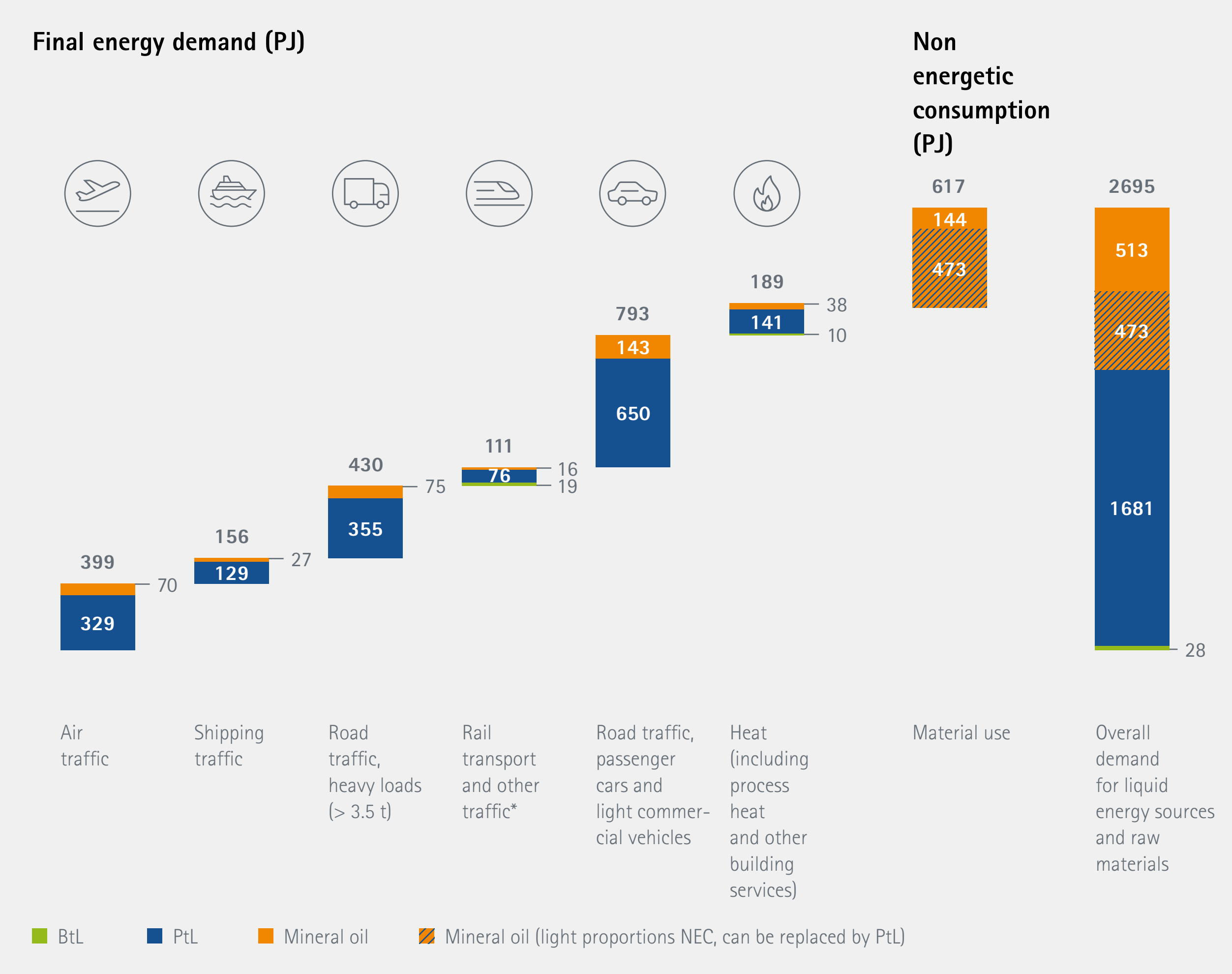
Energy imports offer opportunities

- **Electricity generation from renewable energies** will play an increasingly important role in reducing GHG emissions. The technical potential for electricity generation from renewable energies in Germany is high, but the realisable potential is unclear due to possible area restrictions.

- Many countries in the world have (significantly) greater potential and more favourable conditions for generating renewable energies than Germany. This is another reason why it makes sense to develop **imports** of renewable energies as an option to secure the supply of energy and raw materials in Germany.

- This study looked at the countries of North Africa, the Middle East ("MENA") and Kazakhstan. There was no worldwide search for optimal locations for PtL.

Figure 1: The use of liquid energy sources in Germany in 2050 in the PtX 80 scenario in PJ



Source: researcher's own diagram, *agriculture, construction, public administration, military, NEC: non-energy consumption

- Liquid energy sources can be stored cost-effectively and transported worldwide. This offers an advantage over gaseous energy sources or electricity. The result is a high degree of flexibility in the choice of PtL reference regions that extends beyond the search area of this study.

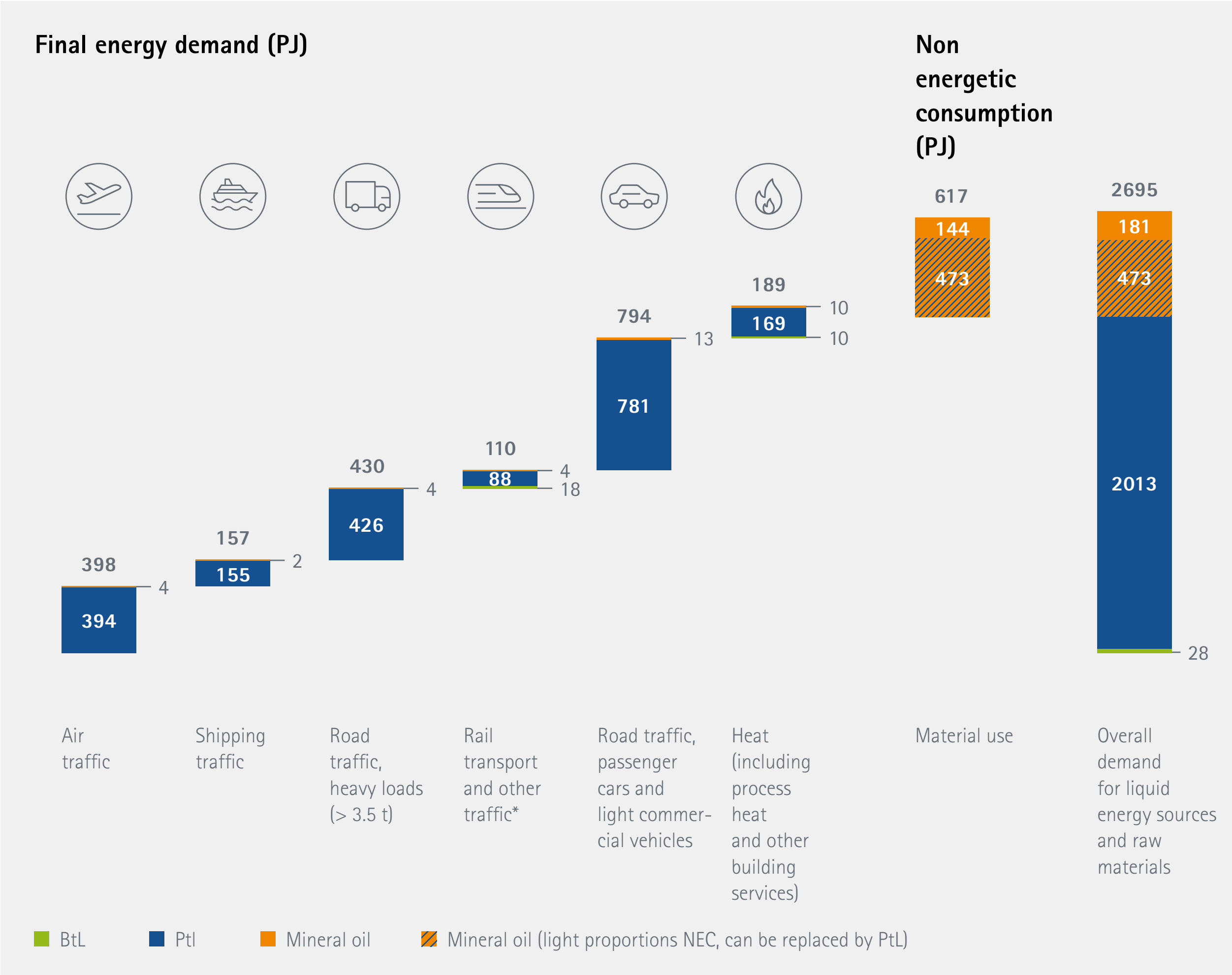
It will be possible to generate PtLs at costs of $€_{2015}$ 0.7 to 1.3 per litre in 2050 at 7 % interest.

- Depending on the local conditions for renewable electricity generation and efficiency, it will be possible to produce greenhouse gas-neutral PtL in 2050 for around $€_{2015}$ 0.5 to 0.9 per litre crude oil equivalent with a return on capital of 2 %. It should be noted that there are only a limited number of locations available in the search area of our study where the low cost level can be achieved.
- At an interest rate of **7 %**, which is also applied in other studies, production costs **of $€_{2015}$ 0.7 to 1.3 per litre** are expected.
- A prerequisite for this is a **large-scale industrial entry** into PtL technology so that learning effects can be achieved and costs can be reduced.
- PtL and PtG achieve approximately the same cost levels (→ fig. 12 to 15)

Scenarios with high PtX proportions require little investment in Germany, as existing infrastructure is largely used. However, higher energy costs must be expected

- By 2050, the cumulative domestic **investments**, at €34 billion (PtX 80) and € 59 billion (PtX 95) up to 2050 respectively, are only slightly above the reference scenario.
- However, annual **expenditure on energy sources** in Germany in 2050 doubles as a result of imports of PtL and PtG compared to a reference scenario without achieving the GHG targets.

Figure 2: The use of liquid energy sources in Germany in 2050 in the PtX 95 scenario in PJ



Source: researcher's own diagram, *agriculture, construction, public administration, military, NEC: non-energy consumption

- In the PtX 80 scenario, the cumulative costs for energy sources over all the years are 44 % higher than the reference scenario (PtX 95: similar scale).

PtL creates economic prospects in the producer countries

- To generate the PtL quantities from our scenarios, electricity generation **abroad** of 900 TWh (PtX 80) to 1080 TWh (PtX 95) in 2050 is required. This corresponds to 1.5 to 1.8 times the current net German electricity generation.
- Investments abroad of around € 44 billion (PtX 80) or € 58 billion (PtX 95) per year (excluding infrastructure investments) would be required on average over all the years up to 2050 for Germany's PtL supply alone. These investments represent a great opportunity and a great challenge that requires comprehensive international support in their implementation.
- The future production of PtL in sunny and windy countries that now export fossil fuels provides them with an alternative business model. It can be assumed that countries that are rich in natural resources will try to exploit their fossil oil and gas reserves without any alternatives to a large extent.

Conclusion

- Based on current knowledge, PtLs are **indispensable** for ensuring a largely greenhouse gas-neutral energy supply.
- From the consumer's point of view, liquid energy sources with PtL can be price-competitive compared to electricity-based solutions.
- PtL offers **consumers an additional option** for finding their optimal low-carbon solution. PtL can also be connected to the existing infrastructure.
- To develop this option and have sufficient quantities available in good time, a **gradual but steady market ramp-up** is to be aimed for. Depending on the phase, various regulatory and economic measures and instruments are suitable and necessary for this purpose.
- Companies and research institutes, for their part, are called upon to increase **research and development efforts** and to develop options. Carbon dioxide capture from the air, electrolysis and synthesis in particular are important fields of research.
- The future generation of PtL in sunny and windy countries can offer these countries **promising prospects for growth**.

2

INTRODUCTION

2.1 BACKGROUND AND TASKS

Carbon is a building block of life. Not only every human cell, but also most of the products and materials that surround us contain considerable amounts of carbon. Carbon also plays a central role in traditional energy supply. The liquid and gaseous energy sources used today, such as petrol or natural gas, are so powerful and user-friendly because they contain carbon.

On the other hand, carbon is a "problem substance" in the atmosphere once it reacts with oxygen in the form of carbon dioxide (CO_2), as it accounts for the largest share of the anthropogenic greenhouse gas effect and the climate change associated with that.

Even before the Paris climate summit, most of the world's states were striving to develop concepts and take measures to reduce greenhouse gas (GHG) emissions. In Paris in 2015, the aim was stated to reach the global peak of greenhouse gas emissions as soon as possible. In the second half of the century, a balance is to be achieved between greenhouse gas emissions and their reduction ("greenhouse gas neutrality"). This aim is intended to limit global warming to "well below" 2° C, in comparison with the pre-industrial era (with efforts to limit it to 1.5° C) (BMWi 2018a).

The German government already presented an energy concept in 2010 in which the reduction of GHG emissions by 80 to 95 % compared to 1990 is a declared target. Since then, numerous measures and implementation steps have been taken to move closer to the goal. Not least due to positive economic growth and the market logic of Europe-wide EU emissions trading, however, it has recently not proved possible to reduce GHG emissions in Germany. For example, the fifth monitoring report on the energy transition for 2015 shows a reduction in GHG emissions of 27.2 % compared with 1990. Since 2009, Germany's GHG emissions have remained at a constant level of around 900 million tonnes per annum – most recently with a slight upward trend. (BMWi 2018).

It is already clear that further efforts are needed to get onto the politically agreed GHG reduction path even when the economy develops positively. Different approaches are being discussed. There is agreement that the increased use of renewable energies and increase in energy efficiency are of central importance for the energy transition. Wind and sun are considered to be the energy sources with the greatest renewable potential.

On the other hand, the question arises as to whether the rate of expansion of **renewable energies** and the necessary upgrade of electricity grids can be sustained or even increased in view of land restrictions and possible acceptance limits.

The **efficiency of energy use** has improved in recent years. However, measures to further increase efficiency, such as accelerating building renovation rates, have recently failed.

The question also arises as to whether, for example, electric vehicles and electric heat pumps can be brought to market quickly enough. Until now, **consumers** have favoured other solutions. Other technologies such as PtL could be an important complement or alternative.

Despite the great importance of electricity, none of the numerous current energy transition studies assumes that the **complete conversion** of all uses of energy to electricity is possible. This is partly due to the limited potential for domestic electricity generation, but above all to the complex storability and transportability of electricity. The term "all-electrical society" that is sometimes used is therefore misleading, since questions regarding issues such as energy storage, the supply of energy for aircraft and other modes of transport or the material use of liquid raw materials for the production of various everyday products remain unanswered.

Potential alternative energy sources and raw materials for material use that are largely greenhouse gas-neutral may be renewable biomass or energy sources (PtL fuels) and raw materials (PtL raw materials) produced using electricity from renewable energies. In simplified terms, hydrogen from renewable generation is combined with carbon dioxide, e.g. from the air, to form a hydrocarbon that is greenhouse gas-neutral.

The German **mineral oil industry associations** commissioned Prognos AG to carry out an analysis of the status quo and the prospects of liquid energy sources and raw materials in the energy transition, in which the following **questions** are examined:

- What is the **significance of mineral oil today** as an energy source, raw material and economic factor for Germany, and what is the significance of liquid energy sources and raw materials in the individual consumer sectors in the long term? Where will they be difficult or impossible to replace?
- How can liquid energy sources and raw materials based on **biomass contribute** to reducing GHG emissions?
- What contribution can the existing **potential** of renewable energies for electricity generation in Germany make to reducing GHG emissions in the consumption sectors?
- Which **technological advances** and **costs** are achievable for the production of largely greenhouse gas-neutral liquid (and gaseous) energy sources and raw materials?
- What are the resulting **prospects** for liquid energy sources and raw materials if the level of development of renewable energies in Germany is lower than the level required?
- What are the **conclusions** for shaping climate protection policy resulting from the findings of the study?

2.2 METHODOLOGY

To answer these questions, this study was compiled by Prognos AG together with UMSICHT and the DBFZ. UMSICHT was responsible for the section on the technologies and costs of PtX production (see chapter 12), while the DBFZ was responsible for the findings in the field of biomass (see chapter 11).

An advisory group from the clients discussed the results with the authors of the study. In addition, interviews were conducted with experts from two German refinery sites.

In the course of the study, the **technology paths** "Power-to-X" (PtX with focus on synthetic liquid energy sources), "Biomass" (potentials and costs) and "Technologies of electrification" (with a focus on wind/sun potential in Germany) were developed. The results were published in an interim report (Prognos AG, DBFZ, UMSICHT 2017) and are documented in more detail in a separate section (B, chapters 10 to 12).

In the second phase of the study, **scenarios** for Germany's future energy and raw material supply were developed. The design of these scenarios is described in chapter 4.1.

The study will be published shortly following the publication of the "Climate Paths for Germany" study, which Prognos and Boston Consulting Group prepared on behalf of the BDI (BCG, Prognos 2018). Since a reference scenario was developed in the BDI study, the present study was able to build on this.

The "PtX 80" and "PtX 95" scenarios were developed independently of the BDI study by Prognos AG for the purposes of this study; for more on this, see chapter 4.

STUDY SECTION A:
SCENARIOS FOR GERMANY'S ENERGY SUPPLY UP TO 2050

3

THE SIGNIFICANCE OF MINERAL OILS FOR THE GERMAN SUPPLY OF ENERGY AND RAW MATERIALS TODAY

Germany's energy and raw materials supply is ensured by a broad energy mix. Mineral oil is one of the most important energy sources and raw material suppliers for the energy system and industry in Germany.

3.1 THE SIGNIFICANCE OF MINERAL OIL FOR THE SUPPLY OF ENERGY

As figure 3 (left) shows, with 4,567 PJ of an overall 13,451 PJ in 2016, mineral oil is the most important energy source in the primary energy supply in Germany and covers around one third of primary energy demand. This share has remained almost unchanged over the last ten years.

Mineral oil is used to produce a variety of energy sources (fuels and combustibles) and raw materials (chemical raw materials, lubricants, building materials, etc.). Figure 3 (middle) shows the annual sales of these mineral oil products in Germany, of around 110 million tonnes in 2016, by application: Around 61 % of sales are in the form of fuels for transport (37.8 % for cars and light commercial vehicles, 13.8 % for heavy goods vehicles/trucks and 9.3 % for air transport and shipping). 16.6 % of sales are in the form of heating oil for heat applications and a further 22.5 % of sales are used for materials (including chemical raw materials; see the paragraph below).

An assessment of the final energy balance also shows the importance of mineral oil in the energy supply. Of Germany's final energy demand of 8,877 PJ in 2015, 37 % was covered by liquid energy sources. Figure 3 (right) shows the distribution of these 3315 PJ produced from petroleum products between the sectors of transport (TRA, 74 %), industry (IND, 2 %), households (HH, 15 %) and commerce, trade and services (CTS, 9 %).

It is clear that mineral oil plays a central role in the transport sector. Around three quarters of the final energy consumption of mineral oil products goes to the transport sector. The transport sector in turn covers approx. 99 % of its energy requirements through liquid energy sources (primarily mineral oil products).

3.2 THE SIGNIFICANCE OF MINERAL OIL FOR THE SUPPLY OF RAW MATERIALS (NON-ENERGY RELATED CONSUMPTION)

Figure 3 shows that 22.5 % of mineral oil product sales in 2016 are for material use. This proportion of mineral oil use forms the basis for a large number of raw materials and supplies that form the basis or elementary component of a multitude of industrial value chains.

About 6 % of material use is direct. This figure includes petroleum coke (electrode and steel production, fuel, etc.), bitumen (construction industry: road construction, structural and civil engineering, sealing materials, etc.), industrial and mineral spirits (solvents and thinners, etc.), paraffins (fuel, seals, pharmaceuticals, cosmetics, preservation, etc.), waxes (candles, shoe polish, etc.), vaseline (cosmetics, pharmaceuticals, lubricants, corrosion protection, grease, etc.).

Figure 3: Use of mineral oil in Germany 2016

Primary energy consumption 13,451 PJ in 2016, 4,567 PJ of which from mineral oil

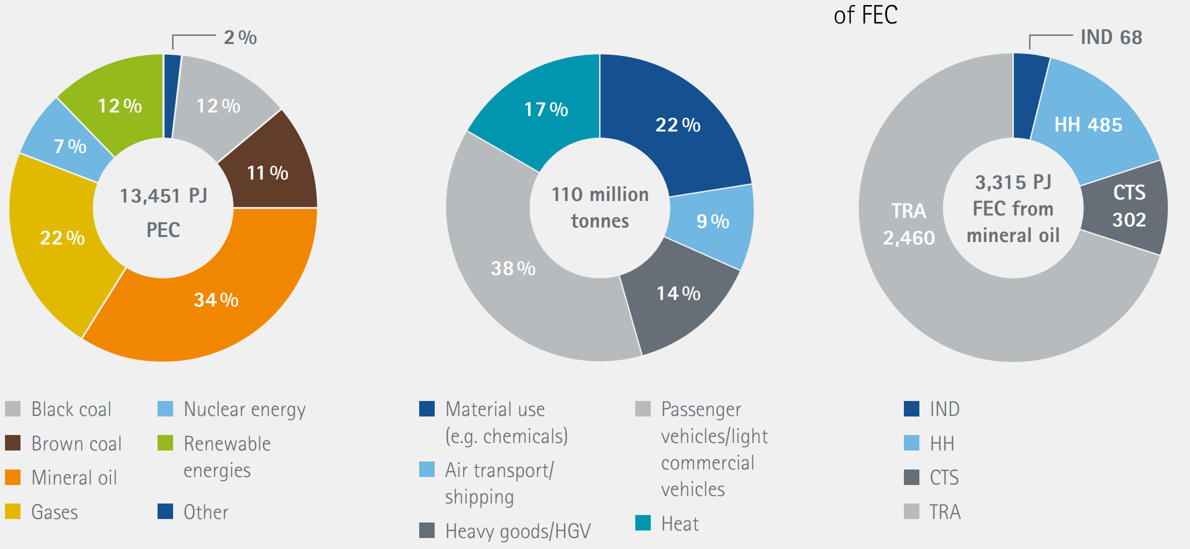
Liquid energy sources and raw materials cover around 34 % of PEC

Sales of 110 million tonnes in 2016

61 % of liquid energy sources and raw materials are used in transport

Final energy consumption of 8,877 PJ in 2015

Liquid energy sources and raw materials cover around 37 % of FEC



Left: primary energy consumption in Germany in 2016 (source: (AGEB, AG Energiebilanzen e.V. 2017)). Centre: sales of mineral oil products by application (source: (MWV 2017)). Right: final energy consumption (source: (AG Energiebilanzen e.V. 2017)). Abbreviations CTS, HH, IND, TRA: Commerce/ trade/services, households, industry and transport consumption sectors.

About 16 % of material use is in the chemicals industry. Figure 4 shows the raw material base of and ramifications for the chemical industry: A small number of raw materials are converted via a small number of basic chemicals and intermediary chemicals into a large number of end consumer products. The end products for everyday use, such as the fibres in a garment, a plastic bottle or a headache tablet, often no longer show any reference to crude oil (see (Petrochemicals Europe 2017)).

Organic chemistry is the **carbon-based** chemistry sector and the main user of mineral oil as a raw material. Approx. 75 % of the organic raw material base of the chemicals industry is covered by mineral oil (VCI 2017), and a large part of that is from naphtha.

In the energy balance, material use appears as non-energy consumption (NEC). This is the quantity of separately reported non-energy sources and the proportion of energy sources not used for energy purposes (e.g. as raw materials for chemical processes). Renewable raw materials are not included in the non-energy consumption in the energy balances.

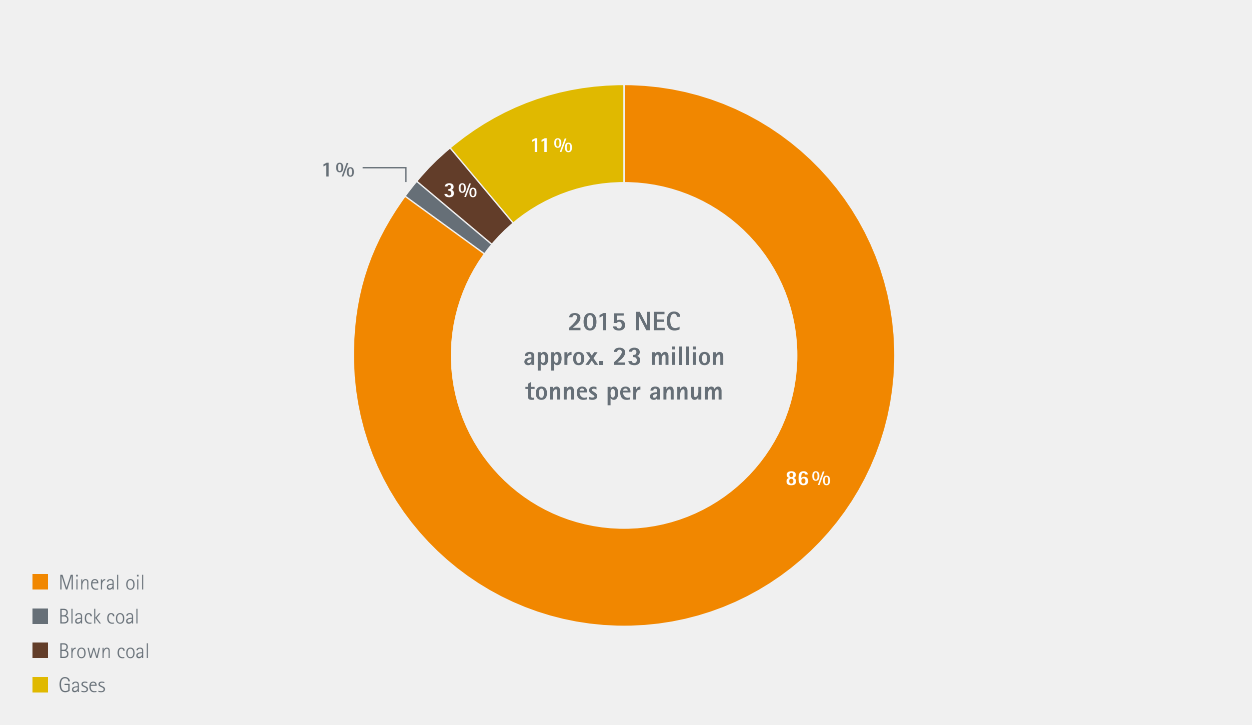
Figure 5 shows the NEC of the 2015 energy balance. It shows that the 23 million tonnes of raw materials involve carbon suppliers and an approximate carbon balance based on typical carbon content results in 19 million tonnes of carbon. With 86 % of the 23 million tons of raw materials in 2015, mineral oil covers around 89 % of the carbon content of non-energy consumption in the energy balance.

Mineral oil thus currently forms a large part of the raw material base of many industrial value chains (see also sections 5.3.2, 6 and 13).

Figure 4: Raw material base in the chemicals industry

Source: own figure based on (VCI 2017) and (Jess and Wasserscheid 2013)

Figure 5: Non-energy-related consumption in the 2016 energy balance for Germany



Source: AG Energiebilanzen e.V. 2017, researcher's own diagram (mineral oil products in summary)

4

SCENARIO DESIGN AND DEFINITION OF FRAMEWORK CONDITIONS

4.1 SUMMARY AND CENTRAL ASSUMPTIONS

Scenario theory

Scenarios are the preferred method for representing potential future developments under different conditions. Since no one can predict the future with certainty, futurologists depend on making assumptions so that they can determine the consequences of these assumptions on future developments. Scenarios are therefore always "if-then" statements that bring causes and effects into a causal relationship.

Forecasts in the narrower sense are a special form of scenario. As a rule, they are intended to describe a future development that is as likely as possible. Forecasts are also sometimes referred to as "best-guess" scenarios.

To classify the present work, the different **types of scenarios** are described below. Their presentation does not claim to be complete. As figure 6 shows, the individual scenario types serve different purposes.

Scientific forward-looking statements are divided into indicative and normative scenarios:

- **Indicative forward-looking statements** describe possible future developments based on the assumptions made. This process involves testing the effects of instruments, policy approaches, technology paths or market designs. As a rule, these scenarios are open-ended, i.e. the achievement of targets is not assumed, especially if they are not yet legally binding.

  Possible subtypes of indicative scenarios include, for example, **reference scenarios** in which the current policy approaches or levels of intervention are extrapolated along with their consequences for the future. Reference scenarios often show the continuation of trends, i.e. the consequences of "continuing as before".

  Explorative scenarios attempt to investigate the consequences of certain assumptions, such as the introduction of a new policy instrument or technical developments. Explorative scenarios: "What happens if…".

- **Target scenarios** must be distinguished from the indicative scenarios. The question here is what measures, instruments or policies are to be used to achieve certain objectives. In these scenarios, the achievement of political goals, such as those resulting from the Paris Climate Conference (COP 21), is assumed. It is assumed that obstacles and difficulties will be overcome.

Actual developments will differ from the scenario results. Examples of causes of such deviations may be:

- Technological breakthroughs, such as the cost degression of photovoltaics, offshore wind energy and power-to-x
- New applications, such as mobile phones
- Political upheavals, such as German reunification or the phasing out of nuclear energy
- Economic shocks, such as the financial and economic crisis in 2009

Figure 6: Overview of scenario types

Scientific forward-looking statements

Indicative scenarios

Reference scenarios
"What happens if we continue as before..."

- Current efforts (policy approaches up to now) are continued, obstacles in the implementation are assumed
- The achievement of targets and optimisation are not specified
- Purpose: reference value for target scenarios

Explorative scenarios
"What happens if..."

- Measures or policy approaches are examined with regard to their target effect
- The achievement of targets and optimisation are not specified
- Purpose: Identifying consequences, playing through solutions

Normative scenarios

Target scenarios
"What has to happen so that..."

- Specific goals are specified
- Measures and instruments are assumed to achieve the objectives
- It is assumed that obstacles are overcome
- Purpose: planning basis for decisions, determining the need for action

Source: own figure

As a rule, these factors cannot be predicted or can only be predicted to a very limited extent. However, it is possible to analyse deviating developments with the aid of **sensitivity analyses**. These analyses describe a corridor of potential divergent developments "around the expected result" of the selected scenario. This study also looks at sensitivities around expected results (for example, see chapter 11.3 or 12.2).

Choice of scenarios for this study

The scenario approach of this study can be characterised as a hybrid of the "reference", "explorative" and "target scenario" types.

The starting point of the study is the **reference scenario**. It is assumed that the trends and technologies of recent years will be continued. The reference scenario is described in detail in the study "Climate Paths for Germany" by BCG and Prognos. Among other things, this scenario assumes effective carbon leakage protection for industry, which exempts industry from direct and indirect CO_2-related additional costs from the European Emissions Trading System (EU ETS) that exceed the current level (BCG, Prognos 2018). Several measures are already associated with additional costs in the reference scenario (e.g. energy transition upgrades in the electricity system). For the **PtX 80 and PtX 95** scenarios, it was observed that the expansion of renewable energies in some German federal states is subject to stringent area restrictions. In addition, according to the fifth monitoring report on the energy transition, energy productivity increased by 1.3 % per year between 2008 and 2015, which is below the target value of the energy concept of 2.1 % per year (BMWi 2016).

The PtX 80 and PtX 95 scenarios in this study assume that this development will continue. As a result, efficiency increases **as described in the reference scenario** and the expansion of renewable energies reaches its limits.

Nevertheless, the objective of the study was to achieve the greenhouse gas reduction **targets** from the German government's energy concept (80 % to 95 %).

However, the security of energy supply, which is particularly important for an industrialised country such as Germany,

Table 1: Characterisation and parametrisation in the scenarios (input)

Parameter	Status 2015	Reference 2050	PtX 80 2050	PtX 95 2050
Climate protection in Europe/World		Business as usual	steady development	ambitious development
Energy prices Crude oil world market ($2015/bbl)	51	115	115	50
GHG emissions Germany based on 1990		Model result (-60 %)	-80 %	-95 %
Energy productivity energy consumption per unit GDP (MJ/€2015)	6.1	2.2	~ as in reference	~ as in reference
Renewable energies installed capacity [GW] – Input Electricity generation [TWh] – Model result	90 178	224 475	230 513	230 506
Electrification – Share of electric heat pumps in heating – Share of electric vehicles – Final energy demand electricity	3.8 % ~ 0 % 515 TWh	14 % 33 % 525 TWh	as in reference as in reference	as in reference as in reference
Use of PtX		No	Yes	Yes
Use of CCS (e.g. industry)		No	No	Yes

Source: Prognos AG

was not discussed in the scenarios. There was no economic cost optimisation. Rather, the costs were assessed from the consumer's perspective.

In this study, the climate protection targets are achieved through a mix of technology. On the one hand, electricity generation from renewable energies in Germany triples, significantly improving the CO_2 balance of the electricity sector. On the other hand, synthetic liquids and gases are used, which in turn achieve significant GHG reductions in the other consumption sectors. The existing infrastructure (e.g. tank infrastructure, networks) and applications for consumers (e.g. vehicles, heating systems) can still be used in this case. Particularly abroad, PtL energy sources and PtL raw materials are produced with electricity from renewable energies.

Put simply, the scenarios in this study describe how GHG savings targets can be achieved in Germany with the help of greenhouse gas-neutral PtX fuels, irrespective of hurdles regarding their acceptance.

Setting assumptions in the scenarios

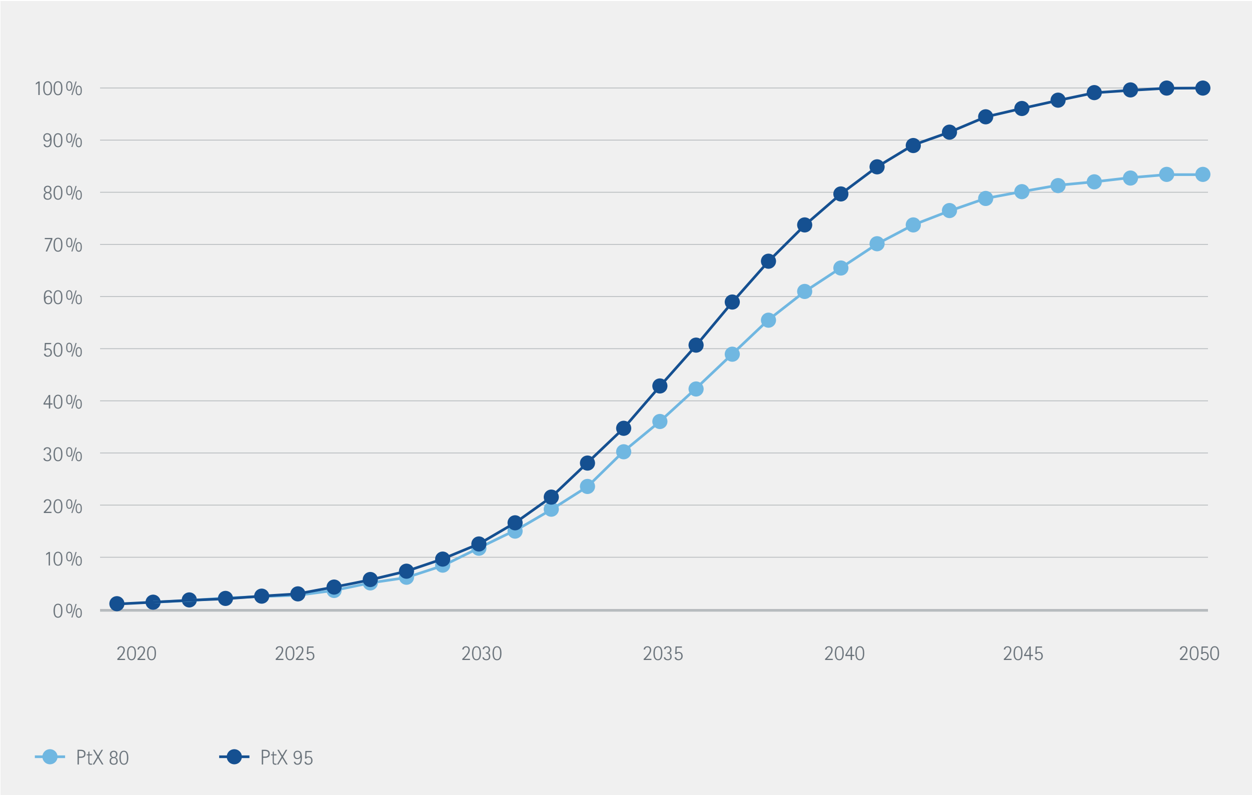
The main assertions and assumptions are briefly explained below. That the assumptions in this study were made in this way reflects the "explorative" nature of the study. There is no statement on the probability or desirability of these assumptions in this regard.

Assumption 1: Climate protection is coordinated at an international level

In all scenarios, we assume that the level of ambition regarding climate protection in Germany is in line with that of the EU and beyond.

No separate scenarios for GHG emissions from other countries were prepared. However, the assumption has an impact, for example, on energy prices and PtX demand. In the PtX 80 and PtX 95 scenarios, we assume that there will also be a growing demand for PtX throughout Europe (at minimum), allowing for learning curves in the relevant technologies.

Figure 7: Blending proportions for synthetic energy sources in the PtX 80 and PtX 95 scenarios



Note: These blending proportions were applied for oil and gas

Assumption 2: Lower energy prices in the case of ambitious climate protection

The reference scenario and PtX 80 assume that the prices of fossil fuels will rise again due to rising international demand. We base this assumption on the New Policies Scenario from the World Energy Outlook 2016 of the International Energy Agency.

In the PtX 95 scenario it was assumed that the demand for fossil fuels would decrease significantly and that the long-term market balance would gradually shift towards lower prices.

Assumption 3: GHG emissions in Germany are being reduced

GHG emissions in the reference scenario were calculated as a model result. The reference scenario is identical to that of the BDI study (BCG, Prognos 2018).

The central premise of the climate protection scenarios in this study is that GHG emissions in Germany must be reduced by 80% and 95% compared with 1990 by 2050. In this respect, the PtX 80 and PtX 95 scenarios are target scenarios. The achievement of the GHG targets in the interim years 2030 and 2040 was not a guideline in the design of the scenarios and has not been considered in the study.

Assumption 4: The increase in efficiency of energy use follows the historical trends

The reference scenario assumes that only economically practical investments in efficiency measures are made in all sectors (private households, commerce, trade and services, transport and industry). It is assumed that the pace of refurbishment will remain the same for existing buildings. These assumptions were used as a basis in all three scenarios.

Assumption 5: Area restrictions for renewable energies

It is assumed that growth limits for domestic expansion will be reached in the forecast period for renewable energies that rely most heavily on land areas. These potentials are assessed separately in chapter 10.1. Due to the wide range of potential, the calculation of the scenarios was based on the simplified assumption that the installed capacity of renewable energies in the PtX 80 and PtX 95 target scenarios in 2050 is identical to the reference scenario. However, the course of events up to 2050 differs between the scenarios.

Assumption 6: Electrification continues to make progress

It is assumed that electrification among consumers will progress in all scenarios as in the reference scenario. For example, the share of electric heat pumps in the heating of living space increases from around 4% (2015) to 14% (2050). The number of electric vehicles also increases: in 2050, we are assuming 14 million electrically powered cars, 5 million of which are plug-in hybrids. This means that in 2050, 20% of cars will be powered purely electrically.

Assumption 7: CCS is used in selected applications

Despite the current political moratorium on the development of CCS (capture and long-term storage of carbon dioxide), from today's perspective CCS is an option that is almost without alternatives for certain industrial applications (e.g. blast furnace gas in steel production). To meet the material demand for long-chain products such as bitumen, refineries sometimes still have to process fossil crude oil. Therefore, CCS would also have to be used here to capture the resulting residual emissions.

Assumption 8: PtX is a central solution in this study

PtL and PtG are used to achieve the GHG reduction targets. The technologies are developed and used throughout Europe (at minimum). This results in learning effects that lead to a reduction in costs. This presupposes that investors are prepared to erect the corresponding plants and have enough space available to erect wind and solar power plants as well as the plants for PtX production. Liquid energy sources become more climate-friendly through the addition of PtL and gaseous energy sources through the addition of PtG. The proportions are the same for liquids and gases. The proportions are set so that the climate targets in the respective scenarios (PtX 80 and PtX 95) are achieved in 2050 (see figure 7).

Assumption 9: MENA and Kazakhstan are the search area for PtX production

The search area for PtX production was limited to a radius of around 5,000 km around the EU. The focus of the literature-based potential analysis was on North Africa (in the MENA states "Middle East and North Africa") and Kazakhstan. This search area contains large areas with high quantities of solar radiation and also very good wind conditions in places. In addition, some countries in this region have an oil and gas infrastructure that can be used for PtX logistics if necessary. A comprehensive worldwide analysis of locations and potential was not carried out within the scope of this study.

Assumption 10: Capital costs of 2% and 7% are assumed

In economic assessments, the assumed discounting interest rate plays an important role. In this study, the weighted average cost of capital (WACC) was used for this purpose. Since the results are in most cases quite sensitive to the assumed value, two interest rates are assumed for reasons of comparability, and are also used in current comparative studies (BCG, Prognos 2018): On the one hand an economic interest rate of 2% is assumed and, on the other hand an interest rate of 7%, which reflects a higher investment risk, especially with private investments abroad. However, interest rates deviating from these rates are also used on a selective basis, such as in chapters 8.2 and 5.2. This is due to other investment environments where financing conditions differ. For example, chapter 8 looks at investments made in the private household sector.

The assumptions used here are primarily for comparison and do not reflect values based on surveys. In the North African search area in particular, high capital costs should be expected in the short term due to the high investment risk.

4.2 ENERGY PRICES

The key guide variables for energy consumption are gross domestic product (GDP), gross value added (GVA), number of persons employed, population, number of households and living space. As a basic principle, identical basic data is used for all three scenarios, with the exception of fuel prices for fossil fuels and CO_2 prices for electricity generation. In the scenario with ambitious global climate protection (PtX 95), lower global prices for fossil fuels are assumed. The reason for this is the lower demand for fossil fuels. On the one hand, this decline in demand compared to the reference leads to the use and, if necessary, the redevelopment of low-cost raw material sources; on the other hand, due to increasing overcapacities in production, there is strong competition among suppliers, which in turn means the goods are brought to market at marginal costs.

Price development of fossil energy sources

Table 2 shows the **price assumptions for fossil energy sources** on the international markets. The real prices adjusted for inflation are shown with the price basis for 2015.

Table 2: International energy prices in the scenarios from 2015–2050, actual prices in $$_{2015}$

	Reference / PtX 80					PtX 95				
	2015	2020	2030	2040	2050	2015	2020	2030	2040	2050
Crude oil ($ 2015/bbl)	51	79	111	120	115	51	70	80	70	50
Natural gas ($ 2015/Mbtu)	7.0	7.1	10.3	11.3	11.6	7.0	6.9	9.2	9.7	9.1
Steam coal ($ 2015/t 6,000 kcal)	57	63	74	74	71	57	56	54	46	33
CO_2 ($ 2015/t)	8	12	33	45	55	8	20	80	140	150

Source: Prognos, for reference/PtX 80 based on the New Policies Scenario from World Energy Outlook 2016; for PtX 95 from BDI study "Climate Paths for Germany", based on the "450 ppm" scenario from the World Energy Outlook 2016* Note: The CO_2 price applies only to the ETS sector. The introduction of a price instrument in other sectors was not assumed.

Table 3: Inflation and exchange rate development 2015–2050

		2015	2020	2030	2040	2050
Inflation Germany	Index, 2015 = 100	100.0	107.8	132.5	165.0	203.1
Inflation USA	Index, 2015 = 100	100.0	108.6	141.4	182.8	234.0
Exchange rate $/€	$ nominal	1.08	1.22	1.35	1.37	1.39

Source: Prognos AG, World Report

It is to be assumed that these international prices will also define German import prices due to the small raw material base or lack of raw material base in Germany. The (nominal) exchange rate between $ and € shown in table 3 and the corresponding inflation trend in the two economic areas were used to derive the German import prices.

Taking into account exchange rate and inflation trends, the **cross-border prices** for the fossil fuels crude oil, natural gas (upper calorific value) and hard coal shown in figure 8 were derived for the calculations in the scenarios. To facilitate a direct price comparison, the prices of the energy sources are uniformly listed in € per megawatt hour. A table showing the border-crossing prices is also attached (tables 48 and 49).

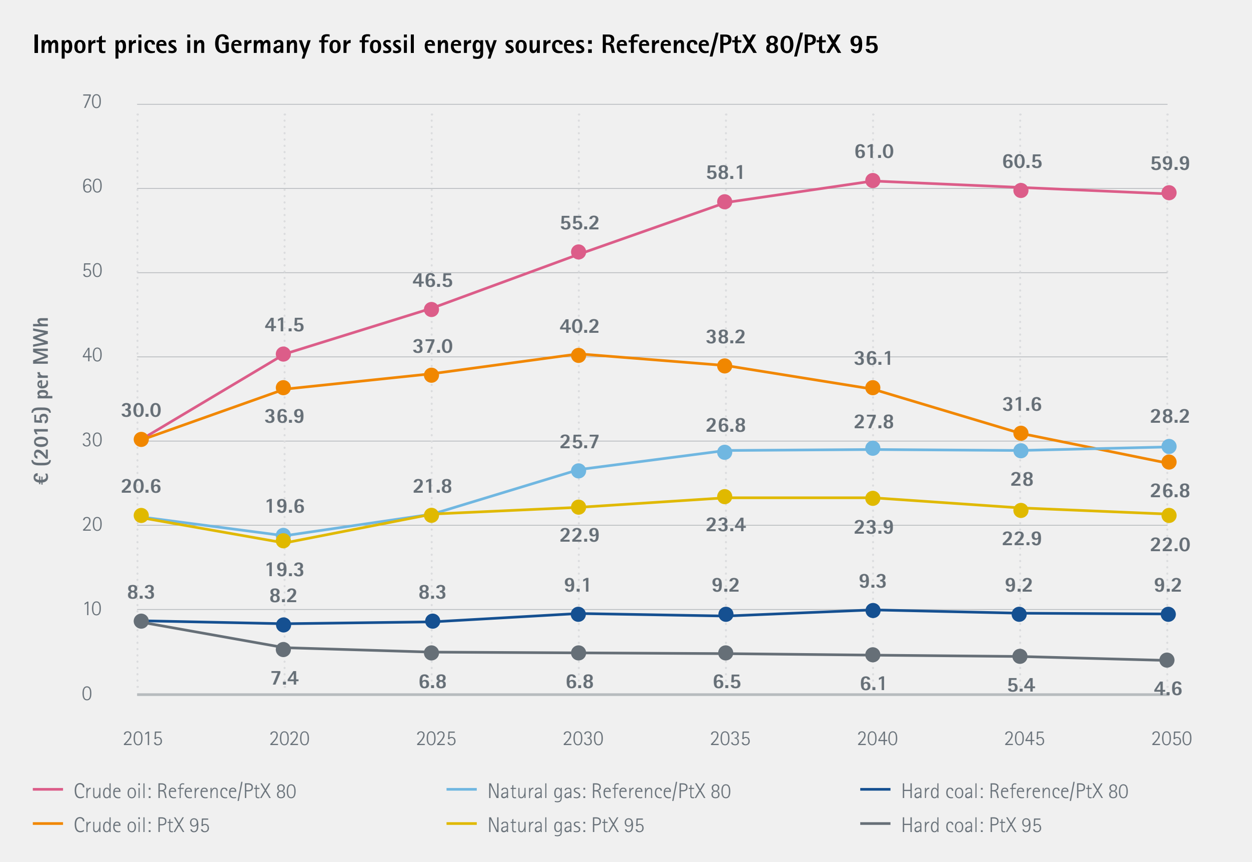
These border-crossing prices (import prices) form the starting points for the subsequent derivation and differentiation of end consumer prices and prices for gas and coal in electricity generation.

As the first step in deriving the **consumer prices**, the processing costs are taken into account in addition to the import prices. They are not required for natural gas and hard coal, which are used without additional processing. In the case of crude oil, they are determined on the basis of the energy required to separate and process the products in the refinery.

Since the costs within a refinery cannot be clearly allocated to the individual refinery products, 5 % of the crude oil is consistently assumed as a loss for all the products and therefore as a surcharge on the crude oil import price.

In the second step, the transport, storage and distribution costs for the individual products and the margins of the processors, dealers and transporters are taken into account. Their levels are derived as mean values for each specific product from historical price analyses and extrapolated for the future as real constant price components.

Figure 8: Cross-border prices of fossil fuel energy sources in Germany from 2015–2050 in the reference, PtX 80 and PtX 95 scenarios, in $€_{2015}$ per MWh



Source: Prognos AG

In the last step, state price surcharges in the form of energy taxes and value-added tax are added. For the scenarios, no changes to the current taxation are assumed for exclusively fossil-based energy sources. The current energy tax rates, which have remained unchanged for many years, have therefore been continued at a constant nominal rate of 19 percent. It should be noted that the nominal continuation will make the energy tax less significant in the future.

The **result** of these derivations for the reference scenario and the PtX 80 scenario are the **end consumer prices** for heating oil and natural gas for heat generation in households and for petrol (gasoline) and diesel for private cars shown in figure 9. Figure 10 shows the corresponding price developments for the PtX 95 scenario.

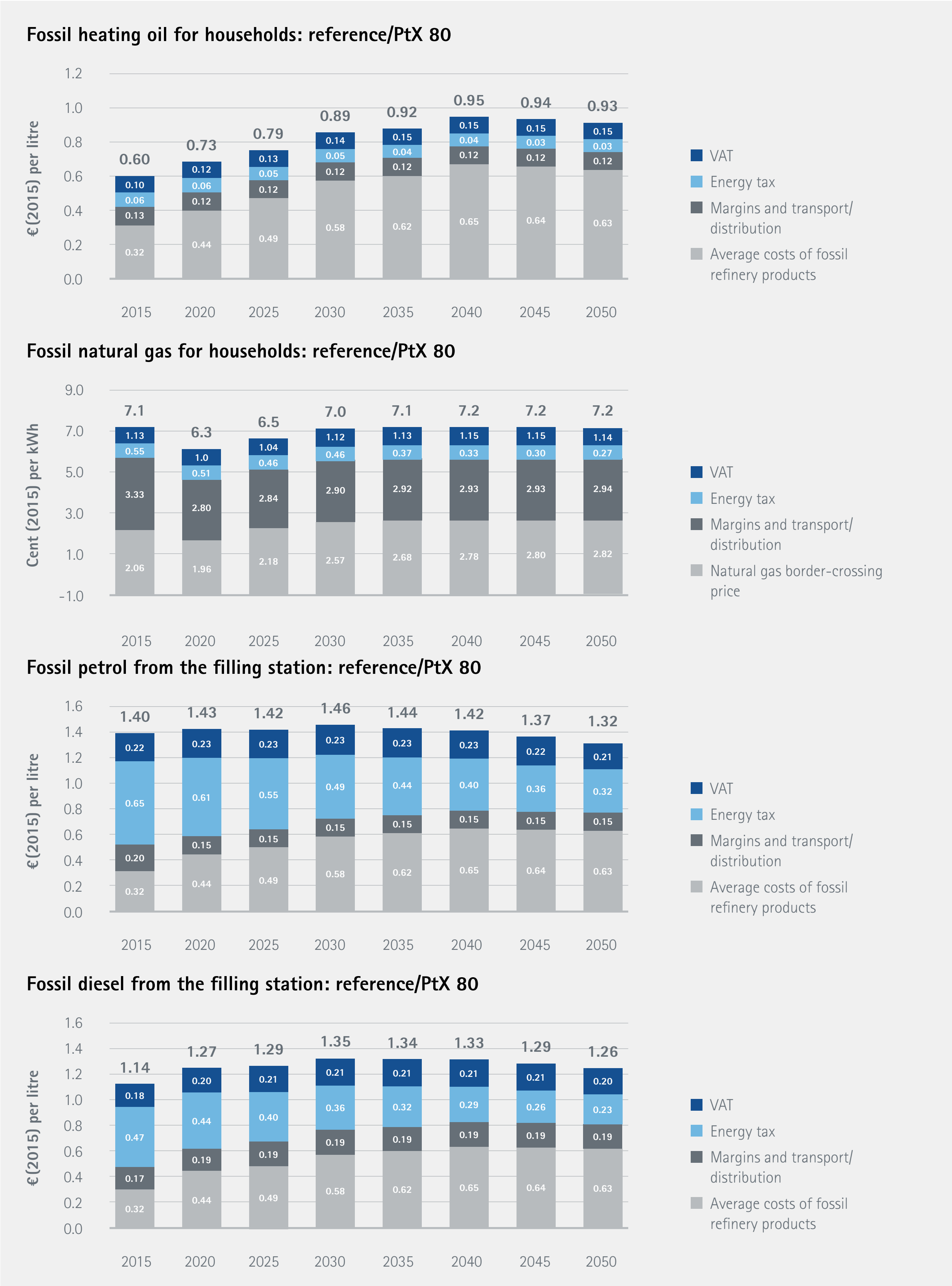
Assumptions for PtX cost development

The analyses in study section B show the generation potential and the costs associated with its development for the production of PtX. The future costs are based on the assumption of large-scale expansion and the resulting potential progress in efficiency and cost degression, as well as the development of optimal locations. Figure 11 shows the possible cost developments for PtL and PtG. On the one hand, a higher price path is shown that considers a slower increase in electrolysis efficiency and a choice of location that is not always optimal for electricity generation from renewable energies (see chapter 10.2). The low price path assumes a better level of electrolysis efficiency and optimal location conditions for electricity generation (see chapters 10.2 and 12.2).

The first figure for 2015 is based on the (small) plants available at that time and on the average electricity costs from renewable energies in Germany at that time and is therefore not directly comparable with future costs. From 2020, significantly lower electricity costs for the production of PtX in new wind and solar parks at favourable foreign locations are applied. It is assumed that any delays that may occur in the first few years can be offset by greater expansion in subsequent years.

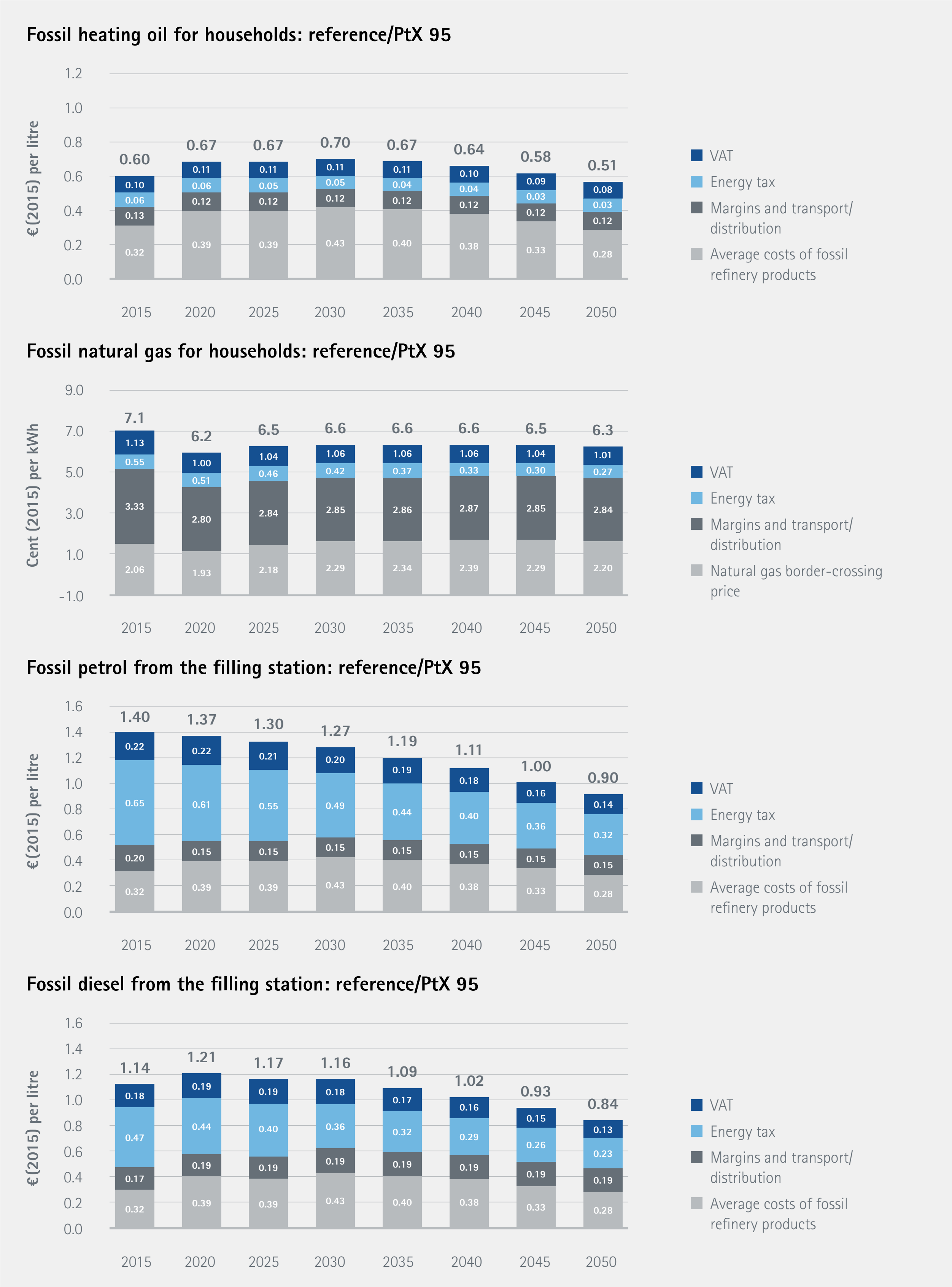
In addition to the production costs of PtX at international

Figure 9: End consumer prices for fossil fuel energy sources in Germany in the reference and PtX 80 scenarios; real prices from 2015–2050 in cent$_{2015}$ per kWh (natural gas) and €$_{2015}$ per litre



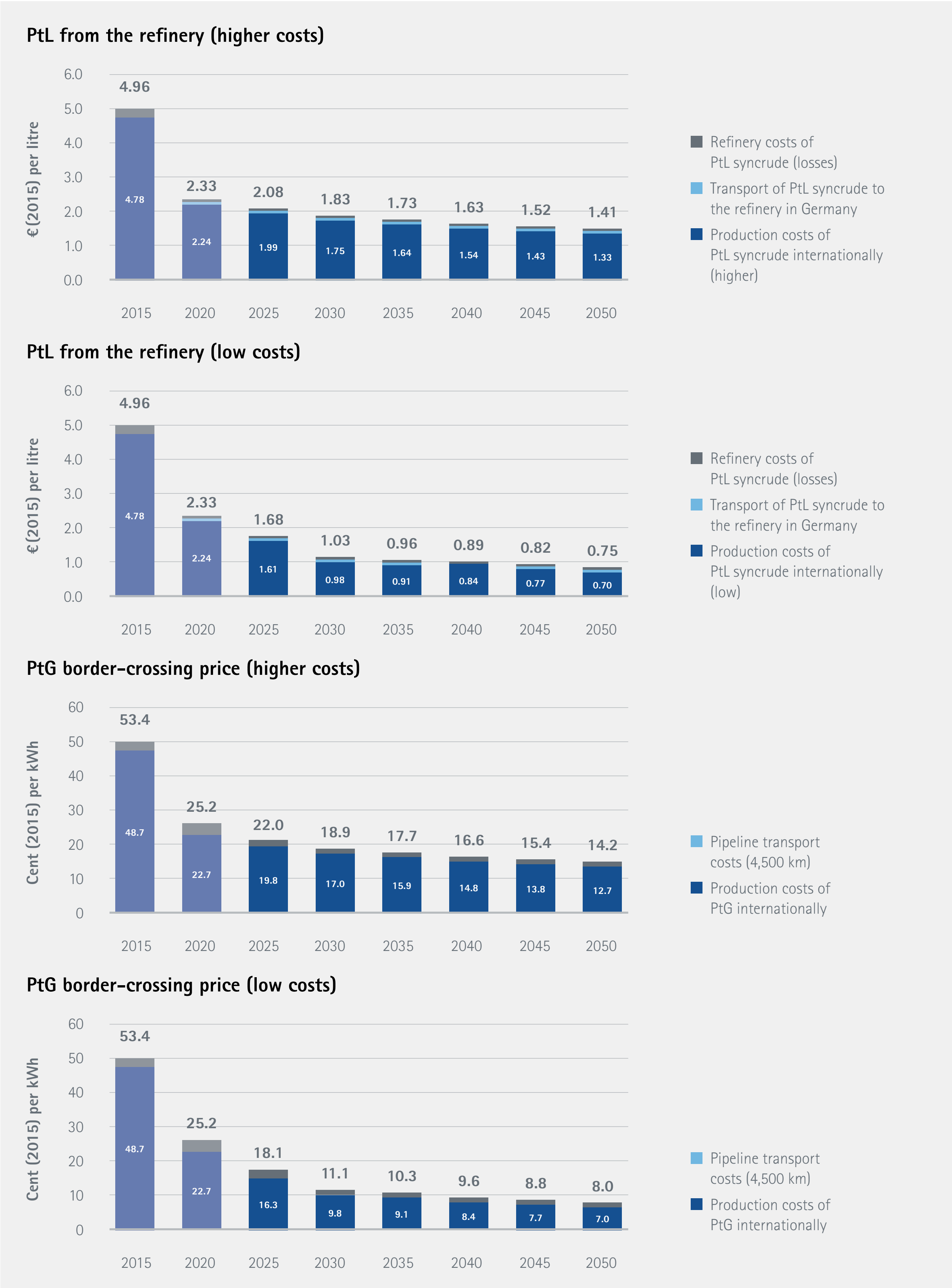
Source: Prognos AG

Figure 10: End consumer prices for fossil fuel energy sources in Germany in the PtX 95 scenario; real prices from 2015–2050 in $cent_{2015}$ per kWh (natural gas) and $€_{2015}$ per litre



Source: Prognos AG

Figure 11: Costs for PtL from the refinery and PtG from the border in Germany in two price paths; real prices from 2015 to 2050 in $cent_{2015}$ per kWh (natural gas) and $€_{2015}$ per litre



Source: Prognos AG

locations, transport costs and, for PtL, processing costs at the refinery are also incurred for the supply of Germany. For the transport costs, assertions had to be made which in reality—depending on the international production site—may differ, but which are not relevant to the result, especially for PtL. The costs for the pipeline transport of PtG were estimated on the basis of corresponding losses and other costs (pipeline losses, additional gas and other costs for compressors, etc.) for the transport of natural gas in the Eastern European pipeline network for a transport distance of 4,500 km.

The costs of transporting unrefined PtL syncrude to Germany by tanker were assumed at a flat rate of 3 % of the costs of the refinery operation (mixture of crude oil and unrefined PtL). As in the case of crude oil processing, the processing costs in the refinery are applied as a lump sum as a proportion of the PtL used. According to the refinery operators, refining losses of 3.5 % are, however, lower than the losses in fossil crude oil. Therefore, 3.5 % of the international PtL production costs are assumed as costs for preparation (see chapter 13).

Price development for mixed PtX/fossil products

The prices for the mixed products from PtL and oil products (heating oil, petrol, diesel) or from PtG and natural gas that are used in final consumption are derived from the prices of the respective mixture components. It is assumed that the energy tax for the mixtures will be levied to the same extent as for exclusively fossil end products. The same applies to the assumed transport and distribution costs, margins and VAT.

The price developments for mixed products in the PtX 80 scenario (higher costs) that are shown in figure 12 are based on the end consumer prices shown in figure 9 for fossil energy sources in the reference and PtX 80 scenarios, the blending proportions for PtX for the fossil energy sources in the PtX 80 scenario and the higher costs for PtX from figure 11.

Figure 13 shows the price developments for the mixed products, provided that the optimum conditions for the cost-effective international provision of PtX can be achieved in the PtX 80 scenario (low costs).

In the PtX 95 scenario, the consumer prices for fossil energy sources are significantly lower in the long term than in the PtX 80 scenario due to the lower international prices. As a result, the end consumer prices for the mixed products are also lower than in the PtX 80 scenario—while the price developments for PtX remain constant. Figure 14 below shows the development of mixed prices for end consumers based on the low fossil energy prices from the PtX 95 scenario, with higher production costs for PtX. Figure 15 shows the corresponding price development with low PtX costs.

4.3 DEMOGRAPHICS AND LIVING

Population and households

Population trends are usually described by **population size** and **age distribution**. Population size is the main factor in our models. The effects of ageing on energy consumption are low [see (Prognos AG 2014)]. However, what has not yet been investigated are the effects of an ageing population on the willingness to make alterations in buildings or to change heating systems.

With a birth rate of around 1.4 children per woman, a further increase in life expectancy and a net influx of an average of 200,000 people per year, the **population** in Germany will continue to **age**. The proportion of over 65 year-olds increases from 21 % today to 30 % (13th coordinated population forecast by the German Federal Statistical Office (2015), variant 2). In the assessed period, the population in Germany not only grows older but also shrinks (table 4). In the medium term, the number of inhabitants increases from 80.7 million in 2000 to 82.1 million in 2020. By 2050, however, the population falls to 76.6 million (-5 % compared to 2000).

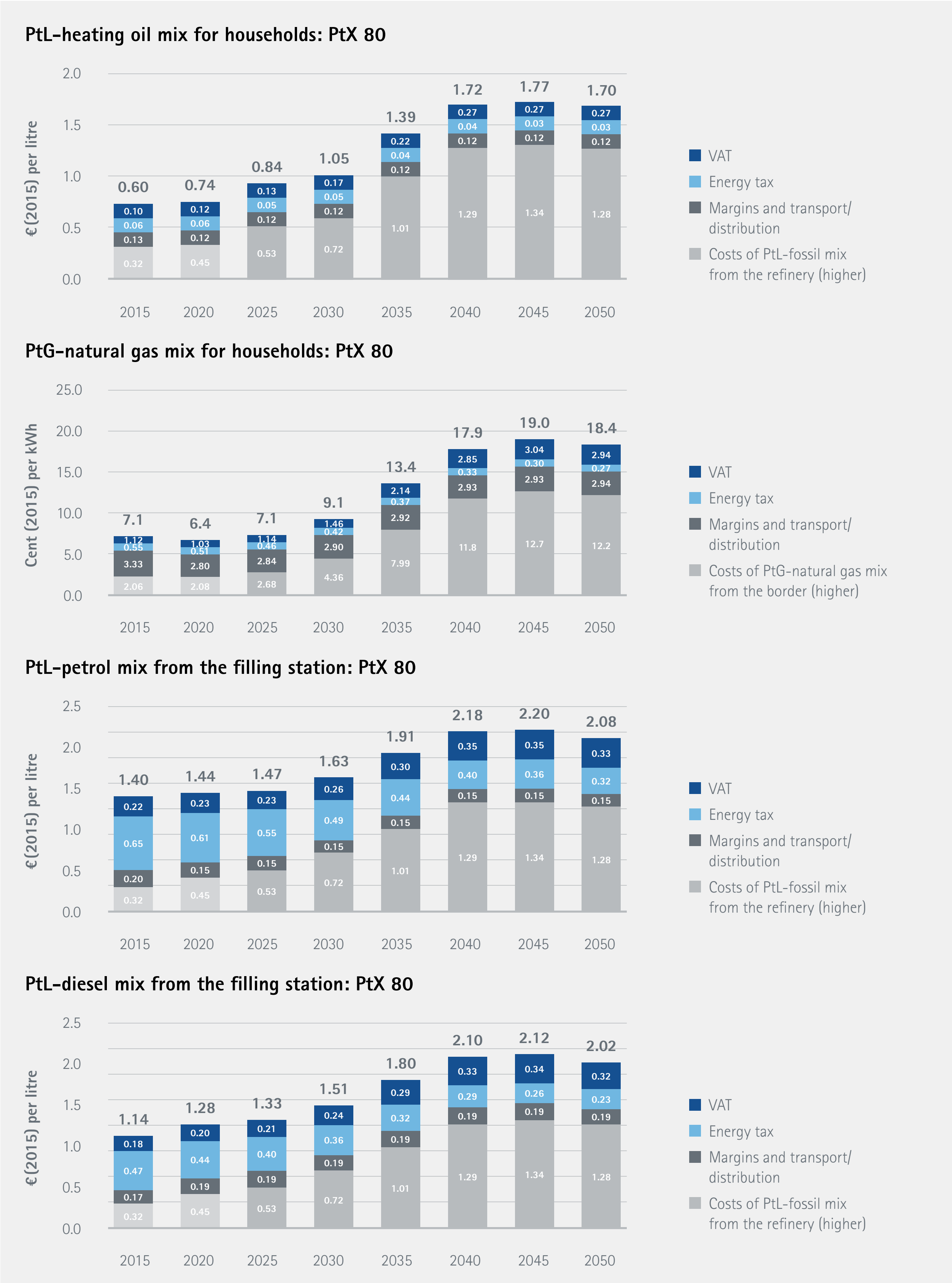
Despite the shrinking population, the number of private **households** initially increases. It rises from 37.1 million in 2000 to 42.3 million in 2035. The reason for this is the continued decline in the average household size. After 2035, the continuing population decline leads to a reduction in the number of households with only a slight decline in the size of households. In 2050, it is 41.4 million, and therefore around 11.5 % more than in 2000.

Living space and heating structure

The number of **dwellings** is linked to the number of households; in general, each household has a dwelling. In line with the number of households, the number of (inhabited) dwellings also rises until 2035 and then declines. However, the total living space continues to increase until 2050 and rises to around 4,223 million m^2 (table 5). That is 23 % more than in 2000. The reasons for this include rising per capita income and smaller households. Both factors increase land consumption per capita.

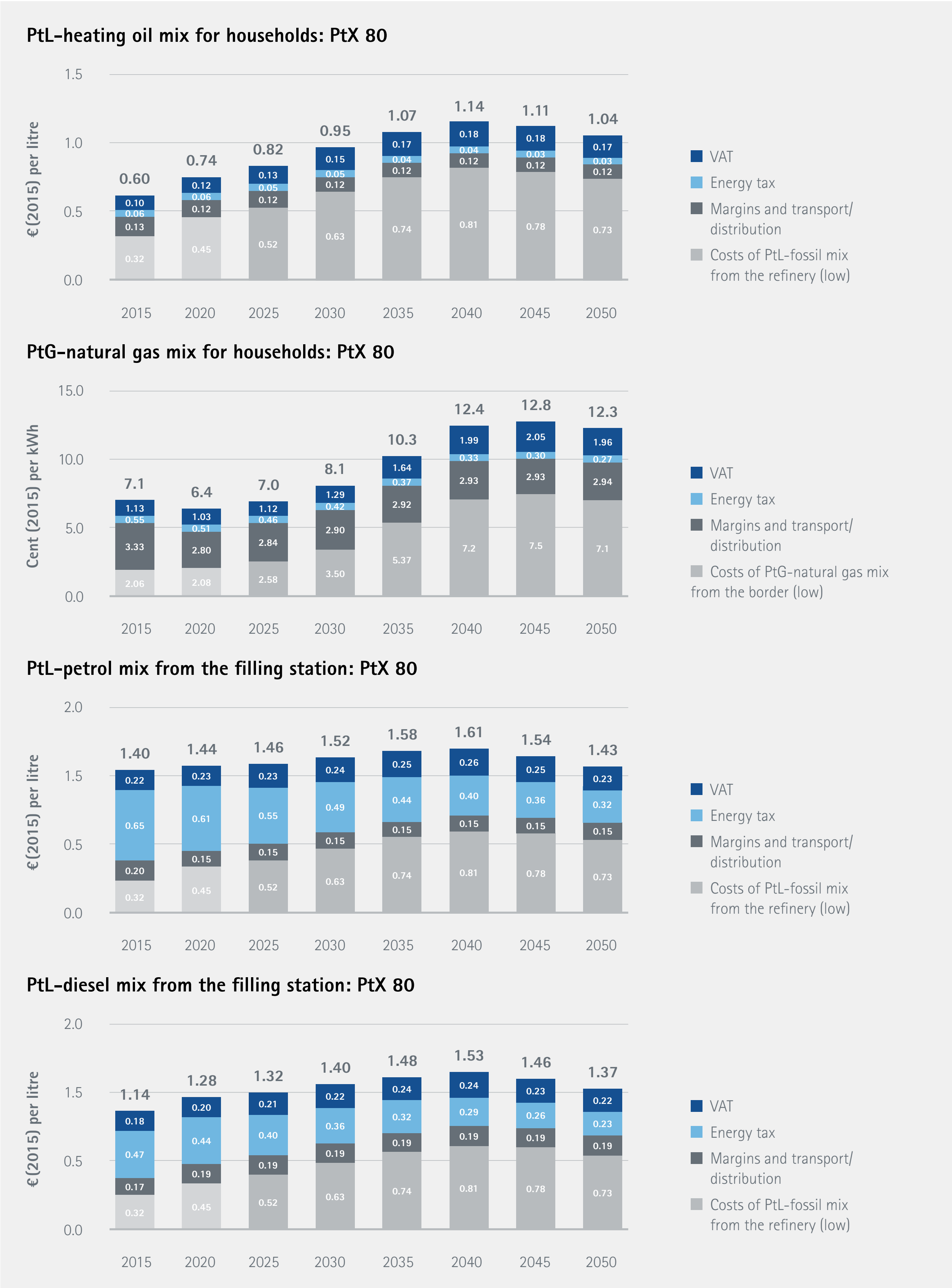
As per the scenario definition, the **heating structure** in the two target scenarios (PtX 80 and PtX 95) is identical to that of the reference. The goals are to be achieved with the reference development infrastructure. The dominant energy

Figure 12: End consumer prices for mixed PtX (higher costs)/fossil products in Germany in the PtX 80 scenario; real prices from 2015–2050 in cent_{2015} per kWh (natural gas) and $€_{2015}$ per litre



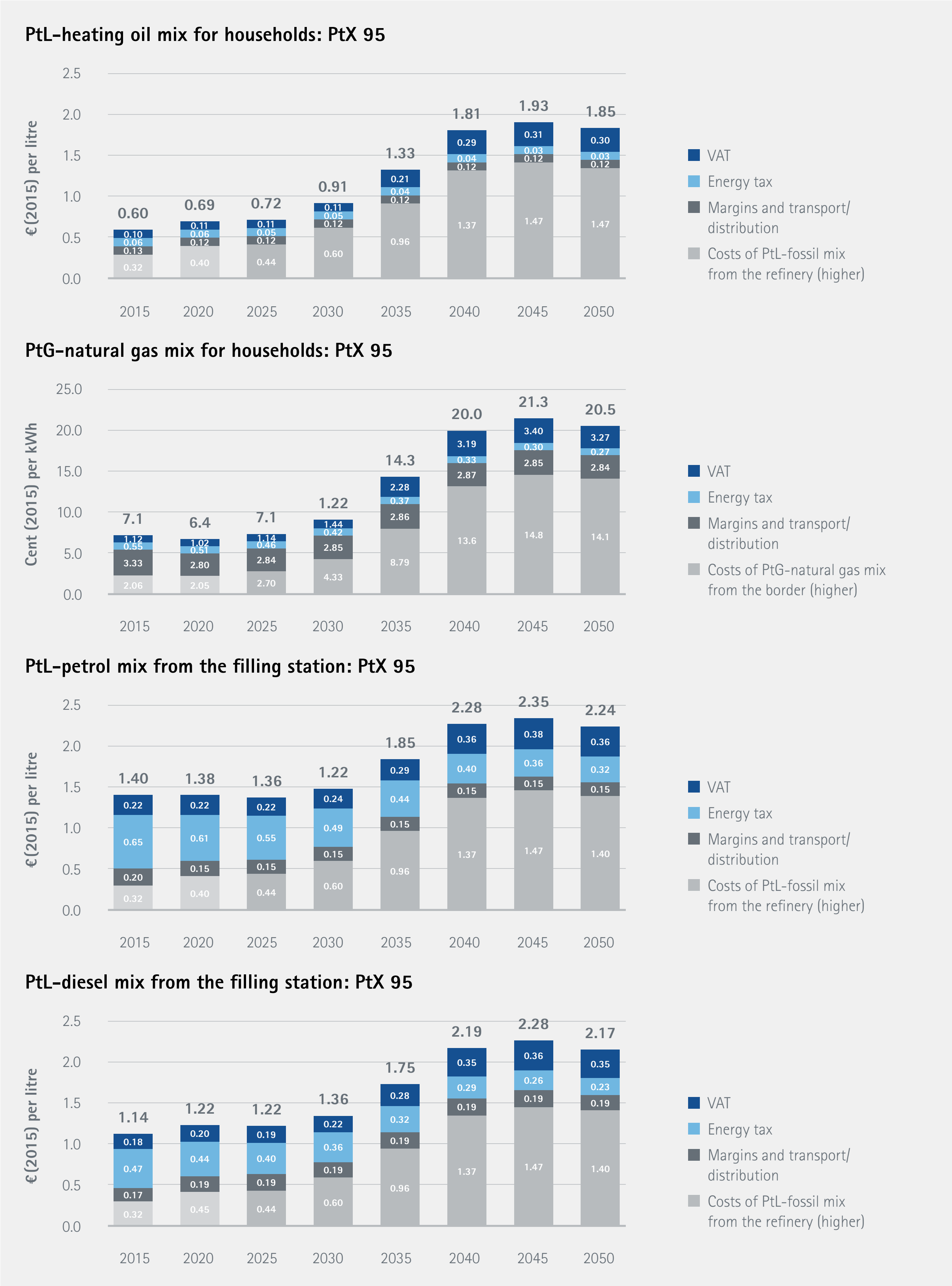
Source: Prognos AG

Figure 13: End consumer prices for mixed PtX (lower costs)/fossil products in Germany in the PtX 80 scenario; real prices from 2015–2050 in $cent_{2015}$ per kWh (natural gas) and $€_{2015}$ per litre



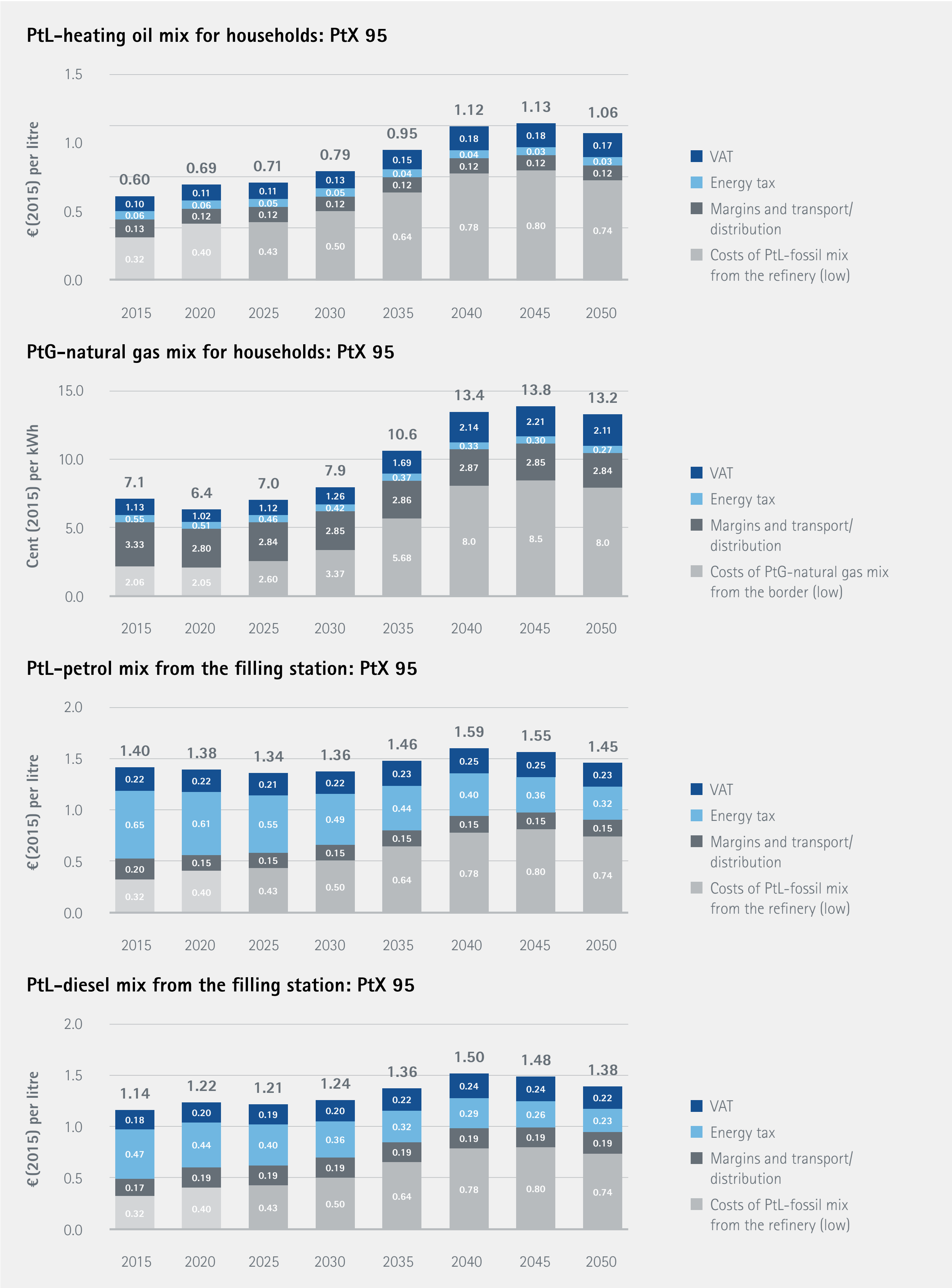
Source: Prognos AG

Figure 14: End consumer prices for mixed PtX (higher costs)/fossil products in Germany in the PtX 95 scenario; real prices from 2015–2050 in cent$_{2015}$ per kWh (natural gas) and €$_{2015}$ per litre



Source: Prognos AG

Figure 15: End consumer prices for mixed PtX (lower costs)/fossil products in Germany in the PtX 95 scenario; real prices from 2015–2050 in cent$_{2015}$ per kWh (natural gas) and €$_{2015}$ per l



Source: Prognos AG

source in these scenarios is and remains gas. The share rises from 43 % in 2000 to around 50 % in 2015 and remains at this level until 2050. The proportion of heating oil sees the greatest decline. Between 2000 and 2015 the proportion decreased by 10 % to 25 %; by 2050 the share falls to 11 %. The heat pump sees the largest increase, with the proportion of living space heated by heat pumps rising to around 14 % by 2050.

4.4 ECONOMY AND EMPLOYMENT

The number of employed persons increased in the ex-post period 2000–2015 (+8 %) and was 43.2 million in 2015 (table 6). In 2000, it was still at 39.9 million. In the medium and longer term, the number of people in employment declines to 38.0 million in 2050 (-12 % compared to 2015). The reason for this is demographic development. The number of people of working age (15–64 years) is 9.1 million lower in 2050 than in 2015.

Despite the decline in the number of people in employment, economic output as measured by gross domestic product increases between 2015 and 2050 at an average annual rate of 1.3 %. Overall, GDP increases from € 2,359 billion in 2000 to over € 2,783 billion in 2015 to € 4,291 billion in 2050 (table 7). This represents an increase of 82 % over the entire assessment period. GDP per capita increases by 92 %, from 29.2 thousand in 2000 to 56 thousand in 2050 (2010 prices).

4.5 TRANSPORT DEMAND

There is currently much discussion as to whether and to what extent **new transport technologies** will influence mobility in the future. Autonomous vehicles are being tested and major research projects are working to achieve ever higher degrees of automation. The main objective of the scenarios in this study is to outline the **changes that are relevant to the energy industry**. Since it is not yet possible to foresee the period in which a significant market penetration of vehicles with high levels of automation is to be expected and to what extent transport performance and energy consumption will be influenced by their availability, a deeper examination of this technological trend is not included in this study.

Irrespective of this issue, no significant changes in traffic behaviour by 2050 are assumed. Therefore, the volume structure for the transport demand is based on established functions, which are essentially based on demographic and economic developments.

Table 4: Population and households by size class, mid-year 2000–2050, in thousand units

	2000	2015	2020	2030	2040	2050
Population	80,677	81,340	82,125	81,250	79,344	76,624
households	37,148	40,525	41,567	42,127	42,181	41,433
thereof						
1-Person	13,336	16,656	17,354	18,030	18,740	18,697
2-Person	12,370	13,900	14,424	15,082	15,259	15,223
3-Person	5,498	4,964	4,905	4,487	4,041	3,764
4-Person	4,328	3,667	3,637	3,370	3,126	2,886
5 (+)-Person	1,635	1,317	1,268	1,137	1,015	863
average household size	2.17	2.01	1.98	1.93	1.88	1.85

Source: Prognos AG, based on German Federal Statistical Office Destatis 2015

Table 5: Heated living spaces, by energy source, 2000–2050, in million m²

	2000	2015	2020	2030	2040	2050
Total living space	3,423	3,801	3,965	4,115	4,181	4,223
thereof						
HEL/PtHEL	1,220	968	875	693	575	478
Gas/PtG	1,472	1,921	2,030	2,123	2,127	2,113
Coal	105	29	22	15	9	6
Electricity	181	118	103	70	48	36
Wood	93	185	217	267	300	326
District heating	339	416	461	521	557	576
Solar	1	19	27	50	73	97
Heat pump	11	144	231	378	493	590

Source: Prognos AG, ex-post period based on German Federal Statistical Office

Table 6: Workforce by economic sector, 2000–2050, in thousand units

	2000	2015	2020	2030	2040	2050
Agriculture, Forestry, Fishery	758	651	624	525	451	403
Mining	120	61	55	42	33	27
Manufacturing	7,828	7,540	7,539	6,873	6,252	5,831
Energy, Water, Waste	516	522	517	471	434	409
Construction	2,894	2,440	2,452	2,280	2,122	1,955
Services	27,801	31,944	32,640	31,541	30,228	29,328
Total	**39,917**	**43,158**	**43,827**	**41,734**	**39,519**	**37,952**

Source: Prognos AG, ex-post period based on German Federal Statistical Office

Table 7: Gross value added and gross domestic product from 2000–2050, actual in prices from 2010, in billion €

	2000	2015	2020	2030	2040	2050
GDP, in billion €	**2,359**	**2,783**	**2,995**	**3,454**	**3,866**	**4,291**
GDP/capita, in thousand €	29.2	34.2	36.5	42.5	48.7	56.0
Gross value added:						
Agriculture, Forestry, Fishery	17	14	14	14	14	15
Mining	7	4	4	3	3	3
Manufacturing	460	590	629	713	785	856
Energy, Water, Waste	70	79	83	95	106	118
Construction	121	102	107	120	131	13
Services	1,448	1,734	1,843	2,151	2,442	2,714
Total	**2,123**	**2,523**	**2,680**	**3,096**	**3,482**	**3,843**

Source: Prognos AG

A key driver for the development of energy demand in transport is the development of traffic volumes. Transport performance is the measure by which the development of transport demand is usually gauged. Passenger-kilometres (pkm) are relevant for passenger transport and tonne-kilometres (tkm) for freight transport.

Rising incomes and growing mobility needs lead to a slight increase in **passenger transport** services until 2020, after which transport services stagnate. The reason for this is demographic development: the population is getting older and as older people statistically have a low transport performance level, passenger transport performance does not increase strongly after 2020 and even decreases slightly after 2030. The modal split changes slightly in favour of rail and bus transport, but there are no structural modal split shifts and thus the MIT remains the dominant mode of transport in the long term with a share of over 80 % in terms of transport performance.

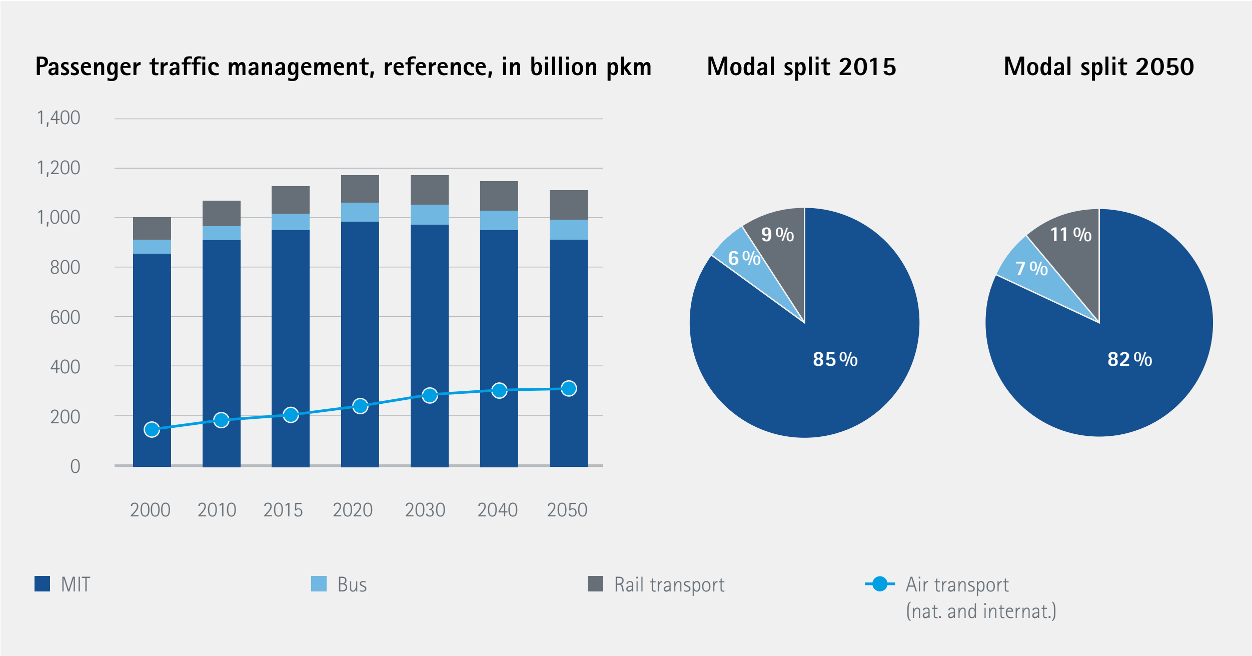
Passenger air transport has a significant share in passenger transport with a transport performance of around 210 billion pkm (transport performance leaving Germany). According to current forecasts, this mode of transport will continue to grow strongly until 2050 and therefore gain in importance.

Development by drive in passenger cars for the reference scenario

The passenger car is by far the most dominant mode of passenger transport, both in terms of transport services and with regard to energy consumption and CO_2 emissions. Mobility by passenger car requires around 1,500 PJ of final energy in 2015. This corresponds to a share of almost 60 % of the final energy consumption of the transport sector in Germany. Both the number of passenger cars and new passenger car registrations are dominated by petrol and diesel vehicle drives (market share of > 98 % in 2015). Driven significantly by the CO_2 fleet limits for passenger cars (European Parliament 2014), the importance of alternative drive systems in new passenger car registrations is increasing significantly (see figure 18).

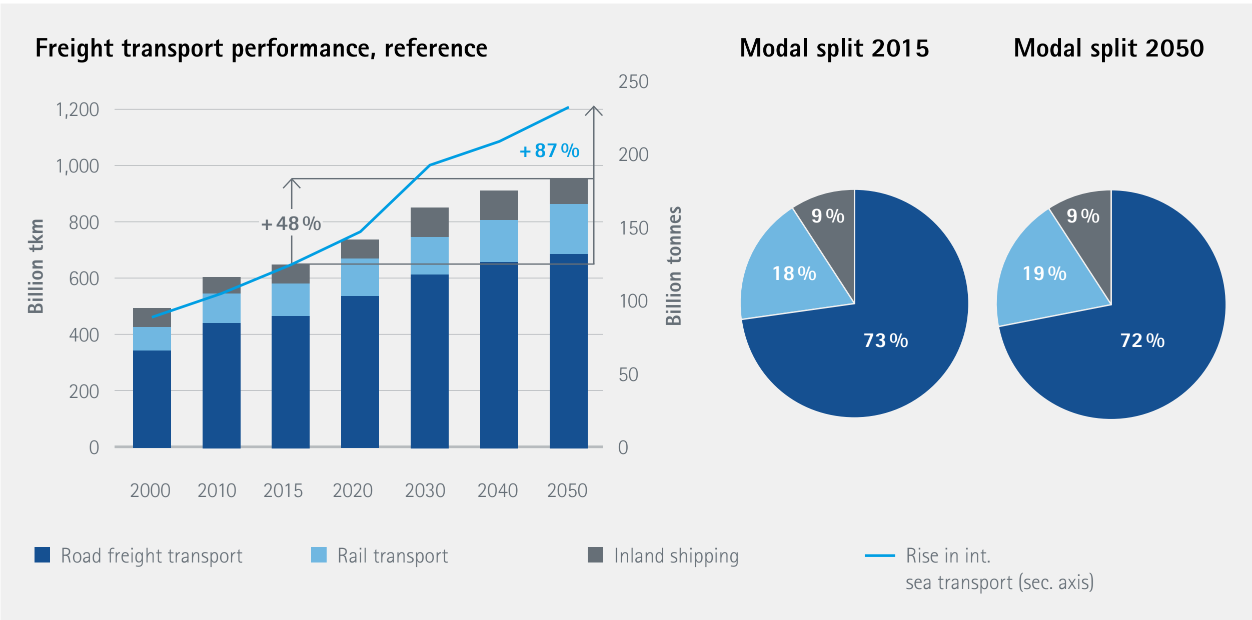
The reference assumes the EU fleet limit values for passenger cars (95 g in 2021). This results in the development of the drive structure and efficiency by 2020. In the reference development, there are no further fleet limits after that because no limits for after 2021 are agreed at the time of the study. The reference development of the drive structure reflects our expectation for the autonomous market ramp-up of various passenger car drive technologies.

Figure 16: Passenger transport performance by mode of transport, reference development, forecast up to 2050, in billion pkm



Source: BCG/Prognos (2018)

Figure 17: Freight transport performance by mode of transport, reference development, forecast up to 2050



Source: BCG/Prognos (2018)

In the reference scenario, 46 % of new registrations in 2020 are for petrol and 35 % for diesel engines. The remaining 19 % of new passenger car registrations are passenger cars with hybrid (9 %), electric[1] (7.5 %) or gas engines[2] (2 %).

The proportion of electrically powered passenger cars increases to 17 % by 2030 and to around 60 % by 2050. The share of all-electric vehicles is 10 % in 2030 and 40 % in 2050.

The development of the passenger car population by drive is based on new car registrations using a cohort model and is shown in figure 18.

In the scenarios in this study, electric cars do not have a substantial share of the vehicle population by 2030. Around 460 thousand electric cars will be registered in 2020. In the reference scenario, a million electric vehicles is reached in 2023 and by 2030 it is expected to be around 3.7 million electric cars, which corresponds to a share of 8 % of the vehicle population. However, new registrations already show a significant proportion of electric vehicles in 2030 (around 20 %), which means that, in the longer term, electric drives for passenger cars also become significantly more important in the reference market. In 2050, they account for around 35 % of the vehicle population. Electric mobility in passenger cars is thus clearly picking up speed in the long term, but combustion engines and hybrids remain the dominant forms of drive in the reference scenario.

Development by drive for road freight transport

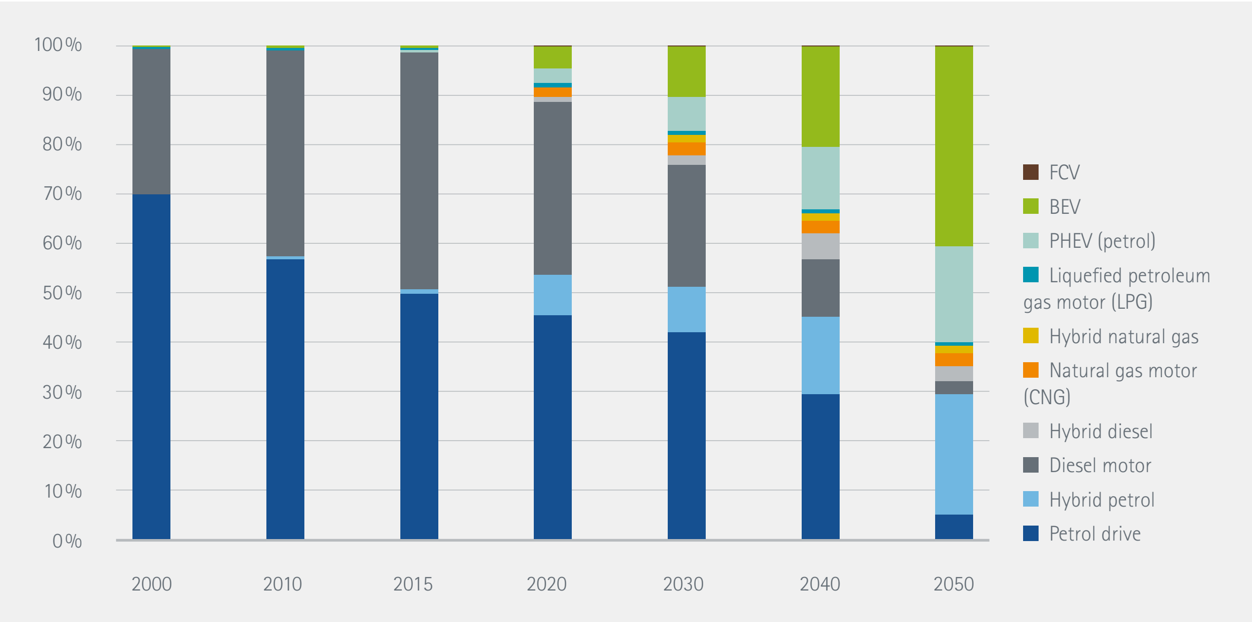
In freight transport in Germany, road freight transport accounts for 70 % of land-based freight transport performance. In terms of energy consumption and CO_2 emissions, the proportions are again significantly higher. The transport performance is mainly provided by heavy road goods vehicles with a maximum permissible mass of more than 3.5 tonnes. In Germany, 713,000 heavy commercial vehicles (HCVs) are registered in 2015. Compared to light commercial vehicles (LCV), with a population of 2.1 million in 2015, the number of HCVs is significantly lower.

The number of HCVs grew to around 2.2 million vehicles in 2015—an increase of +26 % compared to 2000 (and +133 % compared to 1990). Due to the positive market forecasts in the field of use of HCVs, their number continues to grow in the medium to long term. According to current forecasts, saturation in vehicle population development is only reached after 2040.

1 Electric drive: battery-electric vehicles (BEV), plug-in hybrids (PHEV) and fuel-cell vehicles (FCV)

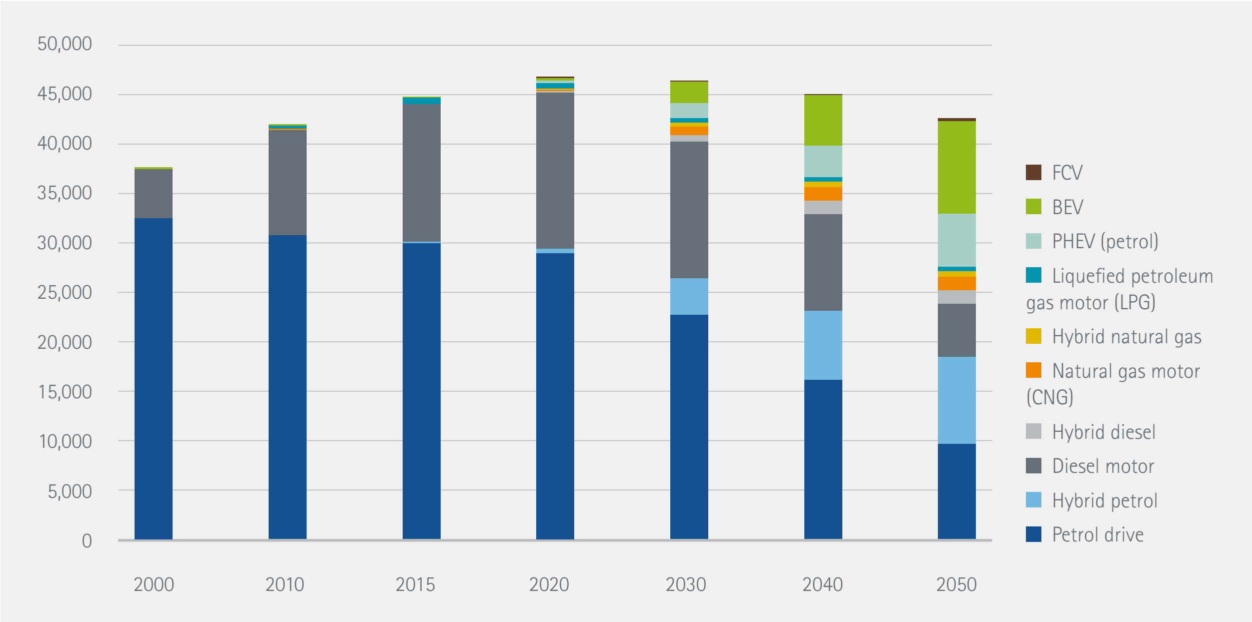
2 Gas drives: natural gas (CNG) and liquid gas (LPG)

Figure 18: New passenger car registrations by motor, reference, up to 2050, in %



Source: Prognos AG, BEV: Battery-electric vehicle, PHEV: plug-in hybrid, FCV: fuel-cell car

Figure 19: Number of passenger cars by motor, reference, up to 2050, in thousand units passenger car

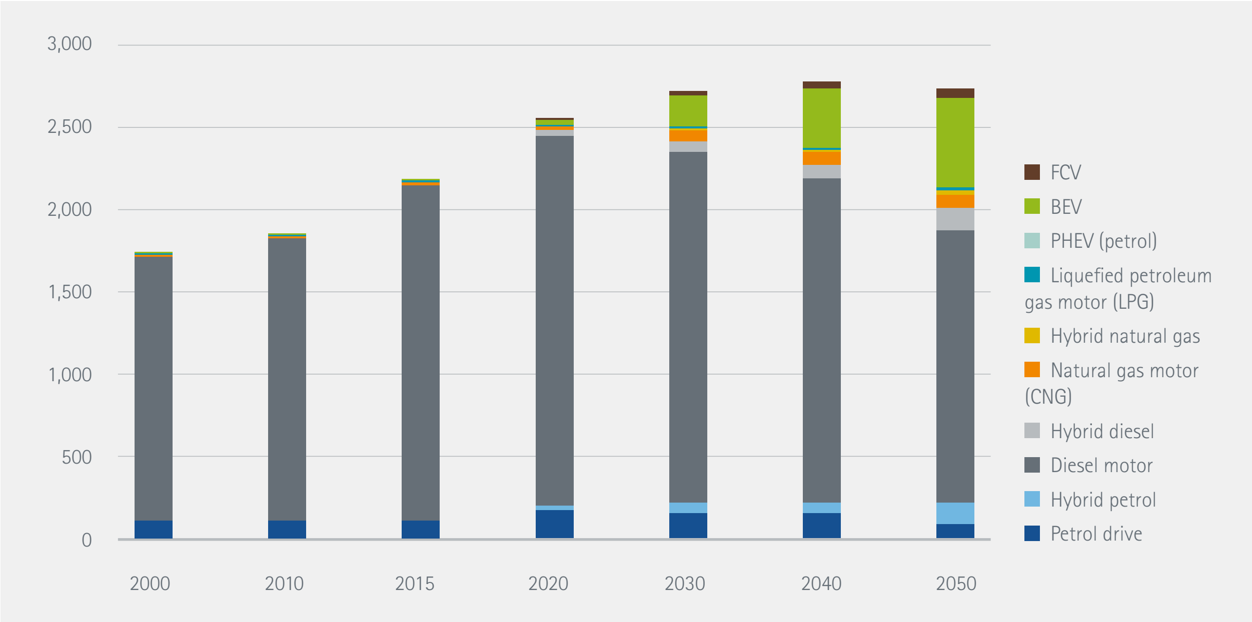


Source: Prognos AG

Since the vehicle technology is similar to passenger cars, it is assumed that the drive structure for HCVs will develop in line with the development of passenger cars. Longer product cycles and a higher cost orientation for the owners typically mean that innovations in passenger cars are implemented about 6 to 8 years later in HCVs. On the other hand, there are reasons why battery-electric drives can develop faster in HCVs. Since the mileage is often higher in a comparatively small radius (especially in the CEP sector), the use of a battery-powered vehicle is economical for a large part of the vehicle cohorts in light commercial traffic.

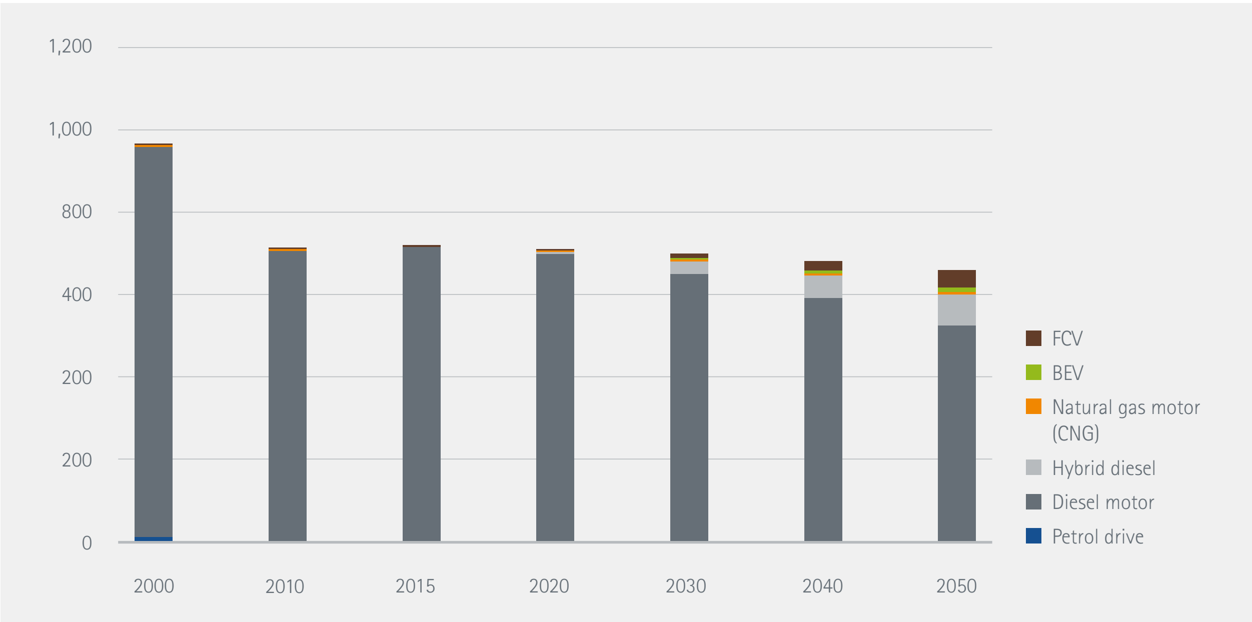
The number of heavy commercial vehicles decreased significantly between 2000 and 2010. This development is mainly due to increasing loads (which means that the same transport performance can be achieved with fewer vehicles) and a shift towards smaller vehicles with a maximum permissible mass of less than 3.5 tonnes. Due to the heavy loads and the high daily mileage, there is no extensive electrification of heavy commercial vehicles in the long term either, according to the reference development. In contrast, a slight hybridisation of the existing fleet (12 % in 2050) and minor penetration with fuel-cell drives is quite likely.

Figure 20: Number of LCVs by motor, reference, up to 2050, in thousand units LCV



Source: Prognos AG

Figure 21: Number of HGVs and tractors by motor, reference, up to 2050 in thousand units



Source: Prognos AG

5

ENERGY RESULTS UP TO 2050

5.1 FINAL ENERGY CONSUMPTION

Final energy consumption is currently dominated by applications for space heating and hot water (2015 share: 32 %), process heat (2015 share: 19 %) and mechanical drives (including mobility; 2015 share: 40 %). The demand for process heat decreases only slightly in the scenario period (-3 %), while consumption for space heating and hot water (-28 %) and mechanical drives (-20 %) decreases significantly (table 8, consumption including international air and sea traffic). The largest increase in consumption can be seen in the reference scenario for cooling and ventilation (50 PJ, +51 %), which can be attributed to the expected level of global warming and further increasing comfort requirements. Overall, final energy consumption in the reference scenario decreases from 8,993 PJ in 2015 to 7,344 PJ in 2050 (-18 %).

Since no additional efficiency measures are applied in the target scenarios in comparison to the reference scenario, the final energy consumption and usage structure basically remain identical to those in the reference. There are minor differences in the industrial sector. The increased use of biogas and solid biomass and the greater decrease in coal consumption result in somewhat lower energy consumption.

The final energy consumption by **energy source** in the three scenarios is described in table 9. Electricity consumption does not change significantly in the 2015–2050 period (+2 %). By contrast, there are significant increases in renewable energies (+316 PJ; +50 %) and district heating (+55 PJ; +14 %). Consumption of fossil energy sources declines in the reference scenario: coal consumption decreases by 90 PJ (-19 %), consumption of petroleum products decreases by 1,443 PJ

(-43 %) and natural gas consumption decreases by 553 PJ (-25 %). The main reasons for the decline in mineral oil products are the decrease in space heating consumption

Table 8: Reference scenario: final energy consumption by application area, 2000–2050, in PJ

	2000	2015	2020	2030	2050	'15 – '50 in %
Space heating and hot water	3,289	2,883	2,867	2,547	2,080	- 28 %
Lighting	257	260	231	188	125	- 52 %
Cooling and ventilation	82	98	103	116	149	+ 51 %
ICT	181	200	194	196	194	- 3 %
Other building services	34	41	41	38	39	- 5 %
Process heat	1,777	1,741	1,704	1,716	1,695	- 3 %
Process cooling	63	67	70	80	93	+ 40 %
Mechanical drives	3,752	3,626	3,698	3,536	2,891	- 20 %
Electrolysis	71	77	76	79	78	+ 1 %
Total	**9,506**	**8,993**	**8,986**	**8,496**	**7,344**	**- 18 %**

Source: Prognos AG

Table 9: Scenario comparison: final energy consumption by energy source, 2000–2050, in PJ. Figures include international air and sea transport

	2000	2015	2020	2030	2050	'15–'50 in %
Reference						
Coal	514	466	424	396	377	- 19 %
Mineral oils	4,203	3,391	3,372	2,875	1,948	- 43 %
Mineral gases	2,364	2,184	2,166	1,960	1,632	- 25 %
Other energy sources	55	71	80	92	100	41 %
Renewable energies	201	627	732	867	942	50 %
Electricity	1,770	1,853	1,833	1,842	1,888	2 %
District heating	400	402	429	462	456	14 %
PtX	0	0	0	0	0	–
Total	**9,506**	**8,993**	**8,986**	**8,496**	**7,344**	**-18 %**
Scenario PtX 80						
Coal	514	466	382	330	286	- 39 %
Mineral oils	4,203	3,391	3,369	2,638	369	- 89 %
Mineral gases	2,364	2,184	2,112	1,541	280	- 87 %
Other energy sources	55	71	110	123	122	72 %
Renewable energies	201	627	769	976	1,245	99 %
Electricity	1,770	1,853	1,832	1,835	1,874	1 %
District heating	400	402	429	462	456	14 %
PtX	0	0	29	602	2,683	–
PtL	0	0	18	326	1,681	–
PtG	0	0	11	276	1,002	–
Total	**9,506**	**8,993**	**9,034**	**8,507**	**7,316**	**-19 %**
Scenario PtX 95						
Coal	514	466	382	330	286	- 39 %
Mineral oils	4,203	3,391	3,370	2,599	31	- 99 %
Mineral gases	2,364	2,184	2,112	1,499	80	- 96 %
Other energy sources	55	71	110	123	120	69 %
Renewable energies	201	627	769	976	1,245	99 %
Electricity	1,770	1,853	1,832	1,835	1,874	1 %
District heating	400	402	429	462	456	14 %
PtX	0	0	29	683	3,223	–
PtL	0	0	17	365	2,017	–
PtG	0	0	11	318	1,206	–
Total	**9,506**	**8,993**	**9,034**	**8,507**	**7,316**	**-19 %**

Source: Prognos AG, PtL: liquid synthetic energy sources, PtG: gaseous synthetic energy sources

Table 10: Reference scenario: Final energy consumption by consumption sector, 2000–2050, in PJ. Transport sector including international traffic

	2000	2015	2020	2030	2050	'15 – '50 in %
Private households	2,584	2,302	2,278	2,015	1,677	- 27 %
CTS	1,566	1,428	1,392	1,308	1,193	- 16 %
Industy	2,523	2,548	2,507	2,506	2,407	- 6 %
Transport	2,834	2,715	2,809	2,666	2,067	- 24 %
Total	**9,506**	**8,993**	**8,986**	**8,496**	**7,344**	- 18 %
Target scenarios PtX 80/95						
Private households	2,584	2,302	2,278	2,015	1,677	- 27 %
CTS	1,566	1,428	1,392	1,308	1,193	- 16 %
Industy	2,523	2,548	2,555	2,518	2,379	- 7 %
Transport	2,834	2,715	2,809	2,666	2,067	- 24 %
Total	**9,506**	**8,993**	**9,034**	**8,507**	**7,316**	**-19 %**

Source: Prognos AG

(better insulated buildings, more efficient plants, warmer climate), replacement with alternative heating systems and the increasing penetration of electric vehicles in transport.

In the **target scenarios**, fossil mineral oils and gases are replaced by **GHG-free synthetic energy sources** . The extent to which they are replaced is determined by the specified blending proportions (see figure 7). A proportion of 82.5 % is reached in 2050 in PtX 80 and 100 % in the PtX 95 scenario. As a result, the demand for PtX in the PtX 95 scenario increases more than in the PtX 80 scenario. In the industrial sector, coal consumption is reduced more in the target scenarios than in the reference. PtX is generally not a substitute for coal; rather, solid and gaseous biomass is used instead of coal.

Energy consumption decreases in all **sectors**, and decreases the most in the private households and transport sectors (table 10). Consumption in the household sector is dominated by consumption for space heating. This kind of consumption has declined sharply over time due to building renovations, the replacement of old heating systems with more efficient new heating systems, the replacement of old buildings with efficient new buildings and the warmer climate. In the CTS sector, too, the decline in consumption is mainly due to the development in space heating. The main driver for the decline in consumption in the transport sector is the increasing electrification of private transport after 2030. The decline is exacerbated by the shrinking population.

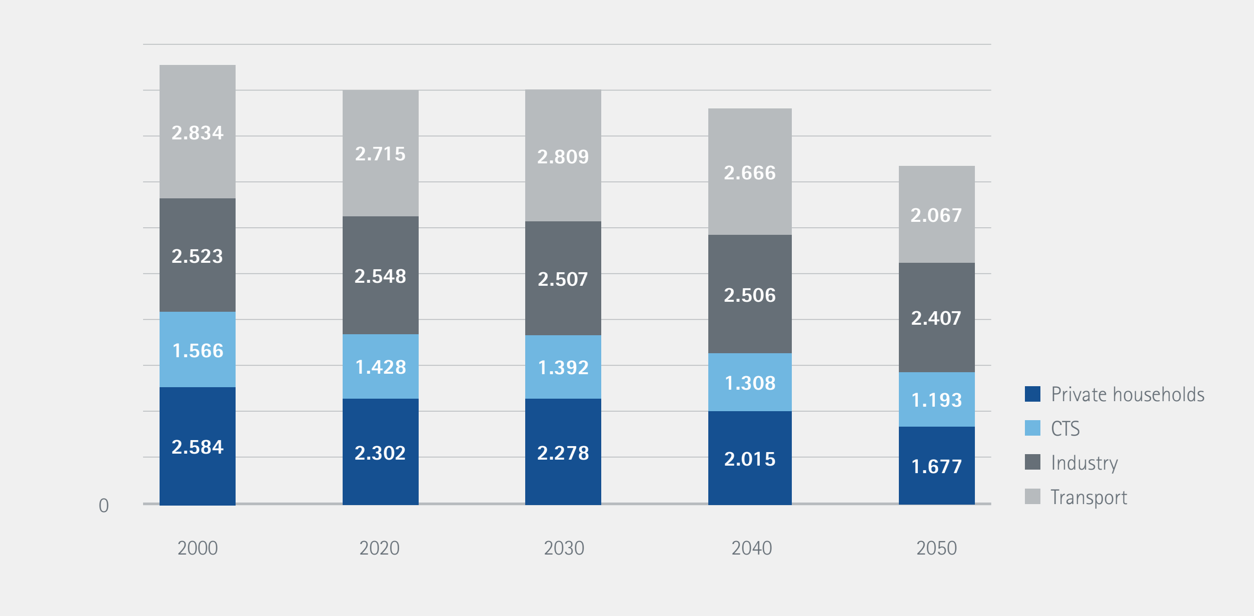
In the private household, CTS and transport sectors, there is no difference between the reference and target scenarios in terms of final consumption. The replacement of fossil heating oils, gases and fuels does not lead to a change in the levels of efficiency of systems and vehicles. As mentioned already, coal is also being replaced in the industrial sector, and at the same time solid and gaseous biomass are increasingly being used. The use of biomass in the industrial sector increases by around 400 PJ compared to the reference. This results in a slightly different level of consumption from the reference development; however, the difference is small (~1 %).

5.2 ELECTRICITY SYSTEM

The basic framework data for the electricity system used in the modelling, including investment costs, operating costs and technical service life, is listed in section 16 in the appendix.

The electricity system in Germany is currently heavily shaped by fossil-thermal generation. In 2015, around 250 TWh of electricity was generated from brown and hard coal, which corresponds to over 40 % of total generation. In addition, 61 TWh of electricity was generated from natural gas and 87 TWh from nuclear power. Furthermore, around 30 TWh was generated from other fossil fuels, such as waste and by-product gases.

Figure 22: Reference scenario: final energy consumption by consumption sector, 2000–2050, in PJ (transport sector including international traffic)



Source: Prognos AG

On the other hand, around 180 TWh of electricity is generated from renewable energies, of which almost 40% was from onshore wind, and 23% each from biomass and photovoltaics. Electricity generation from offshore wind accounted for 4% of total generation.

The reference scenario assumes that the existing regulatory framework will remain in place and that the energy policy measures will be continued. This means that a level of support for electricity generation from renewable energies that is comparable to the EEG will be maintained until 2050. However, no additional measures will be taken.

In the reference scenario, the expansion of renewable energies is therefore based on EEG 2017. The upgrade rates and expansion targets defined for the individual technologies in the act are assumed. In the long term, the expansion is based on the stated goal that in 2050 at least 80% of gross electricity consumption will be covered by renewable energies. In the reference scenario, this leads to net electricity generation of 475 TWh in 2050. The distribution among the individual technologies is based on an overall view that takes into account generation costs, feed-in profiles and social acceptance for the individual technologies. In the reference scenario, wind turbines at sea and on land together generate around 345 TWh. PV electricity generation is 90 TWh. Electricity generation from water and biomass accounts for 20 TWh each. Figure 24 shows the capacities required to do so.

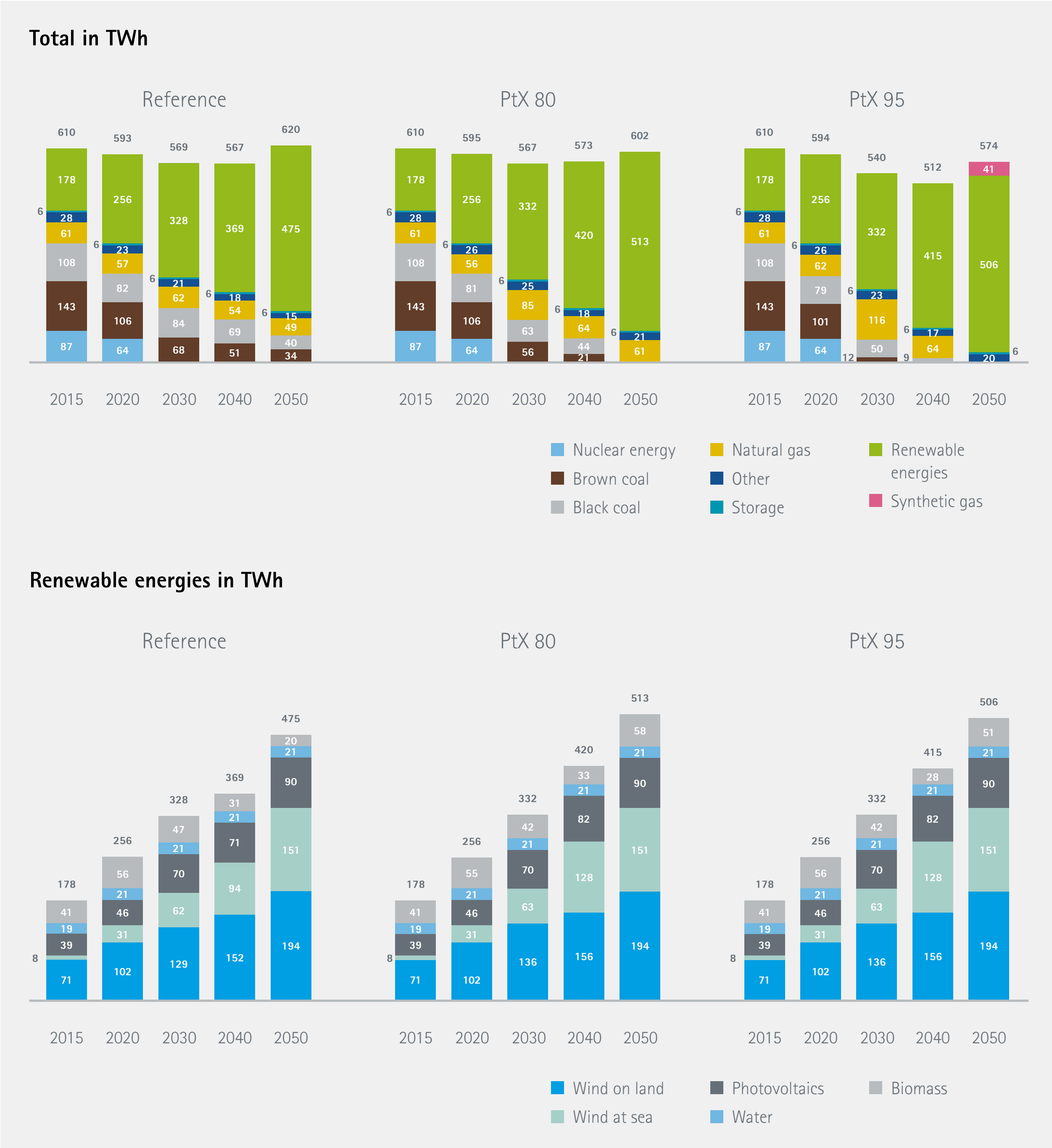
In the reference scenario, the expansion of renewable energies is accompanied by a decline in thermal generation. On the one hand, nuclear power generation is phased out by 2022, due to the phase-out decided in 2011. On the other hand, the majority of today's existing coal-fired power plants are decommissioned due to their age. Of the 50 GW of coal-fired power plants today, 9 GW each of lignite and hard coal are in operation in 2050. New backup gas-fired power plants are needed to ensure that sufficient capacity[3] is available at all times to safeguard the energy system. In addition, CHP gas-fired power plants are upgraded with heat extraction due to the KWKG (German federal combined heat and power act).

Both the PtX 80 and PtX 95 scenarios were defined in such a way that the installed renewable energy capacity is not higher than in the reference. The achievement of the GHG targets in the interim years 2030/2040 has not been considered in the study.

To reduce greenhouse gases in the electricity sector, coal-fired electricity generation must be prematurely phased out. In

3 The amount of guaranteed capacity required is simplified here based on the maximum load for domestic, inflexible power consumption (including a safety margin of 10%).

Figure 23: Net electricity generation in the reference, PtX 80 and PtX 95 scenarios

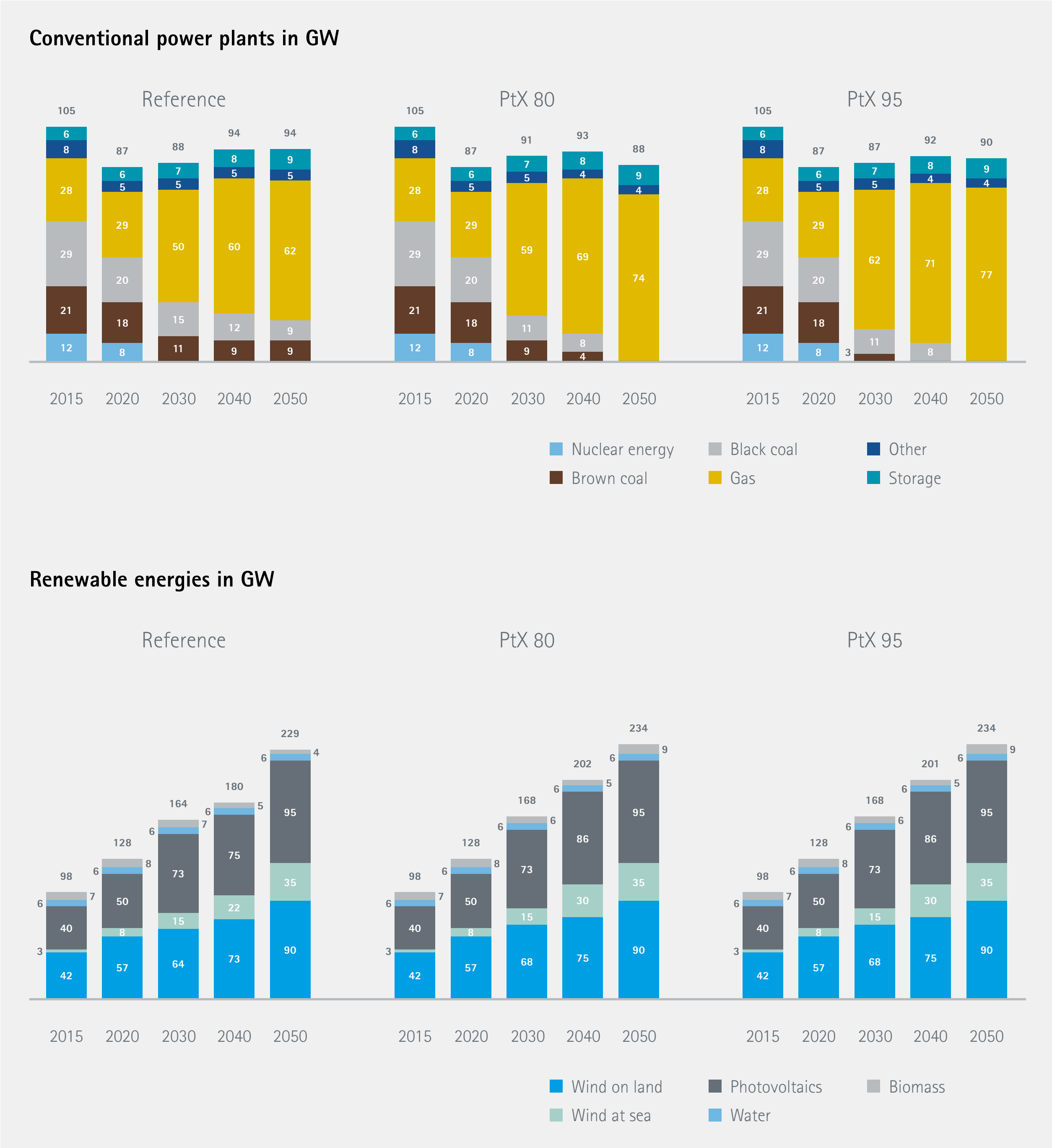


Source: Prognos AG

the PtX 80 scenario, coal-fired electricity generation will be phased out completely by 2050. Since no additional renewable energies can be added in this scenario due to the assumptions (see chapter 4.1), the shortfall in generation is compensated by the increased use of natural gas and biomass. In addition, electricity imports increase in the PtX 80 scenario. Germany develops from a net exporter to a net importer.

In the PtX 95 scenario, a faster decline in coal electricity generation than in the PtX 80 scenario is required due to the higher level of ambition. This decline in PtX 95 is driven purely by the market, based on the assumed CO_2 and fuel prices. In addition, gas electricity generation increases in the short term to more than 110 TWh in 2030. In the long term, however, it falls again. Due to the greenhouse gas target, almost no greenhouse gas emissions will be allowed

Figure 24: Electricity generation capacities (net) in the reference, PtX 80 and PtX 95 scenarios



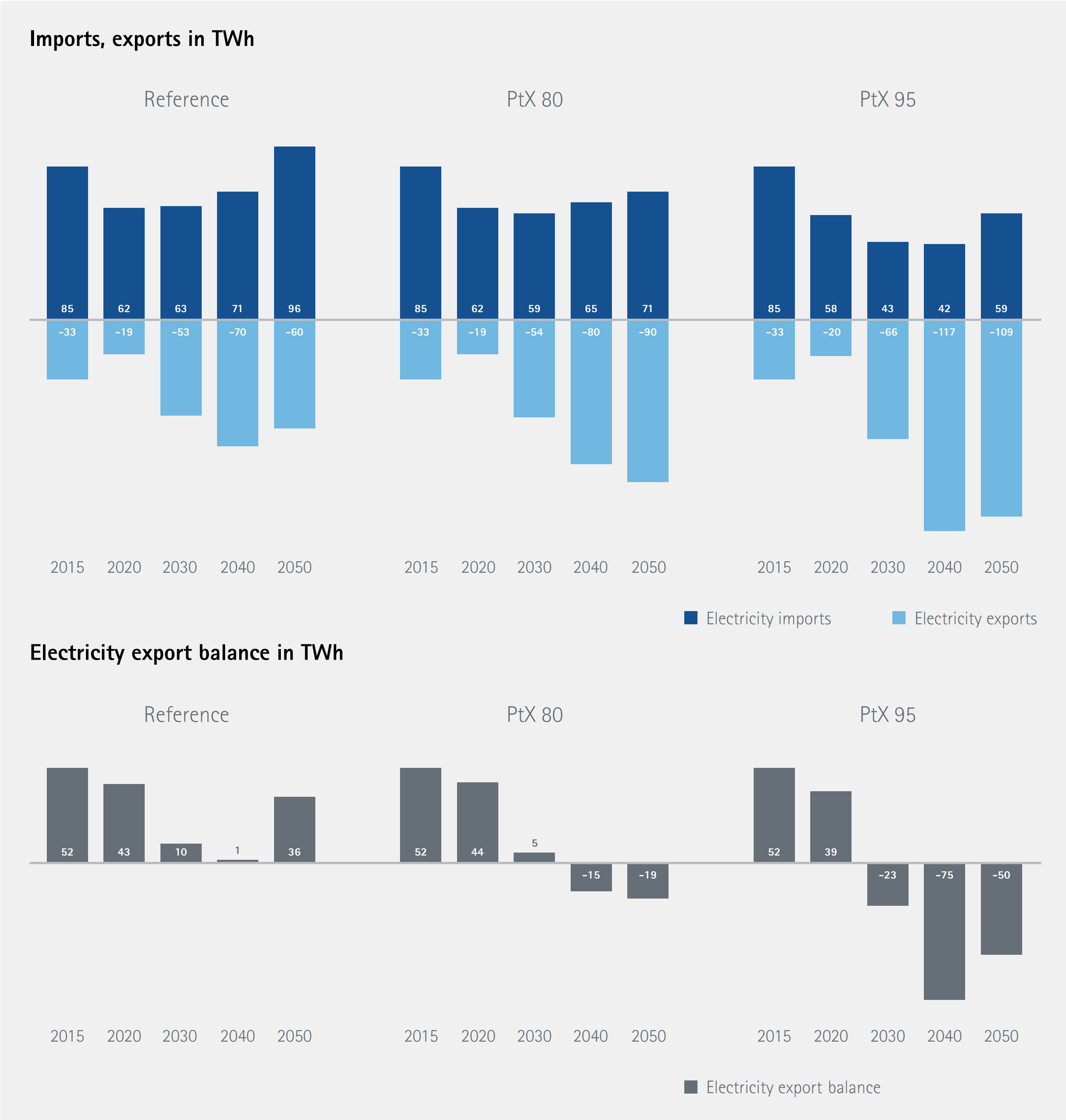
Source: Prognos AG

to be emitted in the electricity sector in 2050. Natural gas must therefore gradually be replaced by synthetically produced PtG from 2040.

Due to the high costs of this fuel and the potential of renewable energies[4] in neighbouring European countries, this results in higher imports in hourly dispatch than in the other scenarios (see figure 25).

4 It is assumed that the other European countries are pursuing similar climate protection ambitions to Germany (see chapter 4.1) and are decarbonising their electricity sectors accordingly.

Figure 25: German electricity imports and exports in the reference, PtX 80 and PtX 95 scenarios



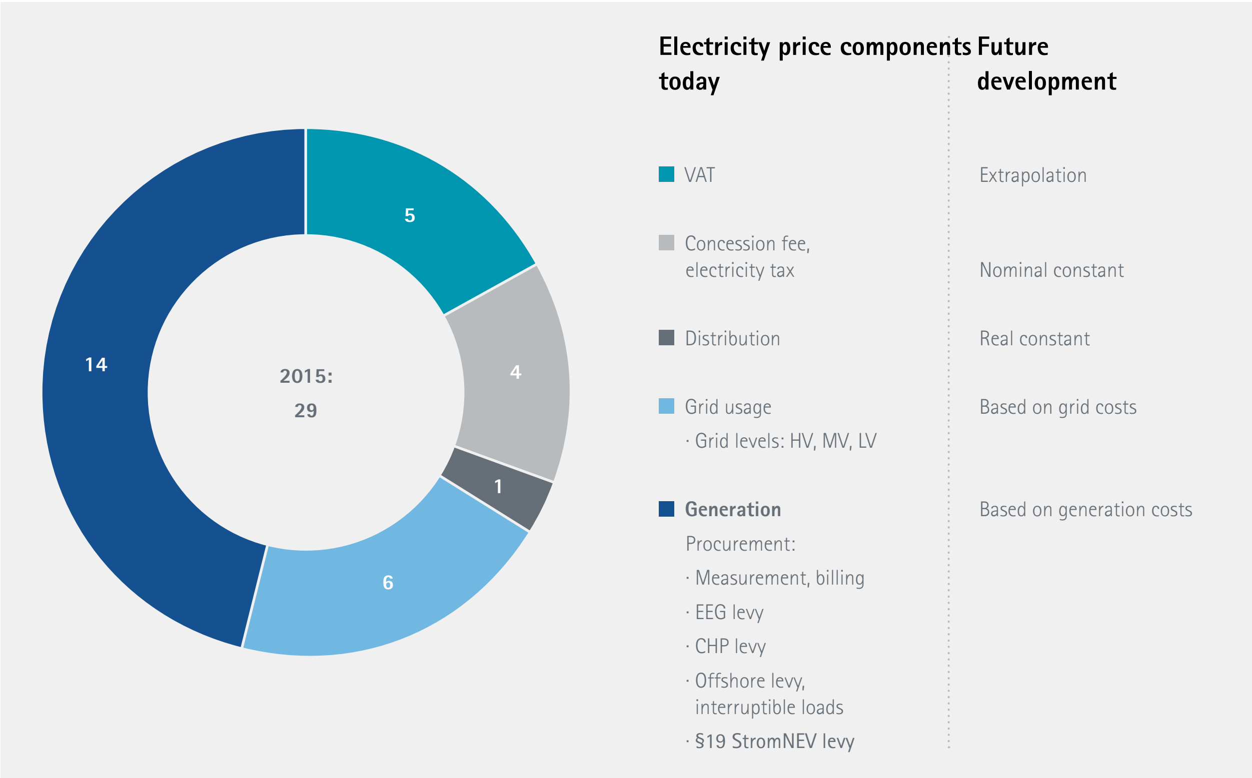
Source: Prognos AG

Electricity prices

The current household electricity price for a demand of 3,500 kWh is roughly 29 cents per kWh on average in Germany. This price is made up of various components. The largest proportion is accounted for by procurement costs, the EEG levy and grid charges. Depending on the power consumption, tariff and grid area, the electricity prices deviate significantly from the indicated average value. Electricity for controllable consumers (e.g. night storage heaters, heat pumps and electricity for electromobility) is significantly cheaper than "normal" household electricity, because the grid operators can provide reduced grid charges for these consumers based on the regulation in §13.2 EnWG (the German Energy Industry Act). These tariffs were not considered in the scenarios. The development of the standard household electricity price in the scenarios is derived below.

For the calculation of future electricity prices, the individual components of today's end consumer electricity price for

Figure 26: Composition of the mean electricity prices today in $cent_{2015}$ per kWh with a reference quantity of 3,500 kWh per year



Source: Prognos AG, researcher's own diagram based on the Federal Association of the German Energy and Water Industries (BDEW) 2018 electricity price (BDEW 2018). Abbreviations: HV (high and extra-high voltage and offshore connection), MV (medium voltage), LV (low voltage)

private households were first arranged into three groups. They were then extrapolated into the future using a variety of methods. These methods are discussed in more detail below:

Generation

The generation block accounts for around 50 % of the total electricity price. It includes the costs for procurement, metering and billing as well as all relevant levies (EEG, CHP, offshore, interruptible loads, §19 StromNEV).

The generation was extrapolated using a calculated index. The index is based on the development of generation costs.[5] The main drivers for generation costs are conventional power plants and renewable energies.

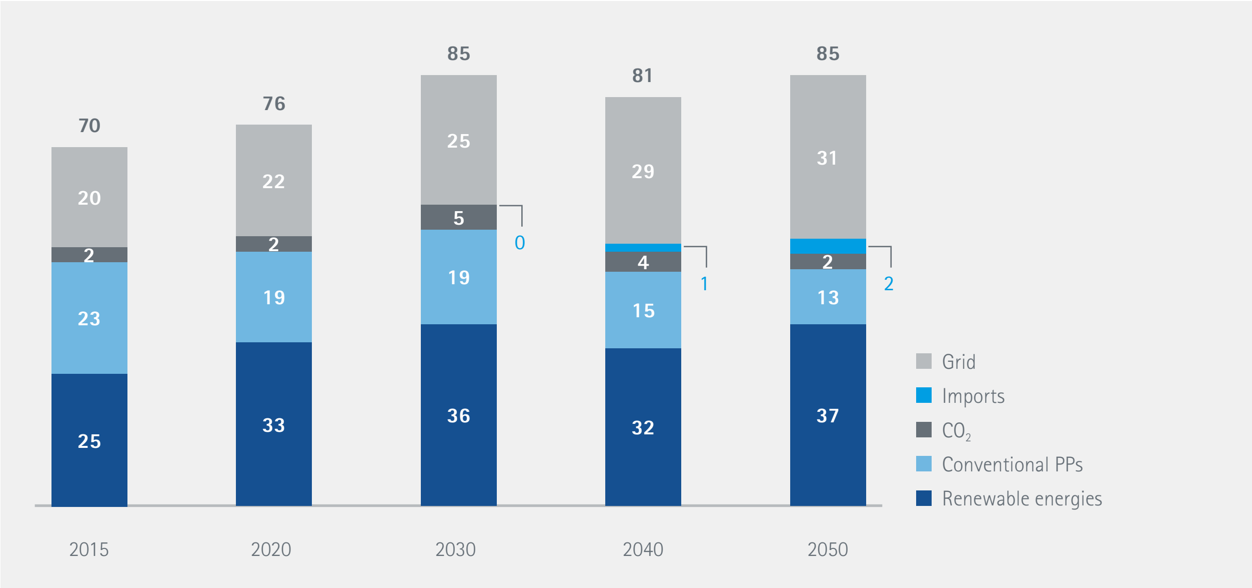
The rising absolute costs for renewable energy generation are offset by falling costs for conventional power plants. In the PtX 80 scenario, they fall from $€_{2015}$ 24 billion today to $€_{2015}$ 13 billion by 2050. On the one hand, fuel and operating costs are halved due to the reduced use of conventional fuels. On the other hand, the future conventional power plant park based on installed capacity is only half as expensive as today.[6] In addition, the costs of CO_2 certificates and electricity imports must be taken into account in the generation costs. Net electricity imports were valued with costs at a flat rate of $€_{2015}$ 80 per MWh. Exports were not evaluated. However, both items are relatively small compared to the other costs.

In the PtX 95 scenario, there are higher CO_2 costs in 2030 and 2040 due to the higher CO_2 price path. In 2050, the use of synthetically produced gas doubles fuel costs compared to today. In addition, the costs for electricity imports rise slightly.

5 The calculation of specific electricity prices for private households is based on the development of the overall costs of the electricity system. The fuel costs are based on the fuel quantities used and the respective fuel prices free power plant (see chapter 3). In addition, the capital costs of the plants (annualised at 6 % over the technical service life), the operating costs and the costs of CO_2 emissions were taken into account.

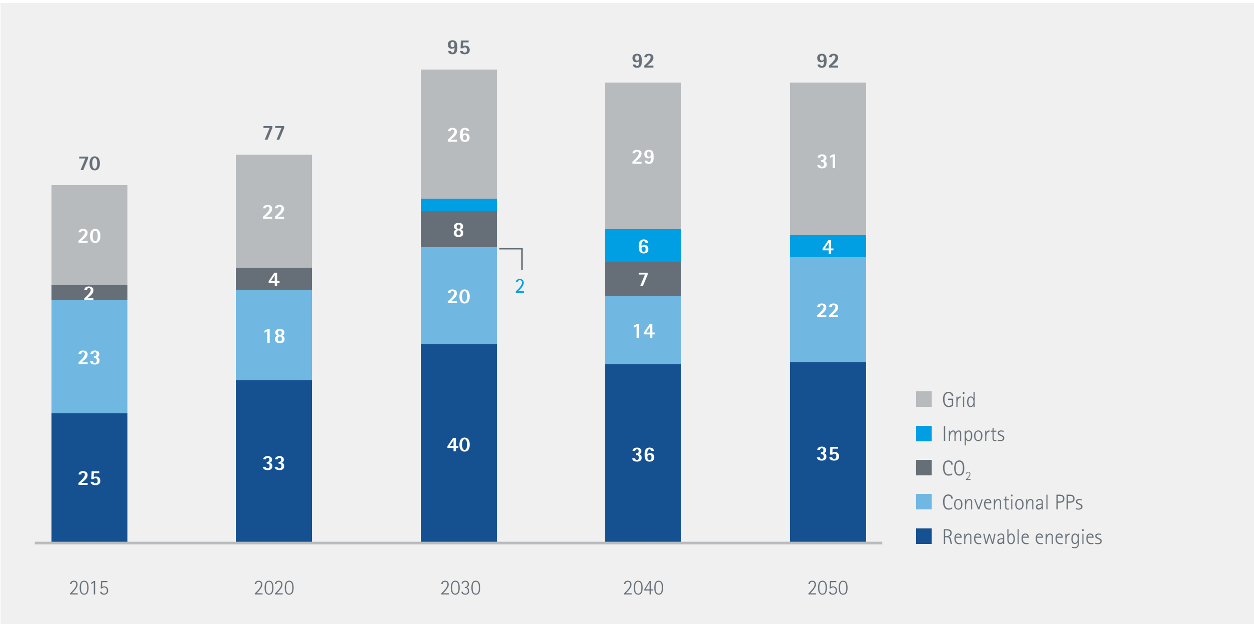
6 Even in the event of early decommissioning, the power plants are fully depreciated over their technical service lives.

Figure 27: Development of electricity system costs in the PtX 80 scenario in billion €$_{2015}$



Source: Prognos AG

Figure 28: Development of electricity system costs in the PtX 95 scenario in billion €$_{2015}$



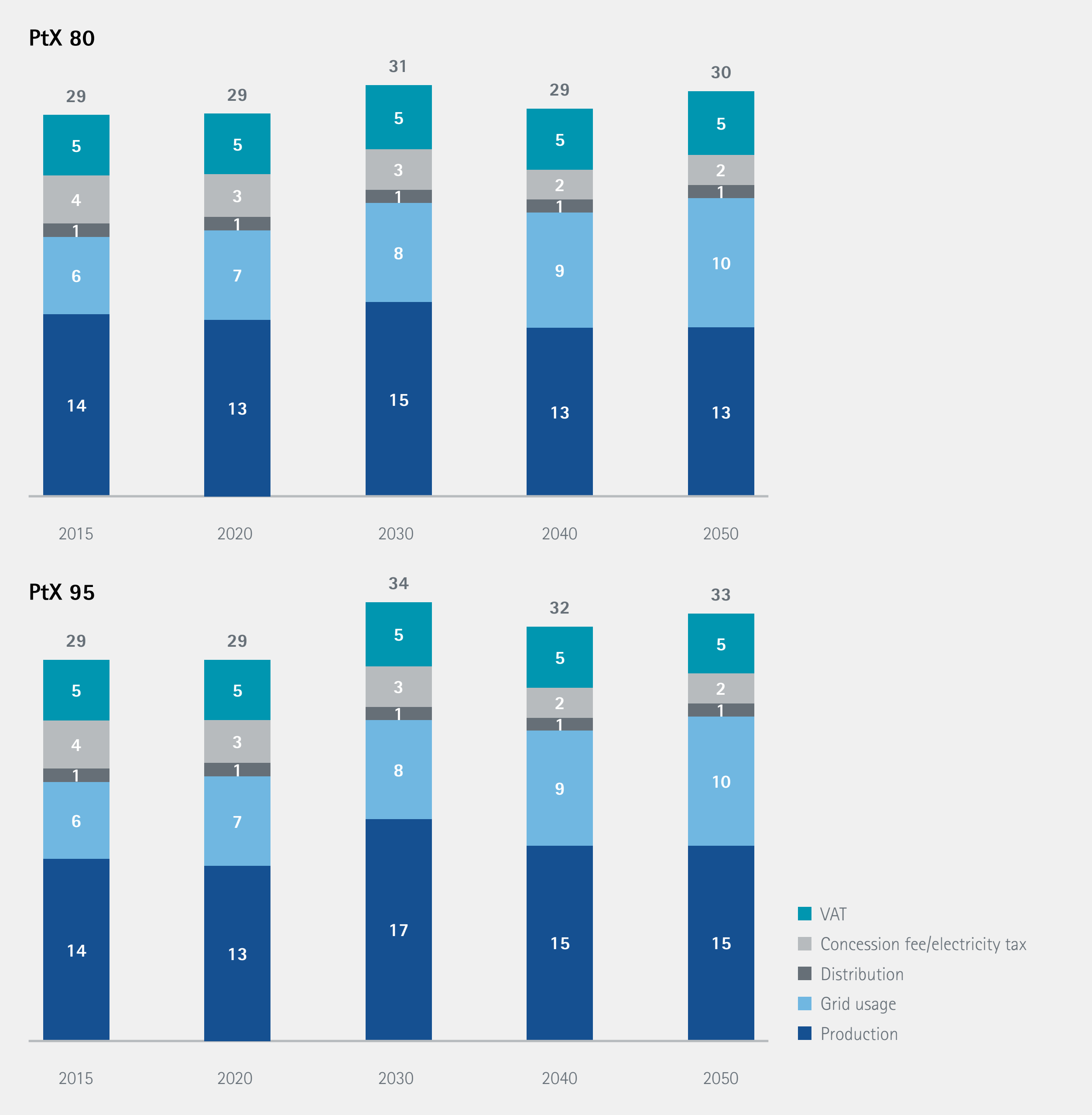
Source: Prognos AG; conventional power plants (PPs) includes the fuel costs of synthetic gas in 2050.

Grids

The grid costs of the electricity system comprise the costs of the existing grid and the additional costs for the transmission grid, the distribution grid (high voltage, medium voltage and low voltage) and for the offshore connection. There are three central drivers for the expansion of the grid: the expansion of renewable energies, which affects all levels of the grid, the development of electromobility with effects on low and medium voltage, and the increased use of heat pumps, which makes it necessary to strengthen the low voltage grid.

At €$_{2015}$ 20 billion, the largest block of grid costs is accounted for by the existing grid. The additional costs in both target scenarios are €$_{2015}$ 11 billion in 2050. Around €$_{2015}$

Figure 29: End customer electricity prices for private households for the PtX 80 and PtX 95 scenarios in $cent_{2015}$ per kWh



Source: Prognos AG

3 billion of this amount is used to expand the distribution grid—primarily driven by the expansion of electromobility. The expansion of the medium voltage grid, primarily due to the expansion of renewable energies, involves around $€_{2015}$ 2 billion. The expansion of the high voltage grid accounts for $€_{2015}$ one billion. The cost increases for the transmission grid and the costs of the offshore connections have been taken from the 2030 grid development plans (2017). They amount to around $€_{2015}$ billion for the transmission grid in 2050 and around $€_{2015}$billion for offshore connections.

In the second step, the costs determined for each voltage level were allocated to the individual consumption groups (private households, CTS, industry) based on the current grid charge structure and a specific cost development was derived for the future grid load of the consumption groups. The development of electricity demand for the consumption groups in the scenarios was used to do so. An index was created from the temporal development of these specific grid costs, and was used to extrapolate the current specific grid costs for private households.

The largest item in the grid costs for private households is the cost of the existing grid. In 2050, these costs still account for almost 80% of grid costs. Around 13% are attributable to additional grid costs due to the expansion of the low-voltage grid (for heat pumps, electromobility and photovoltaics). The remaining 9% results from the expansion of the other voltage levels—including offshore connection. This proportion is comparatively low because it is also supported by the other consumers.

Distribution, concession fee, electricity tax, value added tax

Distribution costs are extrapolated consistently on an actual basis for the calculation of the future electricity prices. The concession fee and electricity tax as well as the energy tax for fossil fuels in the final consumption sectors are kept nominally constant. In the scenarios considered, it is assumed that the regulatory framework for fees and levies remains unchanged from today. In addition, value-added tax was set at a constant 19% over the period under assessment.

The figures below show the end customer electricity prices for private households resulting from these assumptions and calculations in the PtX 80 and PtX95 scenarios. In 2005, the end-customer electricity price in Germany was 20 $cents_{2015}$ per kWh and has since risen to the current level of almost 30 $cents_{2015}$ per kWh, primarily due to the increase in the EEG levy. In both assessed scenarios, the electricity price continues to rise slightly until 2030, to a level of 31 and 34 $cent_{2015}$ per kWh respectively. In both scenarios, the electricity price falls slightly again in the long term after 2030, until 2050.

The end-customer electricity prices shown form the basis for assessing the economic efficiency of individual applications in chapter 8.

5.3 OTHER TRANSFORMATION SECTORS

5.3.1 District Heating

In the assessed scenarios, the demand for district heating and the required district heating generation associated with that increases by about 15% from today to 2030 and then remains at about the same level until 2050. The district heating generation structure changes significantly over time in all three scenarios. District heating generation from coal-fired power plants declines with the gradual decommissioning of coal-fired power plants. This decline is offset in the medium term by increasing district heating generation from gas power plants and increasing proportions of renewable heat generation. In the PtX 80 and PtX 95 scenarios, around 40% of district heating is generated electrically in the long term, mainly by large heat pumps and to a lesser extent by electric boilers. Furthermore, the use of solar and geothermal energy and the use of industrial waste heat to generate district heating increase in the scenarios. The use of biomass declines slightly compared to today due to increasing competition for use.

5.3.2 Refineries

In the energy balance sheet, the provision of mineral oil products to meet demand is covered by two lines. One is the "Mineral oil processing" line that shows the refinery plants for crude oil. In addition, the "Other energy producers" includes the return of mineral oil products from the chemicals industry to the refineries. In the logic of the scenarios, the domestic provision of hydrogen, PtG and PtL syncrude is also listed under "Other energy producers". Therefore, to obtain a complete picture of the supply side for mineral oil and PtX products, both lines must be assessed together. In the PtX 80 scenario, the transformation output of all mineral oil products decreases significantly. However, there is a clear difference between the decline of products used for energy purposes (diesel, petrol, etc.) and products used for material purposes (naphtha and other mineral oil products).

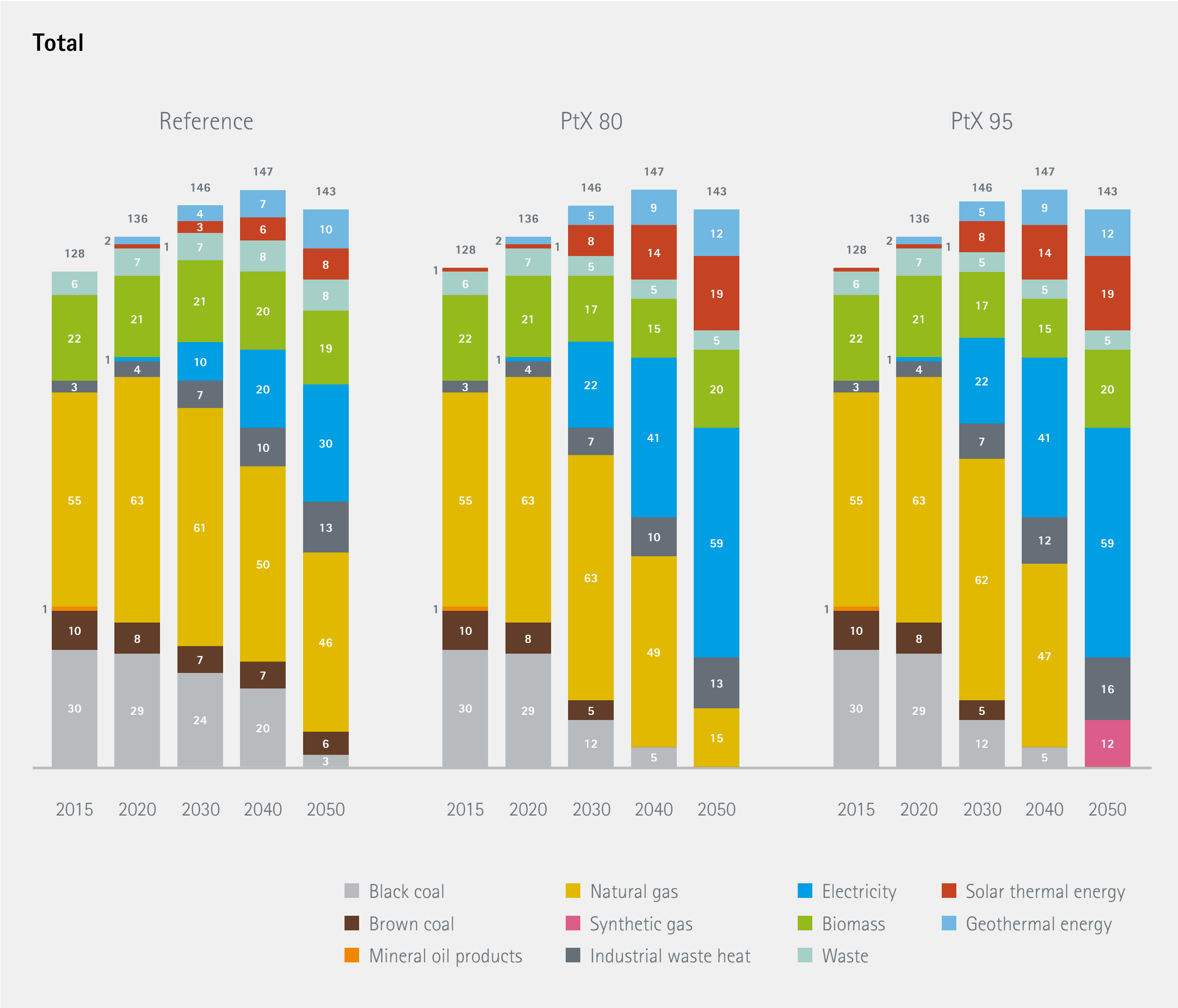
The difference results from the provision of products used for material purposes by refineries, which continue to process some fossil crude oil (see chapters 5.3.2 and 6 for the reasons for this assumption).

In addition, the existing refineries process PtL syncrude into electricity-based fuels that increasingly meet the energy demand for liquid energy sources.

For the chart in table 11, it is irrelevant whether the PtL syncrude and fossil oil are processed in separate or combined plants. According to current estimates, the PtL syncrude can be added up to a certain proportion in the refineries, but modification measures are necessary from a certain proportion onwards, which varies depending on the plant. The extent to which processing takes place in combined or separate plants by the end of the assessment period cannot be conclusively answered.

With regard to the raw material used, imported PtL syncrude is the primary raw material processed. In addition, a small amount of PtL syncrude is produced domestically in pilot plants and is shown as transformation output in table 12. The production of domestic PtG is also based on pilot plants. In addition, a large part of the electricity-based hydrogen demand is still covered domestically.

Figure 30: District heat generation in the reference, PtX 80 and PtX 95 scenarios in TWh



Source: Prognos AG

Due to the decline in demand in all scenarios, refinery processing volumes fall, which also reduces the refineries' self-consumption in all the scenarios. The same applies to emissions caused by the refineries' self-consumption. By about 2030, emissions in the PtX 80 and PtX 95 scenarios are at the same level as in the reference. In both target scenarios, the transformation output decreases more than in the reference; however, the specific self-consumption of the refineries initially increases in a transitional phase due to the blending proportions. The increase is due to the underutilisation of existing plants, which continue to be operated for the processing of conventional crude oils.

In the PtX 95 scenario, emissions are significantly lower than the emissions of the reference and PtX 80 scenario from around 2030 onwards and fall below 0.5 million tonnes by 2050. This development is achieved through the use of CCS in existing oil refineries, which in the PtX 95 scenario provide only material input. Without the use of CCS, the emissions caused by the higher specific self-consumption of these refineries would be roughly at the level of the 80% scenario, with refineries still providing final energy sources.

5.3.3 Waste Incineration

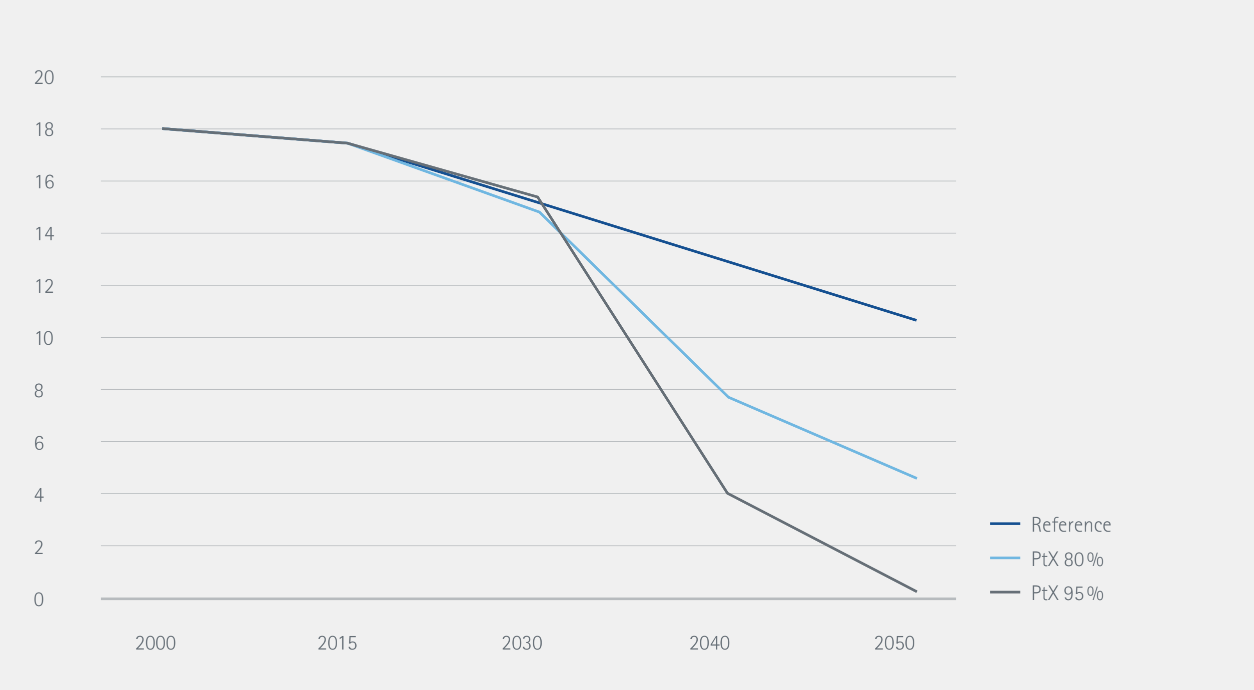
The scenarios assume that plastics contained in products and packaging will continue to be produced from fossil raw materials (see chapter 5). The thermal recycling of waste therefore continues to generate greenhouse gas emissions. Waste that is not based on petrochemical products also generates emissions in waste incineration. In the PtX 80 scenario, these emissions are "tolerated" in 2050. In the PtX 95 scenario, CCS is used in waste incineration to avoid these emissions to the greatest extent possible.

Table 11: Transformation input and transformation output of liquid energy sources and PtX in the PtX 80 scenarios in Germany

	2015	2020	2030	2040	2050	'15–'50 in %
Transformation input in PJ Scenario PtX 80	**4,534**	**4,558**	**4,093**	**3,420**	**2,875**	**-37 %**
Crude oil and mineral oil products	4,534	4,540	3,710	1,748	1,098	-76 %
PtL-Syncrude	0	18	326	1,624	1,681	
Electricity for PtX generation	0	0	4	54	108	
Transformation output in PJ Scenario PtX 80	**4,455**	**4,496**	**3,987**	**3,370**	**2,815**	**-37 %**
Mineral oil products						
Petrol	897	867	711	286	138	-85 %
Naphtha*	454	441	428	412	307	-32 %
Jet fuels	221	247	243	65	20	-91 %
Diesel fuel	1,227	1,327	1,056	261	117	-90 %
Light heating oil	620	599	384	148	81	-87 %
Heavy heating oil	353	356	290	165	103	-81 %
Petroleum coke	60	61	50	23	15	-67 %
Liquid gas	124	79	75	64	46	-64 %
Refinery gas	175	174	140	63	38	-79 %
Other mineral oil products	324	328	278	228	203	-44 %
Total	**4,455**	**4,477**	**3,627**	**1,716**	**1,070**	**-77 %**
PtX						
PtL-Syncrude**	–	–	–	5	10	
Hydrogen	–	–	–	25	53	
PtG	–	–	–	5	11	
PtHEL	–	3	49	24	252	
PtDiesel	–	7	140	739	773	
PtPetrol	–	4	75	349	336	
PtKerosene	–	4	62	229	319	
Total	**–**	**19**	**337**	**1,654**	**1,724**	

Source: Prognos AG. *Theoretically, naphtha can also be produced from PtX. ** This PtL syncrude is manufactured domestically in pilot plants and is therefore listed here.

Figure 31: Emissions development of refineries in the scenarios (excluding refinery power plants) in million tonnes of CO_2e



Source: Prognos AG

6

NON-ENERGY-RELATED CONSUMPTION – THE FUTURE USE OF LIQUID ENERGY SOURCES AS RAW MATERIALS

In the energy balance, non-energy-related consumption (NEC) refers to the quantities of energy sources that are not required for energy use. The majority are mineral oil products and natural gas for material use in the chemical industry (see chapter 3.2). The most important proportion of this is naphtha, which is used in steam crackers, the starting material for numerous plastics, crop protection agents and rubber products. As the basic materials in ammonia production, natural, refinery and liquefied gases form the raw materials for fertilisers and pharmaceutical products. Naphtha can also be used for these purposes.

Other mineral oil products such as light and heavy fuel oils are used for methanol production and industrial carbon black production. Petroleum coke is used in the production of anodes for aluminium production and in steel production. A large number of different mineral oil products are grouped together as "other mineral oil products". They include bitumen for the construction industry (roads, building and civil engineering, sealing materials), lubricants and sealants as well as vaseline, paraffins and speciality fuels. In addition to these products, a small proportion of coal products is also used as material in steel production.

Theoretically, the light proportion of mineral oil products can also be replaced by PtL products. In addition to the approaches considered in this study (PtL, BtL and PBtL), there are also a large number of alternatives to today's material use. For instance, the raw material base could increasingly develop towards the direct use of renewable raw materials in the future, as (Türk 2014) describes. There is also potential and probably also a need to develop towards a higher recycling rate for plastics and other waste streams.

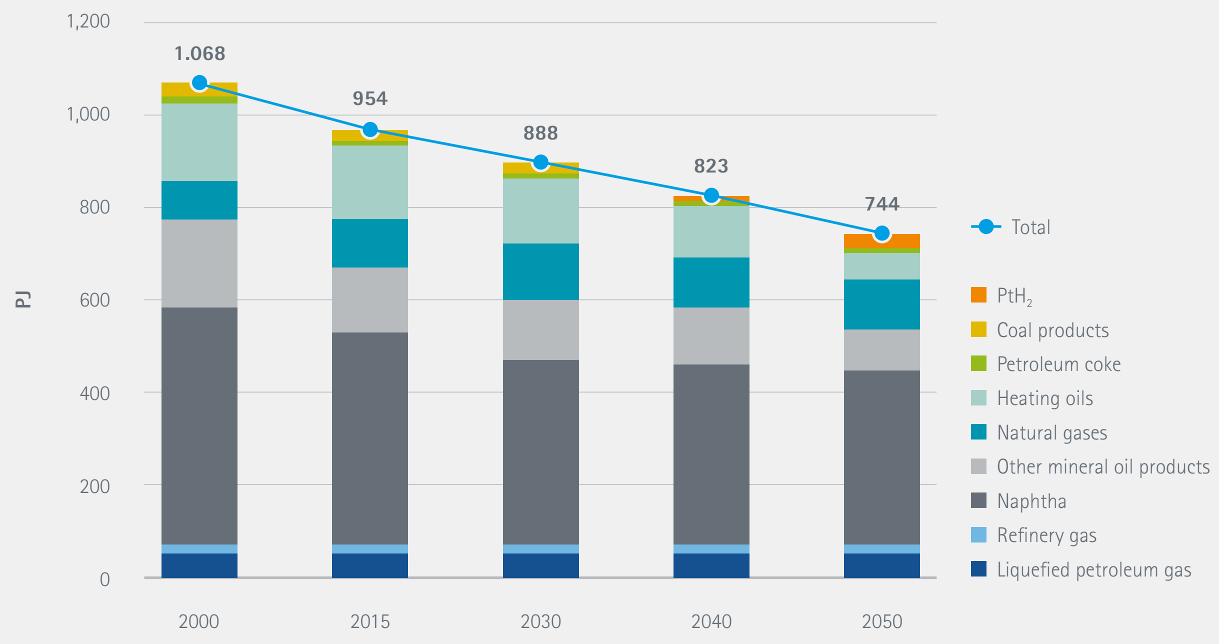
An alternative energy and raw material base to reduce GHG emissions for the European chemicals industry is investigated in (Bazzanella and Ausfelder 2014). The authors of DECHEMA show that the syntheses of chemical raw materials from renewable electricity, water and CO_2 generally have a higher energy requirement and therefore lower efficiency level than syntheses based on fossil raw materials.

In the field of chemical raw materials, the additional costs resulting from the higher energy input have multiple effects on the product price, because they require additional synthesis steps and each synthesis step requires process energy from PtL.

For this reason, the substitution of crude oil-based energy raw materials in non-energy consumption by PtL products is seen as a last option in the scenarios and alternative options for GHG reduction are given preference.

This seems particularly justified against the backdrop of a high level of competition in the global market for chemical products, which means that companies in the chemicals industry are unable to pass the additional costs of PtL input compared to crude oil products on to end customers. In the PtX 80 scenario, the price of crude oil triples by 2050 compared to 2015, and this also suggests that the price of naphtha will triple. However, the PtL costs in 2050 are still 4.3 times higher than the price for naphtha in 2015, which means that the competitive use of PtL in industry would not be possible. Compared to the PtX 80 scenario, the use of PtL products would not lead to a loss of competitiveness in the PtX 95 scenario due to the assumed worldwide climate protection level. However, in this scenario, the crude oil price remains at the 2015 level, meaning that the further use of petroleum-based naphtha in conjunction with CCS is the cheaper alternative.

Figure 32: Non-energy-related consumption: PtX 80 and PtX 95 scenarios in PJ



Source: Prognos AG

PtL is no substitute for the heavy proportion of the mineral oil products used for material purposes: They include, for example, the "other mineral oil products" category. This category primarily includes bitumen, which is used as a sealing material and for road construction. Due to the length of the hydrocarbon chains, these products cannot be produced using the PtL process of Fischer-Tropsch synthesis and must continue to be produced using fossil crude oil.

The development of NEC volumes in the scenarios is based on a production index derived from the development of gross value added in the basic chemicals sector. A moderately rising trend is assumed until 2050. However, as the specific NEC declines compared to the production index, a moderate overall decline in NEC is assumed until 2050. This decline has already been observed between 2000 and 2015 and is also assumed in current industry assessments (see (ExxonMobil 2018)). Within the target scenarios, the same development of NEC is assumed as in the reference. One exception is the use of electricity-based hydrogen, which is used for ammonia production in the PtX scenarios. The proportion of electricity-based hydrogen substitutes the proportion of natural gas in NEC compared to the reference.

The decline in NEC is primarily due to the reduced use of heating oils and natural gases in the chemicals industry. Demand for naphtha and "other mineral oil products" declines only moderately.

7

OVERALL BALANCE

7.1 PRIMARY ENERGY BALANCE

The level of primary energy consumption differs only slightly between the scenarios. Primary energy consumption fell from 14,365 PJ to 13,424 PJ between 2000 and 2015. In the reference development, it drops to 9,241 PJ (-31 % compared to 2015). In the PtX 80 target scenario, primary energy consumption is reduced to 8,998 PJ (-33 % compared to 2015); in the PtX 95 target scenario, it is reduced to 8,875 PJ (-34 %). The greater decline in the target scenarios is mainly due to the development in electricity generation. In the target scenarios, the proportion of comparatively inefficient coal-fired generation is reduced; in addition, less electricity is exported, and towards the end of the assessment period more electricity is imported than exported.

In the reference, primary energy consumption per unit of GDP produced falls from 6.1 MJ/€ to 2.2 MJ/€ (-55 %) in the period from 2000–2050. In the target scenarios, consumption drops to 2.1 MJ/€ (-57 %).

The main differences between the structures of the **energy sources** used in the reference and the target scenarios are as follows:

- The consumption of fossil gases and mineral oils declines more sharply in the target scenarios, which is due to their substitution by synthetic energy sources (PtX).
- The use of **coal** also declines more sharply in the target scenarios, especially lignite. Hard coal remains important in metal production (as a reducing agent).
- On the other hand, **biomass consumption** increases more sharply in the target scenarios. In both target scenarios, the available biomass potential is largely exhausted.
- Towards the end of the period assessed, more **electricity is imported** than exported in the target scenarios (net imports).

There are only minor differences between the scenarios for other renewable energies (including wind, PV, solar thermal and environmental heat). This corresponds to the specifications of the scenario definition with the capped expansion of wind and PV and an identical heating structure in all the scenarios.

Table 12: Primary energy consumption by energy source group, 2000–2050, in PJ, by scenario

	2000	2015	2020	2030	2050	'15–'50 in %
Reference						
Hard coal	1,818	1,480	1,157	1,112	646	-56%
Lignite	1,538	1,555	1,124	712	394	-75%
Mineral oils	5,390	4,397	4,338	3,812	2,709	-38%
Natural gas	3,299	3,197	3,163	3,031	2,458	-23%
Nuclear energy	1,851	1,001	675	0	0	-100%
Electricity (Export/Import)	11	-174	-154	-36	-130	-25%
PtX	0	0	0	0	0	–
Biomass	266	1,202	1,274	1,223	909	-24%
Other renewables	136	573	860	1,266	2,085	264%
Non-renewable waste	56	191	196	193	169	-12%
Total	**14,365**	**13,424**	**12,630**	**11,313**	**9,241**	**-31%**
Scenario PtX 80						
Hard coal	1,818	1,480	1,110	850	284	-81%
Lignite	1,538	1,555	1,105	551	14	-99%
Mineral oils	5,390	4,397	4,256	3,463	986	-78%
Natural gas	3,299	3,197	3,162	2,835	1,057	-67%
Nuclear energy	1,851	1,001	675	0	0	-100%
Electricity (Export/Import)	11	-174	-156	-15	68	-139%
PtX	0	0	29	602	2,712	–
Biomass	266	1,202	1,355	1,293	1,563	30%
Other renewables	136	573	868	1,287	2,132	272%
Non-renewable waste	56	191	222	211	182	-5%
Total	**14,365**	**13,424**	**12,626**	**11,077**	**8,998**	**-33%**
Scenario PtX 95						
Hard coal	1,818	1,480	1,101	750	284	-81%
Lignite	1,538	1,555	1,053	169	14	-99%
Mineral oils	5,390	4,397	4,247	3,401	644	-85%
Natural gas	3,299	3,197	3,157	3,030	364	-89%
Nuclear energy	1,851	1,001	677	0	0	-100%
Electricity (Export/Import)	11	-174	-139	83	181	-204%
PtX	0	0	29	683	3,586	–
Biomass	266	1,202	1,358	1,296	1,481	23%
Other renewables	136	573	870	1,479	2,144	274%
Non-renewable waste	56	191	222	211	178	-7%
Total	**14,365**	**13,424**	**12,575**	**11,103**	**8,875**	**-34%**

Source: Prognos AG

7.2 CONSUMPTION OF MINERAL OIL PRODUCTS AND PTX

The consumption of petroleum products in the reference scenario is shown in table 13. A distinction is made between use in final consumption sectors, use in non-energy consumption (material consumption; see chapter 5) and use in the conversion sector. In terms of **final energy consumption**, only jet fuels and heavy heating oil show increases in consumption during the scenario period. The development of this consumption is strongly influenced by international air and sea traffic (increasing traffic volumes). Consumption of petrol (-323 PJ; -45 %) and diesel (-644 PJ; -43 %) decline sharply. Consumption of petrol has already declined significantly in the past: In the period 2000 to 2015, consumption decreased from 1,253 PJ to 715 PJ. By contrast, diesel consumption rose from 1,264 PJ to 1,499 PJ between 2000 and 2015. The picture for light heating oil is comparable to that of petrol. Between 2000 and 2015, sales fell from around 1,150 PJ to 660 PJ. In the reference scenario, this trend continues, with consumption at around 160 PJ in 2050. Overall, mineral oil consumption in the final consumption sectors decreases by 43 % to approximately 1,950 PJ between 2015 and 2050.

The **non-energetic use** of mineral oils also declines. However, the decline is less than that of final consumption. Material use decreased from 960 PJ in 2000 to 826 PJ in 2015. By 2050, consumption will have fallen to 617 PJ (-25 % compared to 2015).

A small proportion of mineral oil consumption is accounted for by the conversion sector. A small amount of that is used to generate electricity and heat, the remainder is used by the refineries (internal consumption/conversion losses of around 5 %).

In the target scenarios, fossil mineral oils are gradually replaced by greenhouse gas-neutral synthetic energy sources in the **end-consumption sectors**, in line with the assumed blending proportions. Not only fossil mineral oil products, but also fossil gases are substituted.

The use of fossil fuels in **non-energy consumption** (i.e. in the production of raw materials and products (mainly) from oils) does not directly lead to GHG emissions. GHG emissions only arise when these products are thermally recycled as waste. The replacement of fossil raw materials with PtX for non-energy consumption is not absolutely necessary to achieve the targets. Due to economic considerations, comparatively cheaper fossil raw materials therefore continue to be used.

Table 13: Reference scenario: Energy and non-energy-related consumption of mineral oil products in PJ

in PJ	2000	2015	2020	2030	2050	'15–'50 in %
Final energy demand (incl. int. air traffic and shipping)						
Diesel fuel	1,264	1,499	1,550	1,345	855	-43 %
Jet fuels	307	365	390	416	401	10 %
Liquid Gas	42	45	39	23	9	-79 %
Light heating oil	1,149	660	579	351	159	-76 %
Heavy heating oil	166	89	90	112	120	-34 %
Petrol	1,253	715	708	613	392	-45 %
Petroleum coke	8	5	5	4	3	-52 %
Other mineral oil products	12	12	11	11	10	-12 %
Total	**4,203**	**3,391**	**3,372**	**2,875**	**1,948**	**-43 %**
Non-energy-related consumption	**960**	**826**	**788**	**755**	**617**	**-25 %**
Transformation sector	**227**	**180**	**177**	**182**	**144**	**-20 %**
Total consumption of mineral oil	**5,390**	**4,397**	**4,338**	**3,812**	**2,709**	**-38 %**

Source: Prognos AG

Table 14: Use of synthetic energy sources, 2020–2050, by scenario, in PJ

	2000	2030	2040	2050
Scenario PtX 80				
PtDiesel	8	154	760	765
PtG	11	275	945	993
PtH_2	0	1	15	39
PtHEL	4	57	231	237
PtKerosine	2	45	271	329
PtPetrol	4	69	361	350
Total	**29**	**602**	**2,584**	**2,712**
Thereof share of PtL	**61 %**	**54 %**	**63 %**	**62 %**
Scenario PtX 95				
PtDiesel	8	171	914	910
PtG	11	318	1,146	1,528
PtH_2	0	1	17	41
PtHEL	4	63	277	283
PtKerosine	2	51	331	397
PtPetrol	4	79	445	427
Total	**29**	**683**	**3,130**	**3,586**
Thereof share of PtL	**61 %**	**53 %**	**63 %**	**56 %**

Source: Prognos AG

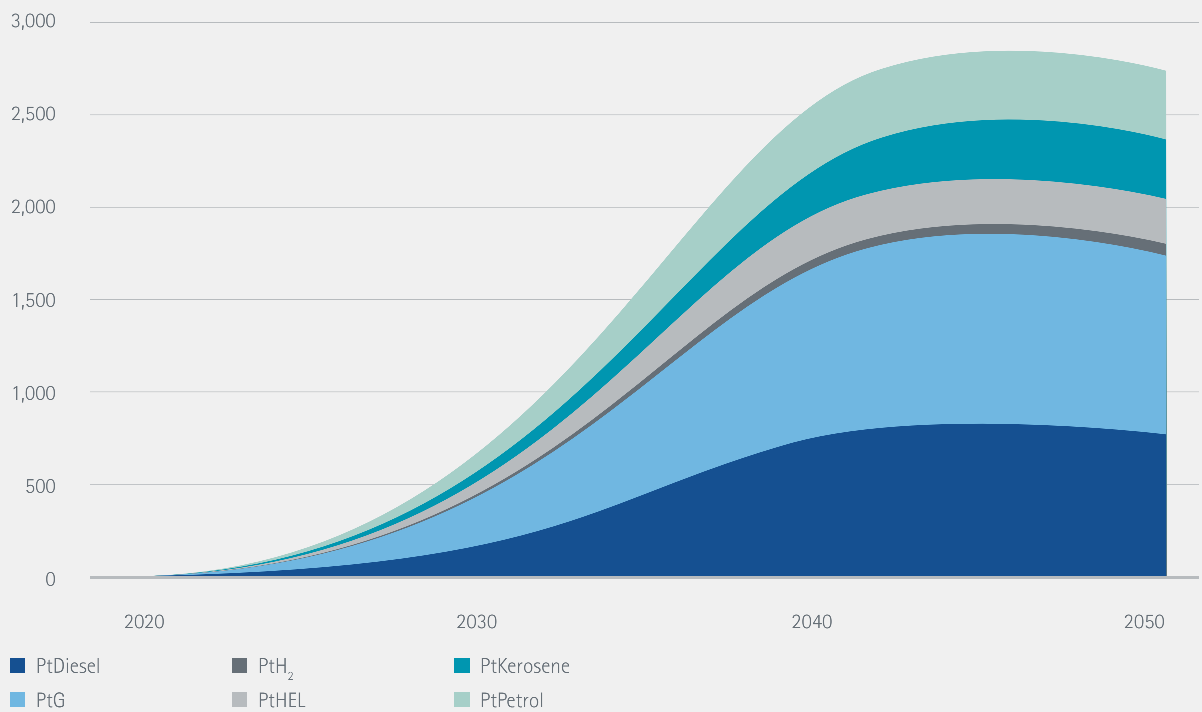
Even if non-energy consumption were to be replaced by synthetic oils and gases, the PtX requirement would be correspondingly higher, by up to an additional 500 PJ PtL.[7] This would make it possible to avoid some of the GHG emissions from waste incineration in the balance. However, since only part of the waste consists of petrochemical raw materials, this measure could not completely reduce CO_2 emissions from waste incineration.

The PtX95 scenario also assumes that CCS provides technology that enables plastics and other products made from mineral oils to be decarbonised "end-of-pipe" at the end of their life cycle. As a result, the use of comparatively more expensive PtL starting materials can be dispensed with. CCS of GHG-neutral synthetic energy sources could generate negative emissions on the balance sheet, which could offset emissions in other areas.

Table 14 describes the total quantities of synthetic energy sources used in the target scenarios. In the PtX 80 scenario, the demand for synthetic energy sources increases to 2,840 PJ in 2045. After 2045, consumption is slightly lower again. The further increase in efficiency and substitution with electricity applications reduces demand to 2,712 PJ in 2050 (figure 33).

Approximately 40 % of the demand for PtX is for gaseous PtX, most of which is synthetic natural gas (PtG). The level of consumption of PtH_2 remains low. Since most of the existing infrastructure can be used, there is no widespread switch to hydrogen drives. Just over 50 % of demand is for motor fuels (PtKerosene, PtDiesel, PtPetrol) and just under 10 % for heating fuels (PtHel).

Figure 33: PtX 80 scenario – use of synthetic energy sources from 2020–2050, in PJ



Source: Prognos AG

In the PtX 95 scenario, the consumption of synthetic energy sources increases to 3,586 PJ in 2050. In the PtX 95 scenario, PtG is also used for electricity generation in the transformation sector from 2045, increasing the proportion of gaseous synthetic energy sources in the PtX 95 scenario to almost 45 % in 2050.

The maximum demand for PtX in the PtX 95 scenario is not reached before 2050. This is due to the additional use in the transformation sector, while consumption in the other sectors declines after 2045, analogous to the -80 % scenario (table 15 and figure 34).

In 2050, most PtX is used in the transport sector and in the household sector (residential buildings). In the PtX 80 scenario, the share of the transport sector in total PtX consumption is 58 % (PtX 95: 53 %) and that of the household sector is 20 % (PtX 95: 18 %). While PtL (especially PtDiesel, PtPetrol and PtKerosene) is used almost exclusively in the transport sector, PtL competes with PtG in the household sector.

For cost reasons, there is no mix with PtX for non-energy-related consumption in the target scenarios; comparatively cheaper fossil raw materials remain the starting materials. One exception is the use of synthetic hydrogen (PtH_2) for ammonia synthesis. This can reduce the use of natural gas for non-energy-related consumption. The amount of synthetic hydrogen used is up to 29 PJ.

Most PtX is used in the transport sector, and around 95 % is liquid PtL. In the PtX 80 scenario, consumption in the transport sector in 2050 is 1,570 PJ; in the PtX 95 scenario, it is 1,884 PJ (table 16, figures 35 and 36). The structure is identical in both target scenarios; the differences between the scenarios are solely due to the different blending proportions. Road traffic accounts for 70 % of the total use of PtX in the transport sector. The development of passenger road transport and freight road transport differ slightly. In passenger transport, maximum PtX demand is reached around 2040, after which demand is significantly reduced again. The main cause is the increasing electrification of private motorised transport. In freight transport, the maximum is reached around 2045. Demand does not change significantly in subsequent years.

The importance of international traffic to PtX volumes sold increases over time. The share increases from 20 % in 2030 to 27 % in 2050.

Table 15: Use of synthetic energy sources in the sectors from 2020–2050, by scenario, in PJ

	2020	2030	2040	2050
Scenario PtX 80				
Commerce, Trade, Services	4	58	283	301
Industry	5	160	300	278
Private households	7	105	507	535
Transport	14	280	1.485	1.570
Transformation sector	0	0	0	0
Non-energy-related consumption	0	0	10	29
Total	**29**	**602**	**2.584**	**2.712**
Scenario PtX 95				
Commerce, Trade, Services	3	65	343	361
Industry	5	189	365	337
Private households	7	117	614	641
Transport	14	313	1.799	1.884
Transformation sector	–	–	–	334
Non-energy-related consumption	–	–	10	29
Total	**29**	**683**	**3.130**	**3.586**

Source: Prognos AG

7.3 GHG BALANCE

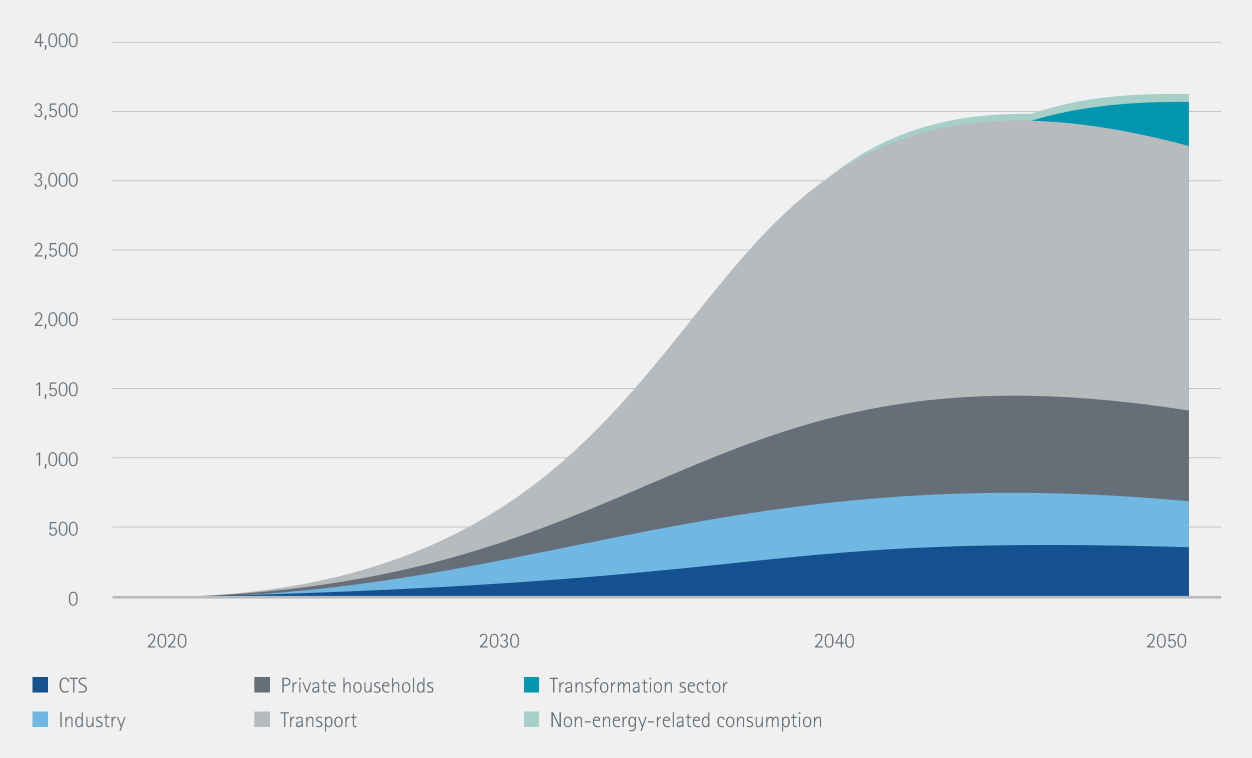
In the reference scenario, GHG emissions fall to 496 million tonnes of CO_2e by 2050 (table 17). Emissions from international air and sea transport are not taken into account. The lower reduction target, a reduction of at least 80 % compared to 1990, is missed by 246 million tonnes of CO_2e in the reference. The largest reductions are in the energy, household and CTS sectors. Emissions in these sectors decrease by around 70 % between 1990–2050. In the industry (-52 %) and transport (-43 %) sectors, the percentage reductions are significantly lower. In the agricultural sector and in industrial processes, emissions have been significantly reduced in the past. In the years up to 2050, however, emissions in these sectors only decrease slightly. High percentage savings have also been achieved in the areas of waste, military and fugitive emissions in the past. In terms of quantity, however, these areas are only of minor importance.

In the PtX 80 target scenario, GHG emissions are reduced to 247 million tonnes of CO_2eq by 2050. This corresponds to a reduction of -80.3 % compared to 1990. The set emission target is achieved (figure 37). In terms of energy-related emissions, the reductions in the household, CTS, transport and energy sectors are all in a range from just under 90 % to 95 %. The reduction in the industrial sector is lower (-75 %). Nearly half of the remaining emissions are in the non-energy sector, particularly agriculture and industrial processes. In agriculture, the emissions are identical to the reference development. In industrial processes, emissions are slightly lower: the use of PtH_2 in ammonia synthesis leads to a reduction here of around 3 million tonnes of CO_2e.

The highly ambitious PtX 95 target scenario aims to reduce GHG emissions to below 65 million tonnes of CO_2eq. Energy efficiency, the heating structure (buildings), but also the drive structure for traffic should develop analogously to the reference. The main strategy for the reduction is to switch to PtX, including for electricity and district heating generation. The proportion of blending increases to 100 % in 2050. In addition, the potential of biomass is fully exploited.

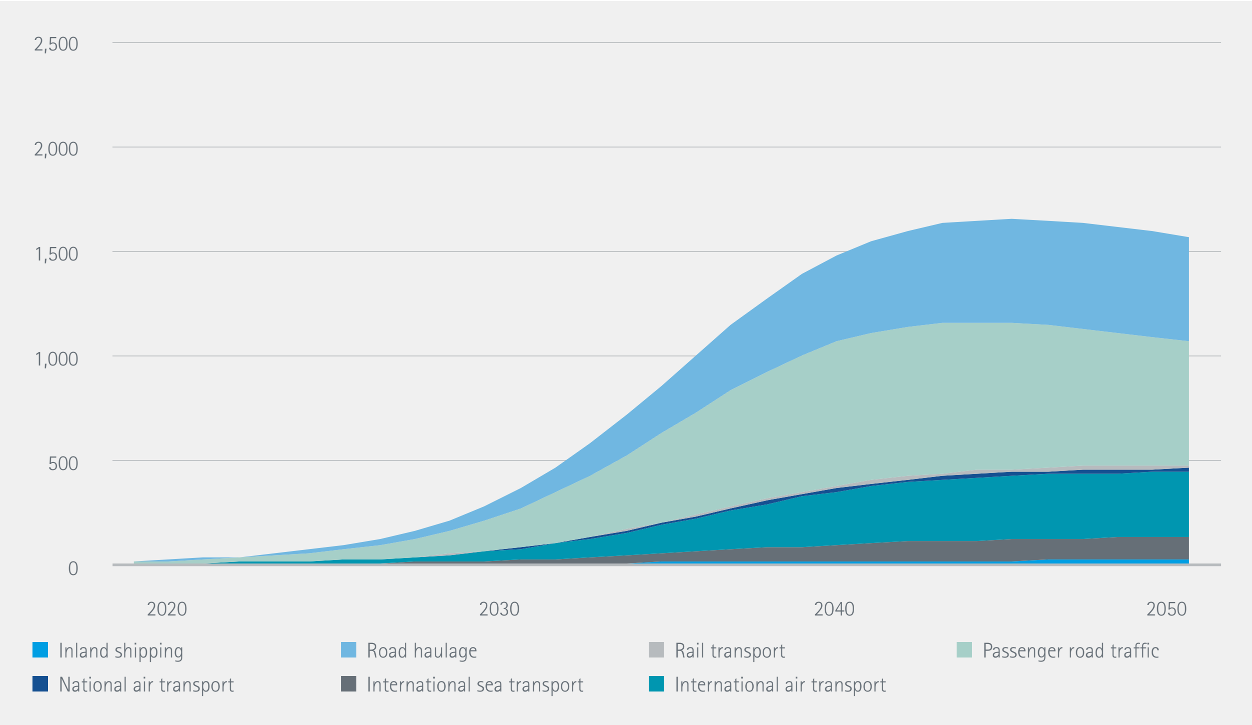
These two measures are not sufficient for a GHG reduction of 95 %. Additional process changes and efficiency measures are needed in the areas of agriculture and industrial

Figure 34: PtX 95 scenario – use of synthetic energy sources from 2020–2050 by sector, in PJ



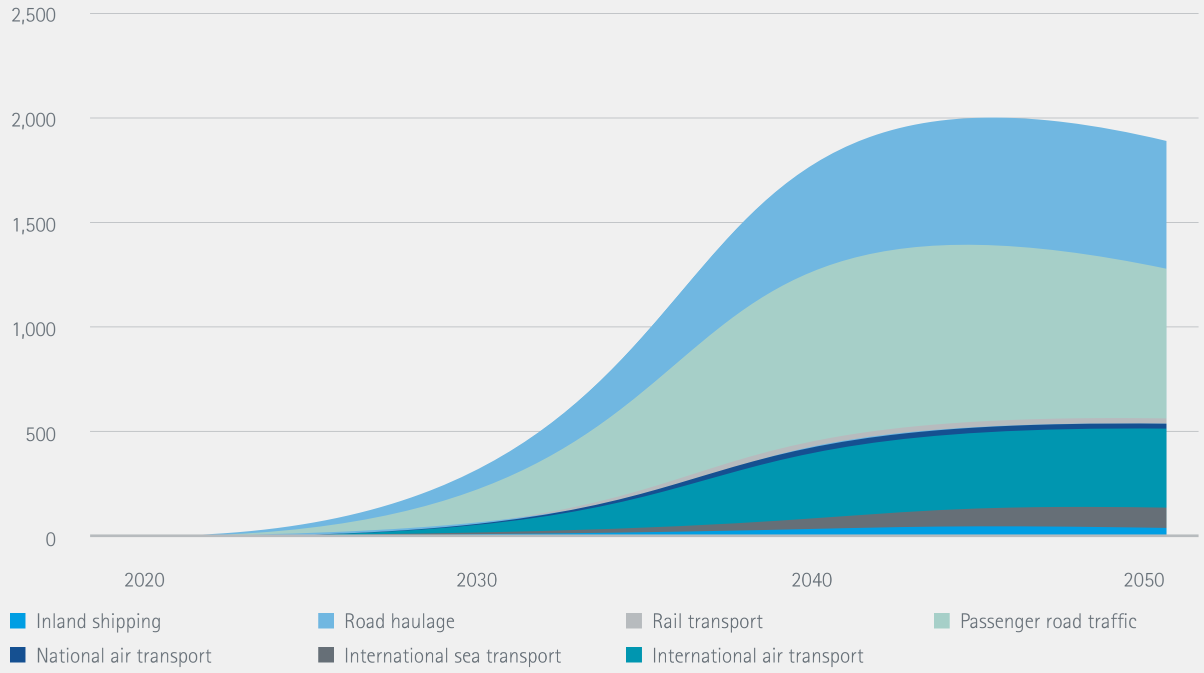
Source: Prognos AG

Figure 35: Transport sector, PtX 80 scenario – use of synthetic energy sources from 2020–2050 by mode of transport, in PJ



Source: Prognos AG

Figure 36: Transport sector, PtX 95 scenario – use of synthetic energy sources from 2020–2050 by mode of transport, in PJ



Source: Prognos AG

processes. The area of agriculture was not separately calculated in this project; the development was taken from an existing study (BCG, Prognos, 2018).

In some processes, including the production of primary steel, PtX does not seem to be a sensible substitute. Following the study by BCG and Prognos (2018), it was decided to capture these emissions using CCS. A possible technical alternative for steel production would be to use hydrogen as a reducing agent instead of coal. This would require far-reaching modifications to the production facilities, which would entail high costs. By using CCS, GHG emissions can be reduced to 71 million tonnes of CO_2eq by 2050 in the -95 % scenario. With a reduction of 94.3 % compared to 1990, the target is almost achieved. The remaining emissions are mainly distributed between agriculture (40 million tonnes of CO_2eq), industry (10 million tonnes of CO_2eq) and industrial processes (12 million tonnes of CO_2eq). In the household, CTS, transport and energy sectors, emissions are almost fully reduced.

Carbon Capture and Storage – CCS

One way to reduce the proliferation of the greenhouse gas CO_2 is to separate it from large emission sources and keep it in long-term storage in deep geological formations. This option is called carbon capture and storage (CCS).

A geological CO_2 store requires porous rock with sufficient pore space to absorb liquid. For the storage of CO_2 to have an impact on the climate, the greenhouse gas must remain underground for at least 10,000 years (BGR 2009).[8] CO_2 can be stored most effectively in the pore space of rocks at a depth of at least 800 m. Due to the prevailing pressure and temperature conditions at these depths, the CO_2 remains in a supercritical phase state. This quasi-liquid CO_2 has a greatly reduced volume compared to the initial gas.

There are a number of different geological storage options, including deep saline aquifers, depleted gas and oil fields, coal seams and salt caverns. The greatest storage potential is assumed to be in deep aquifers, which according to a study by the Wuppertal Institute could contain 2 to 9

8 German Federal Institute for Geosciences and Natural Resources: CO_2 storage (German only), https://www.bgr.bund.de/DE/Themen/Nutzung_tieferer_Untergrund_CO2Speicherung/CO2Speicherung/co2speicherung_node.html

Table 16: Use of synthetic energy sources in the transport sector, 2020–2050, by mode of transport, in PJ

	2020	2030	2040	2050
Scenario PtX 80				
Inland shipping	0	2	13	17
International shipping	0	13	79	112
International air traffic	2	42	257	312
National air traffic	0	3	15	17
Rail transport	0	2	14	18
Passenger road transport	8	145	689	594
Freight road transport	3	72	419	500
Total	**14**	**280**	**1,485**	**1,570**
Thereof share of PtL	**99 %**	**97 %**	**95 %**	**94 %**
Scenario PtX 95				
Inland shipping	0	2	16	20
International shipping	0	15	96	134
International air traffic	2	47	311	374
National air traffic	0	3	18	20
Rail transport	0	2	17	22
Passenger road transport	8	162	834	713
Freight road transport	3	81	507	600
Total	**14**	**313**	**1,799**	**1,884**
Thereof share of PtL	**99 %**	**97 %**	**95 %**	**94 %**

Source: Prognos AG

gigatonnes of CO_2.[9] Based on conservative estimates, the remaining sources could accommodate a further 3 gigatonnes of CO_2.

In the PtX 95 target scenario, CCS is used gradually after 2030. CCS is used in industry, especially in steel production and cement production. CCS is used in electricity generation where non-renewable waste or industrial gases (including blast furnace gas from steel production) are used. These quantities cannot be replaced by synthetic energy sources, or can only be replaced to a very limited extent, because the blast furnace gases are produced anyway. GHG emissions from refineries, which continue to process fossil mineral oils for material use, are also captured by CCS in the PtX 95 scenario. Another possible alternative to the chosen approach would be the use of PtX for non-energy-related consumption. This would reduce emissions from refineries and waste incineration. It would entail higher costs for the chemical starting products. However, CCS could not be dispensed with because emissions are still generated in steel and cement production.

Overall, annual emissions increase to 56 million tonnes of CO_2e by 2050 (table 18). Cumulated over the entire period, this results in a captured amount of 615 million tonnes of CO_2e.

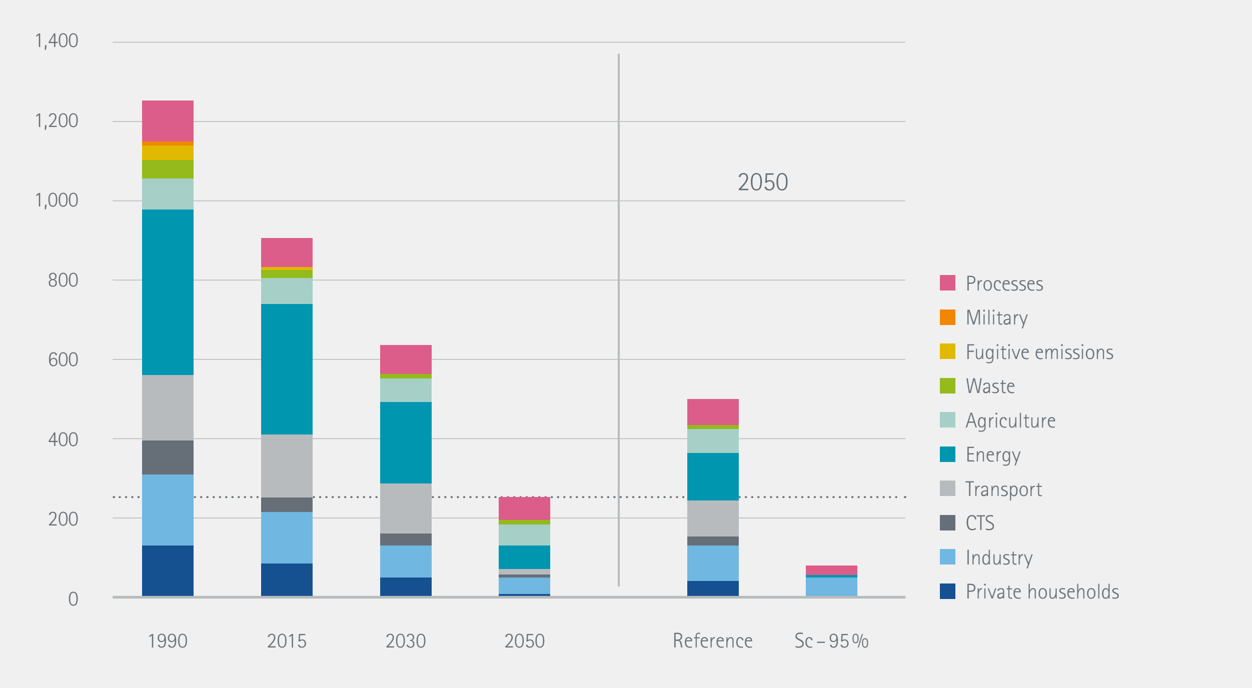
9 Wuppertal Institute for Climate, Environment and Energy (2009) (German only): *CCS – und viele Fragen.* Published in Energie & Management. 15 January 2010

Table 17: GHG emissions by source, 1990 to 2050, in million tonnes CO_2e, by scenario, excluding international traffic

	1990	2015	2020	2030	2050	1990–2050 in %
Reference						
Private households	132	86	80	60	39	-70%
Industry	187	127	101	97	90	-52%
CTS	76	41	42	33	22	-71%
Transportation	164	161	163	145	93	-43%
Energy sector	427	335	274	223	124	-71%
Agriculture	80	67	65	64	60	-25%
Waste sector	38	11	8	4	3	-93%
Fugative emissions	38	11	10	9	7	-81%
Military	12	1	1	1	1	-94%
Process-induced emissions	97	62	62	60	57	-41%
Total	**1,251**	**902**	**806**	**696**	**496**	**-60%**
Scenario PtX 80						
Private households	132	86	80	54	7	-94%
Industry	187	127	100	76	47	-75%
CTS	76	41	41	28	3	-96%
Transportation	164	161	163	135	18	-89%
Energy sector	427	335	273	200	54	-87%
Agriculture	80	67	65	64	60	-25%
Waste sector	38	11	8	4	3	-93%
Fugative emissions	38	11	9	6	1	-96%
Military	12	1	1	1	1	-94%
Process-induced emissions	97	62	62	60	54	-45%
Total	**1,251**	**902**	**802**	**627**	**247**	**-80%**
Scenario PtX 95						
Private households	132	86	80	53	1	-99%
Industry	187	127	100	74	10	-95%
CTS	76	41	42	29	0	-100%
Transportation	164	161	163	133	1	-99%
Energy sector	427	335	264	159	2	-100%
Agriculture	80	67	61	54	40	-50%
Waste sector	38	11	8	4	3	-93%
Fugative emissions	38	11	9	6	1	-98%
Military	12	1	1	1	1	-94%
Process-induced emissions	97	62	56	41	12	-87%
Total	**1,251**	**902**	**784**	**552**	**71**	**-94%**

Source: National trend tables for German reporting of atmospheric emissions 1990–2015, German Environment Agency 2017, new updates by Prognos AG

Figure 37: GHG emissions by source, 1990 to 2050 in the PtX 80 scenario, in million tonnes CO_2e



Source: National trend tables for German reporting of atmospheric emissions 1990–2015, German Environment Agency 2017, new updates by Prognos AG, dotted line: target limit for the -80 % reduction

Not all the CO_2 is captured. Some of the CO_2 emissions escape into the atmosphere despite the CCS. A separation efficiency of 95 % is assumed. The operation of the CCS plants requires energy; induced power consumption increases to 27 TWh. The use of fuel in industry also increases slightly.

7.4 ECONOMIC CLASSIFICATION

The PtX 80 and PtX 95 scenarios show that it is also possible to achieve GHG targets by extensively utilising the infrastructure and the applications on the consumption side and in the infrastructure. The energy costs and the additional investments in infrastructure and applications required in comparison to the reference development are assessed to estimate the direct costs for the energy system in these scenarios. The comparison is made from an overall economic perspective. No second-round effects are taken into account, i.e. effects that result only indirectly from changes in the flow of goods or commodities.

7.4.1 Costs of energy consumption

The **cumulative (totalled) energy costs** in the period from 2015–2050 are assessed. For this purpose, the energy consumption in the scenarios is evaluated using economic energy prices. The border-crossing prices plus the refining costs are also used.[10] Taxes, levies and distribution costs are taken into account in the economic prices. Figure 38 shows the "economic energy costs" used.

Two price paths for the prices of fossil energy sources were defined in the framework data. A reference path with comparatively high prices for fossil energy sources, which are applied in the reference scenario and the PtX 80 scenario. If very ambitious global climate protection targets such as those in the PtX 95 scenario are targeted, the demand for fossil fuels declines more sharply. This leads to lower world market energy prices compared to the reference development. No distinction is made for PtX prices between the two scenarios. The price development corresponds to the derived generation costs. The prices of the upper PtL price path are used (see table 48 in the appendix and chapter 3).

The annual energy costs are made up of the following areas:

- Heating and motor fuel consumption in the four final consumption sectors (households, industry, CTS, transport)
- The transformation input for the generation of electricity and district heating,
- Non-energy-related consumption
- The refineries' self-consumption

By definition, this presentation does not include any costs of capital. The environmental heat used (ambient heat, solar radiation) and wind energy do not result in any energy costs. However, the infrastructure costs are taken into account unless they are already included in the reference development (see the next chapter).[11]

In the reference development, annual energy costs remain almost constant at around € 100 billion until 2040, and decrease to around € 85 billion annually after 2040. The decline is mainly due to declining demand for diesel and petrol.

In the PtX 80 scenario, annual energy costs rise to over € 180 billion in 2040. The increase is mainly due to the increasing blending of more expensive PtX energy sources. After 2040, with the expected decline in production costs for PtX, annual energy costs also decrease. They fall back below € 160 billion in 2050.

In the PtX 95 scenario, highly ambitious climate protection and lower world market prices for fossil fuels are assumed (including internationally). As a result of these lower prices, energy costs initially rise less sharply than in the PtX 80 scenario with the higher world market prices. Due to the higher blending proportions, however, the annual energy costs are higher in the PtX 95 scenario than in the PtX 80 scenario from 2040 onwards.

If the annual energy costs for the years 2015–2050 are cumulated, the total energy costs are € 3,400 billion for the reference scenario and € 4,900 billion for the PtX 80 scenario. The reduction in GHG emissions to -80% compared to 1990, which is greater than the reference development where the target is not achieved, therefore increases the cumulated energy costs by € 1,500 billion (+44%; figure 39).

If the PtX 95 scenario were based on the same world market prices for energy as the PtX 80 scenario (see 4.2), the cumulative additional costs for energy would amount to € 1,800 billion (+53% compared to the reference). This is shown in the third column in figure 39 ("high WMP").

However, based on our assumptions in the PtX 95 scenario, global climate protection reduces the prices of fossil energy sources. In the PtX 95 scenario, the total energy costs for the years 2015–2050 are therefore even slightly lower than in the PtX 80 scenario, although more PtL is used. In total, the cumulative costs are € 1,400 billion higher than in the reference scenario where the target is not achieved.

7.4.2 Required Investment in Germany

For methodological reasons, the investments cannot be specified in the reference scenario. Therefore, the analysis of investments in the PtX 80 and PtX 95 scenarios focuses on the question of which investments must be made **in addition** to the reference scenario. In contrast to energy costs, the additional costs arising from higher investments in the PtX 80 and PtX 95 scenarios are relatively low. This is mainly due to the fact that the existing infrastructure and applications can continue to be used by the end user. Investments are made in the transformation sector because the refineries have to be adapted to the blending of PtL syncrude. To do so, the plants need to be upgraded, especially with the increased of PtL syncrude (see the chapter "Refineries in Germany"). In the 80% scenario, around € 4.5 billion is required for this upgrade work. In the PtX 95 scenario, upgrade costs increase to around € 6 billion due to the higher proportion of blending. In addition to the costs in the refinery sector, higher investments than the reference are made in the electricity sector even though the proportion of renewable energies remains the same in 2050.

11 Since the expansion of wind energy and photovoltaics in the scenario definitions for the PtX 80 and PtX 95 scenarios does not extend beyond the expansion in the reference scenario, no additional investment costs for renewable electricity are required in Germany.

Table 18: CCS in scenario PtX 95 – annual GHG emissions by sector in million tonnes CO_2e and induced power consumption in terrawatt hours (TWh)

	2035	2040	2045	2050
Industry	10	19	28	36
Electricity generation	4	7	11	15
Refineries	3	4	4	5
Total	**16**	**30**	**43**	**56**
Power consumption, TWh	**8**	**14**	**21**	**27**

Source: Prognos AG

In the 80% scenario, the replacement of 18 GW of coal-fired power plants by gas-fired power plants, as well as the earlier expansion of renewable energies, leads to an increase in investments of € 34 billion. In the PtX 95 scenario, the additional investments increase only slightly.

In the PtX 95 scenario, CCS is used to avoid emissions in the transformation sector and in industry. This results in investments of around € 2 billion in the transformation sector for waste and blast furnace gas incineration. CCS is also used for the remaining emissions in the refinery sector, which requires investments of around € 2.5 billion. This does not include the operating costs, which amount to around € 1.5 billion per year during operation.

By comparison, in the industrial sector, steel and cement production for CCS involves significantly higher investments. The necessary investments here amount to around € 18.5 billion. Also not included are the operating costs, which amount to around € 11 billion over the assessment period.

In the 80% scenario, investments for domestic PtX plants amount to around € 5 billion. This figure covers the plants to meet the additional hydrogen demand and the pilot plants for electricity-based PtL syncrude and synthetic methane. In the 95% scenario, the investments are roughly € 1 billion and therefore lower than in the 80% scenario. The reason for this is that there is no production of domestic PtL or electricity-based methane and fewer domestic hydrogen production plants are required. The lower investments in domestic PtX plants in the PtX 95 scenario are due to the fact that CCS is used as the technology in this scenario, which was asserted to be excluded in the PtX 80 scenario.

7.4.3 Investment and Other Effects Abroad

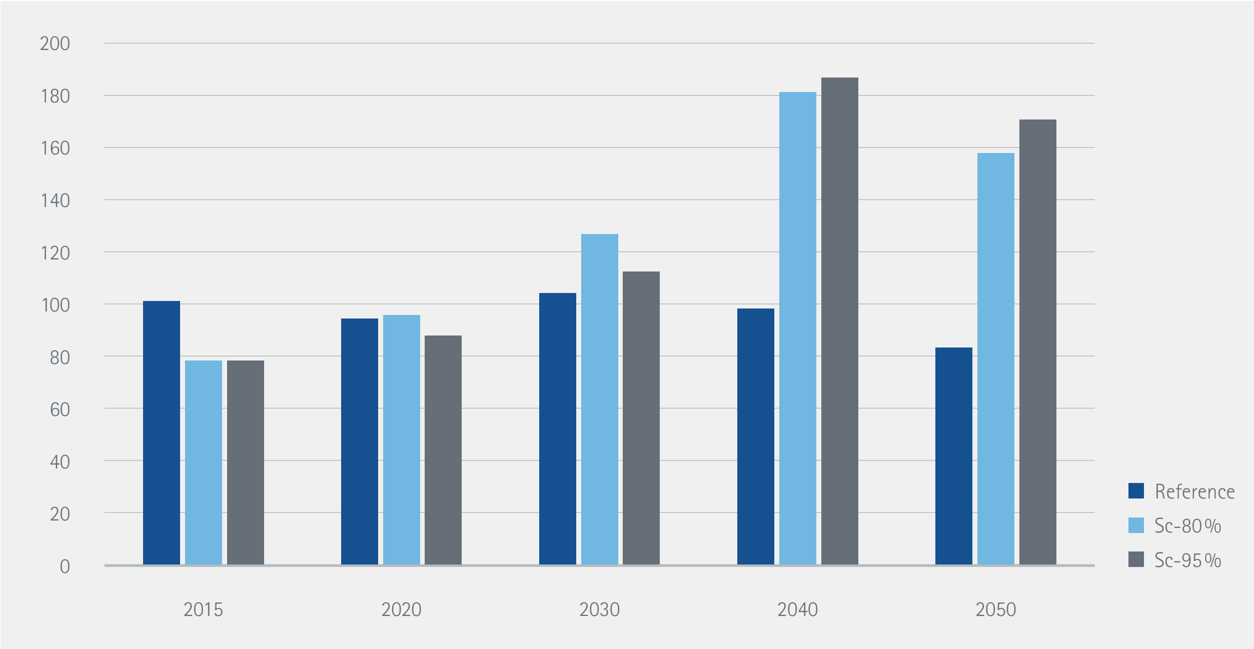
For the overall assessment, it is important to point out that considerable investments have to be made in the countries where the greenhouse gas-neutral PtL or PtG motor and heating fuels are to be produced on a large scale. To estimate the level of investment, we assume that climate protection efforts will be consistent, at least across Europe. In this respect, it can be assumed in a first approximation that the other European countries will also trigger investments in PtX production plants. Only with these investments will the corresponding learning effects be triggered and will the cost reductions identified in this study be achieved.

The demand for PtX for Germany in 2050 was determined to be 2,713 PJ in the PtX 80 scenario and 3,586 PJ in the PtX 95 scenario. To produce this amount of PtX, cumulative foreign investments of € 1,440 billion or € 1,840 billion in the period from 2020–2050 would be required, based on the assumptions made as shown in table 20.

For comparison: Morocco's GDP in 2016 was € 91 billion, while Algeria's was € 141 billion and Kazakhstan's was € 121 billion (at an exchange rate of $1.11/€).

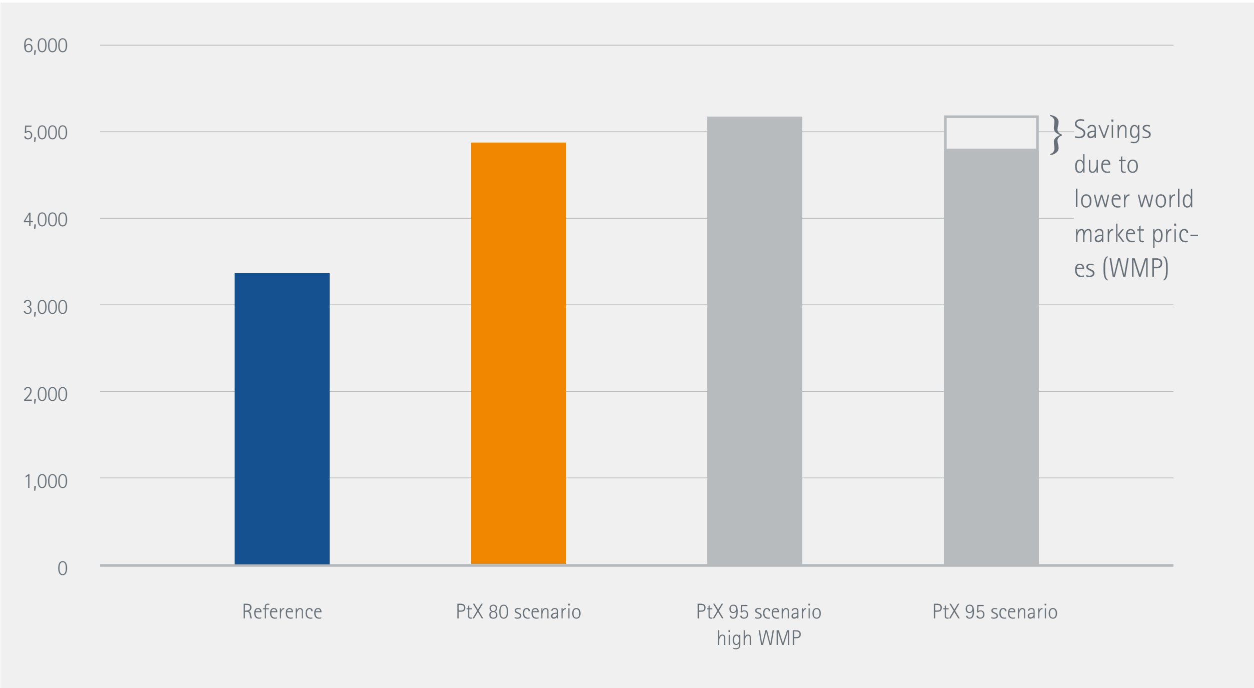
This comparison alone shows that the path to large-scale PtX production described in our scenarios would have considerable economic effects in the countries in our search area. However, without a differentiated analysis, it is not yet possible to predict in detail what these effects might look like (e.g. what proportion of investments leads to value added in the producer countries).

Figure 38: Annual energy carrier costs in billion € (actual 2015) valued at border-crossing prices*, basis for higher PtL price path



Source: Prognos AG, *including refinement

Figure 39: Cumulative economic energy costs between 2015–2050 in billion € (actual 2015), basis for higher PtL price path



Source: Prognos AG

Table 19: Estimated additional investments in Germany compared to the reference, cumulated until 2050

	Scenario PtX 80 Additional investments compared to the reference in billion €	Scenario PtX 95 Additional investments compared to the reference in billion €"
Power supply	24	29
Refinery plant modification	5	6
CCS	–	23
National PtX generation	5	1
Total	**34**	**59**

Source: Prognos AG

A further analysis of the effects abroad should also show that the production of PtL and PtG opens up future opportunities for countries that currently derive a large part of their revenues from the sale of fossil hydrocarbons. Without these perspectives, these countries are less likely to support global climate protection policy. They may also have a competitive advantage, because some of their export infrastructure can continue to be used.

The comparison also gives an indication of the high rates of expansion that have to be achieved by the generation plants in the search area: In the PtX 80 scenario, annual generation capacities of around 30 GW of onshore wind and 9 GW of solar PV must be built between 2030–2050 to meet the blending quotas set for Germany. In the PtX 95 scenario, 40 GW of onshore wind and 13 GW of solar PV per year are required in the same period. Much of the expansion is concentrated in the phase between 2030 and 2040, in line with the assumed strong increase in the blending proportions in this decade (see figure 7).

The question of whether there is enough space available for the necessary facilities in the search area countries was not examined in depth. In particular, the area required for CO_2 direct air capture is currently still unclear. Prognos has estimated the area required for the wind and solar plants needed to realise the investments in table 20, as shown in table 21.

For the wind and solar plants alone, approx. 41,000 km² would be required in the PtX 80 scenario and 53,000 km² would be required in the PtX 95 scenario. If the plants were partly built on overlapping areas, the area required could be reduced to approx. 37,000 km² and 48,000 km² respectively.

Table 20: Estimated investments resulting from German PtX demand abroad by scenario, cumulated until 2050

	Szcenario PtX 80 Estimated investments in billion €	Share	Szcenario PtX 95 Estimated investments in billion €	Share
Wind and solar parks	860	60 %	1,130	61 %
Electrolysis	380	26 %	470	26 %
CO2-Capture	130	9 %	160	9 %
Synthesis plants	50	3 %	60	3 %
Seawater desalination	< 1	< 1 %	< 1	< 1 %
Storage facilities	16	1 %	20	1 %
Total	**1,440**	**100 %**	**1,840**	**100 %**

Source: Estimates/calculations by Prognos AG

Table 21: Estimated surface area required to generate German PtX demand by scenario

Estimated surface in km²	PtX 80	PtX 95
Wind parks	37,000	48,000
Solar parks	4,000	5,000
All other components	Not analysed	
Total	**Not analysed**	

Source: Prognos AG

For comparison: Morocco covers 446,000 km², Algeria 2,382,000 km² and Kazakhstan 2,725,000 km².

If, similar to the procedure described here, it is assumed that the **European** oil and gas demand from the EU 2016 reference scenario (European Commission 2016) is also covered to a large extent by synthetic oil and gas as per the blending proportions from the 95 % scenario, the required electricity generation plants would take up a total area of around 523,000 km².

7.4.4 Total Costs and Classification

In the overall assessment of costs from a domestic perspective, the energy costs, which rise gradually in our PtX scenarios and which towards the end of the assessment period are about twice as high as in the reference scenario, are of particular importance. On the other hand, the investments required in Germany do not reach this magnitude, because most of the existing infrastructure and applications can be used. If energy costs and investments are totalled over the entire assessment period, the additional costs compared to the reference scenario amount to € 1,534 billion in the PtX 80 scenario and € 1,459 billion in the PtX 95 scenario. The lower costs in the PtX 95 scenario can be explained by the lower prices of fossil energy sources, which is used in the PtX scenario due to the ambitious climate protection.

An economic evaluation of the effects on gross domestic product was not carried out.

As we have shown, the investments in our scenarios are made primarily abroad. This creates an economic opportunity for German technology manufacturers, especially if the PtL technology path is developed in good time in Germany. However, it is not possible to assess the macroeconomic effects without an in-depth examination of the external economic relationships.

8

THE PERSPECTIVE OF THE CONSUMER

8.1 INTRODUCTION

Studies on a country's energy development usually do not focus on the **consumer perspective**. What is optimal from an economic point of view can, but does not have to, agree with the individual preferences of consumers. This is exemplified by the development of electromobility: Although the German government considers the development of electric mobility to be a top priority and thus set a target of 1 million electric vehicles for 2020, the number of vehicles has so far fallen short of expectations. There may be a number of reasons for this, such as lack of infrastructure or lack of models. So far, it has not been possible to convince enough consumers to buy battery-powered-only vehicles.

Often an economic incentive is not enough to help a new technology break through. One example of this is natural gas-powered vehicles, which would have been economically advantageous for many drivers because of their tax exemption. However, they were not able to establish themselves on the market.

Products are successful if they receive a positive assessment in the **overall assessment** by consumers. In addition to economic aspects, criteria such as usability ("usage aspects"), environment and emotional aspects are also included in this overall evaluation.

From a scientific point of view (and without a broad empirical basis), only part of such criteria can be analysed. Emotional aspects, which play an important role in the decision to purchase, are difficult to describe analytically.

The following criteria evaluation attempts to **compare the most important technologies** in residential heating and mobility from the point of view of consumers[12] The comparison focuses on liquid energy carriers, but similar arguments could also be made for gaseous energy carriers.

The criteria examined are:

- economic efficiency
- aspects of use
- surroundings

Other criteria that may be decisive for purchasing were ignored, either because they cannot be measured or because they play no role in the comparison between electricity-based and fuel-based systems (e.g. comfort).

The PtX 80 scenario is at the heart of considerations to prevent the number of cases from becoming too large.

8.2 ECONOMIC EFFICIENCY

8.2.1 Heat Supply in Existing Residential Buildings

The following sample calculations are based on the installation of a new heating system in existing residential buildings. The oil heating and electric heat pump systems are compared, whereby increasing amounts of PtL are gradually added to the oil heating system. Amounts vary in the sample calculations. The comparison takes the following variables into account, among other variables:

- The use in various types of residential buildings, including single-family and double-family houses, row houses and multi-family houses
- Various analysis times (e.g., per decade in 2030, 2040, 2050) with mixtures containing different proportions of PtL, different energy carrier prices and different technical status of the systems

12 The perspective of the private consumer was taken into account in the economic efficiency comparison. In the criteria grids in the mobility sector, light and heavy commercial vehicles, which are more likely to be used commercially, are also assessed.

Table 22: Selected building types and their significance in the German housing market

Building type	IWU-Nr.	construction year	Number of dwellings in thousand	Share in dwellings in %	Living space in million m²	Share in living space in %
DFH	EFH_E	1958–1968	1,948	5 %	218	6 %
SFH	EFH_H	1984–1994	1,397	4 %	178	5 %
RH	RH_C	1919–1948	840	2 %	125	4 %
MFH	MFH_E	1958–1968	3,348	9 %	225	6 %
MFH	MFH_H	1984–1994	1,826	5 %	133	4 %

Source: IWU 2011, TABULA – Typology of German residential buildings

- Existing buildings with varying levels of energy quality, including partially renovated buildings with higher consumption and energy-related renovations in buildings with comparatively low consumption.

New buildings are not included in the comparison. The comparison date is based on the year in which the investment is made in the new system. The comparison is made by a private investor. The annual costs for energy, system and capital costs serve as a figure for comparison.

- The cost of purchased energy is calculated from the annual energy consumption and the price of the energy carrier in the year under review [13]

- The investment for the new system and the cost of capital are converted into annuities (amounts remain constant annually).

A service life of 25 years and an interest rate of 4 % for the cost of capital are used as the basis for calculating the investment annuities. Upkeep costs, e.g. maintenance-related, chimney sweeper, disposal costs (e.g. for the tank), are not taken into account in the cost analysis. All calculations are made in real prices.

The installation of climate-friendly heating systems, including heat pumps, is being promoted by the market incentive programme, for example. No funding programmes were taken into account in the following sample calculations.

Hybrid heating systems are not considered in the comparison, e.g. a heating, oil and PtL combination system with solar thermal support or the combination of an oil condensing boiler with a heat pump. The advantage of hybrid heating systems using oil condensing boilers and heat pumps is that no additional electricity is necessary at times with high heating requirements but also a low supply of renewable electricity (e.g., in cold, dark seasons), as the storable liquid energy source can be used in these times. In existing buildings with poorer insulation, hybrid heaters can also compensate for the inherent disadvantage of a heat pump with poorer efficiency when outside temperatures are low and the high system temperatures associated with this by operating the condensing unit.

Selected model buildings

The calculations are based on model buildings using the building typology from the Institute for Housing and Environment (IWU). Five model buildings were selected, which on the one hand represent different building types and on the other hand have a high relevance in terms of the number of residential building. The following table describes the selected model buildings and their representativeness in the German housing market.

For the different model buildings, the IWU building typology describes, among other things, the size, cubic content and energy quality of the components as well as the energy requirements for space heating, hot water and building technology. Since the analysis dates are in the distant future (2030–2050), the initial values of the components were adjusted and provided with various states of renovation. Insulation for two buildings was assumed to be in accordance with EnEV 2009. For the other three buildings, some components were left in their original condition, while others were renovated in accordance with the requirements of EnEV 2002 (i.e., partially renovated buildings). The calculation of the energy requirements of the adapted

13 Only the price of energy for the year under review is used for the energy prices. In cases where energy prices increase over time, average energy costs, which are averaged over the service life of the system, are underestimated.

Table 23: Description of the selected sample buildings, dimensioning and consumption

Building type	IWU-Nr.	Construction year	condition	Living space in m²	Number of dwellings	specific consumption in kWh/m
DFH	EFH_E	1958–1968	partially renovated	242	2	180
SFH	EFH_H	1984–1994	renovated	137	1	117
RH	RH_C	1919–1948	partially renovated	103	1	164
MFH large	MFH_E	1958–1968	partially renovated	2,845	32	139
MFH	MFH_H	1984–1994	renovated	707	8	98

Source: IWU 2011, TABULA – Typology of German residential buildings and own calculations

model buildings was carried out using a building simulation tool, which takes into account not only the dimensioning and energy quality of the components, but also distribution losses and heat gains. The resulting key energy figures and the characterisation of the model buildings are described in the following table.

Heating systems

a) Oil boiler

In the case of oil boilers, condensing boilers with a high annual efficiency are taken into account. An annual efficiency of 0.98 was used for generating space heating. A lower degree of utilisation is used for generating hot water (0.85) due to storage and distribution losses. No further technological improvements are foreseeable. The degrees of efficiency are identical across all points of time considered. A degression of costs is not taken into consideration for system costs. These remain constant in real terms. The dimensioning of the system depends on the calculated annual consumption in the buildings. The parameters of the oil heaters used in the five model buildings are described in Table 24.

b) Electric heat pump

The relevant heat pumps (HP) use the outside air as a heat source; there is no need to drill and install a geothermal probe. The annual performance factor (APF) for room heating depends on the power status of the model buildings. In poorly insulated buildings, a higher flow temperature is required, which has a negative effect on system efficiency. The annual performance factor also depends on the time of installation. Further increases in annual utilisation rates due to technological development and maturation are expected.

The efficiency of hot water generation is also lower for HPs than for space heating. An APF of 2.5 is used for all years and system types. Similar to the procedure for oil heating systems, the dimensioning of the systems is dependent on annual consumption in the building (identical system outputs for both systems). No degression of the system costs is assumed for the HPs. In addition to the system costs, costs of € 40/m² are taken into account for adjusting the heat distribution and radiators. These contain, for example, the enlargement of the radiator surfaces; however, the installation of underfloor heating is not a precondition.

Table 24: Performance characteristics of the oil-fired boilers considered, by sample building

Building type	Plant size in kW therm.	System cost in €	Cost per kW in €	Annuity in €
DFH	20	11,269	563	721
SFH	11	10,400	945	666
RH	11	10,400	945	666
MFH large	170	27,920	164	1,787
MFH	35	16,680	477	1,068

Source: Cost values based on the BDEW (Federal Association of the German Energy and Water Industries) comparison of heating costs for pre-war buildings 2017 and BMVBS (German Federal Ministry of Transport, Building and Urban Development) 2012

Table 25: Development of annual performance figures for air-source heat pumps based on the energetic condition of the buildings and assessment time

	2015	2030	2040	2050
Renovated	3.0	3.3	3.5	3.7
Partially renovated	2.5	2.7	2.85	3.0
New building (not used)	3.5	3.8	4.0	4.2

Source: BCG, Prognos 2018, based on an assessment by dena, own projects for partially renovated buildings

Consumer prices for energy

The energy prices used in the sample invoices are real retail prices including sales margins, grid costs, taxes and duties (Table 27). They are based on the world market prices assumed in the general data and the cost developments for PtL and electricity described in the previous chapters. The basic comparison is based on the PtX 80 scenario. The blending proportions for PtL, the world market prices for energy and the electricity prices for households are taken from this comparison. PtL costs are initially expected to be higher, with production costs of € 1.33 per litre in 2050. In one sensitivity analysis, the comparison with the low power-to-liquid production costs of € 0.7/litre in 2050 was subsequently made.

It was assumed that the energy tax on heating oil would not be adjusted over time and would remain at current levels in nominal terms.

Today, many distributors offer special heat pump tariffs that are cheaper than the average household electricity prices. These were not taken into account in the calculation of economic efficiency.

Results: higher PtL production costs

The results of the cost comparison for the five model buildings with a higher PtL price path are shown in Table 28. The system costs including the costs for adjusted heat distribution and the capital costs are identical across all points in time, as cost degression is not assumed for either system.

With the heating oil PtL solution, energy costs increase along with increasing blending proportions. Between 2040 and 2050, however, energy costs will increase comparatively little, since the cost reduction in PtL synthesis counteracts the increasing blending proportions. Energy costs for heat pumps decrease over time. This is due to technical progress and the resulting higher annual utilisation rates. In addition, the price of electricity will fall again after 2030.

In 2030, the heating oil PtL system will be the more economical solution from a private-sector perspective without taking incentives into account. The annual costs are 23 % lower on average.

In the years following 2030, the cost advantage decreases due to the increasing PtL blending proportions. In 2040, with a blending proportion of 65 %, the HP will be the more

Table 26: Performance characteristics of the heat pumps considered, by sample building, plant costs without the heat distribution proportion, annuity incl. costs for heat distribution

Building type	Plant size in kW therm.	System cost in €	Cost per kW in €	Annuity in €
ZFH	20	24,580	1,229	2,186
EFH	11	19,200	1,745	1,575
RH	11	19,200	1,745	1,488
MFH groß	170	68,120	401	11,558
MFH	35	34,015	972	3,966

Source: Cost values based on the BDEW (Federal Association of the German Energy and Water Industries) comparison of heating costs for pre-war buildings 2017 and BMVBS (German Federal Ministry of Transport, Building and Urban Development) 2012

Table 27: End consumer prices for heating oil, PtL and electricity, in € cent/kWh, actual 2015 prices, basis for higher PtL price path, electricity price based on PtX 80 scenario

	Unit	2015	2030	2040	2050
Heating oil	Cent/kWh	6.0	8.9	9.5	9.3
PtL (higher price)	Cent/kWh	64.0	24.8	22.1	19.4
Blending proportions	%	0 %	10.9 %	65.1 %	82.5 %
HEL-PtL-mixed price	Cent/kWh	6.0	10.6	17.8	17.6
Electricity	Cent/kWh	28.7	30.7	28.5	29.1

Source: Own calculations

economical solution. The annual costs are between 16 % and 42 % lower for the HP. In the case of small buildings, system costs are more important. The cost differences between the systems are less than in the case of larger buildings with larger systems.

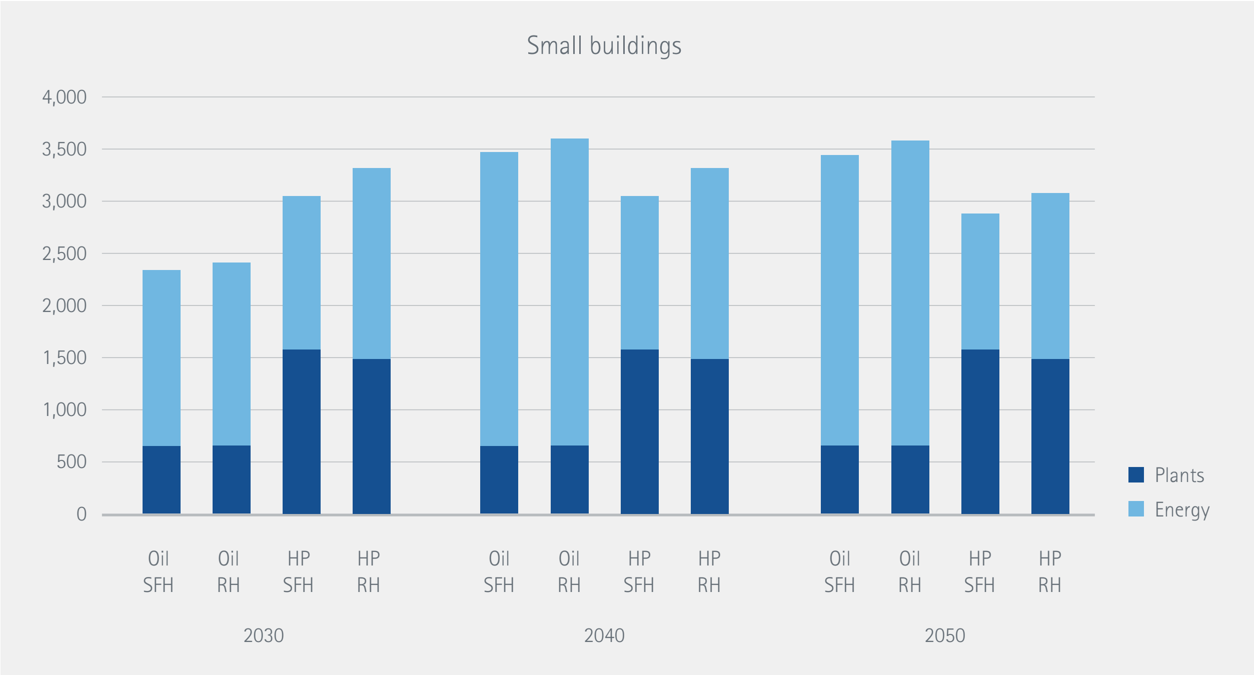
By 2050, the price for PtL will be reduced while at the same time the blending proportion will increase to 82.5 %. The blended price is slightly higher than in 2040. The higher additional costs of the fuel oil PtL system are insignificant compared to 2040. The differences lie between 16–43 % (approximately +30 % on average).

Table 28: Comparison of annual costs, in €, by sample building (actual 2015 prices), basis for higher PtL price path

Building type	Condition	Heating oil			Heat pump			Difference	
		Equipment	Energy	Total	Equipment	Energy	Total	in %	in €
Year under review 2030									
DFH	partialy renovated	721	4,509	5,231	2,186	4,682	6,867	**–24 %**	**–1,636**
SFH	renovated	666	1,661	2,327	1,575	1,468	3,043	**–24 %**	**–716**
RH	partialy renovated	666	1,735	2,401	1,488	1,798	3,286	**–27 %**	**–886**
MFH large	partialy renovated	1,787	41,047	42,834	11,558	42,822	54,380	**–21 %**	**–11,546**
MFH	renovated	1,068	7,219	8,286	3,966	6,591	10,557	**–22 %**	**–2,271**
Year under review 2040									
DFH	partialy renovated	721	7,554	8,275	2,186	4,165	6,351	**+30 %**	**+1,924**
SFH	renovated	666	2,782	3,448	1,575	1,310	2,884	**+20 %**	**+563**
RH	partialy renovated	666	2,906	3,572	1,488	1,601	3,090	**+16 %**	**+482**
MFH large	partialy renovated	1,787	68,756	70,543	11,558	38,277	49,835	**+42 %**	**+20,709**
MFH	renovated	1,068	12,092	13,160	3,966	5,921	9,888	**+33 %**	**+3,272**
Year under review 2050									
DFH	partialy renovated	721	7,502	8,223	2,186	4,060	6,245	**+32 %**	**+1,978**
SFH	renovated	666	2,763	3,429	1,575	1,281	2,855	**+20 %**	**+573**
RH	partialy renovated	666	2,886	3,552	1,488	1,563	3,051	**+16 %**	**+501**
MFH large	partialy renovated	1,787	68,287	70,074	11,558	37,502	49,060	**+43 %**	**+21,014**
MFH	renovated	1,068	12,009	13,077	3,966	5,834	9,800	**+33 %**	**+3,277**

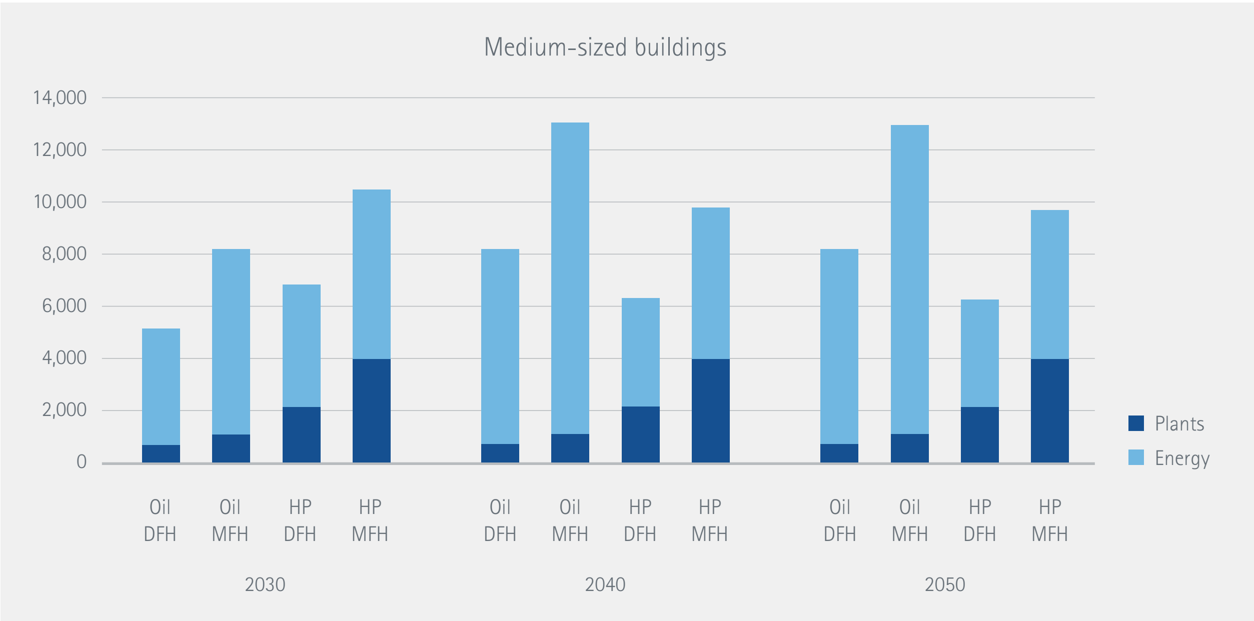
Source: Own calculations

Figure 40: Small buildings – actual annual costs of heating systems by cost type in the higher PtL price path (in $€_{2015}$)



Source: Prognos AG

Figure 41: Medium-size buildings – actual annual costs of heating systems by cost type in the higher PtL price path (in $€_{2015}$)



Source: Prognos AG

Result: low PtL production costs

In a sensitivity analysis, the economic efficiency of the two heating solutions is examined based on the low PtL production costs. According to this lower price path, PtL can be produced in 2050 at a cost of € 0.7/litre. This significantly changes the heating oil PtL blended price. The electricity price remains unchanged with respect to the basic variant (Table 29).

Table 29: End consumer prices for heating oil, PtL and electricity, in € cent/kWh, with lower PtL generation costs, electricity price based on PtX 80 scenario, actual 2015 prices

	Unit	2015	2030	2040	2050
Heating Oil	Cent/kWh	6.0	8.9	9.5	9.3
PtL (lower costs)	Cent/kWh	64.0	14.9	13.0	11.1
Blending proportions		0 %	10.9 %	65.1 %	82.5 %
HEL-PtL-mixed price	Cent/kWh	6.0	9.5	11.8	10.8
Electricity	Cent/kWh	28.7	30.7	28.5	29.1

Source: Own calculations

Table 30: Sensitivity of lower PtL generation costs – comparison of annual costs, in €, by sample building (actual 2015 prices)

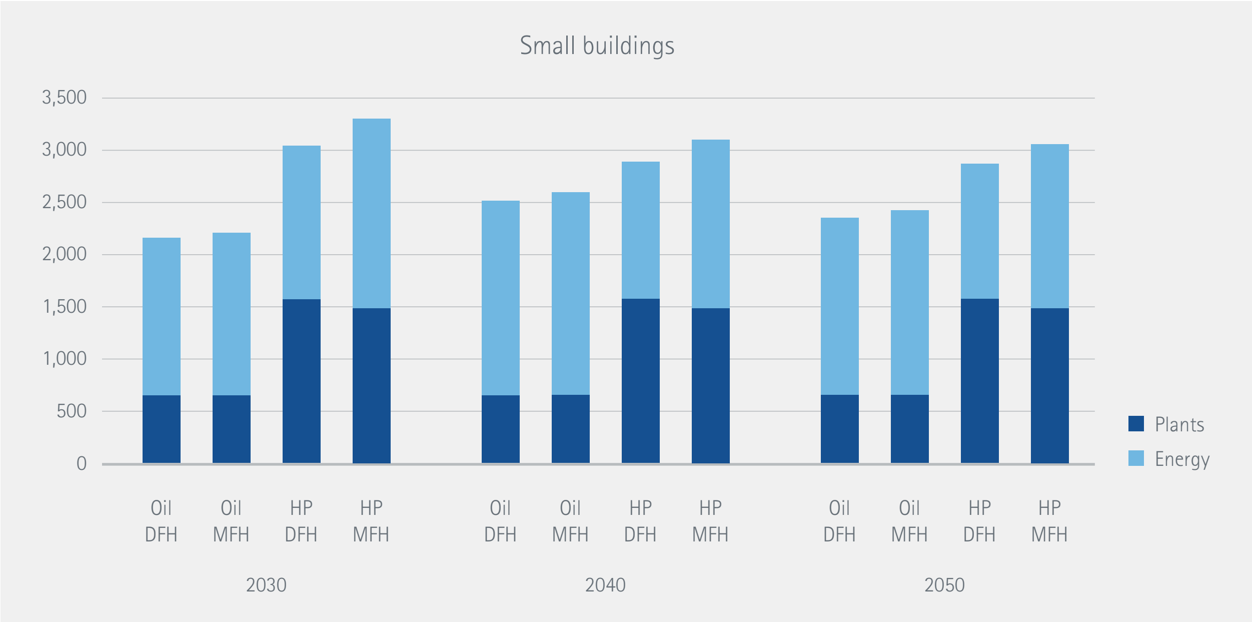
Building type	Condition	Heating oil			Heat pump			Difference	
		Equipment	Energy	Total	Equipment	Energy	Total	in %	in €
Year under review 2030									
DFH	partialy renovated	721	4,022	4,743	2,186	4,682	6,867	**–31 %**	**–2,124**
SFH	renovated	666	1,481	2,147	1,575	1,468	3,043	**–29 %**	**–896**
RH	partialy renovated	666	1,547	2,213	1,488	1,798	3,286	**–33 %**	**–1,073**
MFH large	partialy renovated	1,787	36,611	38,398	11,558	42,822	54,380	**–29 %**	**15,982**
MFH	renovated	1,068	6,439	7,506	3,966	6,591	10,557	**–29 %**	**–3,051**
Year under review 2040									
DFH	partialy renovated	721	5,013	5,734	2,186	4,165	6,351	**–10 %**	**–616**
SFH	renovated	666	1,846	2,512	1,575	1,310	2,884	**–13 %**	**–372**
RH	partialy renovated	666	1,929	2,594	1,488	1,601	3,090	**–16 %**	**–495**
MFH large	partialy renovated	1,787	45,629	47,416	11,558	38,277	49,835	**–5 %**	**–2,419**
MFH	renovated	1,068	8,024	9,092	3,966	5,921	9,888	**–8 %**	**–795**
Year under review 2050									
DFH	partialy renovated	721	4,589	5,310	2,186	4,060	6,245	**–15 %**	**–935**
SFH	renovated	666	1,690	2,356	1,575	1,281	2,855	**–17 %**	**–499**
RH	partialy renovated	666	1,766	2,431	1,488	1,563	3,051	**–20 %**	**–620**
MFH large	partialy renovated	1,787	41,772	43,559	11,558	37,502	49,060	**–11 %**	**–5,501**
MFH	renovated	1,068	7,346	8,414	3,966	5,834	9,800	**–14 %**	**–1,386**

Source: Own calculations

The resulting annual energy and system costs in the sensitivity analysis of low PtL production costs are described in Table 30. The system costs (both heating oil and heat pump) and the energy costs for the HP are identical to those of the basic comparison. Due to the lower PtL production costs, however, the price of the heating oil PtL blend and thus also the energy costs are significantly lower.

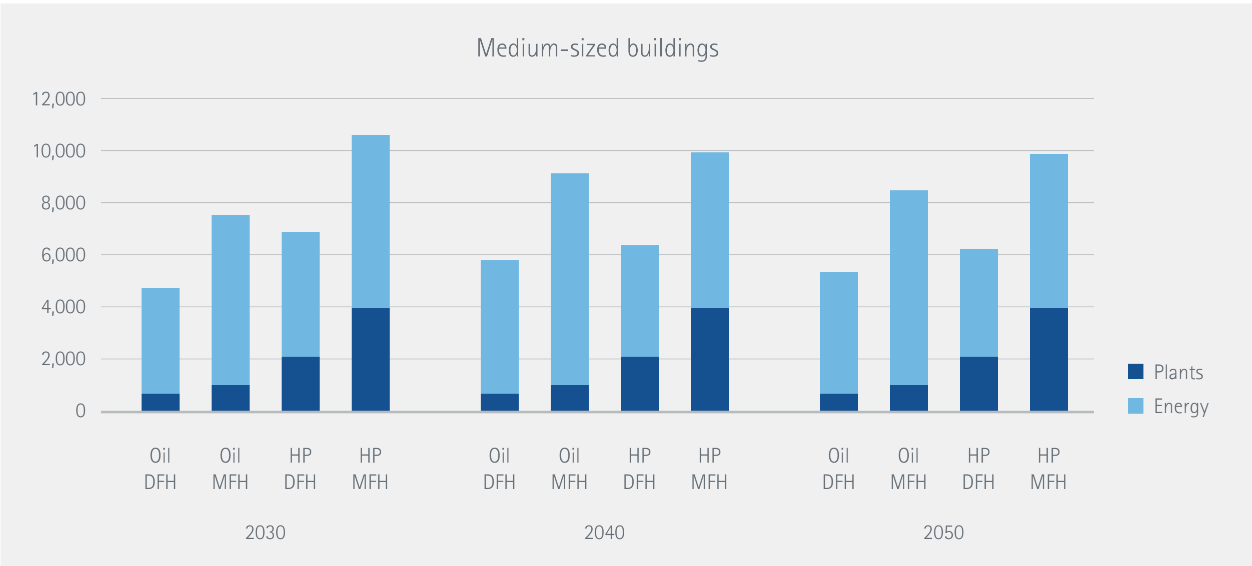
In 2030, the efficiency of the heating oil PtL solution will be slightly higher in comparison to the higher PtL price path. With respect to the average of the sample buildings under consideration, the annual costs for the heating oil system are approximately 30 % lower than those for the heat pump. The cost advantage of oil-based systems decreases over time due to increasing blended proportions, but will remain

Figure 42: Sensitivity of lower PtL generation costs: small buildings – annual costs in comparison, in €, based on energy and system costs (actual 2015 prices)



Source: Prognos AG

Figure 43: Sensitivity of lower PtL generation costs: medium-size buildings – annual costs in comparison, in €, based on energy and system costs (actual 2015 prices)



Source: Prognos AG

until 2050. If the PtL production costs are reduced to this low price level, the heating oil PtL solution would be the **more economical** solution for all buildings across all years. The biggest cost advantage is for small buildings (15–20 %) and the smallest is for large apartment buildings (11 %).

If the heat pumps were operated with a heat tariff approximately € 4.5 cents per kWh under the usual household tariff, the annual costs for the HP would be approximately the same as for the heating oil PtL blended system with low production costs.

Sensitivity: without energy taxes

In another sensitivity analysis, the economic efficiency of the two heating solutions is compared without taking energy taxes into account, i.e. without energy or electricity taxes (cf. analog example calculation for the vehicles). The energy tax currently amounts to € 0.6 cents per kWh for heating oil. The electricity tax is € 2 cents per kWh. With a nominal update of the tax rates, taxes will be reduced nominally to € 0.3 cents per litre for heating oil (and PtL) and approximately € 1 cent per kWh for electricity by 2050. These amounts are deducted from the energy prices of the basic variant (taking VAT into account). This results in the energy prices in Table 31.

In 2030, the price of the PtL blend will be reduced by 5 % and the electricity price by 6 % due to the deduction of energy taxes. In 2050, the difference with respect to the basic variant is smaller. The price for the heating oil PtL blend is 2 % below the basic variant and the electricity price is 4 % below the basic variant.

The energy costs of both systems are also reduced by these percentages. In relation to the total costs, the difference compared to the basic variant is smaller, since the costs for the systems, heat distribution and capital do not change. Compared to the basic version, the elimination of the energy tax reduces the total annual costs for the heating oil PtL blended solution by 2 % and for the heat pump by 2.5 %. Compared to the basic version, the efficiency of the heat pump improves slightly more than the PtL solution (Table 32).

Discussion of the results

The advantage of oil heating over heat pumps is the **lower investment costs**. However, due to lower efficiency and rising energy prices, which are partly due to the blending of PtL, the higher PtL price path after 2030 will result in significantly higher energy costs compared with the roughly unchanged electricity prices calculated here for end customers.

Overall, **energy costs** are more relevant than system costs, especially for larger buildings. In the case of oil heating, they amount on average to about 80 % of the total costs in 2030. In 2050, the average value will be approximately 90 % (see bar length in Figures 40 and 41). With the heat pump, the proportion of the energy costs is smaller. The proportion of the total costs amounts to approximately 60 %.

The results react strongly to the assumed **interest rate** for the investment capital. With rising interest rates, the advantage of oil heating increases (lower investments). The blending proportion also has a strong influence on the results. With increasing blending proportions, the price of the heating oil PtL blend will increase. Starting in 2040, the heat pump in the path with the higher PtL price path will become the more economical solution.

Due to technological development and increasingly better implementation during installation, the annual performance factor of heat pumps will increase during the period under consideration. In addition, the electricity price will be slightly lower in the model calculations between 2030 and 2050 (e.g. due to the decreasing EEG levy in the scenario -80 %). The combination of these two factors significantly reduces energy costs for the HP (-12 % compared to 2030).

Figure 44 describes the **economic efficiency** depending on the **energy prices** for electricity and PtL. The points represent calculated tipping points at which the first/last sample building based on PtL becomes more economical than the heat pump system at a given electricity price. In the middle white range, there are no clear cost advantages for either system. For example, if the electricity price is € 30 cents per kWh, oil heating becomes the more economical solution with respect to a heating oil PtL blended price of be-

Table 31: End consumer prices for heating oil, PtL and electricity, in € cent/kWh, without heating oil tax, respectively without electricity tax, actual 2015 prices

	Unit	2015	2030	2040	2050
Heating Oil	Cent/kWh	5.3	8.4	9.2	9.0
PtL (lower costs)	Cent/kWh	63.3	24.3	21.8	19.1
Blending proportions	%	0 %	10.9 %	65.1 %	82.5 %
HEL-PtL-mixed price	Cent/kWh	5.3	10.1	17.3	17.2
Electricity	Cent/kWh	26.7	28.8	27.0	27.9

Source: Own calculations

Table 32: Sensitivity of calculation without energy taxes – comparison of annual costs, in €, by sample building (actual 2015 prices), basis of higher PtL price path

Building type	Condition	Heating oil			Heat pump			Difference	
		Equipment	Energy	Total	Equipment	Energy	Total	in %	in €
Year under review 2030									
DFH	partialy renovated	721	4,304	5,025	2,186	4,401	6,586	-24 %	-1,561
SFH	renovated	666	1,585	2,251	1,575	1,380	2,954	-24 %	-704
RH	partialy renovated	666	1,656	2,322	1,488	1,690	3,178	-27 %	-857
MFH groß	partialy renovated	1,787	39,177	40,964	11,558	40,251	51,809	-21 %	-10,844
MFH	renovated	1,068	6,890	7,958	3,966	6,195	10,161	-22 %	-2,204
Year under review 2040									
DFH	partialy renovated	721	7,340	8,062	2,186	3,949	6,135	+31 %	+1,927
SFH	renovated	666	2,703	3,369	1,575	1,242	2,816	+20 %	+553
RH	partialy renovated	666	2,824	3,490	1,488	1,518	3,007	+16 %	+483
MFH groß	partialy renovated	1,787	66,814	68,601	11,558	36,292	47,850	+43 %	+20,750
MFH	renovated	1,068	11,750	12,818	3,966	5,614	9,581	+34 %	+3,237
Year under review 2050									
DFH	partialy renovated	721	7,334	8,055	2,186	3,892	6,078	+33 %	+1,977
SFH	renovated	666	2,701	3,367	1,575	1,228	2,802	+20 %	+564
RH	partialy renovated	666	2,821	3,487	1,488	1,499	2,987	+17 %	+500
MFH groß	partialy renovated	1,787	66,753	68,540	11,558	35,955	47,513	+44 %	+21,028
MFH	renovated	1,068	11,740	12,807	3,966	35,955	9,559	+34 %	+3,248

Source: Own calculations

tween € 12.5 and € 14.5 cents per kWh (assuming otherwise identical assumptions). With a PtL blended price of € 17.6 cents per kWh in 2050 (higher PtL price path), the electricity price would have to increase to approximately € 40 cents per kWh for the PtL system to become the more economical solution. With a PtL blended price of only € 10.8 cents per kWh in 2050 (lower PtL price path), the PtL system would be the more economical option in all cases investigated if the electricity price is above € 0.23–0.24 cents per kWh. Economic efficiency of PtL systems is most likely achieved in small buildings with small systems.

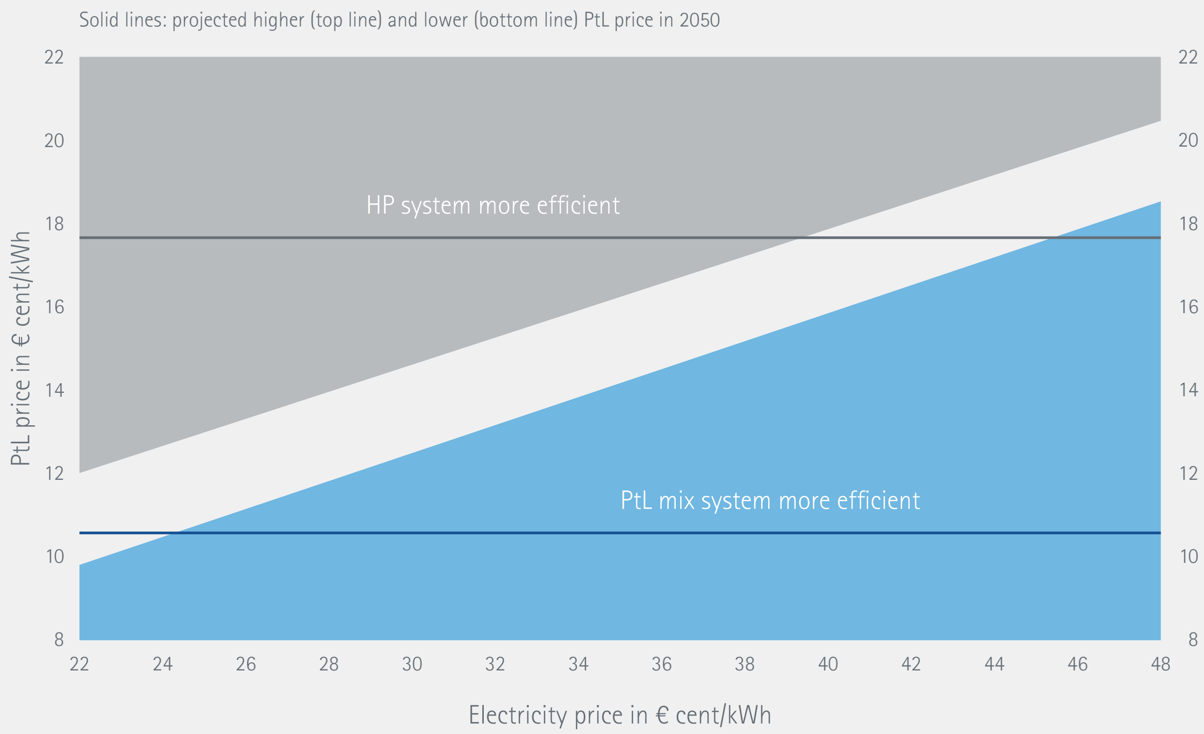
If the heat pump systems in the buildings only reached an APF of about 2 (or lower), the PtL solution would be the more economical option in all cases investigated (in 2050), given otherwise identical assumptions. However, we consider this unlikely due to technical developments.

If the heat pump can be operated with a reduced electricity tariff, the energy costs decrease. It is true that fewer and fewer heat pump tariffs are being offered and/or the discount is decreasing. However, the willingness for flexible operation should also be compensated in the future. In the modelling, it is assumed that some of the heat pumps can be switched off temporarily by the supplier to temporarily balance the load. This improves the economic efficiency compared to the heating oil PtL mixing system.

8.2.2 Traffic – Passenger Cars

This section compares two possible technical approaches to GHG reduction for passenger vehicles in terms of consumer costs. The cost comparison has been carried out for a battery-electric (BEV) and a conventional (ICEV) vehicle with an internal combustion engine. Increasing proportions of PtL were added to the gasoline and diesel over time in accordance with the scenarios in this study. The comparison is based on the total cost of ownership (TCO) for a private

Figure 44: Economic efficiency based on energy prices for electricity and PtL, in the year 2050



Source: Prognos AG

first-time buyer. The comparative calculations show the development of costs between the two approaches over time from today (2015) to 2050. In this economic analysis, four cases are investigated, each with different vehicle sizes, purposes of use, annual mileages and service lives. The cases are defined as follows:

In this way, the efficiency of four different passenger vehicle segments with different usage intensities over time is shown up to 2050. The segment selection is derived from statistics from the German Federal Motor Transport Authority (KBA) on new registrations and number of segment-based vehicles (KBA 2016). KBA distinguished 13 different segments of passenger vehicles with over 800,000 new registrations in the compact class in 2017, the segment with the highest number of registrations. The SUV, small and medium-sized vehicles, segments that are also included in this analysis, occupied second, third and fourth places. Together, the four segments account for just under 65 % of new passenger car registrations in 2017.

Since 2013, the KBA has differentiated between SUVs and off-road vehicles. The SUV segment has become increasingly important in recent years, while the development of newly registered SUVs has remained relatively constant. Vehicles must meet certain technical criteria (e.g. four-wheel drive) in order to be registered as off-road vehicles. As a result, off-road vehicles are generally considerably heavier than SUVs and therefore also consume more energy.

The amount of usage, i.e. the mileage, has a relevant influence on user costs. The annual mileage varies greatly from individual to individual. Various mobility surveys (MiD 2008, Mileage Survey 2014, etc.) show that the average annual mileage depends on various factors, such as vehicle drive, vehicle size, vehicle age, etc. The average mileage for gasoline vehicles is around 11,000 km and for diesel cars it is just over 20,000 km. These fuel-specific average annual mileages are covered in cases 2 and 4. In order to vary the annual mileage in as wide a range as possible, the costs for a user type with low annual mileage (type 1) and for a frequent driver (type 4) are also considered.

Depending on the annual mileage, the service life is also defined, whereby a maximum initial use of 10 years is assumed. For high annual mileages (types three and four), maximum first-user mileage is assumed to be 120,000 km. After the corresponding service lives, the vehicle is sold with a residual value.

Table 33: Case definition for sample calculations for passenger cars

	Type 1	Type 2	Type 3	Type 4
passenger car segment	Small-sized	Compact class	Medium-sized	SUV
				
Purpose	City – short-trip	Allround – private use	FRQ driver – long range	Allround – commercial
Annual mileage (km/a)	5,000	10,900	30,000	20,300
Drive ICEV	Petrol	Petrol	Diesel	Diesel
Sample vehicle	Opel Corsa, Renaul Zoe	VW Golf, e-Golf	VW Passat	Mercedes GLC
Service life (a)	10	10	4	6
Battery change	No	No	Yes	No

Source: Prognos AG

Battery manufacturers currently guarantee mileages of between 100,000 and 160,000 kilometers. The service life of existing batteries in electric cars is currently assumed to be eight to ten years and 500 to 1,000 charging cycles, after which the battery has less than 80 % of the charging capacity. With type three, it is assumed that the battery is replaced during the vehicle use phase due to the high daily mileage and corresponding high number of charging cycles with high charging power (quick charging).

Vehicle purchase

Vehicle purchase covers the costs for the purchase of the vehicle. The acquisition costs are regarded as an investment which bears interest over the period of use and can then be sold on the market at a residual value. The analysis of residual values by vehicle segment, mileage, vehicle age and drive is carried out via an evaluation of the DAT database (Deutsche Automobil Treuhand GmbH) (DAT 2018). The purchase costs have an imputed interest rate of 4 % as an annuity (annual costs) and can be added to the other cost components. In order to update purchase costs in the future, the change in battery prices has been taken into account.

The change in battery prices has been very dynamic in recent years. According to Claire 2017, the cost per kWh Li-Ion battery pack for passenger cars has fallen almost 73 % since 2010 from $1,000 to $273 per kWh. In Lutsey 2016, a meta-analysis of various data and studies was performed in order to estimate future costs of battery development. In the passenger vehicle segment, further cost reductions of up to € 130–180 per kWh are expected for the period up to 2025 (Lutsey 2016). Using a learning curve development with a moderate ramp-up of electric mobility, we anticipate a battery price of € 92 per kWh in 2050.

In addition to this, there will also be costs for the private charging infrastructure for electric vehicles. The costs for the Wallbox are taken into account for the electric vehicle just once. Depending on the charging capacity and equipment, the price currently ranges from € 400 for a Wallbox with a charging current of 3.7 kW and € 2,000 for a Wallbox that allows two cars to charge 11 kW simultaneously (Wallbox Test 2018). In this sample invoice, a flat rate of € 1,000 for the Wallbox and another € 1,000 for the installation is estimated (Amato 2018).

Energy consumption and energy prices

The vehicles under consideration are allocated segment-specific energy consumption. The KBA (German Federal Motor Transport Authority) categorises the specific energy consumption figures for newly registered vehicles according to their drive system and vehicle class. However, the figures for passenger cares with alternative drive systems only specify the number of newly registered vehicles, not the specific fuel consumption figures. As such, the energy consumption figures for the BEVs are taken from an internal car database. The expected purpose of use is also taken into account for the energy consumption figures. Type three (intermediate class) demonstrates a high daily mileage, and much of its energy consumption thus comes from motorway driving. Driving on the motorway at a continuous high speed gives the electric drive little opportunity to recover (energy recovery when braking). The BEV SUV is used more frequently in stop-and-go traffic, and thus has a lower energy consumption than the intermediate-class BEV passenger car.

According to (ICCT 2017) 2016, the consumption figures provided by the manufacturer may deviate upwards by 30 % to over 50 %. The tables below provide an overview of the expected energy consumption figures.

An increase in efficiency is assumed for both drive concepts in future assessments. In terms of the overall vehicle concept, however, a slightly greater potential efficiency increase of around 35 % between 2015 and 2050 is expected for the ICEV passenger car. An increase of 30 % has been applied for the BEV over the same period, primarily due to the higher efficiency already offered by an electric drive compared to an internal combustion engine.

The sample calculations are based on the energy source prices in the 80 % scenario. Since these figures relate to the consumer perspective, the energy prices are calculated inclusive of current tax rates. Due to energy tax, petrol and diesel are subject to higher taxes than electricity. As such, a comparison calculation excluding tax (both energy tax and electricity tax) will also be provided.

The figures for charging electric vehicles may vary depending on the specific situation. Different electricity tariffs may apply depending on the location, electricity provider and charging rate. Three different basic charging situations (public, semi-public and private) are included in the calculations. In addition to this, public charging is split into two sub-categories: quick charge and normal charging. "Semi-public" charging refers to charging while at work or out shopping. While semi-public charging is potentially cheaper than private charging – since companies benefit from lower electricity tariffs than private citizens – quick charges at high charging rates will probably be more expensive. During private charging, owners can use electricity from the public grid. However, they may also choose to use self-generated PV electricity, which is much cheaper than the normal price for domestic electricity. These sample calculations are based exclusively on a domestic electricity price, and thus assume use of private charging. As a result, consumers who frequently travel longer daily distances and (have to) quick-charge away from home will probably have higher energy costs than those shown in these sample calculations.

In addition to the procurement and energy costs, the cost comparison also takes into account vehicle tax and the costs of maintenance and repairs.

Electric vehicles are currently exempt from vehicle tax for 10 years.[14] From 2020 onwards, the vehicle tax for electric vehicles will be charged based on the permissible total weight, and will reach approximately the same level as for petrol passenger cars. Vehicle tax for diesel passenger cars is substantially higher.

While vehicle tax is charged on an annual basis and does not vary depending on actual mileage, outgoings for main-

14 Kraftfahrzeugsteuergesetz (German Motor Vehicle Tax Act), Section 3d "Tax exemption for electric vehicles"

Table 34: Overview of the acquisition costs for the passenger car segments examined

Segment	Drive	Battery capacity in kWh (2015/2050)	Battery cost in € (2015/2050)	Acquisition cost in €	Additional cost electric in €	Additional cost electric in %
Small-sized	Petrol			**18,200**		
	Electric	22/33	7,500/3,000	**24,700**	6,500	36 %
Compact class	Petrol			**24,100**		
	Electric	36/54	12,300/5,000	**33,000**	8,900	37 %
Medium-sized	Diesel			**33,000**		
	Electric	60/89	20,500/8,200	**50,000**	17,000	52 %
SUV	Diesel			**30,000**		
	Electric	55/80	17,100/7,335	**45,000**	15,000	50 %

Source: Prognos AG

Table 35: Specific energy consumption by passenger car segment for the 2015 basis year

		Segment consumption (KBA)	NEDC	Real consumption	Real compared to NEDC
Small-sized	Petrol (l/100km)	4.9	4.5	**6.2**	37.8 %
	Electric (kWh/100km)		13.0	**18.2**	40.5 %
Compact class	Petrol (l/100km)	5.4	5.0	**6.8**	36.0 %
	Electric (kWh/100km)		12.5	**19.0**	52.0 %
Medium-sized	Diesel (l/100km)	4.5	4.1	**6.0**	46.3 %
	Electric (kWh/100km)			**21.5**	
SUV	Diesel (l/100km)	4.8	4.8	**7.0**	45.8 %
	Electric (kWh/100km)			**21.3**	

Source: Prognos AG

tenance and repairs are defined based on mileage. Fewer of the parts installed in electric vehicles are subject to wear, repairs and regular maintenance. For example, oil lubrication, the belt drive, gaskets and many of the wear parts relating to the internal combustion engine and the gearbox are not included in maintenance work for electric vehicles. Likewise, no regular exhaust emissions inspection is required for vehicles with an electric drive. A current cost comparison for BEVs and PtL passenger cars estimated the outgoings for BEVs to be half those for PtL passenger cars (Kasten 2018). Maintenance and repair work was estimated to be between three and four percent per kilometre (segment-specific), and half of this figure for electric vehicles. Battery changes are expected for type 3; the costs of this were included in the procurement costs category.

There are no notable differences between electric and conventional vehicles in terms of vehicle insurance costs; as such, these were not included in the comparison. Likewise, other costs such as outgoings for parking, tyre changes, etc. are not drive specific, and are thus not included in the comparison.

Cost comparison results

The following section presents the results of the TCO calculation for the four passenger car segments included in the study, calculated for regular intervals up to 2050. There are two diagrams for each segment: the first shows the cost structures for the drive variants Battery Electric Vehicle (BEV) and internal combustion engine with PtL fuel for the PtX 80 scenario, while the second compares the overall TCO for different energy price paths for the two different drive variants.

These are followed by a final comparison of results, which shows the costs for 2050 in the compact car segment based on battery size and annual mileage (see Figure 53).

The calculations for the **supermini** segment assume a low annual mileage of 5,000 km; as such, the energy costs for this segment make up only a small part of the total cost. For petrol PtL drives, fuel costs make up 21 % of the TCO in 2015 and 27 % in 2050. The energy costs for BEVs naturally make up a smaller percentage of the TCO; however, the investment costs (fixed costs) for this variant are higher due to the cost of the battery.

For our base year, 2015, the TCO for a BEV is around 30 % higher than that for a petrol-driven supermini with a lower annual mileage. Thanks to falling battery prices and increases in energy costs for the petrol PtL mixture, the difference in the respective TCOs will balance out in the long term. For consumers with low annual mileages, passenger cars with internal combustion engines will remain cheaper than the BEV variant. According to this sample calculation, the petrol PtL supermini will be 4 % cheaper than the BEV in terms of TCO in 2050.

The cost benefit of the ICEV as compared to the BEV increases if we take the lower PtL price path into account. The ICEV supermini with low annual mileage also remains the more affordable option in the comparison excluding tax. With the lower PtL price path, the cost benefit of the internal combustion engine with petrol will be 12 % in 2020, and 8 % in the cost comparison excluding tax.

Calculations for the **compact class** segment were made using an annual mileage of 10,900 km; this corresponds to the average annual mileage for a petrol-driven passenger car in Germany. In 2015, the battery capacity for the electric passenger car is 36 kWh. This gives the compact-class car a range of around 200 km. Thanks to progress in terms of efficiency and an increase in battery capacity to around 50 kWh, the range will increase to 300 km by 2050.

The TCO for a petrol PtL passenger car is a good € 4,000 per year in 2015. Despite its lower energy costs, the BEV has additional costs of around 13 % in 2015 due to its higher procurement costs (fixed costs). Due to falling battery costs, the TCO of BEVs will fall. In this sample calculation, the break-even point (the point at which both drives cost the same) will be reached in 2030. After 2030, the BEV will be cheaper in terms of TCO. In 2050, the cost benefit of the BEV will be around 15 %.

The battery electric vehicle is also cheaper than the internal combustion engine with PtL petrol in the long term in the comparison using different energy price paths. With a lower PtL price path, the TCO for both drive types will be similar in 2050, with the BEV offering a slight cost benefit. There is no change to these ratios in the variant calculation without tax; the only difference is that the BEV takes longer to become the cheaper option in this comparison. The break-even point here is 2035.

The sample calculation for the **intermediate class passenger car segment** is based on a usage profile with a high daily mileage. As such, the battery is charged frequently and at a high charging rate (quick charge) accordingly. In this vehicle segment, it is assumed that a battery replacement will be required during the usage period. Due to the battery replacement, the fixed costs for the BEV are 1.7 times higher than those for an intermediate-class passenger car with an internal combustion engine in our base year, 2015. Thanks to falling battery costs, the electric car remains competitive at a high annual mileage – despite the battery replacement. In 2050, the TCO for both drive variants will be around € 11,500 2015 per year.

With low PtL costs, the internal combustion engine will be cheaper than the BEV in the long term due to the battery replacement. In 2050, the cost benefit will be around 8 %. Likewise, in the calculation without tax, the diesel PtL passenger car is cheaper than the electric car.

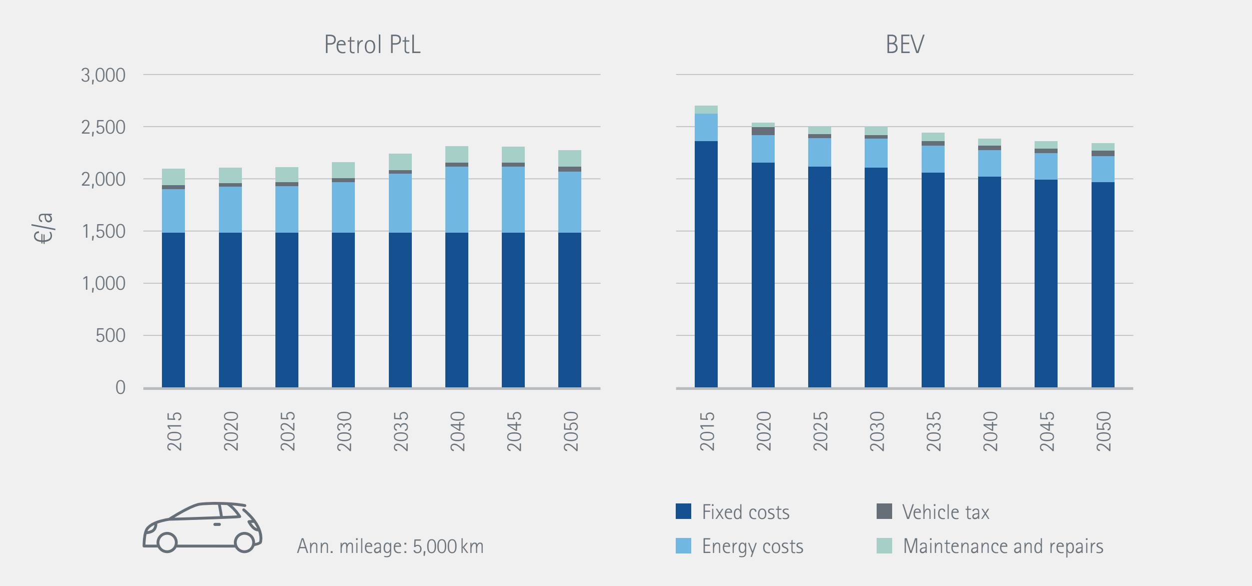
The fourth passenger car class included in the TCO investigation is the **SUV segment**. The fixed costs for an SUV with an internal combustion engine are €5,000$_{2015}$ per year. The additional procurement costs associated with the BEV compared to the ICEV are around 55 % in 2015 and will fall to around 15 % in 2050. In the other cost categories, particularly energy costs, the BEV SUV is significantly cheaper.

Table 36: End consumer prices in the PtX 80 scenario for petrol, diesel, PtL and electricity, in €/l or in € cent/kWh, actual prices (2015 price basis)

	Unit	2015	2030	2040	2050
Petrol	€/l	1.40	1.46	1.42	1.32
Diesel	€/l	1.14	1.35	1.33	1.26
Blending proportions		0 %	11 %	65 %	83 %
Petrol PtL mixed price	€/l	1.40	1.63	2.18	2.08
Petrol PtL mixed price lower cost	€/l	1.40	1.52	1.61	1.43
Petrol PtL mixed price excl. taxes	€/l	0.62	1.04	1.71	1.70
Diesel PtL mixed price	€/l	1.14	1.51	2.10	2.02
Diesel PtL mixed price lower cost	€/l	1.14	1.40	1.53	1.37
Diesel PtL mixed price excl. energy tax	€/l	0.58	1.09	1.76	1.75
Electricity	Cent/kWh	28.7	31.2	29.3	29.9
Electricity excl. taxes	Cent/kWh	26.2	28.8	27.0	27.9

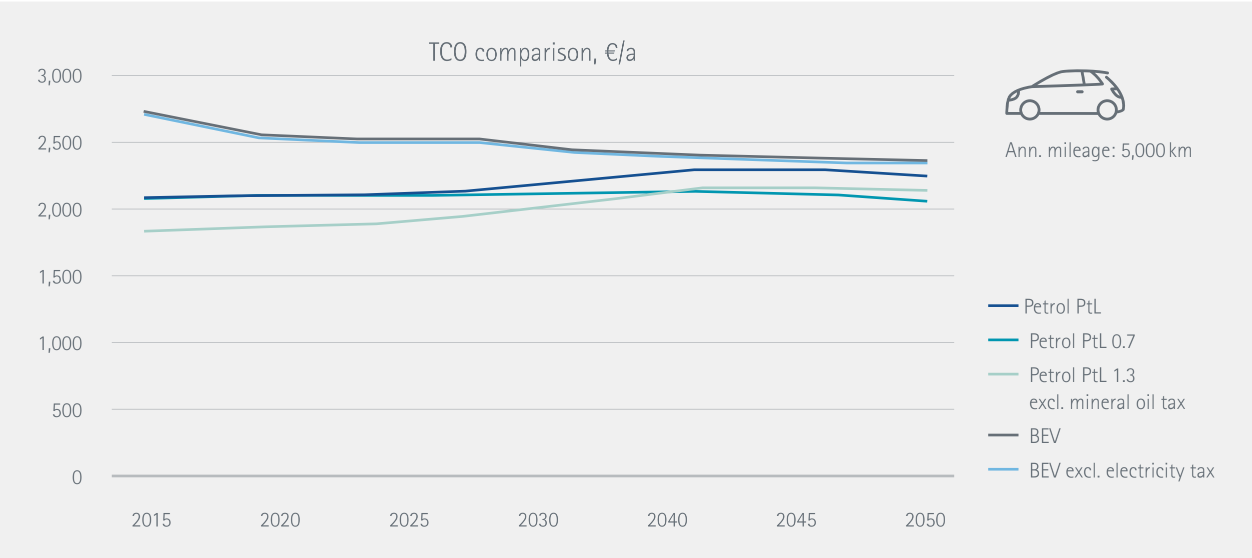
Source: Own calculations

Figure 45: TCO comparison, petrol PtL vs. BEV by cost category, 2015–2050 in €/a, type 1: supermini segment



Source: Own calculations

Figure 46: TCO comparison, petrol PtL vs. BEV, various energy price paths, 2015–2050 in €/a, type 1: supermini segment

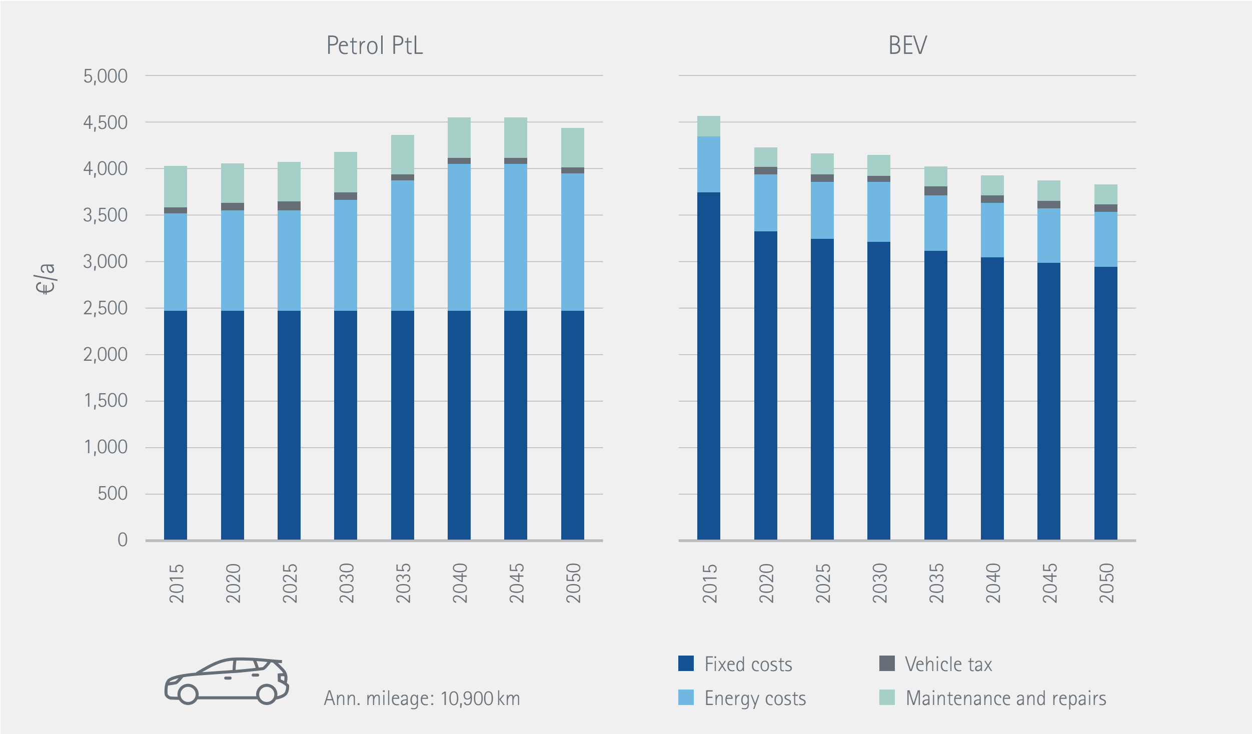


Source: Own calculations

In our base year, the TCO additional costs for the BEV SUV are around 25 %. The break-even point will be reached in 2030; after this point, the BEV-SUV will be cheaper than the ICEV in terms of TCO.

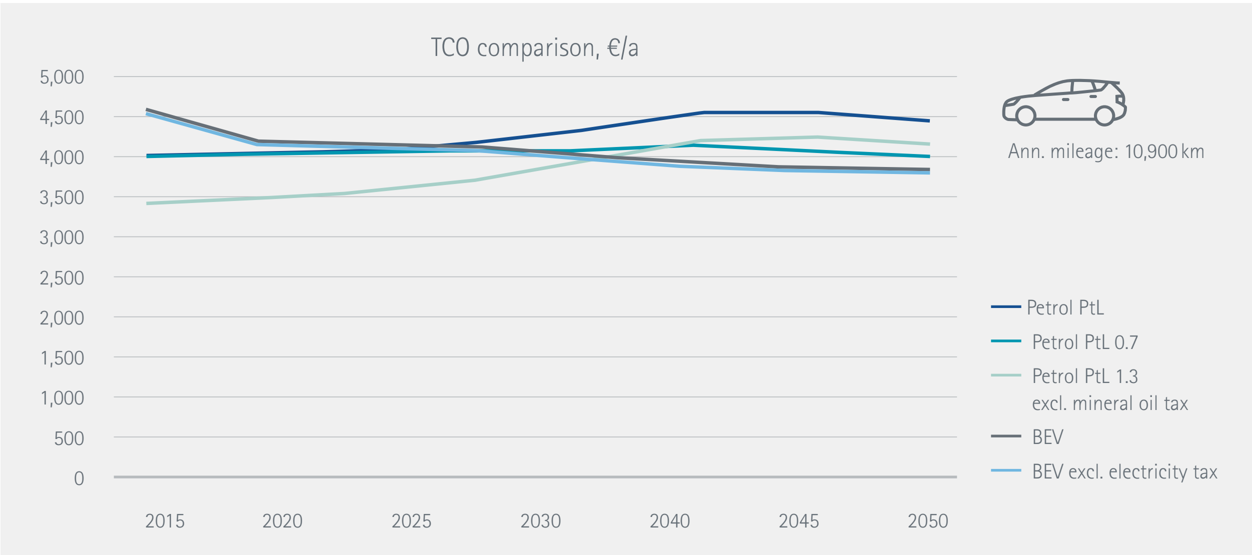
As demonstrated in these four sample calculations, the TCO varies in favour of either the electric drive or the internal combustion engine, depending on the annual mileage and the battery costs. When the annual mileage is equal, the BEV offers a TCO benefit thanks to its lower energy costs. At the same time, greater mileages generally require larger batteries in order for an electric vehicle to achieve the required range. However, larger batteries are a big cost driver for electric cars. As such, electric cars with high battery capacities are more

Figure 47: TCO comparison, petrol PtL vs. BEV by cost category, 2015–2050 in €/a, type 2: compact class segment



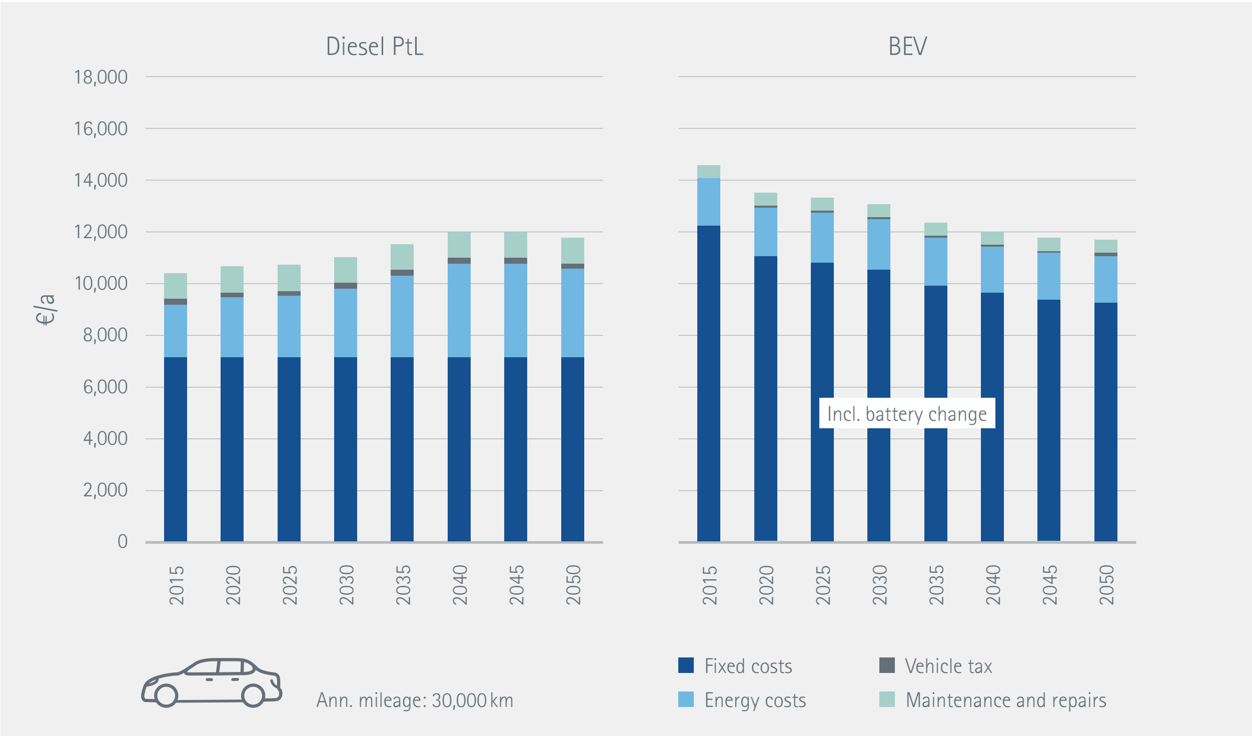
Source: Own calculations

Figure 48: TCO comparison, petrol PtL vs. BEV, various energy price paths, 2015–2050 in €/a, type 2: compact class segment



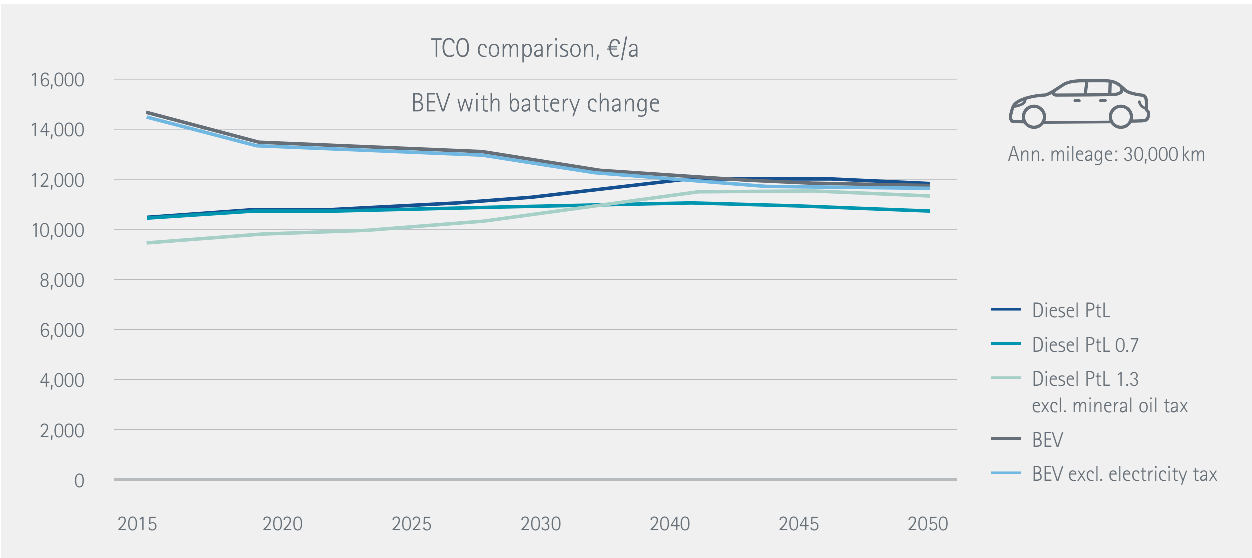
Source: Own calculations

Figure 49: TCO comparison, diesel PtL vs. BEV by cost category, 2015–2050 in €/a, type 3: intermediate class segment



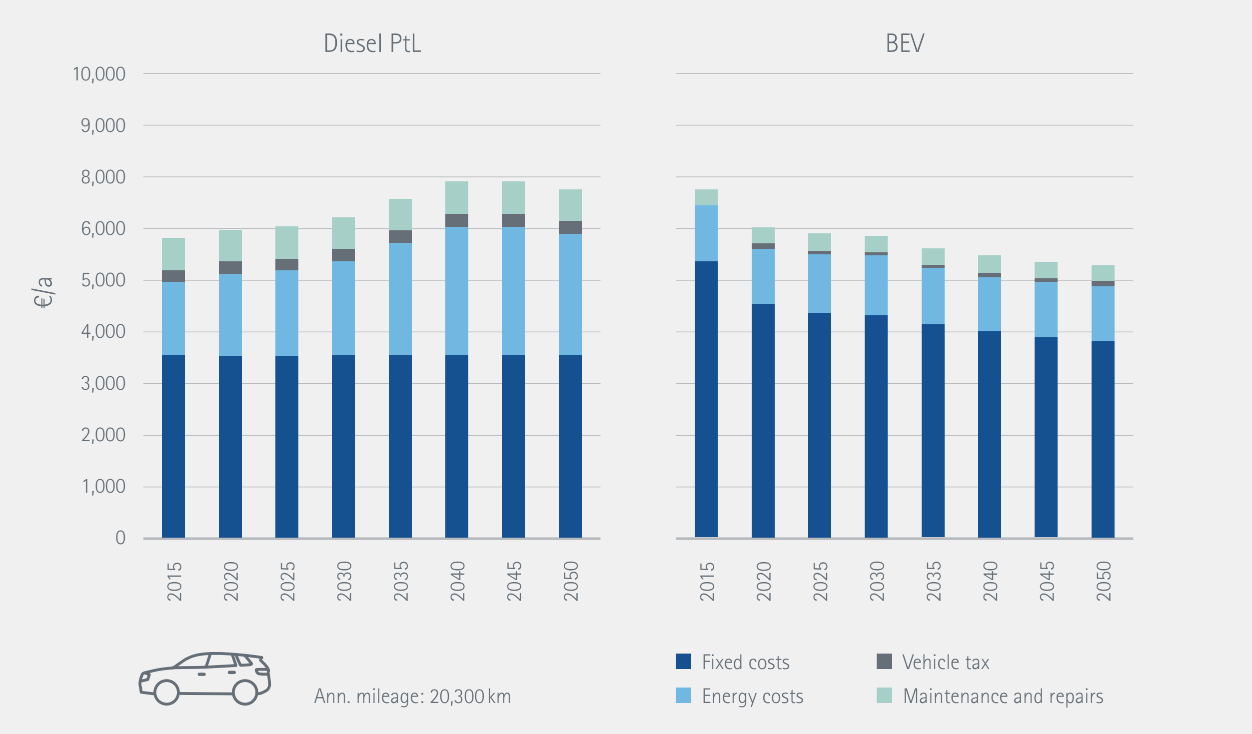
Source: Own calculations

Figure 50: TCO comparison, diesel PtL vs. BEV, various energy price paths, 2015–2050 in €/a, type 3: intermediate class segment



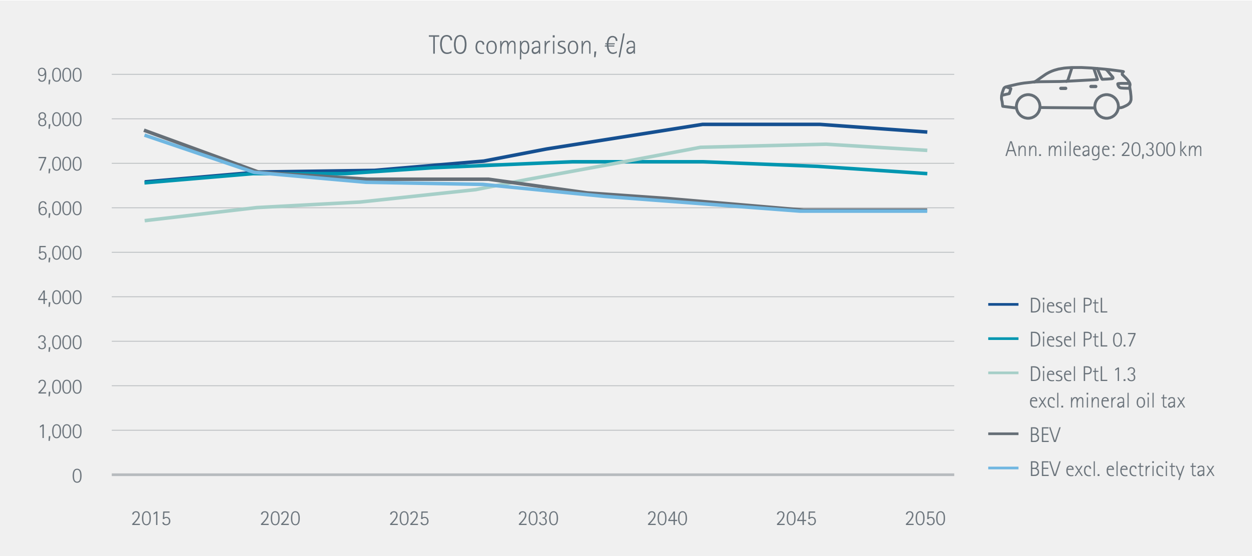
Source: Own calculations

Figure 51: TCO comparison, diesel PtL vs. BEV by cost category, 2015–2050 in €/a, type 4: SUV segment



Source: Own calculations

Figure 52: TCO comparison, diesel PtL vs. BEV, various energy price paths, 2015–2050 in €/a, type 4: SUV segment



Source: Own calculations

expensive, and only more economically efficient than a combustion engine with PtL for consumers with a high annual mileage. The final diagram shows the break-even point for the two drive concepts included in the study, based on the criteria of annual mileage and battery capacity. This is based on the explicit assumption that there will be no variation in the other parameters involved in the TCO calculation (energy consumption, procurement costs, etc.).

Figure 53: TCO comparison for the compact passenger car segment based on battery capacity and annual mileage for the year 2050

Source: Own calculations

8.3 ASPECTS OF USE

8.3.1 Consumer Friendliness Index

Certain heat and traffic applications are experiencing increasing competition between applications based on **electricity** and those based on **liquid fuels.** Based on renewable energy, both options offer the ability to reduce GHG emissions in the respective sectors.

In terms of efficiency in the provision of heat and movement energy, the electricity-based applications offer a clear advantage. There are also a range of other aspects that play a key role in consumer ratings; these shall be discussed and compared in this section under the umbrella term "consumer friendliness".

The **ratings** will be presented using a **scale** with five levels, defined as --, -, 0, +, ++. Since not all the criteria are available with cardinal scaling, this ordinal scale shall be used instead.

"--" is awarded for a major advantage in favour of the electric application, "-" for a minor advantage in favour of the electric application, "0" for if there is zero or only negligible difference between the use of electricity and that of liquid fuels, "+" for a minor advantage in favour of liquid fuels and "++" for a major advantage in favour of liquid fuels.

The applications are rated from a consumer perspective based on an expert assessment that is supported by literary research. A variety of comparison criteria have been divided into the categories of economic efficiency, aspects of use and environment. The economic efficiency rating is based on the sample calculations (see section 8.2).

8.3.2 Heat

The **differences in use** between the heating systems in the field of heat supply are low. The heat pump technology requires less space in the building, but more outside it. The maintenance workload for a heat pump is estimated to be lower than that for an oil heating system. The possibility of failure should be about the same for both systems, but the cost risk associated with incorrect installation is higher for a heat pump, as even small errors made with this technology (e.g. in terms of supply temperature) can lead to relatively high additional consumption. Many towns and cities now have cheap tariffs for heat pumps, providing they can be shut off. Such cases result in a better total cost. Since our calculations are not based on the use of a heat pump tariff, it is not relevant for us to determine whether or not the ability to shut off a heating system results in a disadvantage in use. The overall picture in terms of aspects of use is quite well balanced. Individual circumstances (e.g. relating to construction) can tip the balance.

As shown in the index, from a consumer perspective, the **economic efficiency** rating is primarily determined by the costs of PtL generation. Until 2030, oil-powered systems should be more economically efficient than electric heat pumps. After this, there is a split in the pattern: if the PtL costs develop along the low price path, oil heating systems will remain the "more efficient" solution. In the top price path for PtL, however, electric heat pumps will be cheaper in 2050. Furthermore, no subsidies or discounted tariffs for heat pumps were taken into account in our calculations.

8.3.3 Traffic

For the transport sector, we compared battery electric vehicles (BEVs) and vehicles with internal combustion engines (ICEVs). The vehicles were divided into three classes: passenger cars, light commercial vehicles and heavy commercial vehicles. A typical route was defined for each type of vehicle:

- For passenger cars, two different situations (short and long trip – < 50 km/day and > 200 km/day) were used
- For light commercial vehicles, the typical route was assumed to be approx. 100 km/day
- For heavy commercial vehicles, the typical route was assumed to be approx. 200 km/day

The comparison criteria are discussed below.

Range

The **range per full tank** is calculated using the vehicle's **consumption** and the **energy yield per full tank** (this term also applies to the energy content of the battery). In terms of consumption, the BEV has the advantage due to its more efficient drive; in terms of energy yield per full tank, the combustion engine has the advantage due to the significantly higher gravimetric and volumetric energy density of the liquid energy source.

In 2018, BEVs in the passenger car segment can achieve ranges of around 100 km to a few 100 km per battery charge (based on the New European Driving Cycle, NEDC). Vehicles with an **internal combustion engine** offer an advantage for long journeys, with typical ranges in the passenger car segment of up to **1,000 km** per full tank.

For both drive technologies, deviations from the standard conditions of the NEDC lead to a reduction in range due to the resulting additional consumption. The **"robustness of range"** criteria has been introduced to account for this factor. Due to the lower energy yield per full tank in the BEV, the robustness of range tends to be lower for this drive type:

The **consumption benefit offered by the BEV is reduced at lower temperatures** due to the additional loads drawing power from the battery (winter: heating/summer: air conditioning). Especially in extremely cold conditions, depending on the exact temperature and how well the passenger compartment are insulated, additional consumption may reach 100 % more than the standard consumption. Since vehicles with a combustion engine use the exhaust heat for the heating system, the efficiency advantage offered by the electric drive is lower at extreme temperatures (ÖKV, Austrian Society of Automotive Engineers, 2012).

The **BEV's consumption advantage depends on the consumer's driving profile.** It is more pronounced in short-trip applications and on journeys that require a lot of stop-and-go operations (inner-city/delivery traffic) as, in addition to the general higher efficiency, these situations allow the electric drive to recover energy when breaking, while combustion engines are especially inefficient in such conditions. On journeys where a constant high speed is maintained (motorway driving), the electric drive has less of an advantage over the combustion engine, as such situations offer little opportunity for energy recovery, and also provide the conditions in which the combustion engine runs at optimum efficiency.

In the scenario shown here, we have assumed a battery capacity of 55 kWh for new BEVs in 2050. With a consumption of 16 kWh/100 km, this gives us a theoretical range of 350 km (in reality, it is not possible to run the battery down to 0 %). In our reference scenario, we have assumed the 80 % of all BEVs can be charged flexibly.

Refuelling time

Liquid fuels allow consumers to achieve refuelling rates of up to **15 MW** (calculated at 25 l diesel/min); as such, the refuelling process for a passenger car with an ICE takes just a few minutes.

At the time of writing, an electric vehicle can achieve a charging rate of between 3.5 kW (single-phase domestic outlet) and 350 kW (Tesla Supercharger), depending on the vehicle's equipment (quick charge technology) and the power outlet/charging station. The ultrafast charging option at the top of this range only allows the battery to be charged to 80%.

One benefit of the BEV in terms of refuelling is that vehicles can be refuelled during downtime, providing a parking space with a charging station is available.

Overall, the liquid energy sources have the advantage in terms of the refuelling time criterion, especially when fuel is required for long-range journeys.

For future refuelling figures, we have assumed that further developments in battery and charging technology will allow BEVs to be charged more quickly at quick charge stations when required. However, even in the long term, they will take longer to refuel than ICEVs.

Refuelling infrastructure

The **refuelling infrastructure for liquid fuels** currently extends to approx. 14,000 petrol stations in Germany. It has proven to be effective over the course of several decades, and is also available all around the world.

The refuelling infrastructure for **electric vehicles** (charging infrastructure):

- Theoretically includes all power outlets (approx. 3.5 kW). However, the charge rates are slower accordingly, meaning that refuelling takes longer. Furthermore, practical experience has shown that solutions that use "extension cables" from private outlets are not particularly practical.
- Can be increased to up to 22 kW in households with a high-voltage power outlet (440 V, three-phase alternating current).
- Is still in the process of being built up, with 11,000 public charging stations in Germany at the time of writing.
- Is also poor in immediately neighbouring European countries such as France, Poland the Czech Republic, Italy, Austria and Switzerland, which will remain a problem in the medium term for typical usage behaviour on holiday trips. Requires a change in refuelling behaviour compared to ICEVs: refuelling takes place primarily during vehicle downtimes (when the car is parked, when the driver is shopping or running errands, etc.). Charging during a trip is rare, and is performed using a quick-charge station.
- Offers vehicle users who own their own parking spaces a significant advantage over those who have to rely on public parking spaces. Parking space owners (e.g. people with a garage or a private parking space by a detached house) can install their own charging infrastructure. E-mobility users who park their vehicles out in public, on the other hand, are reliant on the availability of parking spaces with charging infrastructure.
- Has legal hurdles (right to connection, downtimes at public charging stations, cables in public spaces).
- Requires an expansion of the power grid.
- The liquid energy sources have the advantage, particularly when it comes to long-range applications. The central quick-charge infrastructure for BEVs is still being built up.

In the future, if quick-charge stations become available everywhere and have capacity to cater to everyone's needs (due to the longer refuelling times and shorter ranges, the demand for charging stations will rise significantly compared to that for petrol stations), battery electric vehicles will be at less of a disadvantage when it comes to cross-country trips.

Our future figures for the refuelling infrastructure criterion are based on the assumption that electric charging facilities will continue to be expanded. It is likely that we will start to see central charging points similar to modern petrol stations. In addition to this, there are also other locations that could house charging facilities, such as multi-storey car parks, shopping centre car parks, motorway lay-bys, etc.

Degradation

The capacity of a battery deteriorates over the course of its lifetime (Fraunhofer ISI 2013). There are two types of degradation: cyclic ageing (the ratio between battery use and ageing) and calendar ageing (the storage capacity of the battery diminishes over time of its own accord, including when the car is parked or in storage).

The fact that the battery capacity deteriorates with time and use represents a disadvantage compared to the drive of the combustion engine, especially for users who require the full battery capacity.

It is assumed that degradation will reduce in the future due to further developments in battery technology.

Driving dynamics

The key difference between BEVs and ICEVs is in their respective torque curves based on their rotational speed. Battery electric vehicles generally offer very good acceleration from a standing start, since the electric motor can hit its maximum torque straight away. The combustion engine increases its torque gradually as its speed of rotation increases. In terms of acceleration from a standing start, the BEV is thus superior to the ICEV.

An electric motor's torque drops as its speed increases due to the scattering of the magnetic fields between the rotor and the stator. As such, the advantage the BEV offers over the combustion engine in terms of acceleration decreases at higher speeds, in part due to the lack of a gear ratio (and, indeed, a gearbox) (Stan 2015).

General speaking, high speeds can be achieved with both drive types. As a rule of thumb, high speeds lead to a disproportionate increase in consumption regardless of the drive system. Battery electric vehicles are at a disadvantage in terms of top speed, as the additional consumption in turn severely affects the vehicle's range.

Regardless of drive type, increased vehicle speeds and acceleration have negative effects on the environment, such as increased tyre wear and energy consumption.

Maintenance

In Germany, vehicles of all drive types are required to undergo a main inspection (MOT) every 24 months (or after 36 months following initial registration). However, no exhaust gas inspection is required for BEVs. Regardless of drive type, maintenance cycles are required on an annual basis/at certain mileages (annual inspection).

The differences are a result of the **vehicle technology** (wear parts). As a rule, modern electric motors in BEVs do not require any maintenance. The large vehicle batteries in BEVs are usually subject to maintenance. Both drive types have a similar maintenance expense and workload in relation to safety-related components, such as brakes. However, the BEV has a series of advantages compared to the combustion engine in terms of the normal wear parts: There are fewer wear parts, e.g. there is no filter, toothed belt, drive chain, spark plug or exhaust system. No oil change is required. The brakes are generally subjected to less wear, as much of the brake energy used by an electric motor is recovered by the drive system.

In terms of workshop availability, the widespread combustion engine currently has the advantage, as not all car workshops can currently offer maintenance and repairs for BEVs.

Since market penetration is still shallow, spare parts and services for electric cars are not yet available to the same extent as they are for ICEVs, either.

Some of these aspects will change over time, particularly those linked to market evolution. For example, disadvantages of use relating to a lack of infrastructure will already be much less prevalent in 2030, and may no longer be relevant at all by 2050.

8.4 ENVIRONMENT

8.4.1 Heat

In terms of **GHG emissions**, heat pumps in Germany already have an advantage of about one third over oil heating systems. In the medium term (by 2030), this advantage will increase due to the rising proportion of renewable energy involved in the generation of electricity. In the scenarios, this will increase more quickly than the blending of synthetic ingredients into heating oil. In the long term (2050) scenario PtX 95 projects that the rating will drop back to neutral, as blending in of GHG-neutral fuels approaches 100 %.

In terms of air pollution emissions, heat pups have an advantage in the short, medium and long terms, as they do not generate any local emissions. Noise emissions from air heat exchangers may have a role to play, especially in compact spaces. Oil systems offer advantages in this regard.

8.4.2 Traffic

GHG emissions (polluter pays principle)

The polluter pays principle applies to both GHG emissions at the site of use and power generation.

Based on the current electricity mixture in Germany (approx. 530 g CO2/kWh el; cf. (UBA 2017)) an electric car already generally produces lower emissions than a vehicle with an internal combustion engine. In 2030, the electric vehicle will have a significant advantage, since by then the CO_2 factor in power generation will have been reduced significantly due to more widespread use of renewable energy while levels of blended synthetic substances in PtLs remain relatively low.

Table 37: Result of the criteria evaluation from the perspective of the consumer – heat

2018		**Building type**	**SFH/DFH/RH**	**MFH**
Utilisation		Space requirement inside the building	Electricity advantage (minor)	Electricity advantage (minor)
		Space requirement outside the building	Liquid advantage (minor)	Liquid advantage (major)
		Space requirement heating element	Liquid advantage (minor)	Liquid advantage (minor)
		Maintenance workload	Electricity advantage (minor)	Electricity advantage (minor)
		Possibility of failure	Neutral	Neutral
		Cost risk associated with incorrect installation	Liquid advantage (minor)	Liquid advantage (minor)
Economic efficiency with PtL	**1.3**	Cost of procurement	Liquid advantage (major)	Liquid advantage (major)
		Running cost	Liquid advantage (minor)	Liquid advantage (minor)
		Total cost	Liquid advantage (major)	Liquid advantage (major)
	0.7	Cost of procurement	Liquid advantage (major)	Liquid advantage (major)
		Running cost	Liquid advantage (minor)	Liquid advantage (minor)
		Total cost	Liquid advantage (major)	Liquid advantage (major)
Environment		GHG emissions	Electricity advantage (major)	Electricity advantage (major)
		Air pollution emissions	Electricity advantage (minor)	Electricity advantage (minor)
		Noise emissions	Liquid advantage (minor)	Liquid advantage (minor)
2030		**Building type**	**SFH/DFH/RH**	**MFH**
Utilisation		Space requirement inside the building	Electricity advantage (minor)	Electricity advantage (minor)
		Space requirement outside the building	Liquid advantage (minor)	Liquid advantage (major)
		Space requirement heating element	Liquid advantage (minor)	Liquid advantage (minor)
		Maintenance workload	Electricity advantage (minor)	Electricity advantage (minor)
		Possibility of failure	Neutral	Neutral
		Cost risk associated with incorrect installation	Liquid advantage (minor)	Liquid advantage (minor)
Economic efficiency with PtL	**1.3**	Cost of procurement	Liquid advantage (major)	Liquid advantage (major)
		Running cost	Neutral	Neutral
		Total cost	Liquid advantage (major)	Liquid advantage (major)
	0.7	Cost of procurement	Liquid advantage (major)	Liquid advantage (major)
		Running cost	Neutral	Neutral
		Total cost	Liquid advantage (major)	Liquid advantage (major)
Environment		GHG emissions	Electricity advantage (major)	Electricity advantage (major)
		Air pollution emissions	Electricity advantage (minor)	Electricity advantage (minor)
		Noise emissions	Liquid advantage (minor)	Liquid advantage (minor)

Electricity advantage (major) | Neutral | Liquid advantage (major)
Electricity advantage (minor) | Liquid advantage (minor)

2050		Building type	SFH/DFH/RH	MFH
Utilisation		Space requirement inside the building	Electricity advantage (minor)	Electricity advantage (minor)
		Space requirement outside the building	Liquid advantage (minor)	Liquid advantage (major)
		Space requirement heating element	Liquid advantage (minor)	Liquid advantage (minor)
		Maintenance workload	Electricity advantage (minor)	Electricity advantage (minor)
		Possibility of failure	Neutral	Neutral
		Cost risk associated with incorrect installation	Neutral	Neutral
Economic efficiency with PtL	1.3	Cost of procurement	Liquid advantage (major)	Liquid advantage (major)
		Running cost	Electricity advantage (major)	Electricity advantage (major)
		Total cost	Electricity advantage (major)	Electricity advantage (major)
	0.7	Cost of procurement	Liquid advantage (major)	Liquid advantage (major)
		Running cost	Electricity advantage (minor)	Electricity advantage (minor)
		Total cost	Liquid advantage (minor)	Liquid advantage (minor)
Environment		GHG emissions	Neutral	Neutral
		Air pollution emissions	Electricity advantage (minor)	Electricity advantage (minor)
		Noise emissions	Liquid advantage (minor)	Liquid advantage (minor)

Source: Prognos AG

Electricity advantage (major) · Electricity advantage (minor) · Neutral · Liquid advantage (minor) · Liquid advantage (major)

In the long term – i.e. once BEVs and PtL are almost exclusively using renewable electricity – both drive types will offer an option for GHG-emissions-free mobility.

Air pollution: local emissions (tank to wheel)

BEVs produce not exhaust gas at the local level. However, this does not mean that electric passenger cars cause zero air pollution- Particle emissions caused by re-suspension and wear to tyres and brakes are generated by vehicles of all drive types. In addition to this, the combustion process in an internal combustion engine also produces local exhaust gas emissions (soot particles, NOx, etc.).

By their very nature, ICEVs generate local emissions. These can be reduced through the use of synthetic PtL fuels. In the long term, the local emissions of the ICEV will be neutralised by exhaust gas treatment in line with pollution limits.

Noise emissions

Battery electric vehicles are quieter at low and medium speeds. At speeds of approx. 50 to 70 km/h, they mainly produce tyre and driving noises.

Resource consumption

BEVs tend to consume higher levels of energy and resources during manufacturing and disposal. This balance is expected to improve as the technology continues to develop.

8.5 CONCLUSION FROM THE CONSUMER'S PERSPECTIVE

Consumers consider other criteria, such as aspects of use and environmental aspects, to be of equal importance to economic criteria when making a purchase decision. The criteria evaluation shows a varied picture:

Heat

In terms of **economic efficiency** heating systems with liquid fuels have the advantage in **existing buildings** in the short-to-medium term (2030), since they have a lower total cost. However, this projection does not take into account heat pump tariffs or funding measures such as investment subsidies. As such, heat pumps may prove more advantageous to individual consumers even before 2030.

If the requirements for reduction of greenhouse gases increase (thus leading to an increase in the proportion of synthetic fuels blended into PtL systems), the overall cost comparison will present a varied picture. If PtL generation costs increase, heat pumps could be more economically efficient from 2030 onwards. However, this relies on the end consumer prices for electricity in Germany "freezing" at their 2015 price level in the long term. If PtL generation costs remain low, on the other hand, heating systems with liquid energy sources will continue to be more economically efficient than heat pumps.

The rating for the **aspects of use** for combustion heating systems and heat pumps is neutral – there is no clear advantage to either system.

From an **environmental perspective**, heat pumps generate lower emissions at their site of use. While modern oil heating systems cause local air pollution, this is of little relevance to the problem of air quality as a whole, and can also be largely eliminated through increased use of PtL. Greenhouse gas emissions from electric heat pumps today are lower than those of oil heating systems, and will remain so in the medium term (2030). As the proportion of synthetic materials blended into PtL systems increases (after 2040), the difference in GHG emissions levels between the two systems will decrease, and the rating between heat pumps and PtL-based heating systems will be neutral by 2050. This is assuming that both electricity generation in Germany and electricity imports from the domestic European electricity market will be decarbonised by this point, and that PtL will be used as greenhouse-gas-neutral liquid energy sources in the appropriate heating systems.

Traffic

In terms of **use** and taking into account all the criteria used in the evaluation, vehicles with an internal combustion engine offer an advantage over the electric drive and will probably continue to do so for the next few decades. The advantages are particularly pronounced in terms of the robust range, short refuelling time and established, widely available refuelling infrastructure of a vehicle with liquid fuel. These criteria are particularly important to long-distance drivers and drivers of heavy commercial vehicles. The comparison of the evaluation over shorter distances for passenger cars and light commercial vehicles revealed a less pronounced advantage in favour of the ICEV, as long range is weighted less heavily for such situations, and the BEV's driving dynamics can match those of the ICEV in every area, even surpassing them in "stop-and-go" situations. Based on impending technological developments, the disadvantages of using a BEV are expected to be reduced in the future. However, vehicles with combustion engines and liquid energy sources are expected to retain their significant advantages for a long time yet.

The **economic efficiency evaluation** for passenger cars revealed a similar overall picture. Electric applications will become cheaper over time as battery prices fall, while passenger cars with internal combustion engines will be more expensive by 2040 due to the increase in PtL blending. After 2040, the PtL cost reductions will outweigh further increases in PtL blending due to the learning curve. In our base year, 2015, the TCO for an electric car was 15 % to 40 % higher than for an ICEV in all passenger segments. In case of low annual mileages or high battery costs (e.g. when a battery change is required), the TCO calculation shows passenger cars with combustion engines and PtL fuel to be the more affordable option for consumers in the long term, too, due to the lower cost of procurement when compared to an electric car.

Due to their higher storage densities and faster fuelling processes, liquid energy sources will also continue to offer advantages in use in the long term with regard to long-range mobility (holidays and road goods transport). In cases of more frequent use but lower mileage (car sharing, taxis, delivery services), BEVs have the advantage in terms of both economic and ecological factors. Due to their low energy costs, electric drives are cheaper than combustion engines for consumers with high annual mileages. When driving in densely populated areas, it is also important to note that BEVs are relatively quiet (no engine noise) and do not emit any toxic air pollutants.

On the other hand, it should also be noted that electric vehicles also consume more resources from an environmental point of view during manufacturing and disposal. This is due to the energy-intensive battery manufacturing and recycling processes. If the environmental comparison is conducted based on an eco-balance (incl. upstream and downstream effects), combustion engines may also prove more attractive than electric vehicles from an ecological perspective for consumers with very low mileages. However, this depends primarily on the indirect emissions produced during generation of the electricity (both the electricity used to drive the electric vehicle and that used in the manufacturing of the battery).

Table 38: Result of the criteria evaluation from the perspective of the consumer – mobility

2018	Mobility	Passenger car		LCV	HCV
	[km/day]	<50	>200	ca. 100	>200
Usage	New European Driving Cycle (NEDC)	grey	green	blue	green
	Robustness of range	blue	green	blue	green
	Refuelling time (BEV with/without quick charge)	blue/green	green	blue/green	green
	Refuelling infrastucture (city/countryside)	blue/green	green	blue/green	green
	Degradation (cyclic ageing, calendar ageing)	blue	blue	blue	blue
	Driving dynamics (acceleration, maximum speed)	yellow	blue	yellow	blue
	Maintenance	grey	grey	blue	green
Economic efficiency	Cost of procurement	green	green	green	green
	Resale value	blue	blue	blue	blue
	Maintenance	yellow	yellow	yellow	yellow
	Running cost (PtL 0.7 and PtL 1.3)	orange	orange	orange	orange
	Total cost (PtL 0.7 and PtL 1.3)	blue	blue	blue	green
Environment	GHG emissions	yellow	yellow	yellow	yellow
	Air pollution emissions: local emissions (tank to wheel)	orange	orange	orange	orange
	Noise emissions	yellow	grey	yellow	grey
	Resource consumption (manufacturing and disposal)	green	green	green	green

2030	Mobility	Passenger car		LCV	HCV
	[km/day]	<50	>200	ca. 100	>200
Usage	New European Driving Cycle (NEDC)	grey	blue	grey	blue
	Robustness of range	grey	green	blue	green
	Refuelling time (BEV with/without quick charge)	blue	green	blue	green
	Refuelling infrastucture (city/countryside)	blue	blue	blue	blue
	Degradation (cyclic ageing, calendar ageing)	blue	blue	blue	blue
	Driving dynamics (acceleration, maximum speed)	yellow	grey	yellow	blue
	Maintenance	grey	grey	grey	green
Economic efficiency	Cost of procurement	blue	blue	blue	blue
	Resale value	grey	grey	grey	blue
	Maintenance	blue	blue	blue	blue
	Running cost (PtL 0.7 and PtL 1.3)	orange	orange	orange	orange
	Total cost (PtL 0.7 and PtL 1.3)	grey	grey	grey	grey
	GHG emissions	blue	grey	grey	blue
Environment	Air pollution emissions: local emissions (tank to wheel)	yellow	yellow	yellow	yellow
	Noise emissions	yellow	yellow	yellow	yellow
	Resource consumption (manufacturing and disposal)	yellow	grey	yellow	grey
	Ressourcenverbrauch (Herstellung und Entsorgung)	blue	blue	blue	blue

2050	Mobility	Passenger car		LCV	HCV
	[km/day]	<50	>200	ca. 100	>200
Usage	New European Driving Cycle (NEDC)	Neutral	Liquid advantage (minor)	Neutral	Liquid advantage (minor)
	Robustness of range	Neutral	Liquid advantage (major)	Liquid advantage (minor)	Liquid advantage (major)
	Refuelling time (BEV with/without quick charge)	Liquid advantage (minor)	Liquid advantage (major)	Liquid advantage (minor)	Liquid advantage (major)
	Refuelling infrastucture (city/countryside)	Liquid advantage (minor)	Liquid advantage (minor)	Liquid advantage (minor)	Liquid advantage (minor)
	Degradation (cyclic ageing, calendar ageing)	Neutral	Neutral	Neutral	Liquid advantage (minor)
	Driving dynamics (acceleration, maximum speed)	Electricity advantage (minor)	Neutral	Electricity advantage (minor)	Neutral
	Maintenance	Neutral	Neutral	Neutral	Liquid advantage (minor)
Economic efficiency	Cost of procurement	Liquid advantage (minor)	Liquid advantage (minor)	Liquid advantage (minor)	Liquid advantage (minor)
	Resale value	Neutral	Neutral	Neutral	Neutral
	Maintenance	Electricity advantage (minor)	Electricity advantage (minor)	Electricity advantage (minor)	Electricity advantage (minor)
	Running cost (PtL 0.7 and PtL 1.3)	Electricity advantage (major)	Electricity advantage (major)	Electricity advantage (major)	Electricity advantage (major)
	Total cost (PtL 0.7 and PtL 1.3)	Electricity advantage (minor)	Electricity advantage (minor)	Electricity advantage (minor)	Electricity advantage (minor)
	GHG emissions	Neutral	Electricity advantage (minor)	Electricity advantage (minor)	Neutral
Environment	Air pollution emissions: local emissions (tank to wheel)	Neutral	Neutral	Neutral	Neutral
	Noise emissions	Electricity advantage (minor)	Electricity advantage (minor)	Electricity advantage (minor)	Electricity advantage (minor)
	Resource consumption (manufacturing and disposal)	Electricity advantage (minor)	Neutral	Electricity advantage (minor)	Neutral
	Ressourcenverbrauch (Herstellung und Entsorgung)	Liquid advantage (minor)	Liquid advantage (minor)	Liquid advantage (minor)	Liquid advantage (minor)

Source: Prognos AG

Electricity advantage (major) | Neutral | Liquid advantage (major)
Electricity advantage (minor) | Liquid advantage (minor)

9

INTERIM CONCLUSION ON THE SCENARIOS

The scenarios show that the German federal government's GHG targets for 2050 remain achievable even if domestic developments in energy efficiency and renewable energy continue at only a moderate pace. If this turns out to be the case, GHG reduction can be achieved by continually increasing the proportion of GHG-neutral synthetic fuels in conventional liquid and gaseous energy sources.

In the scenarios, **end energy consumption** is projected at the "reference level", as is the maximum expansion of renewable energy in Germany. Due to the stricter requirements, however, the **electricity sector** is de-carbonised more quickly in the PtX scenarios, and more electricity is imported from abroad. In the reference scenario, German generation of electricity still includes coal power plants, while natural gas is the only remaining fossil fuel in the PtX scenarios. In PtX 95, natural gas is projected to be completely superseded by PtG by 2050. This will lead to higher electricity prices. A further increase in electricity prices will be prevented by the European embedding of the German electricity market.

Since PtL and PtG are currently still relatively expensive to produce, we have forecast a gradual market evolution that is not calibrated to the intermediate targets, such as those in the environmental protection plan. This market evolution will not pick up speed until between 2030 and 2040, at which point it will accelerate rapidly. The GHG targets for the energy concept in 2050 will be achieved. The cumulative GHG emissions will thus be higher than for a course that includes the government's intermediate targets.

PtL demand in Germany could reach around 1,700 PJ by 2050 in scenario PtX 80, and around 2,000 in PtX 95. This is equivalent to around 37 % to 44 % of the primary energy consumption currently covered by mineral oil in Germany. Our scenarios also show a significant increase in PtG demand.

Our scenarios require **relatively low investment** in Germany. As a result, most heating customers will retain the same heating system they use today. The number of electric heat pumps and electric vehicles will increase significantly, but they will not dominate the market until 2050. Infrastructure investments, such as those in electricity grids, will also remain moderate. Electricity infrastructure on motorways (for trucks with overhead cables) should not be absolutely necessary. In total , the PtX scenarios for Germany up to 2050 indicate that €34 bn or €59 bn more needs to be invested than in the reference scenario, a third of which (in PtX 95) will go to CCS; based on current understanding, this should not make achieving the targets significantly more expensive. These investments are low compared to other studies.

In order for the market evolution we have projected to actually occur, however, **extensive investment abroad** will be necessary. In scenario PtX 80, this investment totals around €1,440 bn over the entire scenario period, while a cumulative investment of €1,840 bn by 2050 has been assumed in PtX 95 (supply in Germany only).

Large areas will also be required for wind farms and solar parks. There has been no investigation of how much area is actually available for use in the countries included in the evaluation. However, these countries do possess large areas of land compared to Germany, much of which is desert or steppe.

The high levels of investment abroad are reflected in **rises in domestic energy costs.** It should be assumed that the energy costs in the PtX 80 scenario will reach **around €1,500 bn**$_{2015}$ more than in the reference scenario by 2050, without the climate protection targets actually being achieved. The additional cost of energy consumption in scenario PtX 95 as compared to the reference are at a similar level, as we have assumed that ambitious climate protection action on a global scale will cause the price of fossil energy sources to fall.

From a **consumer perspective**, there are several criteria that play a role in the choice of heating system or vehicle type. The factors included in our study are economic efficiency, aspects of use and environment. Up until 2030, combustion-based engines and heating systems will hold a significant advantage over electric vehicles and electric heat pumps in terms of economic efficiency. After 2030, however, assuming that electricity prices remain the same but there is a higher PtL blending proportion, electric solutions will be cheaper in many cases. If PtL costs reach the lower end of the cost range used in this study, PtL-based liquid energy sources will also remain the more economically efficient solution after 2030. However, heat pump tariffs and subsidies for heat pumps (which already exist today) may result in cost benefits for heat pumps.

In terms of aspects of use for heating solutions, the authors of this study see no significant difference between oil, gas and electric solutions. In many cases, building conditions will be the decisive factor. In terms of mobility, electric vehicles are at a disadvantage with regard to aspects of use due to the current physical properties of the batteries and the fact that the charging infrastructure is still under development. Some of these disadvantages will have been eliminated by 2030. Others – such as refuelling time versus charging time – are likely to remain. However, whether or not these disadvantages in use are deemed to be relevant will be a case of individual preference.

From an environmental perspective, electric solutions offer the advantage of not causing air pollution at the site of consumption. GHG emissions from electric solutions are lower than those of combustion-based engines and heating systems, and will remain so in the medium term. As the ratio of GHG neutral PtL blended into the fuel mixture increases, the gap between the solutions will close. High blending proportions – such as those shown in the PtX 95 scenario – will result in a neutral evaluation.

STUDY SECTION B: DESCRIPTION OF SELECTED TECHNOLOGY PATHS

The following description of selected technology paths played a key role on the first phase of this study. At its core, the study focuses on three technology paths:

- First, we wanted to show the potential of wind and solar power generation at both the national and international levels. Wind and solar energy are the only forms of renewable energy with sufficient potential. Despite this, there may still be limits to their growth; we will get to the bottom of these limits in this section. In addition to this, the costs of producing electricity are higher in Germany than in countries with more favourable weather conditions.

- We also focused on the potential and cost associated with biomass. This area of focus was included in the study in recognition of the fact that biomass is already used to produce a portion of our current liquid energy sources. Our aim was to test the hypothesis regarding whether and to what extent domestic biomass seems a suitable replacement for carbon-based energy sources, particularly for the production of liquid energy sources.

- The third technology path investigated in depth in this study is the production of synthetic liquid (and gaseous) energy sources using "renewable hydrogen" and carbon dioxide taken from the air. To this end, we have described the technical processes and costs that make this possible.

The results of part B of this study were used to create the scenarios described in part A.

10

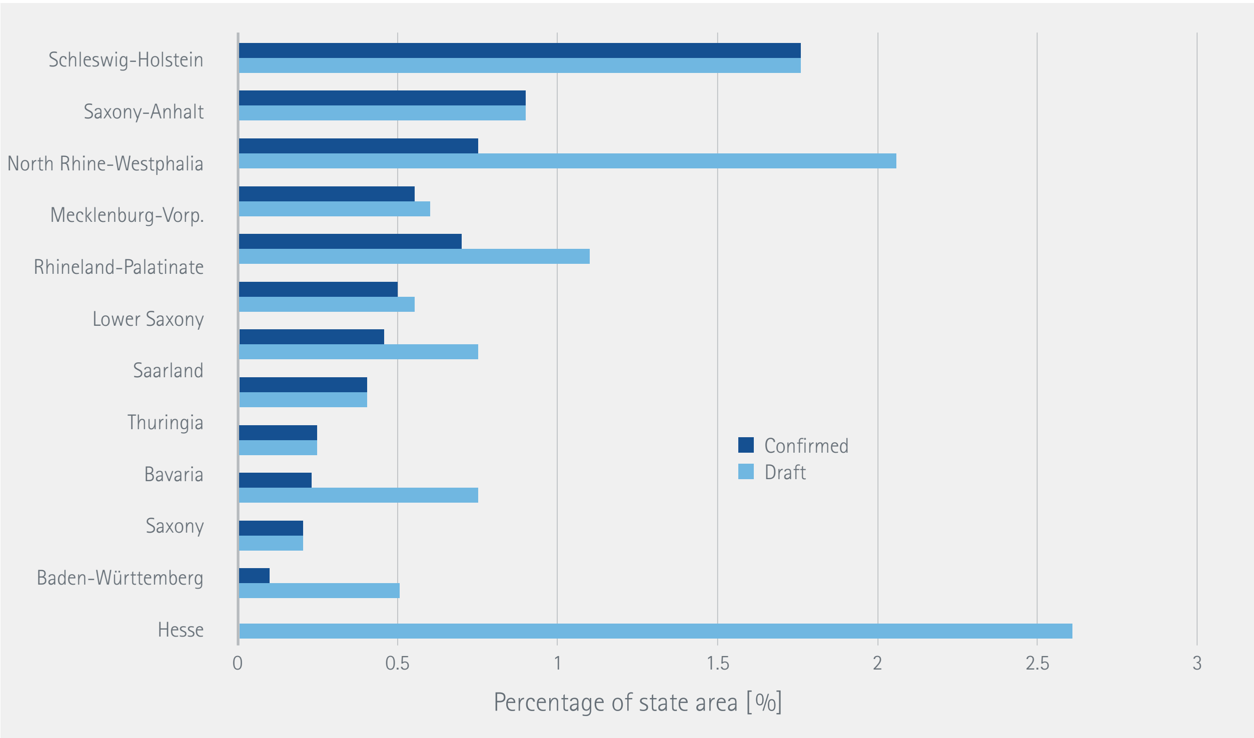
POTENTIAL AND TECHNOLOGIES OF RENEWABLE ENERGIES FOR ELECTRICITY GENERATION

10.1 POTENTIAL AND COSTS IN GERMANY

The generation of electricity using renewable energy has been significantly expanded in Germany in recent years. While only 104 TWh were generated in 2014, by 2016, generation figures had reached around 188 TWh (Umweltbundesamt (German Federal Environment Agency) 2017). 2017 saw a further significant increase to around 217 TWh (BDEW (Federal Association of the German Energy and Water Industries) 2017).

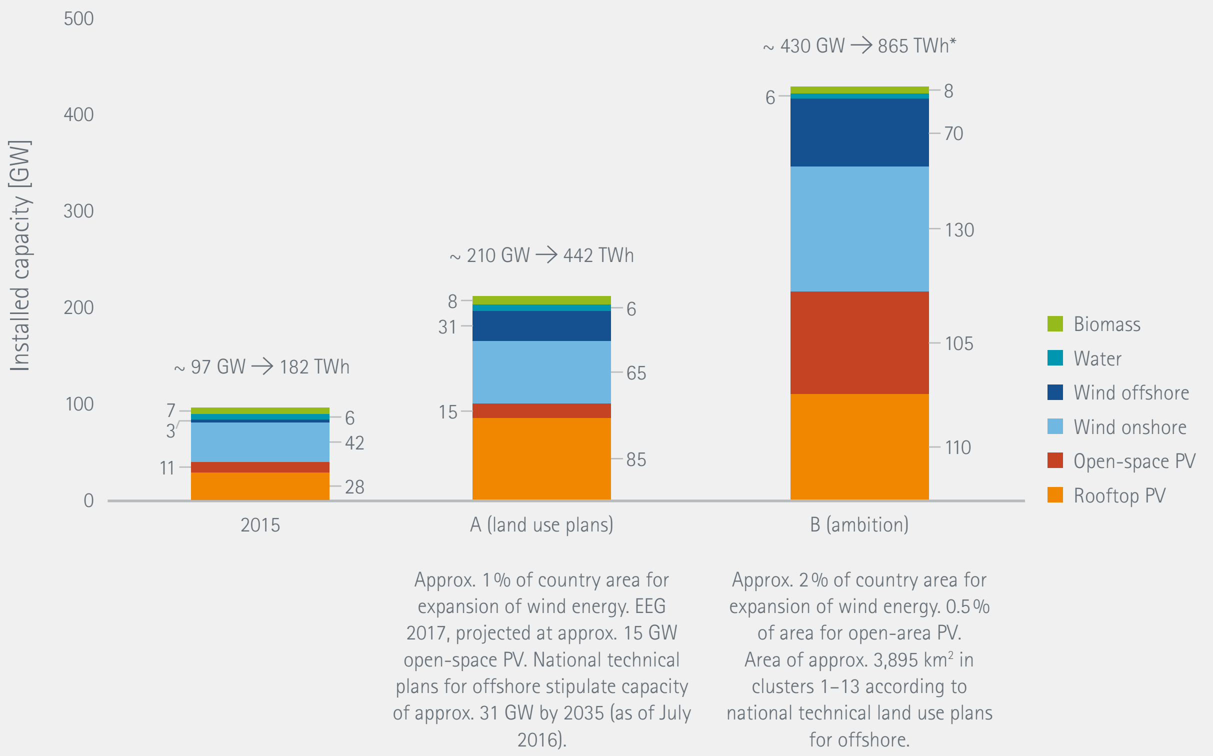
However, spatial development is of far greater importance in the use of renewable energy for power generation is than in the use of fossil fuels. As a result, the issue of availability of areas of potential use is becoming increasingly prominent in the political discussion (BMVI (German Federal Ministry of Transport and Digital Infrastructure) 2015). This begs the question of whether electricity demand in Germany can be covered by domestic generation using renewable energy in the long term, or whether the limits of social acceptance will be reached before this level of generation is attained.

Figure 54: Ratio of designated priority areas for wind power to the overall area of the German federal states*



Source: Own chart based on (Zaspel-Heisters 2015), *date: 2015

Figure 55: Output achievable in Germany in GW and electricity generation potential in TWh of renewable energies



Source: Prognos AG, *Additional offshore capacity in cluster 14 potentially possible, a yet-to-be-developed offshore cluster further out from the coast, with an area of 2,715 km² and an additional installable capacity of ~ 50 GW and generation potential of ~ 200 TWh. (Cf. BSH (Federal Maritime and Hydrographic Agency of Germany) national technical plan for offshore for North Sea/Baltic Sea, 2017)

Generally speaking, acceptance levels for renewable electricity generation in Germany remain high. The annual representative surveys conducted by the Agentur für erneuerbare Energien (German Renewable Energies Agency) have provided a stable picture for many years. The majority of those surveyed rated the generation of electricity using renewable resources in their local area as positive. Solar parks and wind farms received the highest approval ratings. However, project planners and operators of new wind farms have reported experiencing more frequent protests from local citizens affected by their developments on recent projects (Agora Energiewende 2018).

Potential

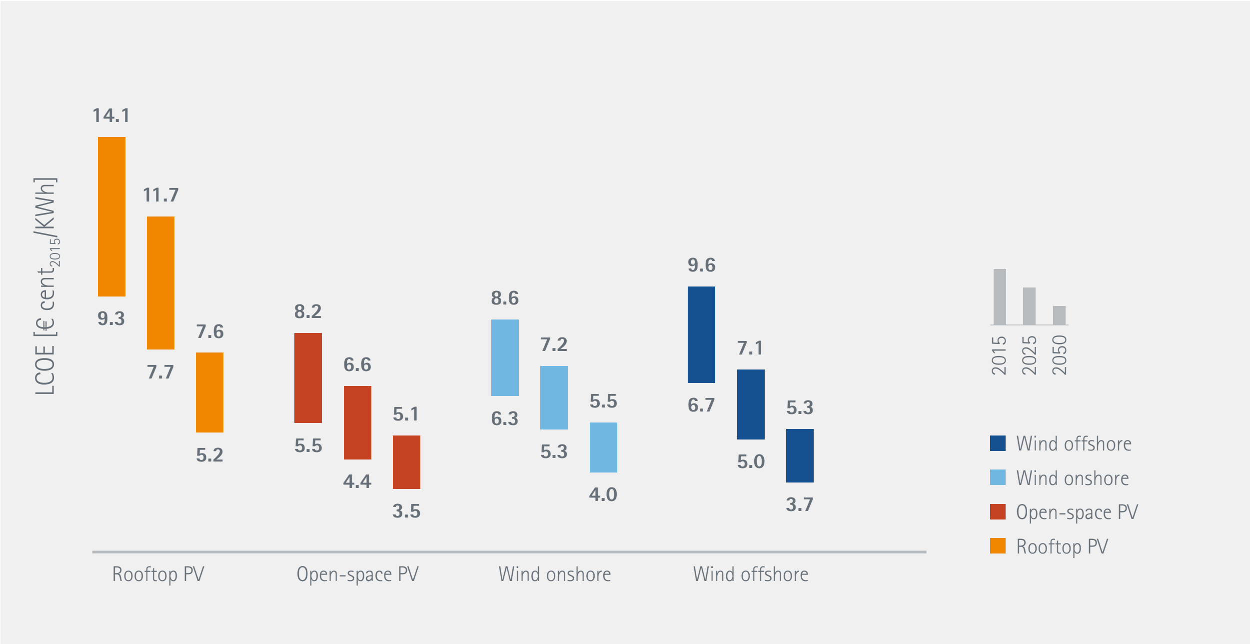
The domestic **generation potential** for electricity using renewable energy is dependent particularly on social acceptance of the use of the land in question. In the long term, we should expect future projects to be limited not by the physical availability of sites, but rather by how much land is permitted to be used for the generation of renewable energy.

At the time of writing, there have been no scientific studies of what level of development is deemed acceptable, particularly for onshore wind energy and open-space solar energy, though such a study would also be difficult to implement with regard to methodology. In some of Germany's federal states, the expansion of renewable energy has been restricted due to strict demands for the distance required between wind farms and residential developments. For example, Bavaria requires a minimum distance that is equal to ten times the total height of wind turbines (hub height plus rotor radius).[15]

The current land use plans for Germany mark out approx. 1 % of the country's area, or 3,515 km², as wind priority areas (as of April 2015). This already includes areas that are thus far only included in drafts and have thus not yet been

15 In exceptional cases and with the permission of the local councils in question, shorter distances can be used in the construction plans.

Figure 56: Electricity generation costs of renewable energies in Germany with capital costs between 2 % and 7 % (actual 2015 prices)



Source: Own calculations

set in stone. Figure 54 shows the distribution of the wind priority areas across the individual states. If these areas are utilised to their full extent, they could be used to install around 65 GW of wind energy. In all the scenarios calculated in this study, this capacity would be exceeded before 2030. Enough area for a further 25 GW would be required by 2050.

If 2 % of the country's area were to be used for onshore wind energy and a further 0.5 % for photovoltaic plants (PV) (a total area of nearly 9,000 km²), this, combined with the other options available (offshore wind energy, rooftop PV, biomass, hydro-electricity) would result in 865 TWh of electricity potentially being produced per year, taking into account moderate developments in the performance of the systems in question.

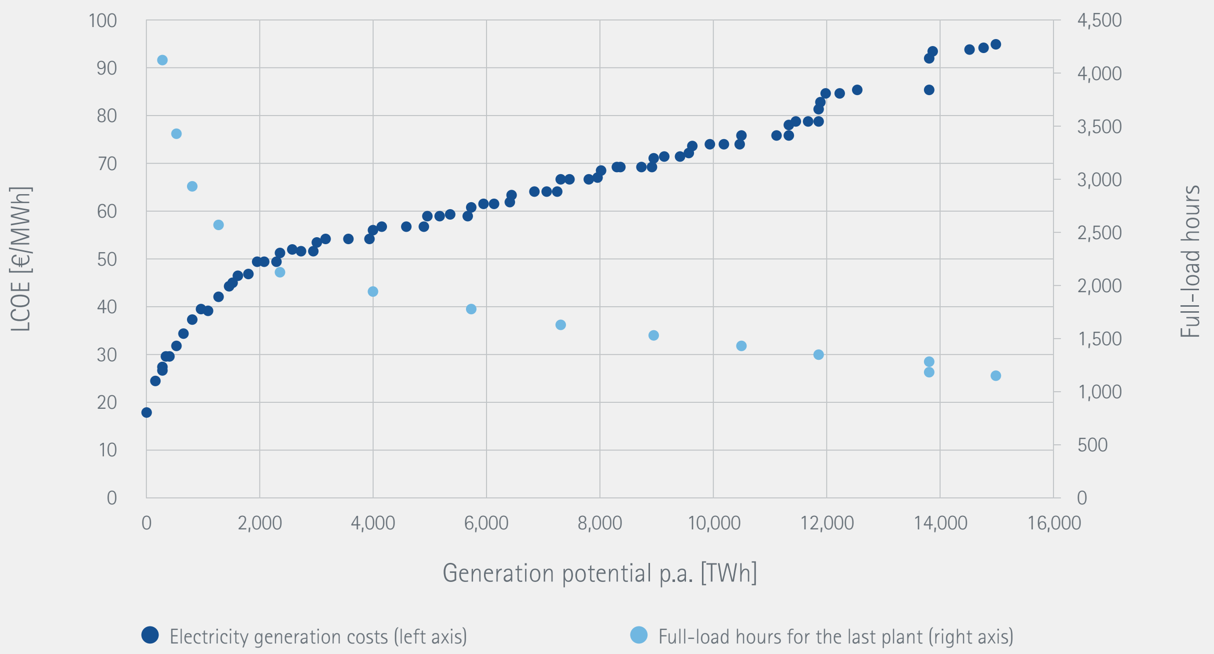
In keeping with this approach, Prognos has drawn up two estimates for the total potential for electricity generated using renewable energy in Germany: one with limited land use (variant A) and one with fewer restrictions on land use and a greater acceptance for the expansion of renewable energy (variant B). This resulted in a feasible potential of between 442 TWh and 865 TWh for the country's annual generation of electricity. Figure 5 shows the results by type of generation technology. The fundamental assumptions with regard to land use are provided in Table 54, in the appendix to this study.

In variant A we deliberately included heavy restrictions on the further expansion of renewable energy in our calculations in order to demonstrate clear alternative methods of environmental protection in comparison to other conventional energy system scenarios. For example, the installed capacity for onshore wind can only increase by 14 GW compared to the capacity level in 2017. The 15 GW total capacity limit for open-space PV plants is also relatively low in view of the high current level of acceptance for PV parks and the spaces available with little competition for use (e.g. alongside motorway, railways, re-cultivation areas, etc.).

At this point, we are not intending to provide an estimation as to which of the two values is most realistic. Nevertheless, the scenarios in this study posit that there will be restrictions in Germany, and that the expansion of renewable energy will remain restricted to somewhere around the level used in the reference scenario.

What is certain is that the full utilisation of the land planned for renewable energy use in scenario A is not sufficient to cover current energy demands alone (gross consumption in 2016 was 595 TWh). An evaluation of various current energy system studies indicates that domestic electricity requirements will reach between 450 and 1,100 TWh by 2050 (Agentur für erneuerbare Energien (German Renewable Energies Agency) 2016).

Figure 57: Cost-potential curve for onshore wind energy in the MENA region for the year 2050



Source: Own chart based on (Zickfeld and Wieland 2012)

Costs

The specific costs of generating electricity using renewable energy have fallen dramatically over the past few years, and are now lower than the costs of generation using fossil-fuel power plants in some cases. It can be assumed that this cost degression will have continued further by 2050. Figure 56 shows the projected development in the costs of producing electricity using renewable energy with based on different capital costs. The fundamental assumptions are provided in Table 54. The upper and lower values are based on capital costs of 7 % and 2 % respectively. The remaining projected parameters[16] remain constant, however. The calculated figures reflect an average for newly installed plants in Germany in the years 2015, 2025 and 2050. This means that some plants may have much higher electricity production costs, especially if there is an aim to realise large potential overall (as in variant B, Figure 55).

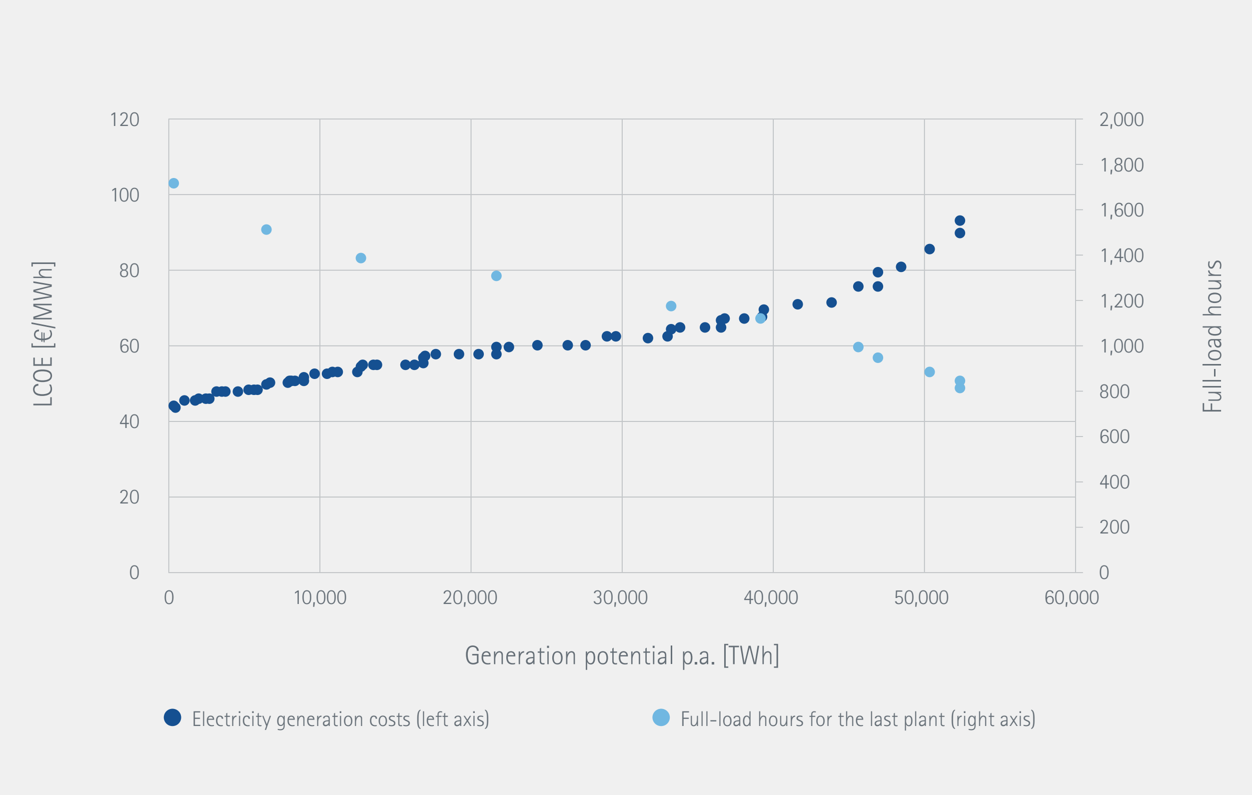
In order to allow a proper understanding of the electricity production costs, it is important to note the following information on the next section, especially for the purposes of comparison: no explicit evaluation of a cost-potential curve for Germany has been conducted in the course of this study. As such, the study does not document the full extent of the potential increase in costs that could result from the need to utilise sites with poorer generation conditions, and thus fewer achievable full-load hours. However, this factor is accounted for in part – particularly for onshore wind technology, where this issue is of particular relevance – by the fact that the calculation uses a lower projected number of full-load hours than many other system studies (e.g. (BMWi, Fraunhofer ISI et al. 2017), (enervis energy advisors GmbH 2017)).

10.2 POTENTIAL AND COSTS ABROAD

As explained in the previous chapter, the increasing utilisation of the domestic potential for electricity generation using renewable energy in Germany may be limited due to restrictions in acceptance and the land approved for use. As an alternative, electricity could be acquired by importing renewable electricity from other European states.

16 Assumptions: Plant service life: 25 years; constant yields and running costs; all investment costs (incl. reserve and demolition costs) incurred at start of project; excl. tax

Figure 58: Cost-potential curve for solar PV in the MENA region for the year 2050



Source: Own chart based on (Zickfeld and Wieland 2012)

For the purposes of this study, the authors have assumed that the other EU nations will be pursuing similarly ambitious climate environmental targets to Germany, and will thus initially prioritise their ability to cover their own domestic electricity requirements. Any surplus could potentially be exported to Germany. However, the transportation of electricity from southern Europe would entail bearing specific grid costs of between 2.8 € cent/kWh and 3.9 € cent/kWh in addition to the specific generation costs.[17]

The "accepted" potential of commercial PtX generation in Germany is not sufficient, nor are the production costs that can be achieved by ensuring greater plant utilisation attractive enough. This would primarily involve sites outside of Europe. As such, the observations in this study are focused primarily on the potential of wind energy and solar PV in the MENO (Middle East and North Africa) region.

Potential

This study illustrates the potential in the MENA region using existing potential estimated from the literature (Zickfeld and Wieland 2012).

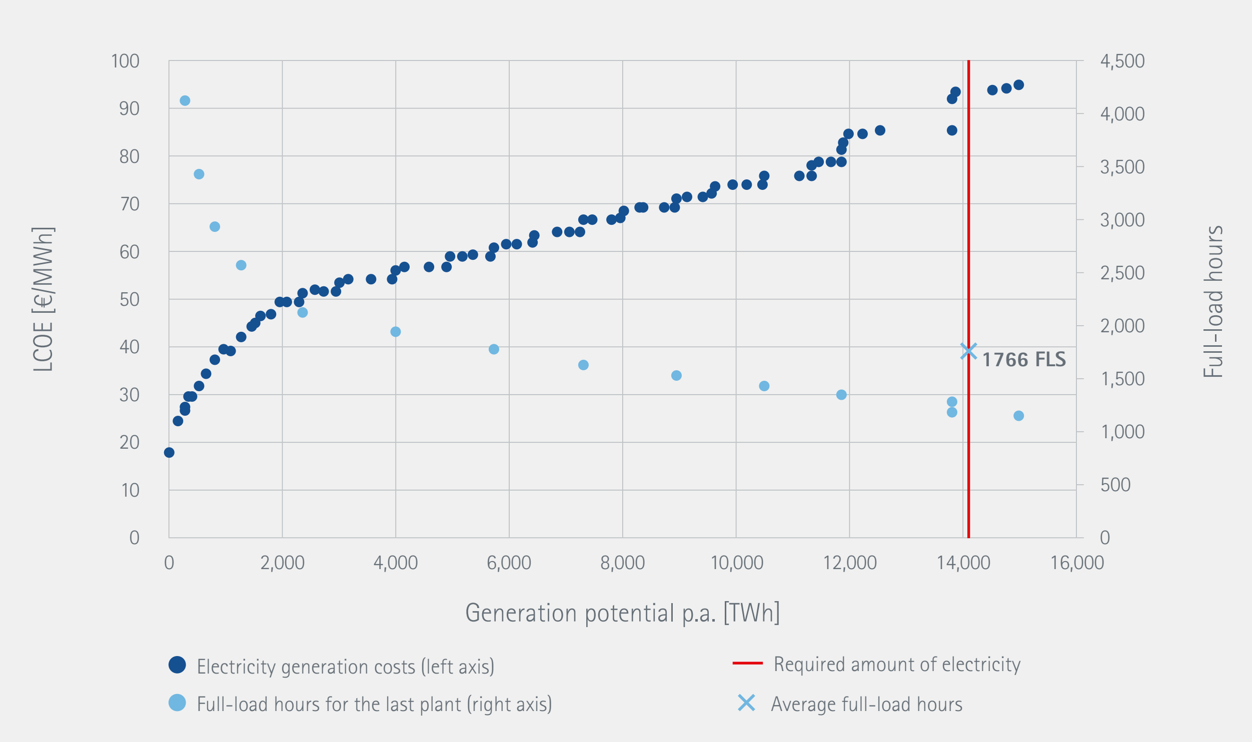
Since large amounts of electricity would be required to supply Europe with synthetic liquid energy sources, it is particularly important to know what amounts of electricity could be provided under what generation conditions (here: achievable full-load hours). Conclusions on this can be drawn using cost-potential curves.

Figure 57 shows the cost-potential curve for onshore wind energy in the MENA region in 2050. The curve illustrates the generation potential together with the associated costs of production and the achievable full-load hours for the last plant erected. At 15,000 TWh per year, the generation potential of wind energy in the MENA region is almost 50 times greater than the feasible potential of onshore wind energy in Germany projected in variant B. However, the curve also shows that only around 2,000 TWh of this can be generated at sites that achieve more than 2,000 full-load hours and thus offer lower generation costs than in Germany.

The cost-potential curve for solar PV in the MENA region is shown in Figure 58. At around 53,000 TWh, the annual generation potential is almost 260 times the projected

17 Based on own calculations. Projected service life of power cable: 40 years; capital costs: 6%.

Figure 59: Mean achievable full-load hours for onshore wind while utilising the necessary potential in the MENA region



Source: Own chart based on (Zickfeld and Wieland 2012)

feasible potential for solar PV in Germany. Of this, around 45,000 TWh can even be generated under better conditions than those available at German sites.

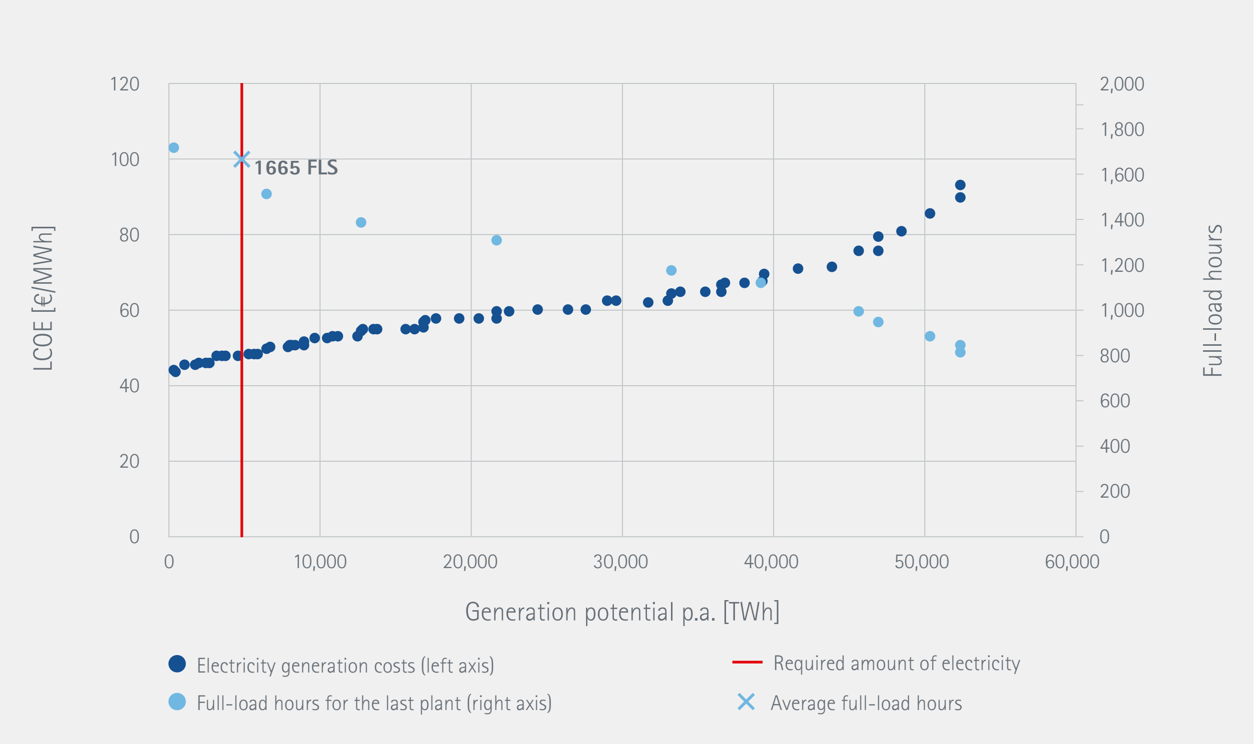
Costs

In order to draw up an estimate of the electricity production costs for the electricity used in the generation of synthetic liquid energy sources, we must first consider what quantities of electricity are required, as not all sites are able to offer the same conditions for the generation of electricity.

Furthermore, it has been assumed for the purposes of this study that a majority of the European demand for oil and gas shown in the EU reference scenario for 2016 (European Commission 2016) must be covered using synthetic oil and gas, in line with the blending ratios in the 95% scenario (see Figure 7). If we assume that the synthesis process offers a total efficiency of 53%, this would required around 18,800 TWh of electricity in 2050 – almost 32 times the electricity required in Germany in 2016. Furthermore, we have assumed that 75% of this electricity will be supplied by onshore wind farms and 25% by solar PV parks. This results in an annual electricity requirement of 14,100 TWh from onshore wind farms and 4,700 TWh from solar PV parks.

If we apply these quantities to the cost-potential curves for onshore wind and solar PV energy, this allows us to estimate the **average** full-load hours that the plants can achieve if the potential required in the MENA region is utilised to the full. Considering the huge quantities of electricity required, it does not seem appropriate to draw conclusions using just the cheapest sites. The corresponding qualities of electricity are marked by the vertical red lines in Figures 59 and 60. The marking on the line shows the resulting average full-load hours for every generation plant, weighted according to quantity. The results for onshore wind energy indicate an average of 1,766 full-load hours, while those for solar PV indicate an average of 1,665 full-load hours. In order to calculate the electricity costs involved in the operation of the electrolysis plants, we will now assume that a utilisation of 5,000 full-utilisation hours will be required for the electrolysis process. To this end, both solar PV and wind energy plants will be installed, and the installed connection capacity for the electrolysis plant will be built over to such an extent that the plant can reach the required utilisation. This will be followed by an hourly supply simulation, which will be generated at the Foum el-Oued site in Morocco using NASA MERRA datasets.

Figure 60: Mean achievable full-load hours for solar PV while utilising the necessary potential in the MENA region



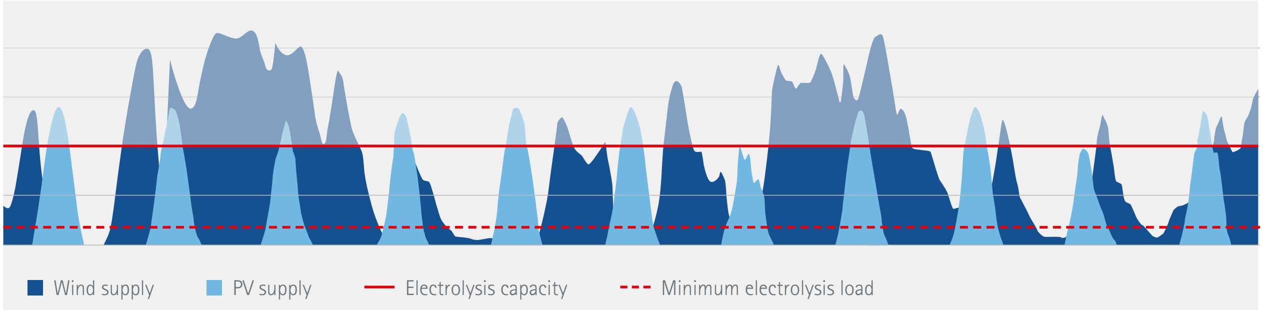
Source: Own chart based on (Zickfeld and Wieland 2012)

An example of the resulting generation profile is shown in Figure 61. The daily supply for the solar PV plants can be seen clearly, while the wind energy plants often cover the night hours during which PV generation is not possible. The solid horizontal line indicates the maximum reference performance of the electrolysis plant. If generation increases beyond this performance, the electrolysis plant will be unable to absorb any more of the electricity. For the purposes of this study, it has been initially assumed that the generation plant would be turned down in such situations, and that no further electricity would be purchased or stored in power stores.

In order to achieve the annual utilisation of 5,000 full-utilisation hours for the electrolysis plant, the dimensions of the electricity generation plants must be designed to ensure higher performance than the electrolysis plant once installed. Based on the hourly yield simulation, the utilisation rate for the electricity generated by the plants would then be only 93.5 %. As a result, the cost of electricity for the electrolysis process will be higher than the plain electricity production costs for the plants (LCOE).

As such, two electricity costs have been calculated for the cost of producing the synthetic liquid energy sources: The

Figure 61: Sample supply profile for electricity generation plants over 10 days



Source: Prognos AG

Table 39: Electricity costs for electrolysis at particularly cheap locations in the MENA region of up to around 400 TWh of annual electricity generation

WACC	2020 [Cent/kWh]	2030 [Cent/kWh]	2050 [Cent/kWh]
2 %	2.3	2.1	1.9
7 %	3.4	3.1	2.7

Source: Prognos AG

Table 40: Electricity costs for electrolysis at average locations in the MENA region up to 18,800 TWh of annual power generation

WACC	2020 [Cent/kWh]	2030 [Cent/kWh]	2050 [Cent/kWh]
2 %	4.8	4.4	3.9
7 %	7.0	6.4	5.7

Source: Prognos AG

first is the electricity cost that would apply at particularly **cheap sites** in the MENA region. Such sites would be on the far left of the cost-potential curve, and could generate around 400 TWh of electricity per year, or 16 m t of PtX[18]. The second is the electricity cost that would apply to an average site in the MENA region. If such sites were utilised to the full extent, they could generate around 18,800 TWh of electricity per year to manufacture 858 m t of PtX[19]. Table 39 shows the electricity costs for the electrolysis process, based on projected capital costs of 2 % and 7 % for a particularly cheap site in the MENA region.

Table 40 shows the electricity costs for an average site in the MENA region, likewise based on capital costs of 2 % and 7 %.

The potential specific sites for the electricity generation plants and electrolysis plants were not investigated in detail. In practice, the distances between the plants will vary from region to region. The greater the quantity of PtL that needs to be produced, the greater the distances between the systems will be. In order to simplify the cost estimates, we have assumed that PtX production will take place in the immediate vicinity of the renewable electricity generators, and that there will be no costs for power grids. If the renewable electricity generated needs to be transported over greater distances, new power lines will generally be required. This would cause the electricity costs to rise accordingly. The detailed assumptions and intermediate results are provided in Table 55, in the appendix to this study.

18 Assuming a total efficiency of 48 % for the synthesis process (in 2030)

11

POTENTIAL AND TECHNOLOGIES OF BIOMASS USE IN GERMANY

With regard to the consumption of liquid energy sources, biomass currently makes a noteworthy contribution to the provision of renewable fuels, and can also be expanded further in the future depending on how much of the national potential is tapped and how the portfolio for conversion plants develops. At the end of 2016, liquid bioenergy sources contributed 497 GWh to electricity generation in Germany, 2,129 GWh to renewable heat (primarily combined heat and power) and 29,558 GWh to fuel supplies in the form of biodiesel, plant oil and bioethanol (BMWi (German Federal Ministry for Economic Affairs and Energy) 2018). In relative terms, liquid bioenergy sources thus cover only a marginal portion of the total demand in the electricity, heat and cooling sectors in relation to the other types of renewable energy. However, they account for the majority of the renewable energy contingent in the transport sector. Prior to the evaluation of future contributions, the following section will first provide an overview of the usable biomass potential, followed by an estimate for various usage priorities.

11.1 BIOMASS POTENTIAL

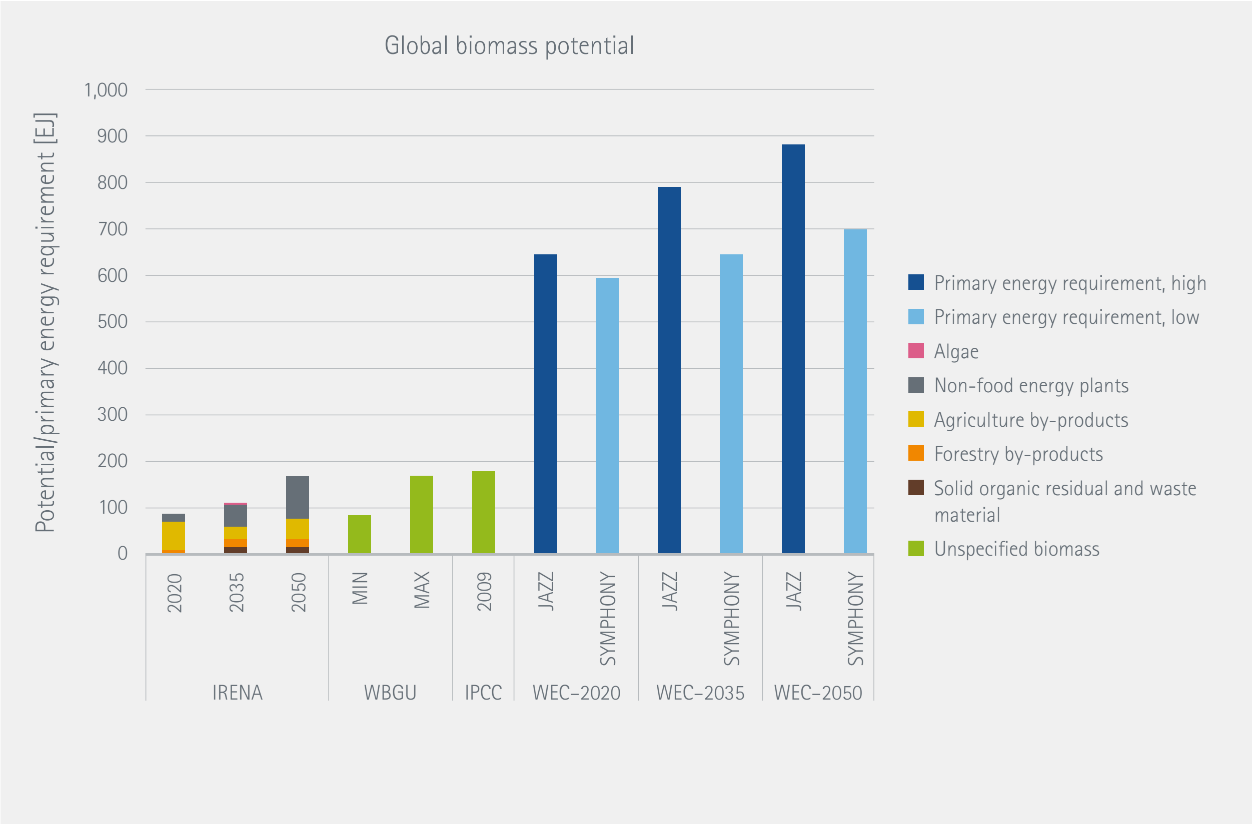
This study aims to focus primarily on the national biomass potential, as it is framed by the working hypothesis that the nations that are part of the Paris Agreement will utilise their individual biomass potential primarily within their own borders as they strive to implement the resolutions of the Agreement. In spite of this, it should be assumed that comparative cost benefits and differences in relative conditions with regard to biomass volume and energy consumption will allow Germany to cover its national demand through the use of net imports from other countries. In this respect, the world trade market gives Germany access to biomass that can be used as energy in order to boost the limited potential. However, since it is not possible to reliably forecast export contributions for the future, we should work with a conservative fundamental assumption that Germany will only be able to use its domestic biomass streams for energy purposes. Nevertheless, in order to provide an overview of the international biomass potential and allow an estimate of the figures in question, a brief digression is required before we discuss the national biomass potential in detail.

11.1.1 Side Note on the International Potential of Biomass

For the purposes of this study, it is assumed that bioenergy will be supplied primarily using the national biomass potential. This is because, in light of the global climate protection targets of the Paris Agreement, it is safe to assume that other countries will primarily use their potential to satisfy their own demands. This assumption is very conservative, as it is likely that future commerce streams will be drive primarily by supply, demand and the resulting market prices.

An overview of the global biomass potential available for use as energy and how it compares to future primary energy consumption will be provided based on (World Energy Council 2013, R. Schubert 2008, Shunichi Nakada 2014). The scenarios presented in this study for the development of global primary energy consumption map out a global energy supply transition strategy up to 2050. In the “Jazz” scenario, the transition processes are determined primarily by consumer action, while the “Symphony” scenario is based on the assumption that politics will play a larger role. The calculations for Figure 62 predict a gradual increase in the global demand for primary energy of somewhere between 700 EJ and approx. 880 EJ, with usable bioenergy figures increasing from 84 EJ to 168 EJ over the same period. As such, the amount of the global demand for primary energy that can be covered by the bioenergy potential shown in the diagram will reach somewhere between 19 % and 24 %. As such, the calculations forecast a dramatic increase in usable potential compared to the estimated coverage of 14 % to 15 % in 2020. However, the potential coverage varies greatly due to differences in primary energy demand. Essentially, we can

Figure 62: Comparison of global primary energy consumption, bioenergy potential and the potential coverage of biomass



Source: DBFZ diagram based on IRENA, WBGU, IPCC, WEC

conclude that the global use of bioenergy can be expanded, though it is still uncertain how much this potential can contribute to covering the total energy demand.

11.1.2 National Potential of Biomass

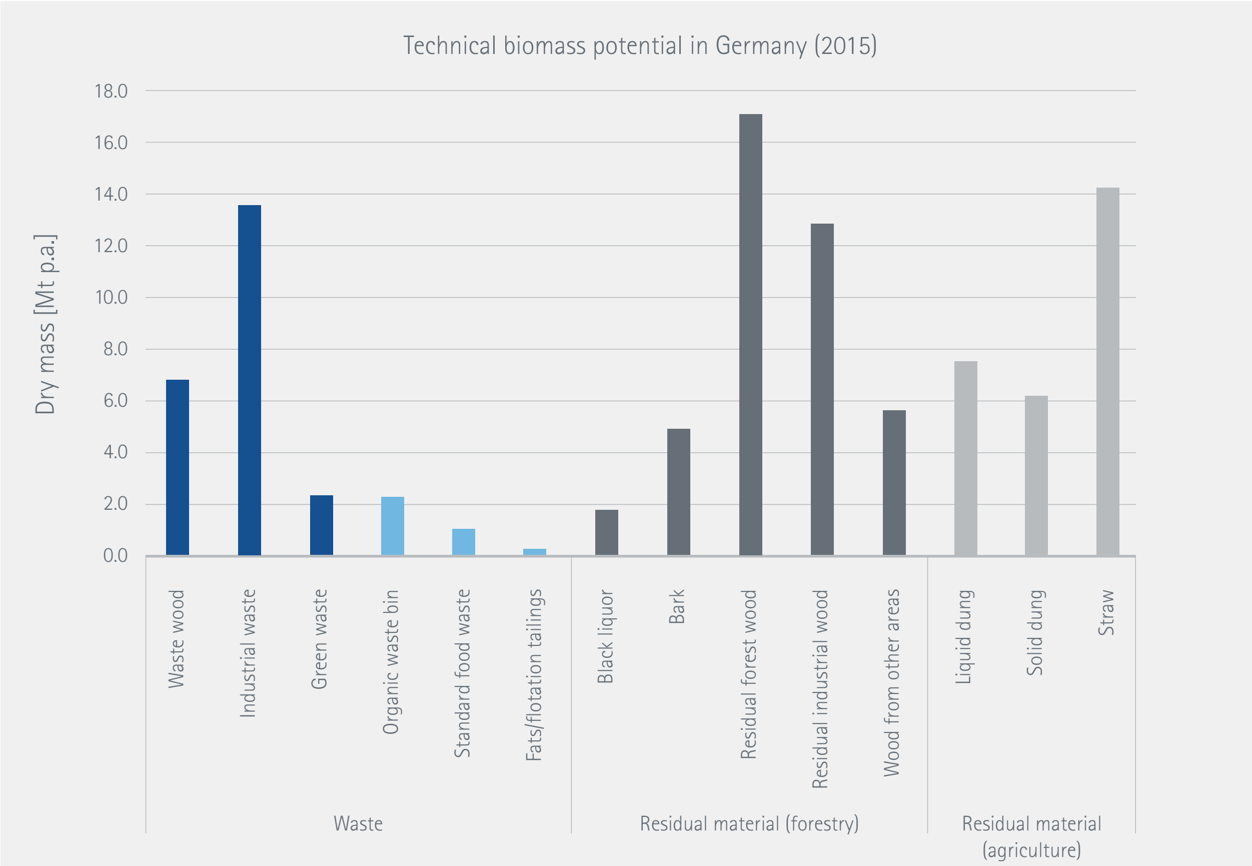
Germany's national biomass potential is mainly drawn from two different sources, and should be seen as technical potential. It covers the portion of the theoretical potential that can be sustainably acquired from a specific area or region, taking into account a series of limiting factors. The technical potential observed in this study is drawn from two sources: residual and waste material from the production of other goods; and cultivated biomass from the agriculture and forestry sectors, which can be converted into energy directly. We will focus first on the residual and waste material, since these material streams involve little potential for conflict and will only experience minor changes in volume in the future. We will then present the potential for cultivated biomass, which is made up less of specific quantities of individual raw materials and is far more dependent on the area available and a number of other constraints that apply to biomass cultivation.

Potential for residual and waste material

The German biomass potential of residual and waste substances is categorised and quantified based on the study "Biomass potential of residual and waste substances – The status quo in Germany" (André Brosowski 2015). Brosowski defines a total of 98 individual biomasses. For the purposes of simplification and since some of the individual biomasses listed by Brosowski are only present in small quantities, making them inconsequential to the purpose of this study, we have aggregated these individual biomasses into 14 groups. In order to draw up an initial estimate of how biomass will develop in the future, we have assumed that the volume will be directly proportional to Germany's number of inhabitants. We have used the 13th destatis coordinated annual population projection – more precisely, Variant 2 "Continuity in case of an increase in immigration" (destatis 2015) – to estimate the volume of residual and waste material up to 2050 (see section 4.3).

A total of **approx. 1,150 PJ of primary energy from residual and waste material** was available in Germany in our reference year, 2015. When evaluating the technical potential of

Figure 63: Technical biomass potential for residual and waste material in Germany (2015)



Source: DBFZ 2018, based on (André Brosowski 2015)

this material, however, it should be noted that this potential is already locked into existing material streams, meaning it is not completely untapped at this point in time, and also that some of the technically usable volume can only be tapped at significant expense. Figure 63 shows the biomass potential of the 14 selected aggregated biomass groups, which have been further grouped into the sectors waste, residual material from forestry and residual material from agriculture. The potential from the waste sector can be seen as a relatively secure framework volume for the future. In forestry and agriculture, on the other hand, both the volume and the allocation are heavily dependent on overriding trends, resulting in a high level of uncertainty in these areas.

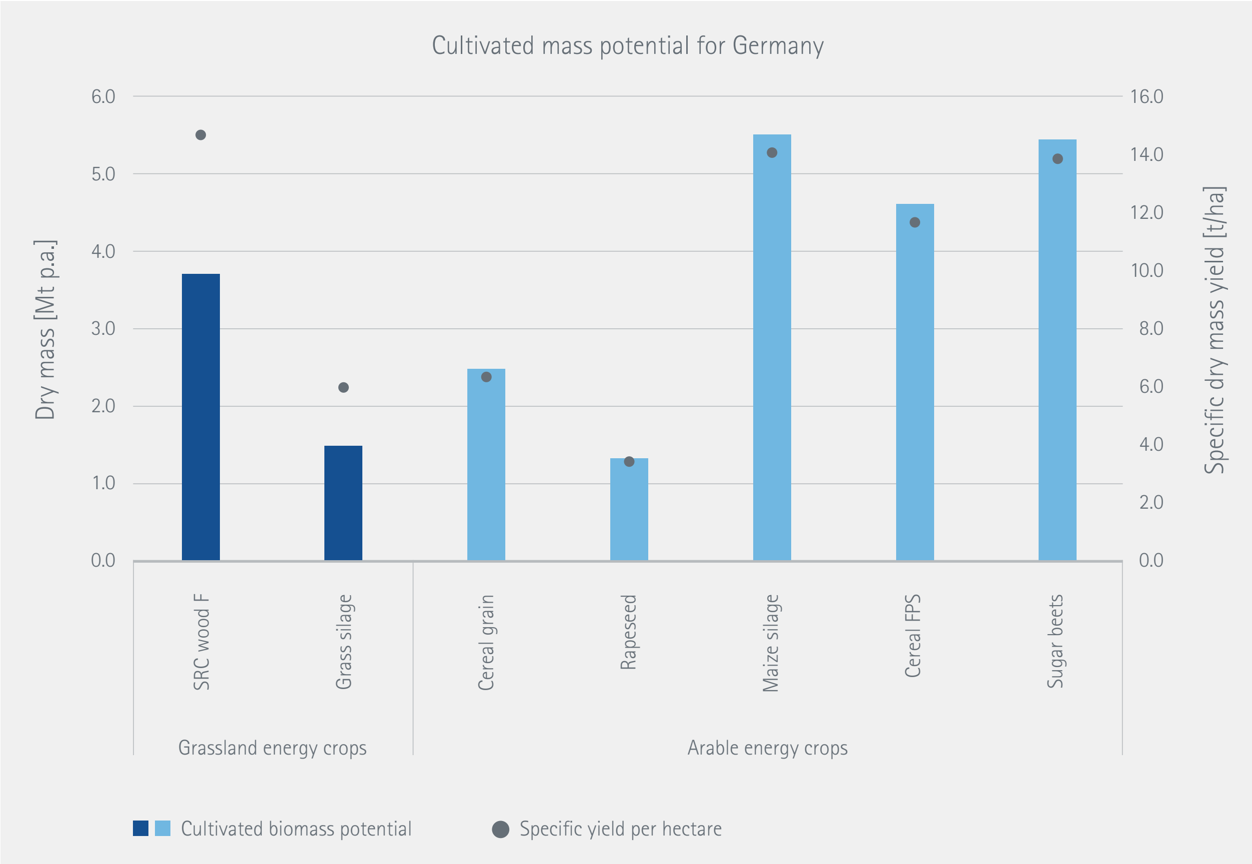
Irrespective of the aforementioned uncertainty, we can clearly see that wooden biomass, liquid dung, solid dung and straw dominate the spectrum of residual and waste material from a quantitative perspective. The "industrial waste" category is a highly heterogeneous materials group, yet almost all types in this category are suited to use in waste biogas plants. This distribution of volumes already shows a certain trend for biomass allocation whereby biogas production, combustion and gasification technologies seem feasible.

Potential for cultivated biomass

The national potential for cultivated biomass is limited primarily by the area available for the cultivation of renewable raw materials. Since biomass from forestry is covered by the residual and waste material described above, the term "cultivated biomass" refers exclusively to agricultural biomass. 2.4 m ha of land in Germany is currently allocated for crops for energy use (FNR 2016). Long-term forecasts predict that an area of at least 2.5 m ha will be available for cultivation without endangering the production of foodstuffs and feed (BMELV 2011).

Since the mass figures are relevant in order to assess energy potential, the yield by hectare for potential crops must be taken into account when evaluating primary energy potential. However, since the composition of these 2.5 m ha is in turn dependent on the intended use paths of the biomass in question, it is not possible to make a blanket statement on how much primary potential 2.5 m ha of cultivation area offers.

Figure 64: Specific acreage yields and potential for energetically usable dry mass



Source: DBFZ 2018, own calculations

In order to account for this uncertainty, this study assumes that the 2.5 m ha will be used for a defined mixture of seven different crops. As such, the total available area of 2.5 m ha is divided into 2.0 m ha of arable land, split equally into 0.4 m ha (20 %) each for silage maize, rapeseed, whole crop silage, grain cereals and sugar beet, and 0.5 m ha of grassland, split equally into 0.25 m ha (50 %) each for short-rotation coppices and grass silage. Due to the differences in specific yield by hectare, the potential dry mass that can be used for energy varies for each of these seven crops (see Figure 72).

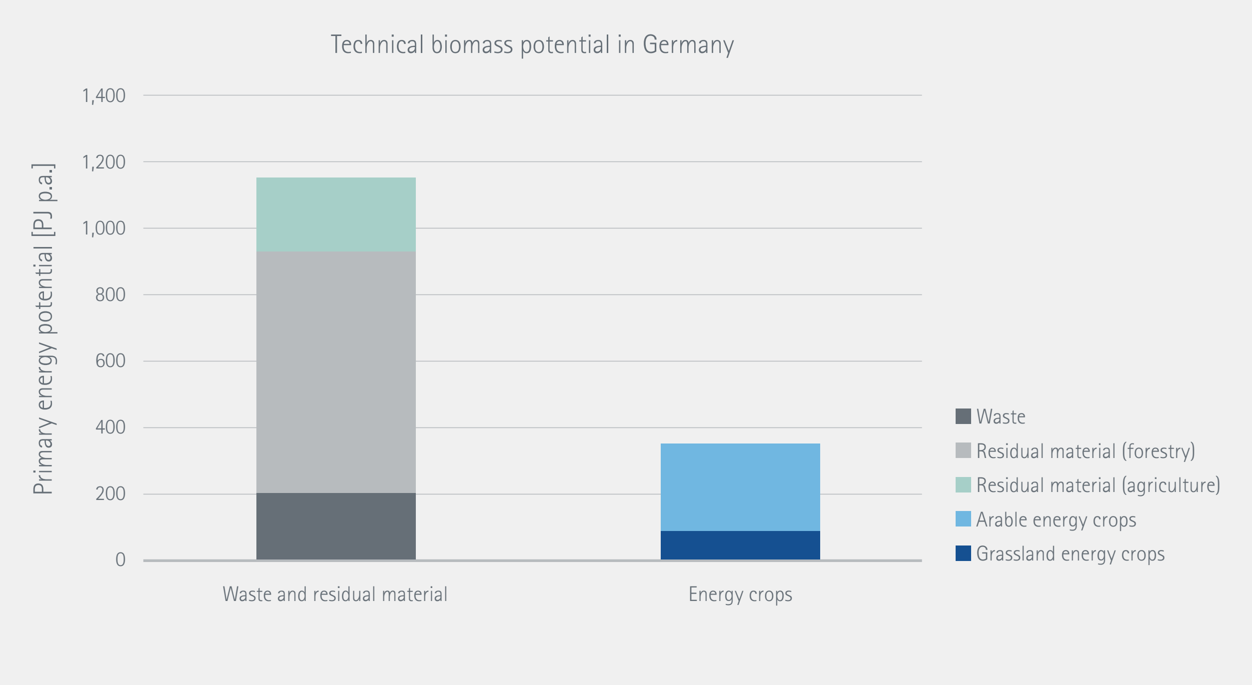
Total biomass potential for use as energy

In the following section, we have taken the volume-based figures for both residual and waste material and cultivated biomass and multiplied the energy content of each of the biomasses by their respective specific energy densities to calculate their primary energy potential. When calculating the technically available potential in the following diagram, however, two caveats must be borne in mind. Firstly, many of the residual and waste materials described here are already locked into established material streams, meaning that their actual untapped potential is significantly lower than that shown in the diagram. Secondly, despite the lack of direct production costs, it is not logistically or technically feasible to mobilise the as yet untapped potential for many of these materials without unreasonable expense, which makes them costly to produce. In order to account for these circumstances, a mobilisation rate of 75 % has been applied across the board for the technical residual and waste material. Similarly, a 10 % deduction has been applied to cultivated biomass to account for various types of loss during production (harvest, transport, storage). The remaining total primary energy equivalent of approx. 1,500 PJ after application of the mobilisation rate and the loss deduction for energy crops is shown in Figure 65.

11.2 Summary of the Portfolio of Conversion Technologies in Germany

For the evaluation of the utilisation of the biomass potential, a portfolio of 20 technologies was compiled, 15 of which are shown with a very high degree of extraction, which 3 or 4 technologies are examined in more detail. The technologies were chosen based on the knowledge that it

Figure 65: Technical primary energy potential from biomass, including mobilisation rate for residual and waste substances (75 %) and overall loss reduction for cultivated biomass (10 %)



Source: DBFZ 2018, own calculations

is not possible to channel the potential resources into arbitrary conversion paths, and that some technologies – such as wood heaters for plant owners who procure their own wood resources – have a high tolerance to changes in their framework conditions. An overview of the 20 technologies is provided in Table 41. The biomethane plant (nos. 8 & 9) was mapped using the same plant technology each time; only the charge materials were changed.

The following parameters were estimated for the 15 technologies mapped in less detail: installed plant capacity (firing heat capacity), charge materials, main product, by-products, conversion efficiency, auxiliary energy requirements and full-utilisation hours. There is no description of the key economic figures, since these were not available for every technology. The key figures and the number of plants installed was then used to calculate the total biomass required and the corresponding potential utilisation.

11.3 Detailed Analyses for 3 Conversion Technologies for Biofuels

A techno-economic analysis was carried out for three technologies used to manufacture fuels: biomethane plants, BtL plants and PBtL plants. This also included a simplified calculation of investment costs, which was also used to derive the specific product costs for the respective energy sources.

The following statements were defined as the overriding assumptions for all three technologies: In contrast to the fully synthetic fuel technologies described in section 12, the learning curve method was not used here, since it was not possible to estimate the global cumulative product quantities for BtL with any certainty whatsoever and these figures are essential defining factors for a learning curve. The investment costs for synthesis and electrolysis plants (as components of the concepts in question) are based on the cost structures used by UMSICHT, and assume a degression in costs due to future market growth. Irrespective of the specific parameters used for the respective plants, there are several main factors that play a key role in determining the production costs:

- Annual full-utilisation hours (fuh) of the plant. Irrespective of fuh, intermittent operation is not feasible for technologies that use biomass gasification, since the relatively long start-up times result in high losses.

- The economies of scale for individual components (design dimensions of the individual plant in question). Fixed-step costs may be incurred here, since different technologies (fixed-bed, fluidised-bed or entrained-flow gasifiers) are used for gas production depending on the size of the plant, for example.

- The catchment area – and thus, usually, the logistics costs – for biomass increase in indirect proportion to the size of the plant.

- Electricity procurement costs of €94/MWh were assumed for the PBtL path in line with the price level for industrial customers in Germany in 2016, as a national plant site was chosen for a high level of utilisation.

11.3.1 Detailed Analysis of Biomass-to-Liquid

The "biomass to liquid" (BtL) conversion technology can be divided roughly into the following process steps: biomass gasification, gas purification, Fischer-Tropsch synthesis and fuel conditioning. The raw material base for BtL processes consists of lignocellulosic biomass. For the purposes of this study, this was drawn primarily from low-ash raw materials from wood biomass (leftover industrial and forest wood and sawing by-products). The product generates a variety of hydrocarbons in the middle distillate (diesel/kerosene) range, the chain lengths and mixture ratios of which are affected to some extent by the way in which the process is conducted. The by-products are naphtha, combustion gas and, if the combustion gas is going to be used directly in a stationary CHP plant, electricity. The technology is currently available for use in test plants in operational environments (TRL 5 (PTJ 2014)). Some pilot plants are available for campaigns in Germany, the USA and Austria.

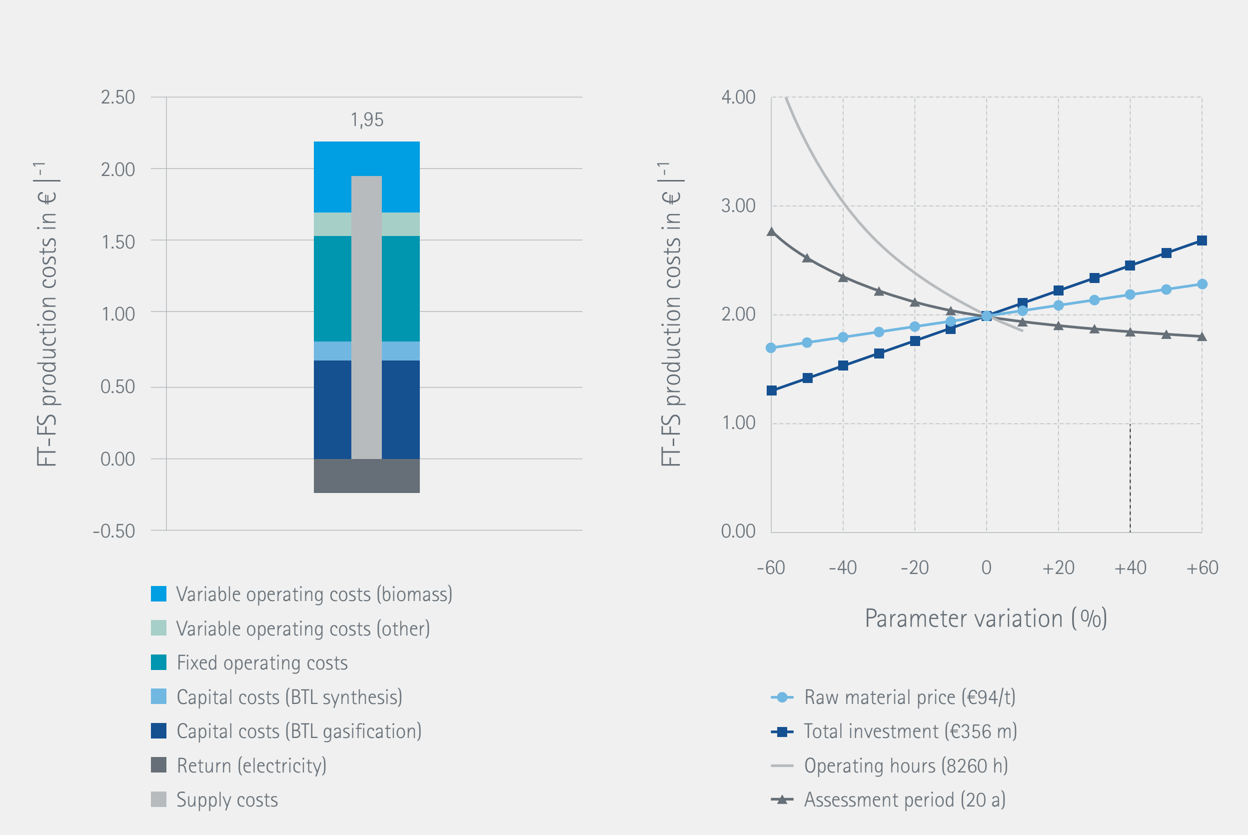
The technology is relatively complex to build, and one of the greatest challenges it presents is how to refine the raw products in a way that meets the requirements for certain products. For example, BtL-based kerosene is ASTM-certified for 50/50 mixtures ASTM for aviation fuels (Sniderman 2011). When used in compliance with the relevant standards, BtL fuels are compatible with most infrastructures. The plant configuration shown here, which has a thermal output of 98 MW, a biomass throughput of 182 kt and produces 24 kt of Fischer-Tropsch fuel per year as well as 102,000 MWh of electrical energy as a by-product, has calculated production costs of €1.95/l for BtL fuel (see Figure 66). The production costs are based on a series of cost assumptions, but primarily on the two major components for biomass gasification (€298 m) and fuel synthesis (€58 m) (Friedemann G. Albrecht 2017).

Table 41: Overview of the technologies considered in the technology portfolio for bioenergy provision

Nr.	Description	Sector	Level of detail
1	Waste wood power plant	Transformation	low
2	Paper and pulp power plant	Transformation	low
3	Wood heating power plant	Transformation	low
4	Bark heating power plant	Transformation	low
5	Fertiliser biogas plant	Transformation	low
6	Renewable raw materials biogas plant	Transformation	low
7	Waste biogas plant	Transformation	low
8	Renewable raw materials bio-methane injection plant	Transformation	high
9	Waste bio-methane injection plant	Transformation	high
10	Straw bio-methane injection plant	Transformation	low
11	Small-scale furnace in household	Households	low
12	Small-scale furnace in CTS	CTS	low
13	Large-scale furnace in industry	Industry	low
14	Starch/Sugar-based ethanol plant	Fuel	low
15	Lignocellulose ethanol plant	Fuel	low
16	Bio-diesel plant	Fuel	low
17	Biomass-to-Liquid-Plant	Fuel	high
18	Power-Biomass-to-Liquid-Plant	Fuel	high

Source: DBFZ

Figure 66: Production costs and sensitivity analysis for the production of Fisher-Tropsch fuel using the "Biomass-to-Liquid" conversion path



Source: DBFZ

The sensitivity analysis for the production costs of the BtL plants in Figure 66 shows that the production costs are determined primarily by the plant utilisation (full-load hours), the absolute investment costs and the projected raw materials costs. A separate sensitivity analysis was conducted to determine the correlation between the supply costs and the calculated interest rate (WACC); these are shown as an overview for the three detailed technology concepts.

11.3.2 Detailed Analysis of Power Biomass-to-Liquid

The "Power + Biomass-to-Liquid" technology concept essentially comprises the BtL technology described above, with a water electrolysis plant in addition to the biomass gasification and Fischer-Tropsch synthesis plants. The hydrogen produced by this technology is used primarily to offset the stochiometric carbon surplus in the biomass, thus increasing the final carbon usage efficiency. In a conventional BtL plant, the synthesis gas, which is partly made up of carbon monoxide (CO), is forced t undergo a water-gas shift reaction (WGS), whereby water vapour is added to the CO to convert it into CO_2 and H_2. As an additional benefit to this process, this means that less CO_2 needs to be filtered out of the synthetic gas stream as a product of the WGS reaction.

The subsequent Fischer-Tropsch synthesis works according to the same principle as in a BtL plant, though it needs to be scaled up (by a factor of approx. 3.8) due to the fact that the carbon is almost entirely converted into synthetic gas. As such, the investment costs for a PBtL plant are much higher than those for a BtL plant with the same biomass throughput (gasifier €276 m, synthesis plant €197 m, electrolysis plant €203 m (Friedemann G. Albrecht 2017)). However, thanks to the 1,353 GWh of electrical energy that is converted to hydrogen by the electrolysis process the same 182 kt of biomass can produce 91 kt of Fischer-Tropsch fuels per year. As a result, the production costs for the fuel produced using this technology are lower than those for the conventional BtL conversion path, despite the higher investment costs for the electrolyser, the larger synthesis stage and the higher operating costs for the power used for electrolysis.

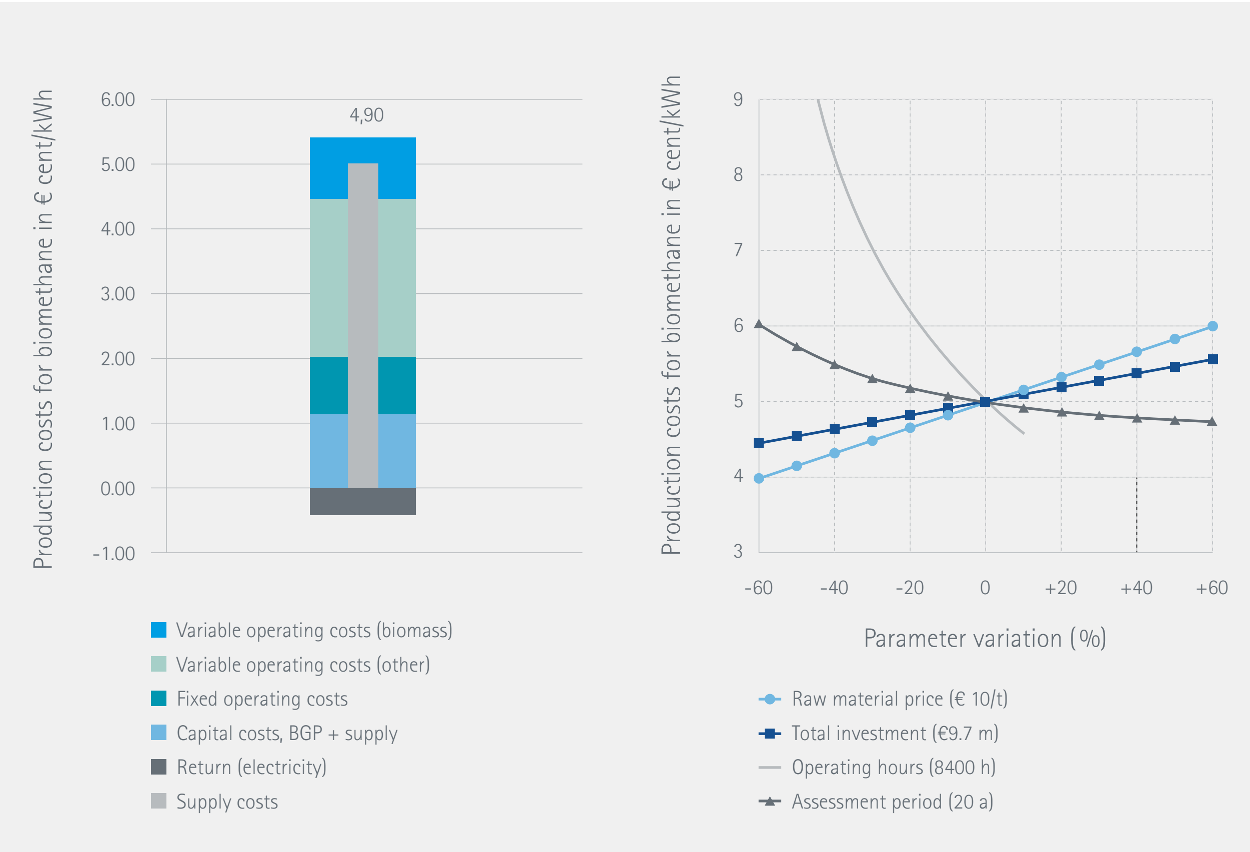
As for the BtL path, the sensitivity analysis for the supply costs shown here is shown in relation to the operating hours, investment costs and raw materials costs, plus the cost of the electricity used for the electrolysis. Like the conventional concept, this technology requires a high level of utilisation in order to keep production costs low. It is also worth noting that the electricity costs have a greater effect relatively speaking on the production costs than they do on the raw material costs for the biomass.

11.3.3 Detailed Analysis of Biomass-to-Gas (Biomethane Path)

The biomass-to-gas conversion path is intended to describe the process for supplying biomethane by means of the anaerobic fermentation of biomass and subsequent gas processing, although other conversion paths are also possible, such as biomass gasification followed by methanisation of the synthetic gases. The first step of the process, biogas fermentation, is suited primarily to aqueous biomasses containing as many fermentable biomass fractions (carbohydrates, fats, proteins) as possible. However, dry raw materials such as cereal grains and straw can also be used in a biogas plant if pre-treated properly. Depending on what raw materials are used, the raw gas produced during the fermentation process will be made up of approximately equal parts methane and carbon dioxide, plus other associated gases (water vapour, hydrogen, hydrogen sulphide and other trace gases). The raw gas is desulphurised and then subjected to gas preparation, a process designed primarily to separate the methane from the carbon dioxide. Most separation processes utilise the differing solution properties of the two gases (carbon dioxide is more soluble in polar substances, methane in non-polar substances) to produce two separate gas streams. The enriched carbon dioxide is usually blown off as an "off gas"; the methane slip may be oxidised if necessary. Current technology usually compresses and odorises the highly enriched methane, then adjusts it to the local fuel value level and feeds it into the gas grid. Unlike in the BtL paths, the biomethane produced here is generally distributed on a grid-bound basis.

The sample calculation shown here is based on a biomethane plant that uses 75 kt of waste and residual materials per year and generates 67 million m³ of methane with a fuel value of

Figure 67: Production costs and sensitivity analysis for the Biomass-to-Gas conversion path (biomethane path)



Source: DBFZ 2018, own calculations

Table 42: Dependency of production costs for BtL, PBtL and BtG based on the interest rate for foreign capital and capital resources (blended interest rate)

Concept	WACC (%)					
	2 %	3 %	4 %	5 %	6 %	7 %
BtL	1.95 €/l	1.97 €/l	1.98 €/l	2.00 €/l	2.01 €/l	2.03 €/l
PBtL	1.81 €/l	1.82 €/l	1.83 €/l	1.84 €/l	1.85 €/l	1.85 €/l
bio-methane	4.90 Cent/kWh	4.99 Cent/kWh	5.08 Cent/kWh	5.18 Cent/kWh	5.28 Cent/kWh	5.38 Cent/kWh

Source: DBFZ

67 GWh. 58 million m³ of CO_2 are generated as a by-product. The specific production costs of the plant run to €9.7 m based on a biomethane fuel value of €0.049/kWh.

The production costs for the biomethane path are also affected mainly and substantially by the plant utilisation. The investment costs are the second most important factor according to the sensitivity analysis. Since raw materials based on waste and residual materials are only subject to logistics costs, these have a smaller effect on the overall costs.

11.3.4 Sensitivity of Production Costs to WACC

The following section will show the production costs for the three technologies described above once again, this time in a separate analysis that calculates them in relation to the interest rate for the investment goods. The standard assumptions have been retained for all other parameters (see Table 3). It should be noted that, in this scenario the Weighted Average Cost of Capital (WACC) refers to the blended interest rate for the entire investment, i.e. the quantity-weighted interest for debt capital and equity.

While the investment costs represent a dominant cost component for all three conversion paths, the WACC has a relatively minor effect on the production costs due to the fact that the overall costs are made up largely by costs relating to consumption and production. As is to be expected, production costs increase as the interest rate rises.

11.4 SELECTED BIOMASS ALLOCATION

Biomass allocation was conducted in two steps and a total of six variants. For technical reasons, we started by allotting certain biomasses to fixed conversion paths. This allocation will probably continue to be used in the future:

- Waste wood → Waste wood power station
- Black liquor → Pulp ind. power plant
- Fertiliser/dung (partial) → Small fertiliser biogas plant
- Brown bin, food waste, ind. waste → Waste biomethane plant
- Bark and wood from other areas → Wood heating power plant

The other forestry biomasses were not allocated explicitly so that this could be done on a flexible basis at a later point. Single-room fireplaces powered using independently procured firewood were excluded from this assessment; such fireplaces were likewise not included in the potential section of this study. This leaves the following biomass groups for the derivation of different biomass allocation variants; the prioritised usage paths for these groups is listed below:

- Forestry biomass → BtL, PBtL
- Straw → Biomethane plant, LC ethanol plant
- Cultivated biomass SRC → BtL, PBtL
- Cultivated biomass field crops → Biomethane plant, biodiesel plant

The biomass allocations shown below are not based on a deterministic derivation, as this would require a significantly higher volume of methodical work than intended within the scope of this study. Our aim was to draw up a consistent allocation for the biomass groups that would reflect the upper range for the generation of liquid bioenergy sources.

In order to estimate the role that liquid energy sources could potentially play in the energy transition, we have thus combined extreme points for key variables on two scales. The first potential scale assumes that only the potential of the residual and waste materials will be available (BMP-A), while the second assumes that an additional 2.5 m ha of cultivated biomass can be generated (BMP-B). The potential generation capacity range for liquid fuels was spread across a second scale, between a gas-fuel-dominated and a liquid-fuel-dominated selection of technology. The following assumptions were taken as general parameters for this evaluation:

- The percentage of first-generation biofuels (biodiesel, starch and sugar-based bioethanol) will not increase
- Raw materials with a low ash softening point (e.g. straw) require more sophisticated gasifying technology, and are thus channelled along the bioethanol path using lignocellulose decomposition.
- Wood biomass types form the basis for the production of FT products in (P)BtL plants
- The calculations for PBtL plants are based on the assumption that the site in question is located in Germany, as this allows for high full-utilisation hours and cheap fuel logistics

The result for the six variants are shown below.

The overall results for biomass allocation in six possible variants (see Figure 68) show that, due to the fact that certain biomasses have been given fixed allocations in all variants, relatively consistent contributions (26 TWh and 13 TWh) can be made to the production of renewable electricity and heat. However, fuel supply diverges significantly from this trend. Firstly, it should be noted here that there is a base contribution to biomethane production of 15 TWh from certain residual material fractions that could not be allocated elsewhere. The production of Fisher-Tropsch fuels (FT products) also has a minimum contribution of 43 TWh in every variant, due to the allocation of certain biomass groups to this conversion path as described above.

Depending on the priorities assigned to certain technologies, however, both the distribution and the total amount of fuel that can be generated may vary significantly. For example, the variants that prioritise biomethane production show that cultivated biomass is primarily channelled into the biomethane path as an allocation to bioethanol, biodiesel and. in part, FT products. Where BtL is prioritised, some first-generation biofuels are also produced, though a large part of the generation in this model is accounted for by FT products. The variants that prioritise PBtL are, in principle, equivalent to those that prioritise BtL, except for the fact that the use of hydrogen and the resulting higher carbon usage efficiency using the same biomass allows for the generation of far more FT products.

11.5 DERIVING RECOMMENDATIONS FOR ACTION FOR BIOMASS

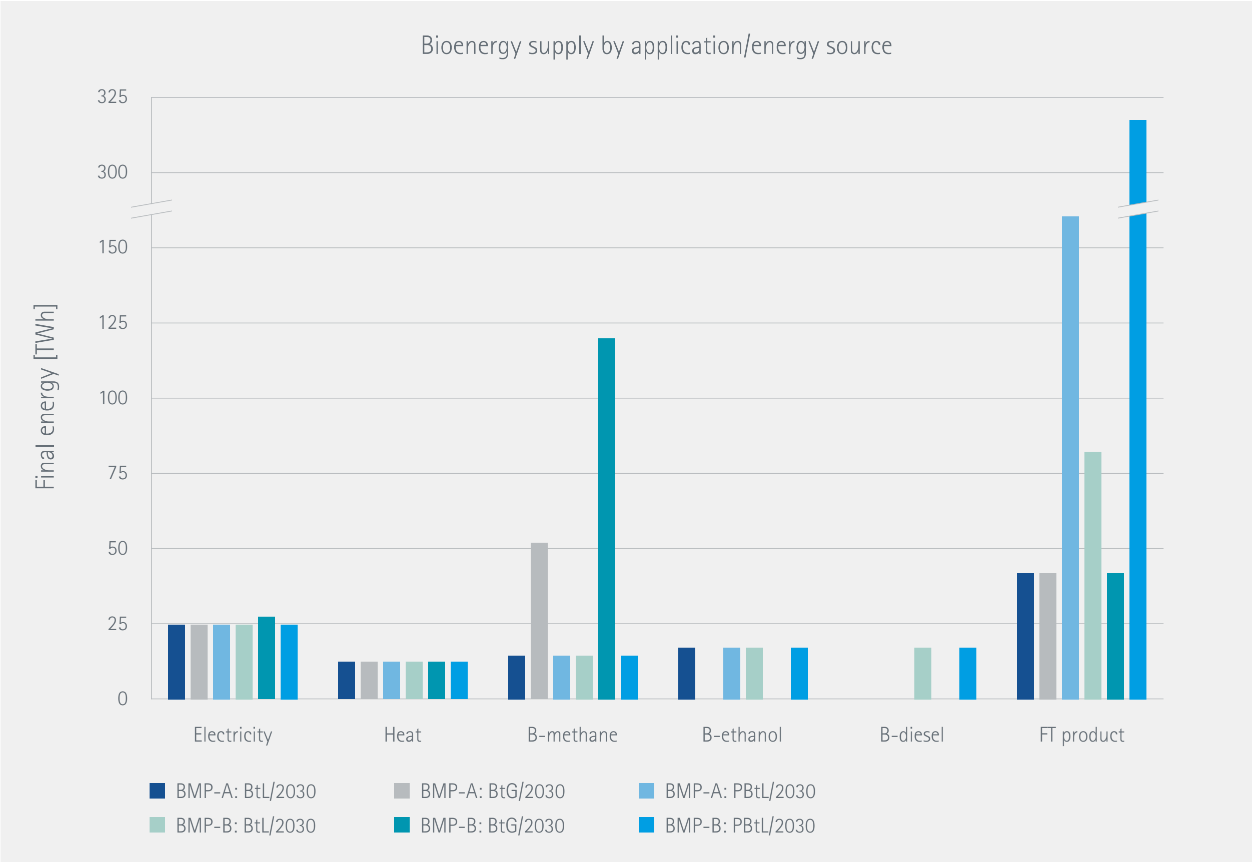
If the biomass potential available in Germany were to be used primarily for the production of liquid fuels, up to 28 % of the country's equivalent mineral oil consumption could be covered, based on primary energy consumption figures for 2016.

As shown above, however, this coverage would only leave marginal quantities of the biomass potential for the electricity and heating sector, which currently uses far more biomass. Furthermore, the figure also assumes an increase in the utilisation of the potential for currently unused residual and waste material and a diversion of material streams that are currently locked into other value chains. This study does not include an evaluation of the socio-economic cost relations for the proposed variants. As a result, the biomass allocations shown here do not necessarily offer the greatest benefit for society overall. Instead, they rather represent the upper limit for the production of liquid energy sources based on assumed parameters and the nationally available biomass. The figures show that, even when using an endogenous prioritisation of the production of liquid fuels and making very progressive assumptions on the maximum utilisation of the existing potential, biomass can only cover a fraction of today's mineral oil demand.

Table 43: Overview of the 6 variants for biomass allocation

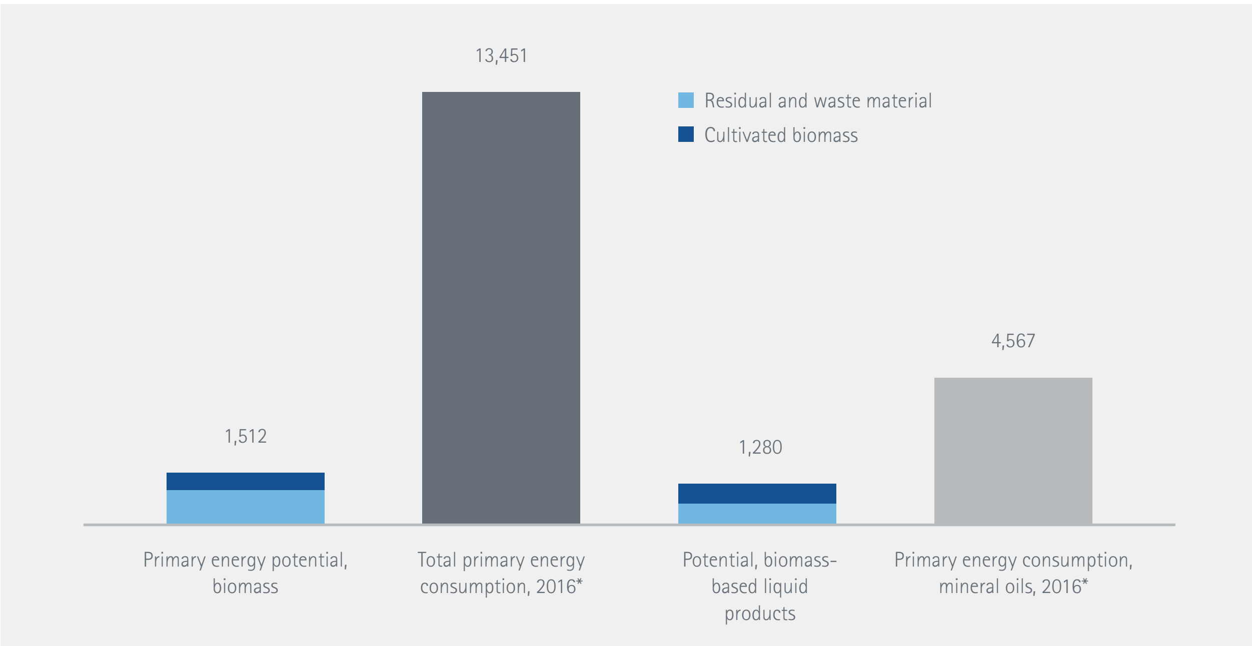
Potential / Priority	Priority: BtL	Priority: Biomethan	Priority: PBtL
Exclusiveley residual and waste	BMP-A: BtL	BMP-A: BtG	BMP-A: PBtL
Residual and waste + cultivated biomass	BMP-B: BtL	BMP-B: BtG	BMP-B: PBtL

Figure 68: Diagram of the results of the biomass allocation in 6 variants



Source: DBFZ 2018, own calculations

Figure 69: Diagram of the maximum technically possible contributions to the fulfilment of German primary energy demand in PJ (without crop and storage losses through the assessed process chains) in relation to overall consumption and the proportion for mineral oil for 2016



Source: Prognos AG

Furthermore, there is a percentage of the biomass that cannot be converted into liquid fuels without unreasonable expense, due to technological restrictions. In addition to the commercial aspects not shown here, this study likewise does not take into account the extent to which political circumstances, such as the RED (Renewable Energy Drive) that is currently being agreed upon, may influence biomass allocation in the future. As such, it is prudent from a social perspective to establish long-term parameters so that the market players have a stable environment and do not need to worry about their investments failing due to political change.

12

POTENTIAL AND TECHNOLOGIES OF PTX

As shown above, PtL fuels present a way of supplying sectors such as air and heavy goods freight with renewable fuels. This section provides a brief description of the technology paths included in this study. It will focus particularly on Fischer-Tropsch Synthesis (FTS), since this process was chosen for the scenario calculations due to its ability to be dropped into existing infrastructures. In addition to FTS, the section will also cover methanol and polyoxymethylene synthesis.

The contents of this chapter were written by UMSICHT.

12.1 PTL TECHNOLOGY PATHS

12.1.1 Fischer-Tropsch Synthesis

FTS can be used to produce higher/longer-chain hydrocarbons using (H_2) and carbon dioxide (CO_2). This process is particularly popular in South Africa, where it has been used since the 1950s to turn coal into diesel and petrol fuels and chemical raw materials, and primarily to produce a coal-based synthetic gas (Albrecht et al. 2013). There are three main paths that could be used to provide a synthetic gas for FTS using renewable energy (RE):

- Low-temperature electrolysis and CO/CO_2 extraction from concentrated sources or the ambient air
- High-temperature electrolysis and CO/CO2 extraction from concentrated sources or the ambient air.
- Biomass gasification

The path with high-temperature electrolysis and CO_2 extraction from the ambient air is describe below, based on the current level of technological development and the quantities of PtL that will be required in the future. The capacity of the individual components is currently available in various documentation projects, e.g. by Sunfire and Climeworks (Sunfire GmbH 2017a), (Sunfire GmbH 2017b). There are several ways of extracting CO_2 from the ambient air, e.g. through the absorption of amine-enriched cellulose, a process currently being demonstrated by Climeworks in Switzerland (Climeworks AG 2017a) , (Climeworks AG 2017b). Figure 70 shows a schematic diagram of this process and its components.

FTS is highly exothermic, which means that a relatively high proportion of the heat required for the high-temperature electrolysis or the inverse CO shift reaction can be covered by a high level of heat integration (Fasihi, Bogdanov and Breyer 2016). The inverse CO_2 shift is required in order to provide CO for the FTS. Hydrocarbon chains are formed according to the following formula:

$$nCO + 2nH_2 \rightarrow (-CH_2-) + nH_2O$$

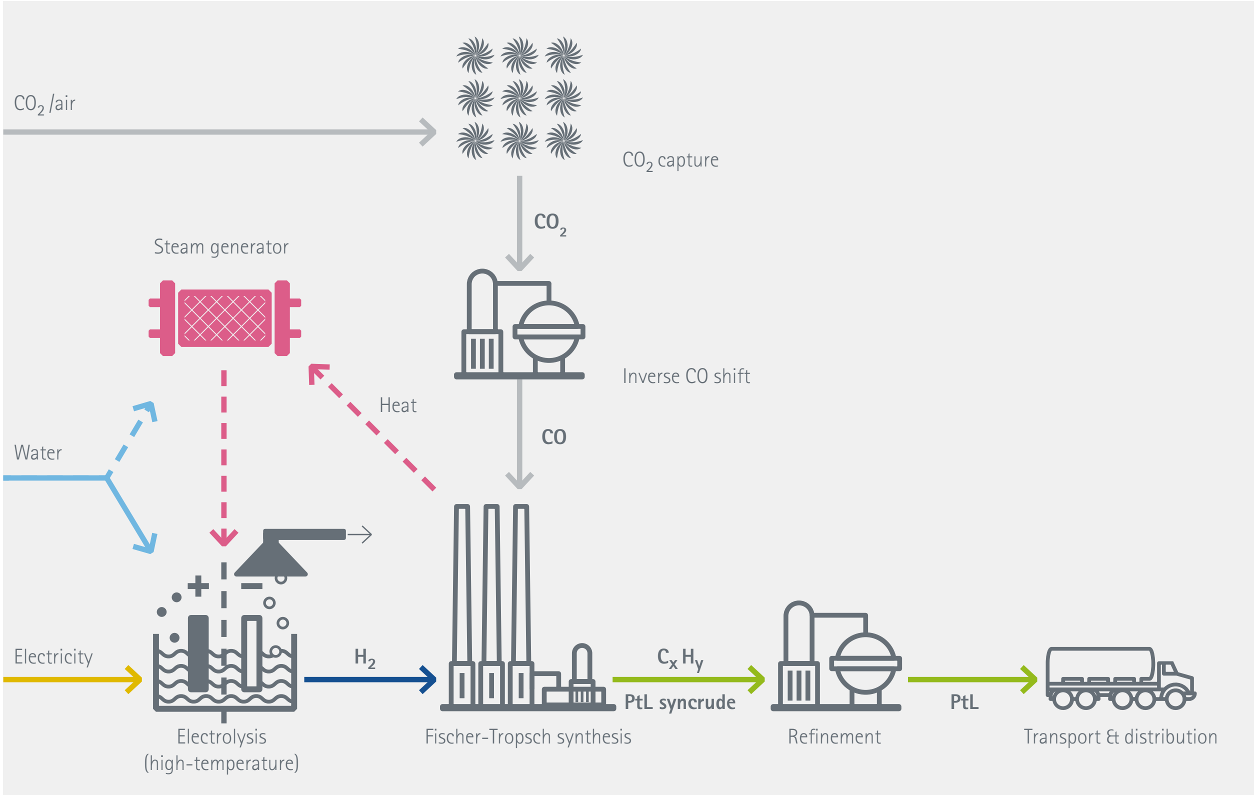
Depending on the operating parameters, pressure, temperature and the catalyst that is used can all affect the chain length of the PtL syncrude. The aim is generally to produce high chain lengths that can subsequently be split into the required fractions by means of hydrocracking (LBST GmbH and Bauhaus Luftfahrt e.V. 2016).

12.1.2 Methanol Synthesis

Traditional methanol synthesis is a process used to synthesise methanol from H_2 and CO. The first industrial plants to employ this process have now been in use for almost 100 years, and the ICI low-pressure procedure with copper/zinc oxide/alumina catalysts has been the standard for large-scale industrial use since the 1960s. The largest conventional plant currently in use is the Lurgi MegaMethanol Plant, which has a production capacity of 5,000 t of methanol per day (Chemie Technik Fachinformation 2004).

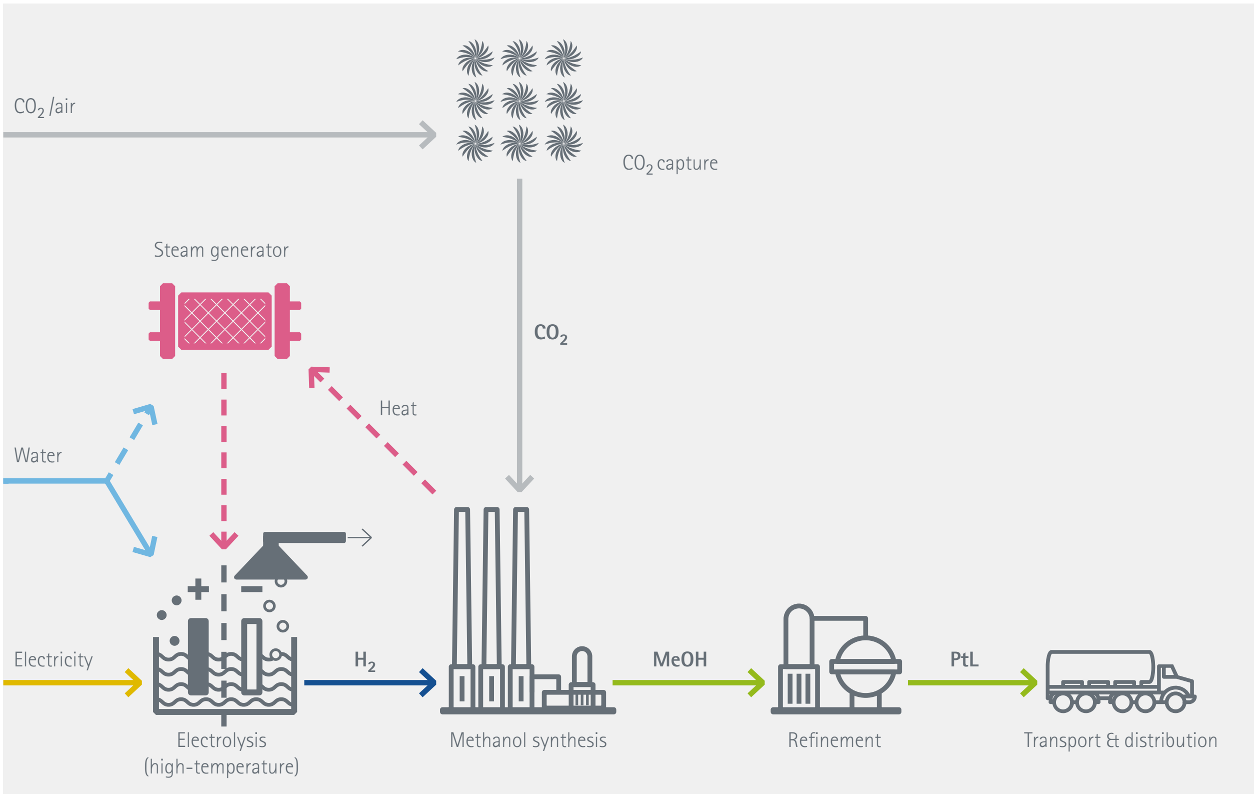
In the field of producing methanol using RE, however, the focus is currently on catalyst research for the direct generation of methanol using CO_2 and H_2, which would negate the need for the inverse CO shift process.

Figure 70: Schematic diagram of the Fischer-Tropsch process



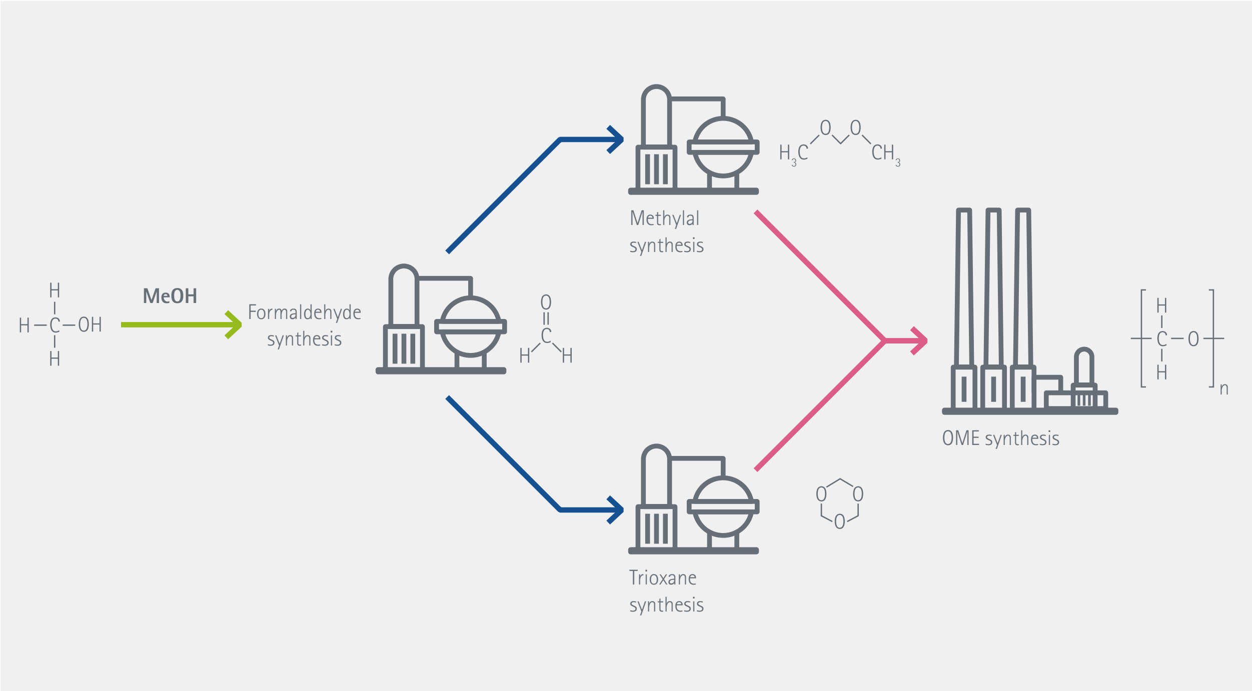
Source: Own diagram, based on LBST 2016

Figure 71: Schematic diagram of methanol synthesis



Source: Own diagram, based on LBST 2016

Figure 72: Schematic diagram of polyoxymethylene ether synthesis



Source: Own diagram, based on Burger 2012

Figure 71 shows a diagram of the process. The total efficiency is between 45 and 55 %; see (Schmidt, et al. 2016). The standard operating parameters are around 300 °C and 80 bar (Ritzkopf 2005).

12.1.3 Polyoxymethylene Ether Synthesis

Polyoxymethylene ether can have a soot-mitigating effect when used as a diesel additive, and can burn without soot in its pure form (Maus et al. 2014). As such, it provides a promising option for supplementing or replacing diesel fuels. Polyoxymethylene ether synthesis is based on the methanol synthesis process, and requires methanol as a charge material. First, the methanol is synthesised into formaldehyde. This is synthesised in turn into methylal and trioxane, before the actual OME synthesis takes place in the final step (see Figure 72). Due to the number of different synthesis stages involves in this process, it offers a total efficiency of just 38 % – a relatively low figure compared to FTS and methanol synthesis.

12.2 COSTS OF PRODUCTION OF PTL

This section will describe the production cost calculation process for the FTS route. The cost calculation is based primarily on figures from the literature and assumptions made during the course of the project.

12.2.1 Investment Costs

The investment costs for FTS were calculated for the individual assemblies seawater desalination, Direct-Air-Capture (DAC) and the synthesis unit. A constant rate of € 65/kW of rated electrolysis power was set for the integration of an intermediate tank for the H_2 produced by the process. The calculated specific costs of the assemblies were projected for the study periods 2030 and 2050 with the aid of learning curves (National Energy Technology Laboratory (NETL) 2013) and our own assumptions on further expansion. The resulting specific investment costs are shown in Table 44.

12.2.2 Calculation of Costs of Production

The production costs/the Levelised Cost of Fuel (LCOF, cf. [VGB2015]) per litre of PtL syncrude were calculated using the specific investment costs and other assumptions regarding the operation of the plant and the efficiencies of the individual steps. The calculations were based on the baseline assumption that it would be possible to set up plants with an annual production of 10 m t per year with electrolysers providing 5,000 full-load hours per year. This would result in a total investment of € 22.57 bn for the realistic case model in 2050.

Table 44: Specific investment costs and assumptions for the individual assemblies

		2030				2050			
CAPEX*									
Electrolysis**	€/kW_{el}	705				370			
Reinvestment Stack (after 15 years)	€/kW_{el}	430				300			
DAC	€/(t CO_2*a)	366				246			
Synthesis	€/(l*a)	0.54				0.42			
Seawater desalination	€/(l H_2O*a)	0.0023				0.0023			
Storage facilities	€/kW_{el}Electrolysis	65				65			
		cheap		**realistic**		**cheap**		**realistic**	
Electrolysis efficiency (H_s)		**78 %**		**66 %**		**86 %**		**73 %**	
WACC		7 %	2 %	7 %	2 %	7 %	2 %	7 %	2 %
Cost of electricity	Cent/kWh	**3.1**[a]	**2.1**[a]	**6.4**[b]	**4.4**[b]	**2.7**[a]	**1.9**[a]	**5.7**[b]	**3.9**[b]
Generation cost PtL-Syncrude	**€/l**	**0.98**	**0.70**	**1.75**	**1.23**	**0.70**	**0.49**	**1.33**	**0.92**
	Cent/kWh	10.3	7.3	18.3	12.9	7.3	5.1	13.9	9.6

Source: (Fasihi, Bogdanov and Breyer 2016), (Caldera, Bogdanov and Breyer 2016), (Albrecht et al. 2013), (Becker, et al. 2012), (LBST GmbH and Bauhaus Luftfahrt e.V. 2016), (E4Tech and Element Energy 2014) (Climeworks AG 2017b) and own calculations], * Applies to plants with production volumes of 10,000 kt/a, ** 5,000 full-utilisation hours of electrolysis and synthesis, [a] Applies to particularly cheap sites in the MENA region. The potential for these costs is limited (cf. Table 39); [b] applies to average sites in the MENA region. The potential for these costs is around 18,000 TWh/a (cf. Table 40)

Two price paths were calculated; the framework data and results of each are presented in Table 44. The electrolysis should achieve an average efficiency of 86 % in 2050 according to the optimistic case model, or 73 % according to the realistic case model(based on the upper calorific value).

Table 45 lists the specific energy consumption figures for the individual process steps for the realistic case model. The assumed fuel value for PtL syncrude is 9.56 kWh/l (calculated based 43 MJ/kg, 0.8 kg/l). This results in an efficiency of 53 % for the entire process in the realistic case model, without product treatment.

The consumption figures listed in Table 45 have been converted for the low-temperature requirement of the DAC/the high-temperature requirement for RWGS in case of thermal energy requirement, using the efficiency figures and the performance factor for heat pumps (Albrecht et al. 2013), (Fasihi, Bogdanov and Breyer 2016). These consumption figures are used to calculate the variable associated operating

Table 45: Specific energy requirements for the individual process steps of FTS

Process step	Specific electrical self-consumption in kWh/(l FTS)
DAC	2.35
SWDS	0.0033
Electrolysis	8.89
Synthesis RWGS	6.69
Total	**17.93**
Efficiency (H_s, realistic case)	**53 %**

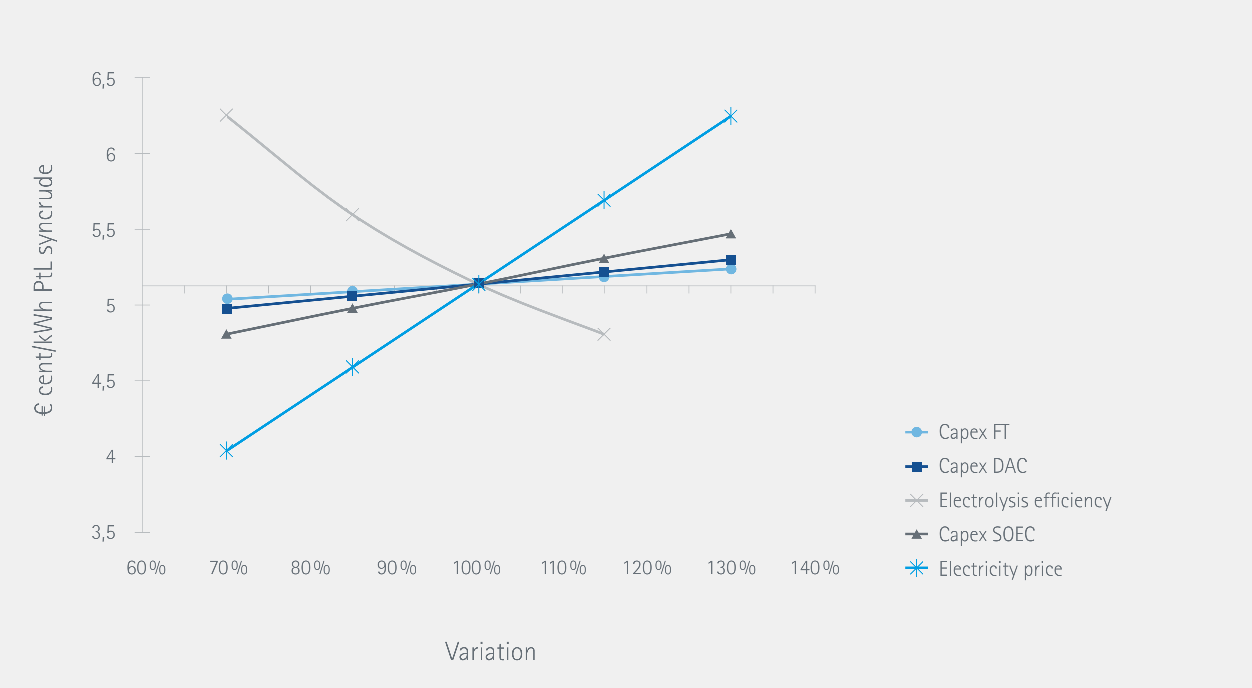
Source: (Fasihi, Bogdanov and Breyer 2016), (Caldera, Bogdanov and Breyer 2016) and own calculations

Table 46: Service life and fixed associated operating costs of the FTS assemblies

Assembly	Service life	Opex_fix
FTS	30 a	3 %
SOEC	15 a	3 %
DAC	30 a	4 %
SWDS	30 a	4 %
H_2-storage	30 a	2 %

Source: (Fasihi, Bogdanov and Breyer 2016), (Caldera, Bogdanov and Breyer 2016), (E4Tech and Element Energy 2014) and own assumptions

Figure 73: Sensitivity analysis of the production costs of PtL syncrude on the basis of FTS, 2050



Source: Own diagram based on calculations by UMSICHT, cheap case model, 2 % WACC

costs of the plant. In addition to this, the fixed associated operating costs listed in Table 46 must also be taken into account.

12.2.3 Sensitivity Analysis

A sensitivity analysis was carried out in order to determine the factors driving the production costs and establish a price range, which is shown below.

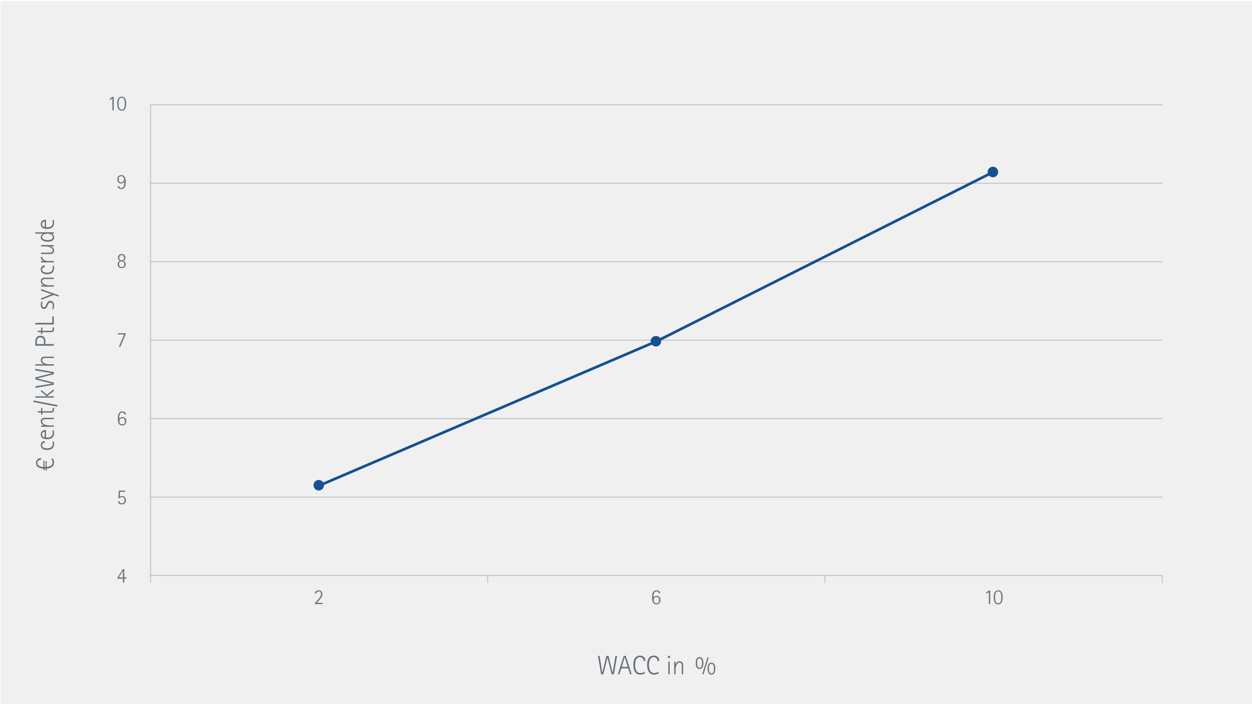
Figure 73 clearly shows that the efficiency of the electrolysis and the electricity production costs are the deciding factors. In addition to these two factors, the calculated interest rate (WACC) also has a significant impact on the production costs (cf. Figure 74).

Based on these findings, realistic and optimistic production costs were calculated for both 2030 and 2050, with corresponding variation in these key parameters (cf. Table 44).

Combined with the electricity costs at cheaper and average-priced RE sites in the MENA region[20] for two interest rates (7 and 2 %), this gives us the cost ranges for the generation of PtL syncrude. These are shown in Figure 75.

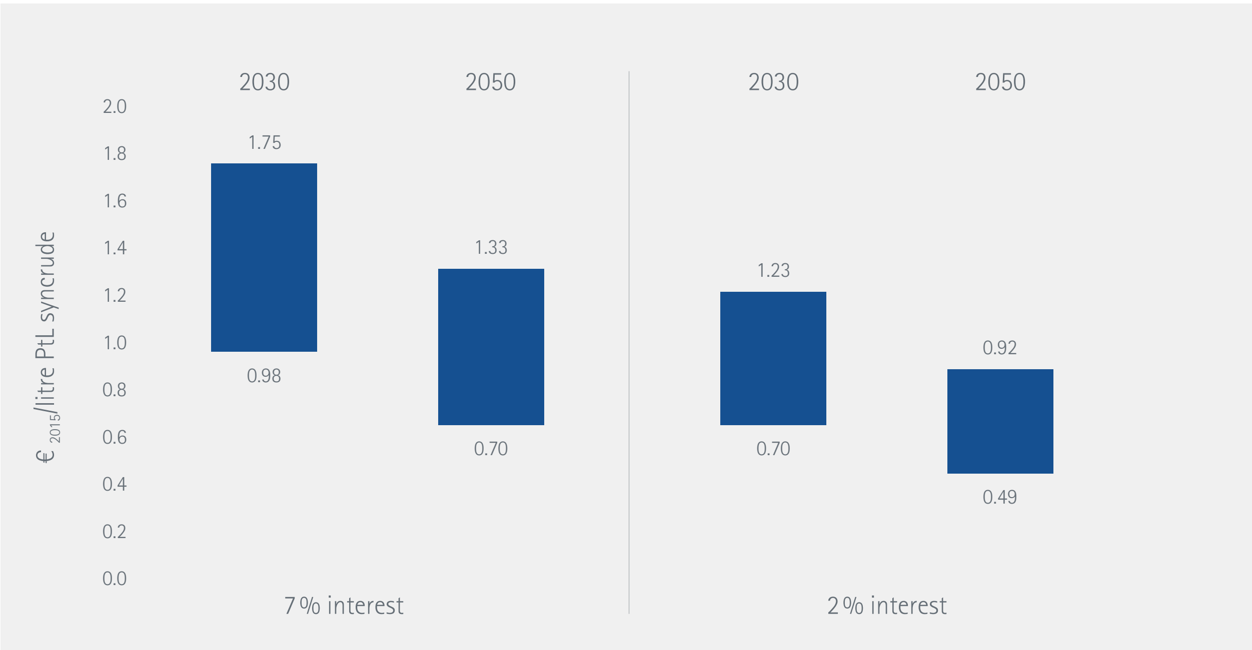
20 An explanation of the volume potential for these costs is provided in Section 10.2.

Figure 74: Effect of the imputed interest rate on PtL syncrude production costs on the basis of FTS in 2050



Source: Own diagram, cheap case model, 2 % WACC

Figure 75: Range of production costs of PtL in 2030 and 2050, in $€_{2015}$/litre (Fischer-Tropsch process)



Source: UMSICHT (electricity costs: Prognos)

Table 47: Assumptions on costs and efficiencies of methanation (PtG)

Year	**2030**				**2050**			
Location	Cheap		Realistic		Cheap		Realistic	
WACC	2%	7%	2%	7%	2%	7%	2%	7%
Cost of electricity in €/kWh	0.024	0.035	0.045	0.065	0.021	0.031	0.040	0.058
CAPEX €/kWh CH_4	250				200			
OPEX	2%							
Service life in years	30							
Total efficiency (H_s)	61%		52%		67%		57%	

Source: Prognos AG

With a WACC of 7%, the calculated generation costs are between € 0.98/l and € 1.75/l of PtL syncrude for 2030, and between € 0.70/l and € 1.33/l of PtL syncrude for 2050.

12.3 POWER-TO-GAS TECHNOLOGY AND PRODUCTION COSTS

Since this study focuses on liquid energy sources and raw materials, it does not go into the same depth on synthetic natural gas. Synthetic natural gas is methane (CH_4) produced using carbon dioxide (CO_2 from DAC) and hydrogen (H_2) in a methanisation reaction, which can be either a catalytic or a natural process. Like the PtL processes, this synthesis process generated water and exhaust heat, which can be used in DAC and electrolysis processes.

This study assumes that a catalytic synthesis process will be used. Kazakhstan was chosen as the sample site for the synthesis process, as this location offers both a high level of potential for the generation of renewable electricity and a connection to existing gas transport infrastructure (the Central Asia Centre Pipeline).

The same assumptions with regard to cost and efficiency that were applied to the PtL process were also made here for the processes of hydrogen production, extraction of carbon dioxide from the air, seawater desalination and intermediate storage.

The site-specific costs for the generation of electricity using solar and wind power are listed in Table 47, together with the projected costs and efficiency of the synthesis process.

As with the synthesis of liquid energy sources and raw materials, we have assumed that the costs of synthesis with be reduced dramatically due to economies of scale for large-scale technical applications and installation volumes that break the GW barrier. The projected costs of € 200/kWh CH_4 for 2050 are around the same level assumed in (Frontier Economics, IAEW, 4 Management, EMCEL 2017).

STUDY SECTION C: REFINERY CASE STUDIES

Over the course of the study, technical discussions were held with two large-scale refinery sites in Germany. The aim of these conversations was to improve our understanding of how refineries would act in the GHG reduction scenarios. The focal point of these discussions was the aim of reducing greenhouse gas emissions from liquid energy sources and raw materials.

This section will start by focusing on the general role of refineries in the energy system and the industrial value chain in Germany. In addition to this, it will also explain and discuss the opportunities, challenges and requirements for a successful, gradual reduction of greenhouse gas emissions from liquid energy sources and raw materials based on the results of the technical discussions.

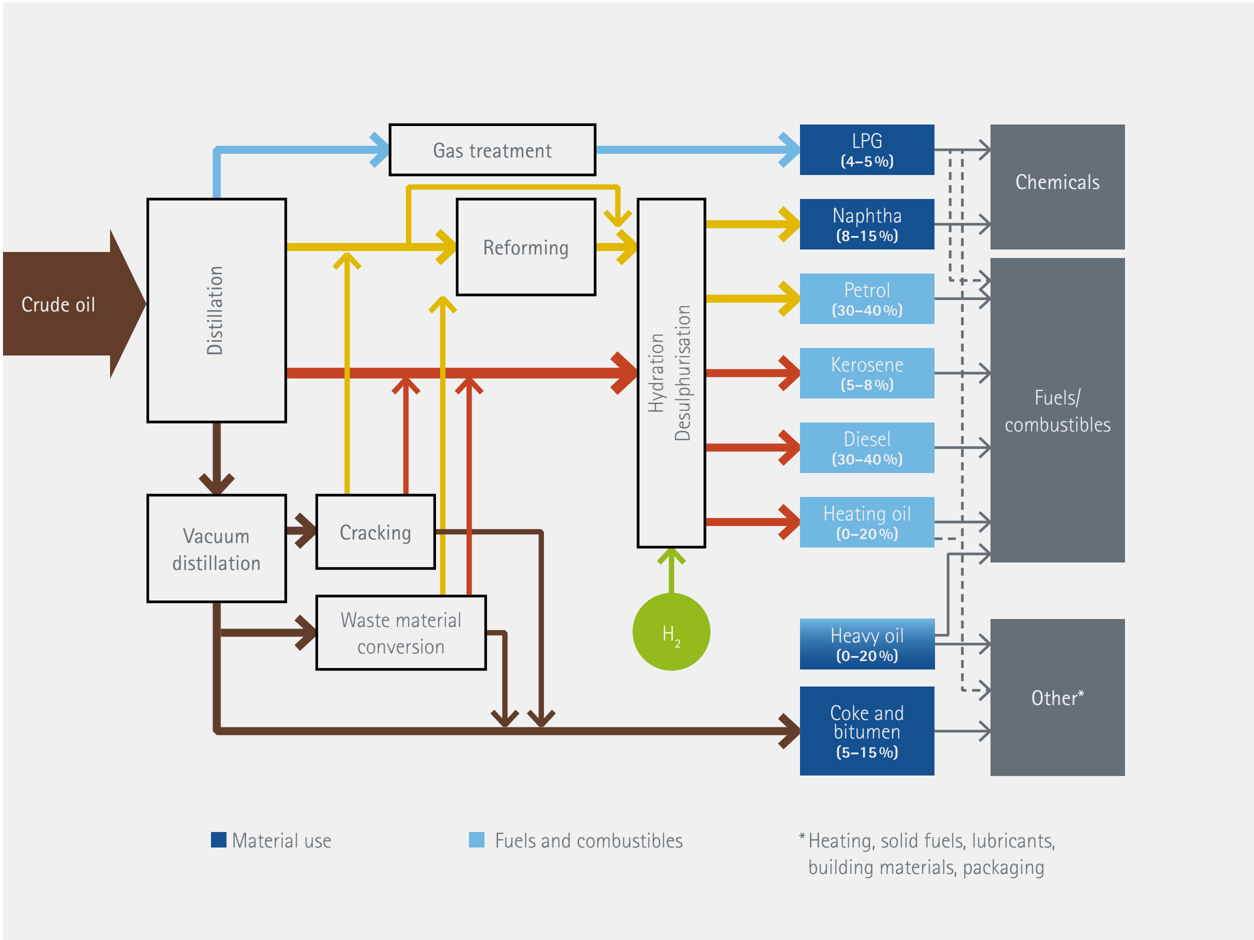
13

REFINERIES IN GERMANY

For the purposes of this study, the term "refineries" refers to general oil refineries. These are complex plants in which crude oil is broken down into a variety of liquid energy sources and raw materials. Specifically, these include the secondary energy sources petroleum and diesel, kerosene and heating oil, as well as LPG and various raw materials such as gases, naphtha and aromatic streams as chemical raw materials (plastics, pharmaceutical products, fibrous materials, etc.), lubricants, anode coke and bitumen.

There are currently 13 refinery sites in Germany, with a total annual processing capacity of 102 million tons of crude oil (MWV 2017). Each refinery site is structured differently, with different plant configurations, raw oil type requirements, product ranges and product emission ratios. The oil is usually supplied via crude oil pipelines, while the product is output via product pipelines, rail, ship and tanker truck. The crude oil refinement process leaves almost no waste materials. This means that the majority of the components are used up during the process, either flowing into the products themselves or being recycled in refinery power plants for energy supply. The refineries' in-house consumption and the generation of energy in the refinery power plants produced emissions of 25.3 million tonnes of CO_2 in 2016.

Figure 76: Coupled production in a typical sample European refinery



Source: Own diagram based on (Fuelseurope 2017)

Figure 76: "Coupled production in a typical sample European refinery" is a representative flow chart for a typical sample European refinery: The crude oil is processed using a procedure known as **coupled production** (or "interlinked production"). This production process generates multiple main products and by-products in **parallel**. The process parameters can be varied (depending on what plants are installed) to shift the product percentages within certain boundaries (percentages shown in brackets in Figure 76). In order to allow for changes that exceed the flexibility of around 10 to 20% constructional modifications must be made to the refinery plants. By investing in the refineries and adapting the equipment, it is theoretically possible to shift entire fractions, e.g. converting petrol into the naphtha fraction in order to increase the chemical feedstock in the product portfolio. The higher a refinery's energy-intensive conversion percentage as a result of its attempts to satisfy market demand for raw materials and energy sources, the higher its in-house usage will be, too.

Reducing greenhouse gas emissions

Within the framework of the specified scenario with the GHG reduction targets described in section 4.1, the targets can only be reached by reducing the emissions of the liquid energy sources and raw materials. This presents a particular challenge for the refineries as the central processors of large volumes of primary energy (crude oil) to produce a wide range of secondary energy sources and raw materials. The following areas have been identified as factors that can give the refineries the leverage they need to reach their emission targets: **efficiency improvements, incorporation of renewable energy, change in the raw material base** and **CO_2 capture** (CCS).

13.1 EFFICIENCY IMPROVEMENTS

German refineries are some of the most efficient in the world, though efficiency levels vary significantly from one refinery to the next. Crude oil processing in refineries is usually highly efficient thanks to the integration of the energy and material streams within the refinery and, in some cases, in association with affiliated chemicals companies (e.g. chemistry parks). Equipment expenses are high, taking the form of heat exchangers, insulation material, pipelines, etc. In 2015, in-house consumption of mineral oil at German refineries was around 5%.[21] However, improvements in this efficiency will be difficult to realise due to a number of different trends:

- Due to the rising global demand for crude oil, companies are increasingly turning to new processes. This is causing a decline in the average quality of crude oil, as reflected in the moderate trend towards heavier crude oils that contain sulphur.
- At the same time, the demands placed on the refineries' product are getting stricter (lower sulphur content and other emissions-related parameters).
- Likewise, there is also increasing global demand for lighter, higher-quality energy sources.

These trends are causing an increase in processing workload, which causes a refinery's CO_2 emissions to rise[22] and tends to result in greater quantities of waste products. At the same time, raw material efficiency can be improved by converting waste products instead of burning them to generate steam or power, as has been done traditionally. In addition to increasing energy efficiency, another way of reducing CO_2 emissions is to convert to natural-gas firing in the processes and power plants, assuming this has not already been done in Germany. As with every industrial plant, lower utilisation rates (plants running at partial load) and increased flexibility (start-up and shut-down, "hot standby") lead to reduced energy efficiency and an increase in specific CO_2 emissions.

13.2 INCORPORATION OF RENEWABLE ENERGY IN THE PROCESSES

The next step that can be taken to reduce the refineries' emissions is the incorporation of renewable energy into the processes.

The buzzword "green hydrogen" is being used in refineries to discuss the option of incorporating renewable electricity into their production processes using hydrogen generated by means of electrolysis as a secondary energy source. Hydrogen is generated as a by-product in refineries, e.g. during the catalytic reforming of crude petrol. It is also consumed in a number of refinery processes, such as hydrotreating (desulphurisation and the removal of impurities) and hydrocracking (the conversion of hydrocarbons using hydrogen). German refineries consume more hydrogen than they produce in-house, leading to a net hydrogen requirement of around 140 kilotons per year (Vanhoudt W. 2016). This is currently produced primarily by means of steam reforming using natural gas.

21 This figure refers solely on in-house consumption of mineral oil products. Total in-house consumption for 2015 was higher, at 6.9%.

22 Based on the inclusion of GHG emissions from electricity and steam generation in refinery power plants.

The potential for reducing greenhouse gas emissions by substituting green hydrogen produced via electrolysis in for the hydrogen generated by means of steam reforming is dependent on the emission factor of the electrical energy used for the process. Roughly 10 tons of CO_2 per ton of green hydrogen can be saved in the refinery, if the electrical energy is drawn from completely CO_2-neutral sources. With the current electricity mixture, this would increase emissions in the electricity sector by around 22 tons of CO_2 (equivalent to a 12-ton increase in total emissions).

As such, the GHG balance of electrolysis hydrogen is not yet able to compete with hydrogen generated by means of natural gas steam reforming with the current percentage of renewable electricity. However, this will improve as the percentage of electricity generated renewably continues to improve, eventually leading to a better CO_2 balance.[23]

Despite this, there are also political and economic concerns due to the necessary learning curves for the electrolysis technology, as outlined in section 14.2.

13.3 CHANGE IN THE RAW MATERIAL BASE

The term "change in the raw material base" for a refinery means the replacement of crude oil with alternatives, such as synthetic energy sources and other raw materials (Power-to-Liquid: PtL, Biomass-to-Liquid: BtL)

These measures offer the most effective leverage for reducing the refineries' GHG emissions and, above all, their products. They are also the only way of completing the carbon cycle for liquid energy sources and raw materials. The potential and technology is explained in section 12.

Based on the technical discussions, it is already possible to incorporate enough PtL into the refinery process to account for up to one fifth[24] of its input without making any major modifications to the plant configuration. This would allow electricity-based PtL syncrude to act as a substitute for approx. 20 m tons of the crude oil currently processed in Germany.

The synthetic raw material can be incorporated at several points. The simplest method is to blend it into the crude oil. In this scenario, the PtL goes through the entire refinery process, starting with atmospheric distillation. However, PtL syncrude does not contain any impurities such as sulphur or heavy metals, and thus does not need to be subjected to process steps like hydrotreating (desulphurisation). Another method would be to incorporate PtL syncrude directly using hydrocrackers or catalytic crackers.

If the percentage of PtL syncrude used in the refinery process continues to rise, the refinery configuration will need to be adjusted in order to account for the changes in composition compared to crude oil. We are assuming that these adjustments would be part of the refineries' regular investment cycle, leading to additional costs of 15 %.

Plants such as the vacuum distiller, the entire waste material processing system and plants used to filter out impurities (heavy metals, sulphur, etc.) may not be required for PtL syncrude processing, or will have much lower loads. The differences in composition between FTS-based PtL syncrudes and crude oils is the main reason for adjusting the plant configuration in a refinery, as it results in changes to the product yield. For refineries that sell products such as lubricant oil, bitumen, anode coke and other specialist products, it may be necessary to keep using a small percentage of crude oil as a raw material, as such products are impossible to produce using PtL syncrude, at least without great additional expense.

The projected blending proportions used in the scenarios and the resulting decrease in crude oil percentage in processing would require a change of approach in the refinery sector. In addition to the change in product percentages, a decline in conventional refinery capacity should also be expected. There are clear site advantages for refineries involved in production for the chemical association, and thus enjoy an additional offset flexibility option.

Blending in PtL may lead to an initial increase in relative energy consumption based on the volume of raw materials used for processing (cf. (de Klerk 2008)) if there is a change in the refineries' educt composition, bringing it closer to the maximum percentage possible for the refinery in question without technological adjustments. In the long term, as the percentage of PtL syncrude increases, we can assume that the consumption will sink again due to the light-oil-like properties of syncrude and the completion of adjustments to the refinery.

If refineries adapt to the processing of PtL syncrudes over the course of time, these sites will be able to compete with the combined synthetic refinery sites that may appear outside of Europe.

23 With an emission factor of approx. 197 g CO_2/kWh_{el} or lower, water electrolysis has lower CO_2 emissions than steam reforming using natural gas (assuming 75 % efficiency for both water electrolysis and steam reforming)

24 Higher percentages also feasible, depending on plant configuration

13.4 CO_2 CAPTURE IN REFINERIES

In principle, it is possible for refineries to capture their CO_2emissions and store them in geological formations (Carbon Capture and Storage, CCS). However, there are a number of hurdles facing this development, most notable social acceptance.

As long as the refineries cover their in-house consumption using completely GHG-neutral energy sources[25], it will be feasible for them to use the captured CO_2 as a raw material (Carbon Capture and Utilisation, CCU) for PtL synthesis. This would complete the carbon cycle.

25 According to the energy balance, in-house consumption at German refineries was 6.9 % in 2015. This in-house consumption can be made GHG-neutral by underfiring the refinery processes using synthetic gas, for example.

14

CONCLUSIONS AND OPTIONS FOR ACTION

14.1 GENERAL

Liquid energy sources and raw materials are of **great importance** to today's energy mix, and form the foundation of important industrial value chains in Germany (e.g. in chemical production).

Especially in important parts of the national and international transport sector and in the chemicals industry, liquid energy sources and raw materials are difficult or impossible to replace. This is the case in the air traffic, shipping, long-distance road haulage, construction, agriculture and forestry sectors, to name just a few. In other areas that are currently largely supplied with liquid energy sources, including passenger car traffic and the heating sector, competition will arise between GHG-neutral energy sources and systems (incl. Power-to-Liquid, PtL).

Since liquid energy sources continue to be needed, the development of the power-to-liquid technology path is a no-regret measure from a climate protection perspective. The German demand for PtL could reach up to 2,000 PJ. Our scenarios indicated a PtL demand of around 550 PJ for outgoing air and water traffic from Germany alone. This is supplemented by up to around 1,600 PJ of PtG and PtH_2.

PtX technology increases the robustness of a demanding GHG reduction path. This will be especially important if it proves impossible to overcome the resistance to other technologies in Germany. As climate protection measures become stricter, the volume of PtX required increases. Significant investment will be required, especially abroad, in order to establish the production capacity required to cope with this. However, our scenarios predict comparatively low investment in Germany.

14.2 OPTIONS FOR ACTION

Develop a PtL roadmap

What do we need to do in order to establish PtL as a substantial option for GHG reduction? The measures and tools described below would allow us to expand PtX in the future, especially the PtL option. The list is not exhaustive; studies are still ongoing to determine whether these measures will be enough to ensure that the minimum quantities of PtL will be available when required. In order to allow a systematic analysis of the obstacles to and potential measures for a PtL market evolution, we need to develop a **PtL roadmap** that lists and evaluates the tools and establishes a timeline for their introduction. Efforts must be made to ensure that sufficient consultation is conducted with the relevant stakeholders.

Expand R&D capacity and setting up real labs

In order to expand our own expertise in the field of PtL and ensure that we acquire in good time the knowledge we need to make a decision on how to bring PtL onto the market, we recommend setting up research and development budgets in the business and science sectors. It is particularly important to ensure the involvement of important sectors such as the mineral oil industry, the automotive industry, the chemical industry, the mechanical engineering and plant construction industry, and government authorities Since the availability of cheap RE electricity is an essential component in the PtL value chain, we recommend searching for suitable potential sites.

Establish research funding

Large-scale PtL generation requires technology that is often still associated with significant learning curves. Some technology is still in the early stages of its development and has not yet been put to large-scale use. As such, the appropriate research funding should be secured at an early stage in order to ensure that the projected learning curves for these types of technology can be completed. Specific fields of research are addressed in section 14.3, below.

Provide support for a PtL market launch

As with the market launch of renewable energy for electricity generation in the 1990s, suitable conditions must first be established before an innovative and promising energy source such as PtL can be brought to market. The first plants that offer large-scale PtL generation will require much greater funding than subsequent plants. Tender models may present a suitable means of attracting investment during this initial phase. A regulatory – and, most importantly – a financial framework must be developed for this process.

Adjust regulatory frameworks for blending in PtL

It makes sense to increase the use of PtL gradually. This can be done by blending it with conventional energy sources. This will allow the market to evolve gradually. All energy-source-related regulations must allow complete offsetting for the blending in of sustainable, renewably generated PtL. This is already established at the European level in Renewable Energy Directive II. An additional option would be to permit PtL offsetting for the emission thresholds for fleets on a temporary basis.

Make CO_2-free energy sources exempt from tax, duties and levies

Investigations must be carried out to determine the extent to which CO_2-free energy sources can be made exempt from tax, duties and levies to ensure that renewably generated PtL products are marketable and become economically competitive in their long-term applications without further funding.

These investigations must ensure that the conditions intended to accompany conversion up to the achievement of a GHG-neutral energy supply are not in any way limited to purely environmental aspects; they must also account for the social aspects and limits of acceptance, taking into account sector-specific variables.

Provide funding for the use of renewable hydrogen in refineries

The use in the refinery process of hydrogen that is generated in electrolysis plants using renewable energy reduces GHG emissions in the generation of oil products. This encourages the evolution of electrolysis plant use on a large scale, which will also be necessary for PtL generation at a later stage. In order to ensure that PtL contributes to the protection of the environment, we will need to use additional electricity generation plants that are not funded by the EEC. An obvious way of funding this measure would be to offset the GHG reduction achieved through the use of renewable hydrogen in the refinery process against the GHG reduction quota. Balancing questions must be resolved in order to ensure that nothing is offset twice.

Specify the national level of biomass use

Liquid, biomass-based energy sources and raw materials have many uses and can play an important supplementary role in reducing GHG emissions. Biomass can also be used in conjunction with PtL technology (PBtX). However, the national potential for this is limited. As such, it would be helpful to analyse the long-term position of the nationally available biomass in terms of an optimum allocation path within the future GHG-neutral energy mix in Germany.

Fund international collaboration in RE regions

Tapping renewable resources in countries suited to such technology will play a key role in the expansion of the PtL infrastructure. This could require partnerships with countries, an exchange of knowledge and the strengthening of economic and political relations. Since PtL products in particular can be transported flexibly and at low cost over long distances from their production site to their site of use, we recommend tapping renewable resources in countries that are particularly suitable to their utilisation. International collaboration presents opportunities for both sides – PtL generator and recipient alike. They should be initiated as soon as possible.

Develop indices for PtL production sites

Comprehensive indices should be developed for the selection of suitable PtL generation sites. These should provide sufficient transparency with regard to the opportunities, risks and potential for investors. There are a variety of factors that could be decisive in the choice of site. These include the climate conditions on site, the area available, the presence of existing infrastructure that can be used for PtL generation, the capital costs (WACC), and the chance of overcoming potential risks of failure (e.g. by means of credit guarantee). Any local government support for the construction of PtL infrastructures is also relevant. Political and socio-economic potential for development should also play a role.

Define standards for the sustainability of synthetic fuels

As with other energy sources, sustainability standards should be drawn up for synthetic fuels and combustibles. For example, a certificate of origin could be required for the electricity needed for the electrolysis process, or for the hydrogen and carbon source. Binding international standards will allow us to transparently verify the sustainability of synthetically generated fuels and combustibles.

14.3 RESEARCH QUESTIONS

This section will identify concrete areas where research is required in order to contribute to the realisation of the technological development projected in the scenarios. Other research questions on the future of liquid energy sources and raw materials are not included in the scope of this study, and should be mentioned here for the sake of completion. The central areas of research will be listed and described. The order of the research questions follows the path used for the synthesis of liquid energy sources and raw materials, and does not represent a ranking of priority.

Renewable electricity generation and potential around the world

In order to be successful PtL technology requires renewable electrical power with high full-load hours. In-depth analyses of **renewable energy around the world** can help us to hone our understanding of the actual potential available from renewable electricity. This research should focus on the cost-supply curves in order to strengthen our knowledge base with regard to PtL generation costs.

This study has used combined PV and wind potential at reference sites as the basis for the generation structure for electrolysis plants. Here too, a more in-depth global analysis can help us to identify sites with particularly favourable combined RE potential.

Combination with solar thermal processes

In addition to renewable electricity, a combination with solar thermal processes could prove useful for PtL generation, and should be investigated for the following reasons:

a) It may allow us to further increase the full-load hours for electricity generation (solar thermal power plants with thermal storage).

b) It may be necessary to supply the required process energy using solar thermal technology.

Renewable raw materials as a basis for synthetic energy sources and raw materials

Water, **CO_2** and biomass form the raw material basis for greenhouse-gas-neutral synthetic energy sources. Since water is scare in many potential generation regions, **seawater desalination plants** should be developed further, as these will play a key role in supplying water for electrolysis.

The process of capturing **CO_2** from the air, **Direct-Air-Capture** (DAC), is a young technology that is currently still cost-intensive and has thus far only been used in isolated pilot plants. This technology must be developed further at a rapid rate, especially in view of the projected cost degression for DAC. The evaluation of DAC will become part of the general discussion with regard to the evaluation of negative emissions, projections for which are part of many climate gas reduction scenarios. In this studies must be conducted to determine which concentrated CO_2 sources are unavoidable, and thus can and should be used.

The potential contribution of **BtX and PBtX applications** is competing with the use of biomass in other sectors. An analysis of the global biomass potential for sustainable use in BtX generation may provide us with important information on this topic. Biomass is a scarce resource, and PBtX applications make better use of it due to their increased carbon efficiency. As such, the further development of these applications should be a priority.

Plastic waste represents an alternative raw material basis for liquid energy sources. Synthesis processes and the potential relating to **Waste-to-Liquids** were not included in the scope of this study; nevertheless they may play a role in the future of liquid energy sources and raw materials, as well as presenting a solution to the global "plastic waste problem".

Water electrolysis

Irrespective of the specific technology it uses, water electrolysis represents the key step from electrical energy to the chemical energy source hydrogen, and is thus of great importance in terms of PtX generation. At the same time, it represents a highly sensitive cost factor. In order for us to achieve the projected learning curve, great progress and cost savings are required in this area. There is also potential for further development in terms of the load flexibility, long-term stability, service life and efficiency of the various technologies involved.

Synthesis using renewable energy and raw materials

Large-scale **Fischer-Tropsch synthesis** has thus far only been tested using various fossil carbon carriers and hydrocarbons as a basis, not with a process **based on electrolysis hydrogen and CO_2**. The activation of CO_2 – initially an "inactive element" – for chemical synthesis differs from the process used so far of gasifying a fossil energy source. In view of the projected cost degression for FT synthesis, this is also an area in urgent need of research. This research should focus on the generation of a stable **synthetic gas using electrolysis hydrogen and CO_2**.

Other synthetic processes for liquid energy sources, such as methanol synthesis, are not the focus of this work, though they should still be developed in parallel to Fischer-Tropsch synthesis. The same applies to **catalyst research,** which plays a key role in many synthesis processes.

Direct **power-to-chemical processes** also offer a means of shortening the path from renewable electricity to the target substance, especially for basic chemicals. This would save more process energy than a synthesis method that uses a synthetic hydrocarbon mixture such as PtL syncrude.

System integration and optimisation

Generation plants for synthetic energy sources and raw materials are based on a multitude of plants and auxiliary equipment. The act of harmonising generation plants for renewable energy, water treatment plants, CO_2 capture plants, electrolysis plants and synthesis plants to create an **integrated production process** represents an ongoing optimisation task and a key area of research. After all, in order to **integrate** the volatile process of RE generation into a synthetic energy source production process that is as continuous as possible, we will need to ensure that the components are harmonised to the optimum degree. This will require the use of **storage technology** at various locations, such as intermediate hydrogen storage tanks.

In addition to this, further **upscaling** is required for both the sub-plants and the overall processes of the PtL plants. This means that the findings from the lab and technical trials on the plants need to be translated to an industrial scale so that they can be tested and applied in real plants. After all, industrial-scale use is the only way of generating the required volumes and unlocking the potential for cost reduction.

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TABLE APPENDIX

Table 48: Cross-border prices*, € cent/kWh, actual 2015, basis of higher PtL price path

	Reference, PtX 80			PtX 95		
	2015	**2030**	**2050**	**2015**	**2030**	**2050**
Hard coal	0.8	0.9	0.9	0.8	0.7	0.5
Lignite	0.7	0.6	0.6	0.7	0.6	0.7
Heating oil	3.2	5.8	6.3	3.2	4.2	2.8
Natural gas	2.1	2.6	2.8	2.1	2.3	2.2
Biomass (solid)	2.5	3.4	3.8	2.5	3.3	3.3
Petrol	3.2	5.8	6.3	3.2	4.2	2.8
Diesel fuel	3.2	5.8	6.3	3.2	4.2	2.8
Jet fuels	3.2	5.8	6.3	3.2	4.2	2.8
PtPetrol	51.8	19.2	14.8	51.8	19.1	14.8
PtDiesel	51.8	19.2	14.8	51.8	19.1	14.8
PtG	53.4	18.9	14.2	53.4	18.9	14.2
PtKerosine	51.8	19.2	14.8	51.8	19.1	14.8
PtHEL	51.8	19.2	14.8	51.8	19.2	14.8

Source: Prognos AG, *including refinement

Table 49: Cross-border prices*, € cent/kWh, actual 2015, basis of lower PtL price path

	Reference, PtX 80			PtX 95		
	2015	**2030**	**2050**	**2015**	**2030**	**2050**
Hard coal	0.8	0.9	0.9	0.8	0.7	0.5
Lignite	0.7	0.6	0.6	0.7	0.6	0.7
Heating oil	3.2	5.8	6.3	3.2	4.2	2.8
Natural gas	2.1	2.6	2.8	2.1	2.3	2.2
Biomass (solid)	2.5	3.4	3.8	2.5	3.3	3.3
Petrol	3.2	5.8	6.3	3.2	4.2	2.8
Diesel fuel	3.2	5.8	6.3	3.2	4.2	2.8
Jet fuels	3.2	5.8	6.3	3.2	4.2	2.8
PtPetrol	51.8	10.8	7.8	51.8	10.8	7.8
PtDiesel	51.8	10.8	7.8	51.8	10.8	7.8
PtG	53.4	11.1	8.0	53.4	11.1	8.0
PtKerosine	51.8	10.8	7.8	51.8	10.8	7.8
PtHEL	51.8	10.8	7.8	51.8	10.8	7.8

Source: Prognos AG, *including refinement

Table 50: Investment costs based on commissioning date in $€_{2015}$/kW

$€_{2015}$/kW	2015	2020	2030	2040	2050
Hard coal power plants	1500	1500	1500	1500	1500
Lignite power plants	1800	1800	1800	1800	1800
Natural gas-GuD	1000	1000	1000	1000	1000
Natural gas-GT	600	550	550	550	500
Engine cogeneration plant (MW size)	800	750	750	700	700
Biomass	2500	2500	2500	2500	2500
Storage (batteries)	1200	500	300	250	200
Windpower onshore	1300	1200	1100	1050	1000
Windpower offshore	3300	2900	2200	2100	2000
Open space PV	750	650	550	500	450
Rooftop PV (single family house)	1300	1200	950	700	650

Source: Prognos AG, GuD = gas and steam, GT = gas turbine, PV = photovoltaic, complete costs including planning, excl. interest during construction

Table 51: Fixed operating costs based on commissioning date in $€_{2015}$/kW/a

$€_{2015}$/kW/a	2015	2020	2030	2040	2050
Hard coal power plants	40	40	40	40	40
Lignite power plants	35	35	35	35	35
Natural gas-GuD	20	20	20	20	20
Natural gas-GT	15	15	15	15	15
Engine cogeneration plant (MW size)	15	15	15	15	15
Windpower onshore	30	28	27	24	24
Windpower offshore	80	64	60	58	58
Open space PV	12	12	12	12	12
Rooftop PV (single family house)	16	16	16	16	16

Source: Prognos AG, GuD = gas and steam, GT = gas turbine, PV = photovoltaic, complete costs including planning, excl. interest during construction

Table 52: Technical service life in years

	technical service life in years
Hard coal power plants	50
Lignite power plants	50
Natural gas-GuD	40
Natural gas-GT	40
Engine cogeneration plant (MW size)	40
Windpower onshore	25
Windpower offshore	25
Open space PV	25
Rooftop PV (single family house)	25

Source: Prognos AG, GuD = gas and steam, GT = gas turbine, PV = photovoltaic, complete costs including planning, excl. interest during construction

Table 53: Average trading capacity in GW

	Import	Export
2015	20	19
2030	25	22
2050	32	28

Source: Prognos AG

Table 54: Assumptions for the calculation of electricity generation costs for renewable energies in Germany

Year	2015	2025	2050
Rooftop PV			
service life [a]		25	
Full load hours new plants [h/a]	930	930	930
CAPEX [€2015/kW]	1300	1075	650
OPEX [€2015/kW*a]	20	17	15
Space requirement [MW/km²]		166	
Open space PV			
service life [a]		25	
Full load hours new plants [h/a]	950	950	950
CAPEX [€2015/kW]	750	600	450
OPEX [€2015/kW*a]	14	11	10
Space requirement [MW/km²]		59	
Wind Onshore			
service life [a]		25	
Full load hours new plants [h/a]	2000	2086	2300
CAPEX [€2015/kW]	1300	1150	1000
OPEX [€2015/kW*a]	60	53	40
Space requirement [MW/km²]		18	
Wind Offshore			
service life [a]		25	
Full load hours new plants [h/a]	4000	4114	4400
CAPEX [€2015/kW]	3300	2550	2000
OPEX [€2015/kW*a]	100	75	60
Space requirement [MW/km²]		18	

Source: Prognos AG

Table 55: Assumptions and partial results for the calculation of electricity costs for the generation of liquid energy sources in the MENA region

Year	**2030**				**2050**			
Location	Cheap		Realistic		Cheap		Realistic	
Type of generation	Wind	PV	Wind	PV	Wind	PV	Wind	PV
Full load hours of RE generation [~ h/a]	4,200	2,100	1,800	1,700	4,200	2,100	1,800	1,700
CAPEX [€/kW]	1,100	550	1,100	550	1,000	450	1,000	450
OPEX [€/kW]	27	12	27	12	24	12	24	12
Utilisation rate of the generated electricity [%]	93.5 %				93.5 %			
Full utilisation hours of the electrolysis plant [h]	5,000				5,000			
WACC of 2 %								
LCOE [Cent/kWh]	2.0	1.9	4.6	2.5	1.8	1.7	4.2	2.2
Cost of electricity for electrolysis [Cent/kWh]	2.1		4.4		1.9		3.9	
WACC of 7 %								
LCOE [Cent/kWh]	2.9	2.9	6.7	3.7	2.6	2.4	6.1	3.1
Cost of electricity for electrolysis [Cent/kWh]	3.1		6.4		2.7		5.7	

Source: Prognos AG

Table 56: Installable capacity of renewable energies in Germany in two variants

Technology	**Installed capacity (GW)**			**Electricity generation [TWh/a]**		
	Ist 2016*	A	B	Ist 2016*	A	B
Rooftop PV	40.9	85	110	37.5	75	100
Open space PV		15	105		15	105
Wind power onshore	45.5	65	130	77.8	155	310
Wind power offshore	4.1	31	70		127	280
Hydropower	5.6	6	6	19	22	22
Biomass	7.1	8	8	46	48	48
Total	**90.5**	**210**	**430**	**115.3**	**442**	**865**

Source: Prognos AG

Heavily affected by area | Partially affected by area | Barely affected by area

PUBLICATION DETAILS

Status and Perspectives of Liquid Energy Sources in the Energy Transition

Commissioned by
Mineralölwirtschaftsverband e.V. (MWV)
Institut für Wärme und Oeltechnik e.V. (IWO)
MEW Mittelständische Energiewirtschaft Deutschland e.V.
UNITI Bundesverband mittelständischer
Mineralölunternehmen e. V.

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Typesetting and layout: STÜRMER & DRÄNGER – Visuelle Kommunikation Gmbh
Graphic design: STÜRMER & DRÄNGER – Visuelle Kommunikation Gmbh
Translation: text & form GmbH
Photo credits: Cover Copyright: IWO AdobeStock_103230565 and AdobeStock_143524486

Published: May 2018 (German Version), September 2018 (English Version)