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Position Paper

Coupling the different energy sectors – options for the next phase of the energy transition

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Coupling the different energy sectors – options for the next phase of the energy transition

Preface

The German energy transition is stagnating. Although wind power and photovoltaics have been massively expanded in recent years and already cover some 20 percent of power consumption, about 80 percent of the German energy supply remains based on fossil energy sources. A linear projection of this development shows that unless substantial changes are made, Germany will miss its climate objectives by a large margin.

If we wish the energy transition to succeed, we must therefore rethink and increase the pace. To this end, we need to consider the energy system in its entirety and interlink the power, heat and transport sectors more closely. For so far, the sectors are run independently from each other and with different momentum, like individual cogs that do not interlock.

A Working Group of the Academies‘ Project “Energy Systems of the Future” (ESYS) has examined how the engine of the energy transition can be set in motion. The present position paper outlines possible development paths and policy options for Germany. The guidelines for a systemic integration include a significant expansion of renewable energies, energy-saving measures and energy efficiency, a more extensive use of electricity in all sectors and of innovative energy sources such as hydrogen and synthetic fuels, along with a consistent, effective carbon price. The accompanying analysis *“Coupling the different energy sectors«: Analyses and considerations for the development of an integrated energy system“* provides detailed background information and calculations. We would like to express our sincere thanks to the scientists and the reviewers for their commitment.

Germany must enter a new phase of the energy transition. Owing to the continuous evolution of wind power, photovoltaics and biomass in the last few years, the basic technologies for a comprehensive coupling of the energy sectors are now available. It is up to the political echelons to set the course today to strengthen Germany as a high-tech location and to make the energy supply flexible, technology-neutral and sustainable. This is a prerequisite for participating in the globally growing markets for the future energy supply, and the only chance for us to meet our international commitments and reach the Paris climate goals.

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Abbreviations and units

Abbreviations

CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CO_2	Carbon dioxide
EEG	German Renewable Energy Sources Act
EU ETS	European Emissions Trading System
CCGT plant	Combined cycle gas turbine plant
CHP	Combined heat and power

Units

g	gramme
GW	gigawatt
GWh	gigawatt hour
kWh	kilowatt hour
m^3	cubic metre
TWh	terawatt hour

Summary

More than 30 percent of the power in Germany is currently generated from renewable energy sources. It is foreseeable that wind power and photovoltaics, which today contribute close to 20 percent, will dominate future power generation. The heat and transport sectors, on the other hand, are lagging far behind in the implementation of the energy transition. In order to achieve climate protection targets, these sectors must likewise switch to an energy supply based mainly on climate-neutral sources.

In this scheme, electricity (increasingly generated in wind and solar power plants and, if necessary, temporarily stored) will play a key role. There are three main fields of use for power in the energy system – especially in the sectors that today resort primarily to fossil fuels:

1. The power is used directly to provide heat or mobility, for example in heat pumps or battery electric vehicles (direct electrification).

2. The power is used to generate hydrogen, which is stored and later employed as an energy source, e.g. in fuel cells, or reconverted to power by means of combustion.

3. The hydrogen is further processed to synthetic fuels such as methane (natural gas) or petrol. Biomass, solar thermal and geothermal energy can supplement the energy supply from renewables and help to limit the expansion of wind and solar power plants.

Thus, new interfaces are emerging between the power, heating and transport sectors. They are growing together to form an integrated energy system. This position paper describes policy options for possible development paths by 2050 towards such an energy system that can ensure the security of supply while meeting climate protection goals. In addition, how the legal and economic framework conditions can be adapted in order to make the next phases of the energy transition as cost-effective as possible is discussed.

Methodology

On the basis of available data and sources, **discussions between experts** were held to analyse various future technologies. This involved the quantitative assessment of efficiency levels, costs and potentials. Together with further considerations, such as user-friendliness, acceptability and research and development requirements, this formed the basis for an appraisal of the role the respective technologies might play in the future energy system. At the same time, the working group carried out **model calculations**, enabling us to better understand potential developments in the energy system by 2050 in all their complexity, to examine correlations and parameter dependencies, and to compare the different technologies in terms of their potential contributions and their impact on the overall costs. In addition, **energy scenarios** from published studies were evaluated and **compared** along the lines of a meta-analysis. The working group further analysed what regulatory framework seems necessary in order to achieve climate

protection goals. Obstacles were identified and proposals made as to how they might be overcome.

By means of these three approaches – discussions between experts, model calculations, scenario comparisons – we can sketch possible paths towards a climate-friendly energy supply and specify key technologies and possible uses. The results are, of course, not the only possibilities and are not to be understood as predictions of the future; rather, they present exemplary options for a transformation of the energy supply system. All of the results presented in this paper have proven to be robust in most approaches, an obvious exception being the largely unknown factors of future acceptance and social implementation.

Results

Electricity will become the dominant energy source in the overall energy system and will be largely generated in wind and solar power plants. With the increasing use of electricity in the heating and transport sectors, **future power demand is bound to rise significantly**. It is possible that in 2050, Germany may consume more than 1,000 terawatt hours, *i.e.* almost twice as much as today. This would require an installed capacity of up to 500 gigawatts of wind and photovoltaic systems (about six times the existing capacity), provided carbon emissions are indeed to be reduced by 85 percent. While this seems feasible, it does come with significant technical and social challenges.

However, in order to maintain public acceptance for the energy transition, the expansion of wind power and photovoltaics and thus also of the power grids should be limited as far as possible. This can primarily be achieved by means of **energy savings and increased conversion efficiencies**, which should be given higher priority. **Solar thermal energy, geothermal energy and bioenergy** can likewise contribute to limiting the required expansion of wind and solar power. However, their potential is not indefinite. Bioenergy, for instance, is already competing with other uses (cf. *e.g.* the “food versus fuel problem”) and is moreover criticised with regard to the environmental and climate footprint of energy crops. Against this backdrop, the import of **synthetic combustibles and fuels** produced in windy areas (coasts) and good solar sites (deserts) is considered. The opportunities such alternatives offer (cost reductions) should, however, be carefully weighed against the risks (new import dependencies).

In most of the development paths examined in this paper, annual expansion rates of some 8 to 12 gigawatts of **wind power and photovoltaics** are required to meet the climate targets. This equates to more than twice the expansion in each of the last five years. **The expansion corridors provided for in the 2017 German Renewable Energy Sources Act will hardly suffice to meet the growing power demand in a climate-friendly way**. Only if we succeed in drastically reducing energy consumption by means of ambitious efficiency measures, while simultaneously realising an efficient use of bioenergy potentials and importing large quantities of carbon-free energy sources, is there a chance of achieving the climate protection goals without extending the expansion corridors.

In the **building sector**, we can expect comprehensive measures for thermal insulation as well as a high demand for renewable energies for the generation of heat to be necessary. In all probability, **heat pumps** will play an important role in this context: Operated mainly with renewable energies, they are very energy- and climate-efficient. However, in order to become profitable, they require a regulatory framework ensuring lower relative electricity prices. In any case, each time heating systems are renewed in the coming years, the opportunities should be used for the installation of more climate-friendly heat generation and distribution technologies (heat pumps, solar thermal systems, heating grids, heat storage facilities), as heating systems tend to have a very long life cycle. Moreover, it will probably be necessary to refurbish the entire building stock by 2050. For this purpose, the current **refurbishment rate** of less than one percent per annum is clearly too low.

So far, the **industry** has made the largest contribution to reducing carbon emissions. Hence, many easily realisable efficiency potentials have already been tapped.[1] As regards the conversion of industrial processes to low-emission energy sources, possible options include the use of biomass as well as the electrification of heat-intensive processes. The latter, however, is problematic with regard to the often very high temperatures required: Heat pumps cannot be employed for temperatures above about 200 degrees Celsius, and alternative technologies such as electrode boilers are less efficient. Also, the energy carriers used in industrial processes often have additional chemical or mechanical functions. Industrial **waste heat** harbours greater efficiency potentials: At present, waste heat often remains unused once the possibilities for utilisation at the production site are exhausted. If this heat were fed into **heating grids**, it could serve to heat buildings.

In the **transport sector**, battery electric cars will foreseeably play a key role. According to the model calculations, the number of electric vehicles will have reached about nine million by 2030. For a successful transition, battery technology must be further developed in order to increase the range and reduce costs. Also, the charging infrastructure must be expanded across Germany. With regard to long-distance and freight transport, on the other hand, a definitive solution remains to be found, since here the advantages of readily storable and transportable fuels with the highest possible energy density, such as hydrogen, methane or liquid fuel, are of great importance. Therefore, overall, an energy mix seems inevitable in the transport sector, even in the long term. Hence, the transition to low-carbon drive systems should be combined with intensive efforts to drastically reduce energy consumption by means of traffic prevention and modal shifts and to establish more efficient traffic flows.

Technically, it is usually **more efficient and therefore less expensive to use electricity directly** (for instance in heat pumps and electric vehicles) than to convert it into hydrogen or synthetic fuels. A widespread use of synthetic fuels would moreover require significantly more wind and solar power plants. Therefore, a high degree of direct electrification is desirable in order to limit the expansion of wind power, photovoltaics and power grids to a socially acceptable level.

Nevertheless, **combustibles and fuels will remain indispensable even in the long term**, above all because easily storable energy sources are not least required to supply energy during lengthy weather periods with little wind and sun coming with a high need for heating ("cold, dark and windless periods"). All in all, we can say: **The less energy-related carbon emissions we wish to produce, the more important synthetic combustibles and fuels will be.** Assuming a carbon emissions reduction of 85 percent by 2050, the model calculations indicate that by using just under one third of the existing power to produce hydrogen, synthetic methane and liquid fuels, a macroeconomically optimal result would be achieved. But even with much less ambitious climate protection goals, it would be reasonable to

1 However, the reductions achieved also include reductions due to the relocation of energy-intensive processes outside Germany.

generate hydrogen to some extent, since otherwise unused power would not have to be curtailed, and the strain on the grids would be relieved.

With regard to fluctuating power generation from wind and solar power plants, the **coupling of the energy sectors** will help to create **buffering capacities**. These should be complemented by adjusting the demand-side to the fluctuating supply ("demand response"). This requires the availability of the necessary control technology and of suitable business models. Otherwise, we run the risk that the technologies employed to interlink the sectors enhance the strain on the energy system during peak consumption periods, for instance should the majority of electric vehicles or stationary battery storage systems be charged at the same time of day or electrically operated heat pumps and electrode boilers run at full-power at the wrong time.

For long-term storage, other than tanks for liquid fuels, the **natural gas grid** with the corresponding cavern and pore storage facilities is an important asset. It can store 250 terawatt hours' worth of natural gas, biomethane or synthetic methane – enough to cover almost a third of the current annual demand for space heating and hot water.

In addition to storage systems and more flexible consumption structures, we will nevertheless still require **reserve power plants** on a large scale to ensure the supply in all weather conditions and seasons. In all probability, the required capacity will amount to around 100 gigawatts even in the long term, which means that the demand for directly available generation capacity will hardly decrease compared to the currently installed capacity of 100 gigawatts. However, with regard to climate protection, preference should then be given to gas-fired power plants or fuel cells operated with hydrogen, natural gas or synthetic methane from long-term storage. Flexible combined heat and power plants (CHP plants) fuelled with biogas or stored gases can likewise contribute to a secure supply. Coal-fired power plants, on the other hand, should no longer play a role in the future.

However, these power plants as well as electrolysers will partly have to be operated at rather low utilisation rates. This complicates the refinancing of investments and hampers the profitability of the plants. Their operation can only succeed if the **energy markets** introduce business models for flexibility providers with only a few hundred operating hours per annum and accept the corresponding higher costs.

Due to the capacity necessary to compensate for fluctuating feed-in, the **power system will become much more complex in terms of power generation than it is today**. The total installed power generation capacity could, for instance, increase from currently around 200 gigawatts to some 600 gigawatts (500 gigawatts from renewable energies plus 100 gigawatts worth of reserve power plants). This could be complemented with up to 100 gigawatts worth of electrolysis and methanation plants and battery storage systems of equal dimensions.

Due to the substantial investments required for these energy plants and for new consumer appliances and other measures (such as energetic refurbishment), the transformation of the energy system is expected to incur **annual additional costs of around one to two percent of today's GDP over the next thirty years**. This assessment is based on a comparison of model calculations with a reference system: In the model calculations, a reduction of 60 to 85 percent in energy-related carbon emissions was assumed, while in the reference system, only 40 percent of carbon emissions are saved compared to 1990. Such cost estimates, although fraught with uncertainties, nevertheless serve to illustrate the magnitude of the project "energy transition", which might well be compared to that of the German reunification. Therefore, it is essential to avoid unnecessary additional costs by means of carefully set framework conditions.

To achieve climate protection goals, the coupling of the energy sectors and a systemic integration – i.e. the holistic optimisation of the energy system – are indispensable. The above-mentioned individual technical solutions must be interlinked and coordinated. Merging these various elements is a huge task for everyone involved. It will not least require the use of technologies that are, as yet, still in their infancy. However, establishing new technologies on the market is currently rather a feat. For instance, electricity being much more heavily burdened with charges, levies and taxes than natural gas and heating oil, electric heating is so far economically unattractive compared to conventional technologies. If the coupling of the energy sectors is to realise its potential, the markets for electricity, heat and mobility should converge and offer fair and equal conditions for all energy sources. In this context, a **consistent price signal for all carbon emissions** can play a pivotal role.

This can be achieved by extending the **European Emissions Trading Scheme (EU ETS)** to all sectors and significantly increasing the price of emissions allowances. This would mean that in addition to the power plants and industrial facilities already taking part in the EU ETS, the emissions of a very large number of small consumers would also have to be recorded. This is most easily organised via the primary suppliers of fossil energy sources. In addition, or alternatively – should it be politically impossible to realise a modification of the EU ETS in the near future – a **national carbon tax** could be levied. In view of competition considerations, acceptance issues and the expenditures involved, this should be flanked by a reduction of existing energy policy instruments such as taxes and levies on energy sources. As an alternative to the current allocation of free emissions allowances to industrial companies, the **taxation of emission-intensive imports** could be considered. This would ensure internationally fair competitive conditions.

In any case, a more fundamental **reform of the funding structures for the expansion of renewable energies** should be envisaged, even if a uniform carbon price cannot be implemented immediately or only gradually. Options include a partial financing of the costs of the German Renewable Energy Sources Act (EEG) from general taxation or an extended EEG levy on fossil fuels in all sectors. This would reduce the costs of electricity relative to other energy sources, and would tend to make the coupling of the energy sectors more viable. It could also be a step towards a consistent carbon price. However, it has to be taken into account that low energy prices do not incentivise energy savings. From a macroeconomic point of view, therefore, climate targets might be hard to reach efficiently.

However, a consistent carbon price, although highly important, is not a magic bullet. Even if it is high enough for low-emission technologies to compete with conventional ones, there may be obstacles to the market launch or widespread use of such technologies. For instance, market players might not choose the most economical alternative, owing to a lack of information; there might be no incentives for companies to invest in public goods, or, indeed, a disparity between long-term benefits and short-term viability. To remove these obstacles, supplementary measures may be necessary. In addition to **financial incentives** such as investment grants, tax reductions, market incentive programmes and the public co-funding of infrastructure, which almost invariably entails the risk of economic inefficiency, regulatory provisions such as emission limits and technical standards may be expedient. Investments in research and development, information and consultancy services, and training programmes for specialists can also help new technologies to gain a foothold.

With regard to climate goals, **short-term action** within the next five years is particularly indicated in the fields of building renovation, the conversion of the heating systems in buildings, the expansion of renewable energies and power grids, and the transport sector. Synthetic combustibles and fuels will probably be required to a greater extent **from 2025 onwards**, when more and more stringent climate protection requirements will compel the increasing replacement of fossil energy sources by climate-neutral, easily storable alternatives. In the next few years, therefore, we will have to focus on developing various production processes further and testing the entire chain from production over transport to use, for instance in model regions. An adjustment of the legal and economic framework enabling the widespread use of hydrogen and synthetic combustibles and fuels must likewise be considered in a timely manner, as without appropriate incentives, there will be no investments and no intensified developments.

However, a precondition for the various stakeholders to even consider investing in climate-friendly technologies is planning security. A strong political commitment to climate protection, the possibility for stakeholders to rely on the **binding nature of the climate protection goals** and on the long-term reliability of carbon prices are therefore essential. Individual instruments – in particular those designed to bridge the current phase of low carbon prices or to help new technologies enter the market – should remain readjustable and should be constantly evaluated in terms of their necessity, effectiveness and value for money.

1 Introduction

The German energy transition, including the decision to phase out nuclear energy, was supported by a broad political majority. At the time the decision was taken in 2010 and 2011, there was likewise a major public consensus on the subject. Experts and public opinion had (and still have) little doubt that global warming has anthropogenic causes. Therefore, there is a broad consensus in Germany and Europe – and, indeed, almost worldwide – regarding the necessity of a massive reduction in the emissions of climate-damaging trace gases. Nevertheless, the German energy transition is stagnating, and opinions differ widely with regard to the relevance of individual technologies and to the importance and necessary modifications of regulatory and political measures for the achievement of the goals.

For instance, despite the massive expansion of renewable energies over the past decade – especially of power generation from wind, photovoltaics and biomass – energy-related carbon emissions remained more or less constant between 2009 and 2015[2], sparking a debate on the relevance of renewable energies and the rate of their expansion. The German Renewable Energy Sources Act (EEG) is likewise highly controversial: Some experts and social groups consider the EEG a great success, as increased market demand for renewable energies resulted in massive reductions in the generation costs of power from renewable sources.[3] It was this fact that made a significant contribution of renewable energies to the energy supply possible in the first place. Critics, on the other hand, refer to the high costs that have been and still are being borne, particularly by electricity customers. These funds, it is argued, could have been employed more efficiently for other measures to reduce carbon emissions; also, the same cost degression and expansion rates could have been achieved with more cost-effective instruments. Whether the energy transition entails more burdens or opportunities is the subject of a further controversy: While international agreements frequently use the term "burden sharing", the same points are referred to elsewhere as "opportunity sharing".[4] Opinions differ just as much with regard to the effectiveness of the European Emissions Trading System. In this context, the sense of national energy and climate policies pursuing different or more stringent objectives than the European policies is also questioned. And finally, the public is no longer willing to unanimously support all aspects of the energy transition. This is particularly true for citizens directly affected by the respective measures, such as the expansion of power lines or wind turbines.

The many different positions on possible measures and approaches for the transformation of our energy supply testify to the complexity of the subject – notwithstanding a broad consensus as to the overall goals. This complexity begins at the technical level: In the future, far more smaller generation plants will contribute to the energy supply; power generation will become less predictable and more volatile; and

2 Cf. UBA 2016-1.

3 REN21 2014.

4 For instance, by State Secretary Rainer Baake (Federal Ministry for Economic Affairs and Energy) at the event "Baustelle Energiewende. Strom, Wärme und Verkehr ökologisch modernisieren", organised by the Heinrich Böll Foundation on June 28, 2017.

the different production and consumption sectors – electricity, heat in buildings and industrial processes, mobility – will be increasingly interlinked. The greater complexity at the technical level is not least reflected in the economic dimension: The market organisation structures of the previous energy supply system, which have evolved over the last few decades since the liberalisation of the energy markets, no longer seem to produce satisfactory results. Here again, the increasing interaction of consumer sectors that were previously organised within their respective regulatory framework, is an important factor. The fact that the overall system is embedded into the European framework adds to the complexity. And finally, no solution will succeed unless it has the broad support of the public.

The Working Group "The Coupling of the Energy Sectors" in the project "Energy Systems of the Future" (ESYS) had the following task: Starting from the overarching goals – in particular from the aims for the energy supply resulting from the German climate protection targets – it was to derive robust statements as to the sensible and necessary developments of the German energy system. What developments and measures will very probably be necessary? And where is there scope for actively shaping the system? In a first step, this is approached from a techno-economic perspective – more precisely, by means of an overall systemic analysis of possible technical development paths involving all energy sources and all consumption sectors in an integrated overall system (Chapter 2). On this basis, possible designs for the regulatory framework are discussed and presented as options (Chapter 3). While issues of social acceptance and participation were not the focus of the analysis, they were taken into account at various points in the discussions and evaluations.

In dealing with a topic of this complexity, it is inevitable that numerous aspects are omitted. For instance, we have not explicitly addressed the issue of "digitisation", although it is of great significance for the energy transition in two different respects: On the one hand, future information and communication technology solutions (ICT solutions) constitute the necessary basis without which the organisation and operation of the complex future energy system would not be possible. On the other hand, developments in ICT and digitisation may, for example, influence consumption patterns or production processes, the impact of which on the development of future energy consumption is great but hard to predict.

1.1 Starting point

The present position paper is based on the energy concept currently in force in Germany,[5] which the Federal Government adopted in 2010 and modified with respect to the phase-out of nuclear energy in late 2011. It describes expansion targets for renewable energies and reduction targets for energy consumption and greenhouse gas emissions by 2050, specifying concrete interim targets. These goals are complemented by the "Climate Action Plan 2050", which the Federal Government adopted in November 2016 to implement the agreement of the **2015 United Nations Climate Change Conference** in Paris.[6] It comprises additional specific reduction targets for individual sectors until 2030.

These resolutions constitute the framework and central driving force for the transformation of the energy system by 2050. Fossil fuels used for the supply of energy services account for some 85 percent of the current greenhouse gas emissions; of these energy-related greenhouse gas

5 BMWi 2010.
6 BMUB 2016.

emissions, 99 percent are CO_2 emissions.[7] Energy-related carbon emissions are hence pivotal in achieving the desired climate protection goals.

In order to explain the concept of the coupling of the energy sectors and the reduction targets set for individual sectors, it is expedient to a) define the term "sector" and to b) take a look at the energy consumption rates in the individual sectors. The term "sector" essentially refers to the categories of energy consumption. In the simplest case, it can be distinguished between the three sectors *power consumption, mobility/transport* and *heat consumption*, with the heating sector frequently being further subdivided into the two sectors *low temperature heat* (space heating and hot water) and *process heat* (industry). Other sectoral distinctions as found, for instance, in the Climate Action Plan, also include the agricultural sector.

To understand the challenge we are facing, it is helpful to take a closer look at the current energy consumption rates in these four energy sectors (cf. Figure 1). This reveals, for instance, that power, although clearly dominating the public discourse, accounts for only about 20 percent of final energy consumption. The two heating sectors, on the other hand, are responsible for about 50 percent of final energy consumption, with the transport sector accounting for the remaining 30 percent. In view of this large share of energy consumption, these three sectors are, besides the power sector, of great importance for the overall emissions and consumption balance. This is further substantiated by their high proportion of fossil combustibles and fuels, to which we must add the fact that about half of the power generation is still based

7 UBA 2016-2.

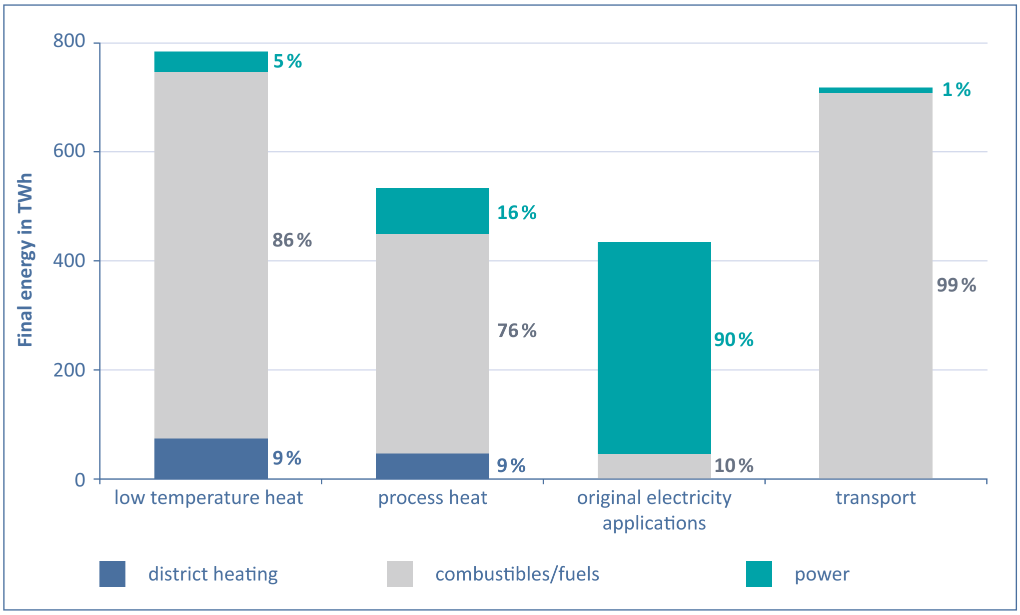

Figure 1: Final energy consumption in Germany in the four areas of use.* In the case of final energy, we distinguish between the three main forms of combustibles and fuels, electricity, and district heating (last update: 2015). Combustibles and fuels comprise solid, liquid and gaseous fuels of fossil and biogenic origin.

*BMWi 2017-2.

on fossil fuels.[8] The magnitude of the task ahead of us is further highlighted by the fact that while the share of wind power and photovoltaics has reached over 20 percent due to the significant expansion efforts in the past few years, they still do not account for more than about four percent of the total final energy consumption. The illustration clearly shows that it is inadequate to deal separately with the sectors; only with a cross-sectoral transformation of the entire energy system can the ambitious goals of the energy transition be realised. This holistic development of an integrated energy system is therefore frequently connected with or described by the term "coupling of the energy sectors".

1.2 Realising an integrated, sustainable energy system by coupling the energy sectors

In the long term, there are two crucial levers to reduce the 85 percent of greenhouse gas emissions from the fossil fuels mentioned above:[9] Firstly, the reduction in energy consumption and secondly, the use of energy generation methods that produce no or significantly lower carbon emissions than fossil energy generation methods. On the one hand, this implies increasing conversion efficiencies and saving energy and, on the other hand, focussing much more on the "coupling of the energy sectors" than before. The coupling of the energy sectors involves, for instance, using renewable energies in all fields of the energy supply – directly or indirectly – and optimising the energy system across the sectors. The still rigid borders between the sectors power, heating and transport with their different infrastructure systems, markets and regulations have to be broken up. Energy sources such as power, natural gas, synthetic fuels and biomass must be used flexibly and based on needs in all fields of application. The potential of other renewable energies such as hydropower, biomass and geothermal energy being limited in Germany, wind power and photovoltaics will inevitably play an important role for the provision of heat and mobility.

In order to use wind and solar power in the heating and transport sectors in a system of coupled sectors, there are basically three approaches. These are not to be taken as alternatives, but as components of the future energy system. Nevertheless, their respective weighting may differ, not least according to the general conditions, the will of the public and the market situation:

1. **Direct electrification**: Applications hitherto powered with combustibles and fuels are switched to electric power. Electric vehicles and heat pumps are prominent examples.

2. **Hydrogen**: Power is used to produce hydrogen by means of electrolysis. The hydrogen is stored and reconverted to power via gas turbines or stationary or mobile fuel cells. It thus contributes to a decentralised electricity supply or to the powering of vehicles. In addition, hydrogen can be used in chemical processes in the industry.

3. **Synthetic combustibles and fuels**: Combined with carbon dioxide, hydrogen can be converted into other sources of energy such as methane, alcohols or tailor-made synthetic combustibles and fuels. These are easy to store and can therefore be readily used in conventional combustion processes. Synthetically produced hydrocarbons can replace substances of fossil origin in the chemical industry.

8 Power generation accounted for around 40 per cent of carbon emissions in Germany in 2016 (UBA 2017-1). The share of carbon emissions for each of the four areas of use is depicted in the German analysis *"Coupling the energy sectors«: Analyses and considerations for the development of an integrated energy system"* (Ausfelder 2017), Chapter 2.1, Figure 5.

9 Carbon Capture and Storage (CCS) technologies are not considered in this paper.

In distinction from direct electrification, the methods involving hydrogen and synthetic fuels are sometimes referred to as **indirect electrification**.

The increased expansion of alternative renewable energy sources is an additional option:

4. **Biomass, solar thermal and geothermal energy**: These alternative renewable energy sources can supplement energy generation and can therefore possibly play a role in the coupling of the energy sectors. They can be employed in various fields to cover part of the energy demand without producing significant emissions. A targeted use could be expedient where other sustainable solutions are not available or very cost-intensive, or appear unacceptable for other reasons.

Currently, the coupling of the energy sectors plays but a minor role in the energy supply: So far, the number of buildings equipped with heat pumps is very limited, only a few industrial processes use electricity for heating, and there are still only a few electric vehicles on the roads. Hydrogen is almost exclusively (96 percent) being produced by the steam reformation of natural gas, i.e. from fossil sources.[10] Synthetic fuels such as biodiesel or bioethanol have so far only been produced to any significant extent from biomass.

However, if carbon emissions are to be massively reduced, there is no way around a closer coupling of the energy sectors and an overall systemic approach. A comparison of the energy demand and the potentially available renewable energy sources moreover leaves no doubt that power from solar and wind power plants will be by far the most important source of energy.[11] As their generation capacities largely depend on the time of day and the weather conditions, one vital aspect is increasingly coming into focus: If the future energy system is to guarantee supply security, it must offer a high level of **flexibility** so as to be able to balance generation and consumption at all times. This will probably require not only dispatchable (thermal) power plants and various different energy storage systems, but also a significant flexibilisation of energy consumption by means of smart control systems and according market models.

In this context, the coupling of the energy sectors can contribute very significantly to a more flexible energy system: Energy can be stored in heat reservoirs or in the form of chemical energy sources such as hydrogen and synthetic fuels. By resorting to various energy sources, according to the time of day and the season, smaller units (for instance CHP plants) can likewise optimise the generation, storage and consumption of heat. Incidentally, the combination of direct power use with fuel cell technology or with combustion engines running on synthetic fuels offers flexible solutions for mobility or decentralised power supply systems.

1.3 Methodology

The position paper is based on the results of numerous discussions between experts, a comparison of different (published) scenarios of the long-term development of the German energy system and own model calculations. The methodological approach, a more detailed documentation of the assumptions and test results as well as a detailed discussion of the implications are presented in the German analysis *»Coupling the different energy sectors«: Analyses and considerations for the development of an in-*

10 Decourt et al. 2014.

11 Cf. for instance Ausfelder et al. 2017, chapter 5.3.

tegrated energy system.[12] The following section contains a few guidelines for a better understanding of the statements and conclusions.

The **discussions between experts** had a twofold aim: For one thing, the technology options were analysed qualitatively and – as far as possible – quantitatively on the basis of the available data and sources. For another, economic, regulatory and social challenges and possible solutions were identified. The discussions between experts were initially confined to the members of the Working Group "The Coupling of the energy sectors" of the Academies' Project "Energy Systems of the Future". Eventually, experts from industry, academia, politics and civil society organisations were likewise included, for instance in the "Trialog" of the HUMBOLDT-VIADRINA Governance Platform, discussion forums at the Annual ESYS Conference and a technical discussion on interim results of the Working Group.[13]

For the **scenario comparison**, several current studies were evaluated along the lines of a meta-analysis, and individual energy scenarios compared with regard to the role and importance they attach to the coupling of the energy sectors. While sharing a common time horizon until 2050, the scenarios are based on different models of the energy system and tend to differ significantly in terms of assumptions and priorities. They thus cover a wide range of possible developments of the energy system.[14] The carbon emissions reduction targets range from 80 to 100 percent in 2050. All scenarios considered technologies for the coupling of the energy sector, albeit to varying degrees: Heat pumps, electric mobility, hydrogen production, methanation and bioenergy are of different importance in the individual scenarios.

For the **own model calculations**, various possible system developments were calculated using the simulation and optimisation model REMod-D[15] developed by the Fraunhofer Institute for Solar Energy Systems (ISE). In each case, different reduction targets for carbon emissions were specified and broken down to fixed values for every year. For the predefined reduction path, the model calculates how the composition of all relevant producers, converters, storage systems and consumers of the energy system must evolve over time in order to keep the total costs of the energy system over the entire transformation period as low as possible.

The calculation also includes the expenses for infrastructure, such as grid expansions or charging infrastructure. These were taken into account as mark-ups to the costs. The calculations do not include detailed modelling of the grids. Consumption had to be covered at all times on an hourly

12 Cf. Ausfelder et al. 2017.

13 The results of the Trialog "Sector coupling – from electricity transition to energy transition" were summarised in a report (cf. Höh et al. 2016). The Trialog and the expert discussion were held in the Project Office on July 11, 2016 and May 9, 2017 respectively (ESYS 2017 and ESYS 2016).

14 The following six scenarios were selected for the comparison: The "target scenario" from the study *"Development of Energy Markets – Energy Reference Forecast"* (Prognos et al. 2014), "Climate Change Scenario 95" *from the study "Climate Change Scenario 2050"* (Öko-Institut/Fraunhofer ISI 2015), the study *"Germany in 2050 – a greenhouse gas-neutral country"* (UBA 2013), the scenario "85/amb/Mix/beschl." from the study *"What will the Energy Transformation Cost?"* (Fraunhofer ISE 2015), the "Cross-sectoral target scenario 2050" from the study *"Interaction of the renewable energy, heat and transport sectors"* (Fraunhofer IWES et al. 2015) and the scenario "100-II" from the study "*GROKO – II German Energy Supply Scenarios Based on the EEG Draft Bill – with a particular focus on the impact on the heating sector*"(Nitsch 2014).

15 Further information on the model REMod-D can be found in Erlach et al. 2018, Palzer 2016 and Fraunhofer ISE 2015.

basis[16], and the carbon emissions ceilings had to be adhered to for every year. The aim was not to predict the future. Rather, we endeavoured to examine how energy-related carbon emissions can be reduced according to a given reduction target and at the lowest possible total cost without jeopardising supply security. Another motivation for the complex calculations was to learn more about the systemic correlations and parameter dependencies of the German energy system and to test the sensitivity for different boundary conditions.[17,18]

An important result achieved with the calculation model was to identify the demand for different system components by means of which a cost-optimised transformation path can be realised under given conditions. These include, for instance, the capacities of the various generation plants (conventional power plants, various renewable energy plants), conversion systems such as electrolysers, storage systems such as battery or thermal storage (in individual buildings and for heating grids), efficiency measures such as the energetic refurbishment of existing buildings and the composition of vehicle fleets. Under certain assumptions, it was even possible to compare the overall costs for various reduction targets and to make deductions as to the temporal evolution of all parameters mentioned.

A total of seven model calculations were realised, each with different assumptions: A crucial point was to examine what effects different carbon reduction targets until 2050 would have on the development of the overall system. In four calculations, energy-related carbon emissions were hence reduced to 60, 75, 85 and 90 percent respectively by 2050.

In a second step, the influence of an increased use of hydrogen or synthetic combustibles and fuels on the overall system was analysed. If the choice of technologies is left to the model, power will mostly be used directly. However, the consumers' decision for an electric car, a fuel cell vehicle, or a combustion engine depends not only on the cost, but on many other factors that cannot be reflected in the model calculations. Therefore, two further models were calculated, both with a carbon emissions reduction target of 85 percent, but with different technological specifications: In the first model, the market shares of hydrogen vehicles were set to reach 100 percent by 2050, and hydrogen is likewise used more extensively in the heat supply sector. In the second model, the share of heat pumps was limited to 40 percent and that of battery electric vehicles to 50 percent, so that space heaters and vehicles are mainly operated with synthetic fuels or gases.

16 For conventional power applications, process heat in industry and hot water, the consumption is specified to the hour. The original power demand remains at the current level of about 500 terawatt hours, the process heat requirements of the industry at 440 terawatt hours. In the transport sector, the number of lorries and passenger cars and their time-resolved driving behaviour are included as assumptions in the calculation; the number of cars was assumed to decrease by 5 percent by 2050, and the number of lorries to increase by 5 percent. The space heating requirements, on the other hand, are calculated on the basis of today's load curves, but subject to the standard of building insulation.

17 The assumptions included in the model calculations are discussed in Ausfelder et al. 2017, chapter 5.1. All assumptions (such as interest rates, biomass availability, cost curves, etc.) are also published as Materials (Henning et al. 2017).

18 The model calculations assume that prices for fossil fuels will remain at the current level (see Ausfelder et al. 2017, chapter 5.2). Price fluctuations within a certain range, which invariably occur in the markets, would not significantly change the results of the calculations. What is more important, however, is that the costs are not expected to increase significantly by 2050. The price of natural gas has in some cases been subject to considerable fluctuations in recent years (10 to 30 euros, EEX 2017). The price of €33.1/MWh, which was determined at the start of the calculations, exceeds the current value of about €17/MWh (EEX 2017). However, experiences with the calculation model REMod suggest that with the amounts of permissible carbon emissions fixed, the shares of primary energy in the system will change but slightly with a lower natural gas price.

In all model calculations with a carbon emissions reduction target of at least 85 percent, the installed capacity of wind power and photovoltaic systems reaches the upper limit of a total of 500 gigawatts, which is determined by the limited space available in Germany and constitutes a parameter of the model. Therefore, in a final step, an additional model was calculated with various assumptions aiming at minimising the required expansion of wind and power and photovoltaics. These include energy savings, the increased use of solar thermal energy and the possibility of exchanging more electricity with neighbouring countries by extending the number of interconnectors in the power grids.

2 Technology options for the future energy supply

As far as power generation is concerned, the expansion of wind and solar power plants constitutes a technically feasible way of replacing fossil fuels with renewable energies. However, in order to achieve the politically agreed climate protection goals, the heating and transport sectors will likewise have to increase their efforts to replace conventional fossil combustibles and fuels with climate-neutral energy sources. So far, these sectors mainly resort to bioenergy – the availability of which is limited – to increase their share of renewable energies. Admixtures of biogenic fuels in the transport sector or the use of solid wood, pellets and biogas for heating purposes are cases in point. Electricity, on the other hand, currently plays but a minor role in heat supply and transportation (Figure 1).

This chapter will first consider technological options for the future energy supply in the three important consumption areas of heat supply in the building sector (section 2.1), transport (2.2) and industrial processes (2.3). The potential use of power as an alternative to currently employed fossil fuels will be a central point of discussion. The subsequent analysis of the development of the power sector will focus on the expansion of photovoltaic and wind power plants, i.e. on those energy generation technologies that are, from today's point of view, predominant (2.4), as well as on the ensuing need for storage systems and reserve power plants (2.5) and the respectively available technical options. Chemical energy sources will continue to play a significant role in the long term, since they are available on demand. In addition to biomass and the combustibles and fuels that can be produced from it (2.6), hydrogen and any synthetic, hydrocarbon-based energy sources derived from it (2.7) are an option for the future energy sector. This is followed by considerations as to the costs of the transformation of the entire energy system (2.8) and finally by a discussion of the phases the energy transition is, from today‘s perspective, likely to undergo (2.9).

The argumentation consistently follows a systemic approach, which takes the multiple and increasing interactions between the different sectors and energy sources into account. Only thus can the complex future energy system be adequately appraised. Energy efficiency and concepts for reducing consumption are intrinsic elements of this systemic approach. It becomes very clear that successfully implemented measures to reduce the energy demand will not only imply lower overall costs, but will, above all, limit the required installed capacity of renewable energy plants – particularly solar and wind power plants. In view of the growing scepticism among the population, in particular regarding a further massive expansion of wind turbines and a further large-scale cultivation of biomass for energetic use, this is an important consideration.

2.1 Heat supply in the building sector

The Federal Government is pursuing the long-term goal of a „climate-neutral building stock“. To this end, the share of fossil primary energy used for the building stock is to be reduced to a maximum of 20 percent of its current value.[19] The provision of low-temperature heat for heating and hot water accounts for the bulk of the energy consumed in buildings. The current consumption rates give an idea of the quantities of fuels that need to be replaced: In the low-temperature range, final energy consumption averaged 780 terawatt hours between 2011 and 2015, which equates to around 32 percent of Germany‘s total final energy consumption (cf. Figure 2). Detached and semi-detached houses account for just below 40 percent; the same goes for non-residential buildings. Multifamily buildings account for the remaining twenty-odd percent. Of the total final energy demand for low-temperature heat in buildings, some 660 terawatt hours are used for space heating and 120 terawatt hours for hot water.[20] The carbon emissions involved amounted to around 175 million tonnes in 2014, accounting for almost 20 percent of all greenhouse gas emissions in Germany. Since insulation used in construction has but a limited potential to reduce the need for space heating, efficient conversion technologies and renewable energy sources are indispensable to lowering greenhouse gas emissions in this area to the desired target values.

2.1.1 Reducing the carbon emissions from the heating of buildings

The level of carbon emissions generated in order to provide low-temperature heat depends on two factors: The energy demand and the average carbon emissions rate of the technologies used, i.e. the amount of carbon dioxide emitted per amount of useful energy provided. It follows that carbon emissions can, on the one hand, be reduced by energetic refurbishments in the building sector, as this directly reduces the need for space

19 BMWi 2015.

20 The values vary due to weather conditions; the specified values are the average values from 2011 to 2015, based on BMWi 2017-1.

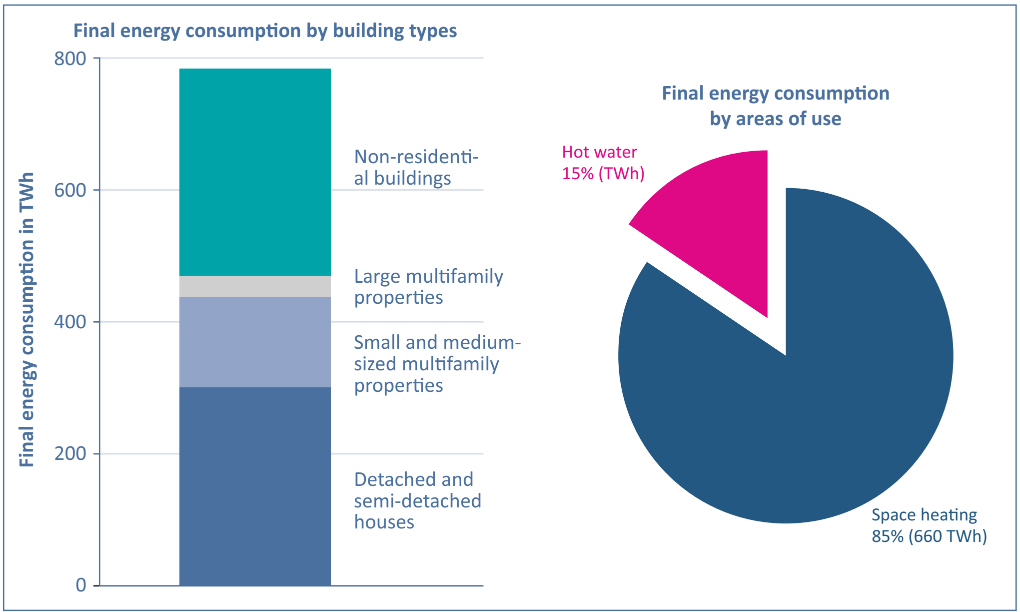

Figure 2: Final energy consumption for the provision of low-temperature heat in buildings – according to building types (data for 2015) (left) and according to the areas of use averaged over the period 2011 to 2015 (right).*

*Own calculations, based on data from BMWi 2017-1 and Palzer 2016.

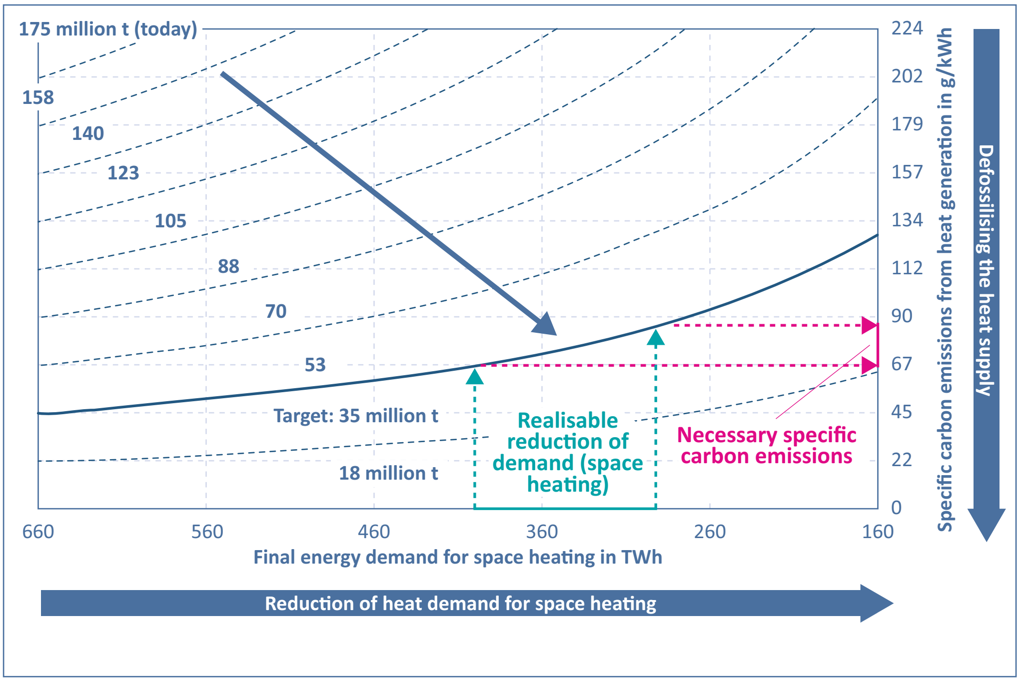

Figure 3: Possible reduction in carbon emissions from the provision of low-temperature heat in buildings. Currently, these carbon emissions amount to a total of 175 million tonnes. The dashed lines correspond to reduced absolute values of these emissions. A reduction of 80 percent equates to a reduction to 35 million tonnes of carbon dioxide (solid line). If we succeed in reducing the final energy demand for space heating by 40 to 55 percent by means of heat insulation in construction, the amount of emitted carbon dioxide would sink to an average of around 65 to 85 grammes per kilowatt hour of heat. The diagram assumes that the energy requirements for hot water remain unchanged.

heating; on the other hand, heat can be supplied by technologies with lower carbon emissions rates.

The demand for hot water in private households being slightly on the increase for reasons of comfort, its importance is rising with view to the steadily decreasing space heating requirements in buildings. The demand for space heating depends primarily on two factors: The development of the heated living space and the development in the area of heat insulation used in construction. However, due to insulation restrictions and economic considerations, the opportunities for reducing the space heating requirements in the building sector through the use of insulation are realistically limited to around 45 to 60 percent of today's value.[21] In order to reduce the carbon emissions in the low-temperature heat range to a maximum of 20 percent of their present value, the specific heating supply emissions must be reduced to about one-third of today's value, viz. from an average value of 224 g/kWh to about 65 to 85 g/kWh.[22] This correlation is depicted in Figure 3.

What options do we have to significantly reduce the carbon emissions generated in connexion with the provision of low-temperature heat? An analysis of the future development of the energy system which considers the interaction of all sectors and takes systemic overall costs into account yields the following main results:

- In order to achieve the goals, a combination of two approaches appears reasonable: On the one hand, constructional heat insulation measures and heat recovery ventilation must

21 Henning et al. 2013.

22 By way of comparison: The specific emissions of a modern natural gas condensing boiler with an efficiency of 90 percent amount to some 240 g/kWh (specific emission of natural gas based on the fuel value: 217 g/kWh including upstream chains). For an electric heat pump with a coefficient of performance of 3 and using the average carbon emissions of the current electricity mix, the specific emissions amount to 176 g/kWh (2016: 527 g/kWh).

be employed to reduce the demand for space heating, on the other hand the heat supply must be realised with technologies with significantly reduced carbon emissions rates. From a financial point of view, it is not advisable to fully exhaust the technical possibilities in the field of energetic refurbishment.

- In order to reduce the carbon emissions resulting from the use of fuels, we can resort to more efficient energetic conversion methods. The most important technologies in this context are gas heat pumps and combined heat and power plants.

- It is vital to include renewable energies in the scheme. In this context, we should particularly consider renewable energies that can be used locally in buildings, for instance solar energy (solar thermal energy, photovoltaics) and environmental energy (soil, outside air) in conjunction with heat pumps.

- From a systemic point of view, electric heat pumps prove to be a key element of a decentralised heating supply in individual buildings. Unless they are employed on a large scale, climate protection targets will be difficult to achieve in the building sector in the medium and long term.

- Heating grids will continue to be important in the future. In addition to large municipal district heating grids in dense urban areas, smaller heating grids in urban neighbourhoods may be a sensible option.

The last two points essentially concern the coupling of the energy sectors and will be elaborated in more detail below.

2.1.2 Decentralised provision of heat in detached buildings

Today, low-temperature heat is mainly generated from the direct combustion of fuels. For this purpose, we mainly resort to natural gas and heating oil, and, to a smaller degree, to biomass. Modern boilers have achieved efficiencies that cannot be increased any further by technical development. Hence, processes involving direct combustion in a boiler will invariably generate high carbon emissions unless fuels with accordingly lower specific carbon emission rates are used. This mainly includes biomass fuels and, in the longer term, synthetic chemical energy sources produced with electricity from renewable sources.

However, the systemic analysis – taking into account the interaction of all sectors and the total systemic costs – shows a high direct use of electricity to be advantageous compared to direct combustion technologies. Electric heat pumps, in particular, should play a central role in the future supply of the building sector with low-temperature heat. However, this result is at odds with the current low market share of electric heat pumps: Only some 10 percent of all newly installed heating systems use heat pumps, with the rate in new buildings ranging around 30 percent. Moreover, heat pumps are currently mainly used in detached and semi-detached houses. In this sector, the share of heating systems with heat pumps amounts to about 5 percent, while multifamily buildings barely reach 1 percent.

Various obstacles impede a wider adoption of heat pumps:

- Costs: Users are particularly put off by the high costs. On the one hand, the purchase and installation costs of electric heat pumps exceed those of boilers. On the other hand, the retail price of electricity is currently so much higher than the retail price of natural gas or heating oil that, as a rule, the use of heat pumps does not offer any economic advantage – not even if the life cycle costs are considered.

- Composition of the entire heating systems: The efficiency of heat pump systems strongly depends on the temperature at which heat is released: The lower the temperature, the higher the efficiency. Low temperature transfer systems, such as underfloor heating systems, are found above all in new buildings and refurbished old buildings. Heat pumps being particularly expedient in these heating systems, measures to promote the use of heat pumps should be aimed especially at these cases.

- Load peaks in the power supply: Electric heat pumps require the highest amount of electrical power when outside temperatures are low. A rapid expansion of electric heat pumps can therefore entail the necessity for higher peak power, which would increase the strain on the power grids. Possible solutions include combining heat pumps with heat reservoirs, or the use of so-called hybrid heat pumps. Hybrid heat pumps (electric base load heat pumps with peak load boilers) combine an electric heat pump and a boiler and are already widely available as fixed units in the low power range, i.e. for detached and semi-detached houses. The heat pump functioning as a base load device covers the bulk of the energy demand, while the gas or oil boiler covers the peak load. By using two energy sources, it will be possible to switch back and forth in the future energy system – for example according to the power price or the supply.

- Multifamily buildings: For multifamily buildings, customised solutions must be developed. On the one hand, sufficiently high temperatures must be ensured for the supply of domestic hot water[23] and hygienic requirements must be fulfilled; on the other, cost-effective solutions must be devised for low temperature transfer systems in existing buildings. In addition, there are issues of noise emissions to be considered, especially in closely spaced urban areas.

- Installation: How the heat pump systems and the hydraulic systems are installed has a great bearing on their efficiency. Steps to increase the market penetration of heat pumps should therefore be accompanied by measures broadly ensuring a high quality of installation. These include not least training and further education initiatives for planners and installers.

A further renewable energy source to be used in buildings is **solar thermal energy**. Today, solar thermal systems cover about one percent of the final energy demand for space heating and hot water. In view of the seasonal time lag between solar gains and space heating demand, the use of solar thermal systems is, in particular, an option for the hot water supply and, if necessary, to some extent for the supply of space heating, especially in spring and

23 In the case of large volumes of hot water in the pipeline network and in hot water storage systems (as used in multifamily buildings), current regulations require the entire amount of water to be heated once a day to a temperature of at least 60 degrees Celsius to ensure reliable protection against legionella. In small buildings, where the respective volumes are not reached, the requirements are accordingly lower. Alternative options such as ultrafiltration or ensuring regular water withdrawals may possibly make these temperature requirements redundant even in multifamily buildings.

autumn. An overview of heat production technologies for individual buildings and their qualitative assessment can be found in the appendix.

2.1.3 Heating grids

Municipal district heating grids can increase the flexibility of the overall system and prove to be an interesting option for urban energy management. In this context, the possibility of integrating large, cost-effective heat storage units is an important element, not least since it enables energy management in interaction with the power supply: In times of high electricity feed-in from volatile renewable sources, heat can be generated in large heat pumps or electric boilers. This heat can be used for the heating supply – if necessary at a later point in time. At times of insufficient power generation from renewable energies, CHP plants can generate electricity and heat. Here, larger plants connected to a heating grid are more cost efficient than microsystems for individual buildings. At the same time, heating grids can resort to additional heat sources, thereby further increasing their flexibility and efficiency. Examples of such sources include waste heat from industry, solar thermal energy or deep geothermal energy. In some German metropolitan areas (e.g. Munich), the latter has the potential to provide large amounts of heat. Further efforts are required to evaluate and perhaps develop this potential.[24]

In addition to large urban district heating grids in dense urban areas, smaller heating grids in urban neighbourhoods can be an expedient option. Several buildings or groups of buildings can be connected to these heating grids. The use of storage units (which can be integrated more cost-effectively in neighbourhood systems than in individual buildings) increases the potential for the self-consumption of locally generated power from renewable sources, as well as the potential for grid stabilising consumer behaviour. Under appropriate market conditions, new business models can evolve in this field.

2.1.4 Conclusion

In order to achieve the climate protection targets in the heating sector, we have two basic options: For one thing, we can introduce measures to reduce consumption, and for another, we can resort to technologies with lower specific emissions. Alone, neither of these basic options will suffice to achieve the goal. A direct use of electricity for the provision of heat seems particularly expedient where electric heat pumps can be introduced without undue effort. Against this background, development efforts to expand the possible fields of application appear reasonable. However, even in the medium and long term, there will probably be areas of the building sector in which the installation of electric heat pumps will, for various reasons, prove difficult to implement. From today‘s point of view, therefore, the other technical options such as gas and hybrid heat pumps, solar thermal energy and combined heat and power plants should also be pursued. Heating grids likewise play an important role in the future energy system, especially in urban agglomerations. This statement is also borne out by the results of the model calculations: In the analyses (model calculations) that were carried out, between 20 and 35 percent of all buildings are supplied via heating grids.

24 The topic of urban heat supply based on deep geothermal sources is addressed by a separate acatech Working Group.

2.2 The transport sector

Regarding the energy transition goals, the transport sector has so far been the least successful. Despite the ambitious targets set by the Federal Government (minus 10 percent by 2020, minus 40 percent by 2050), final energy consumption in the transport sector has increased by about 20 percent since 1990 – from about 600 terawatt hours to some 730 terawatt hours per annum.[25] In private transport, 76 per cent of the passenger kilometres are covered by petrol- or diesel-powered cars; in freight transport, lorries account for 70 percent of the tonne-kilometres.[26] At present, electricity covers only 1 percent of the final energy demand in the transport sector,[27] mainly in trains, undergrounds and trams. The share of renewable energies in transportation has been stagnating at around 5 percent for eight years.[28] This share results mainly from the admixture of bioethanol and biodiesel to fuels[29] and from the share of power from renewable sources used on the railways. Taking not least into account that transport services are expected to increase even further,[30] meeting the climate protection goals set for the transport sector does seem to present a very great challenge indeed.

2.2.1 Passenger transport

Battery electric vehicles enable the efficient use of power from renewable sources. Electric drives are less noisy than internal combustion engines and, locally, do not produce any harmful emissions such as ultra-fine particles and nitrogen oxides. In addition, they are more efficient than combustion engines: If all conventional cars

25 BMWi 2017-1.

26 In 2012, a total of 1,206 billion passenger-kilometres were covered: 76 percent motorised private transport, 5 percent air transport, 6 percent public road passenger transport, 7 percent rail transport and 6 percent pedestrian and bicycle traffic (BMVI 2014-1).

27 BMWI 2017-1.

28 BMWi 2017-2.

29 The carbon footprint of biofuels is controversial and may vary greatly depending on the crops used and where they are cultivated. According to EU sustainability guidelines, the carbon emissions of biofuels must, as of 2017, be at least 50 percent lower than those of conventional fuels (Directive 2009/28/EC, implemented in Germany with the Biokraft-NachV 2009).

30 UBA 2016-3; BMVI 2014-2.

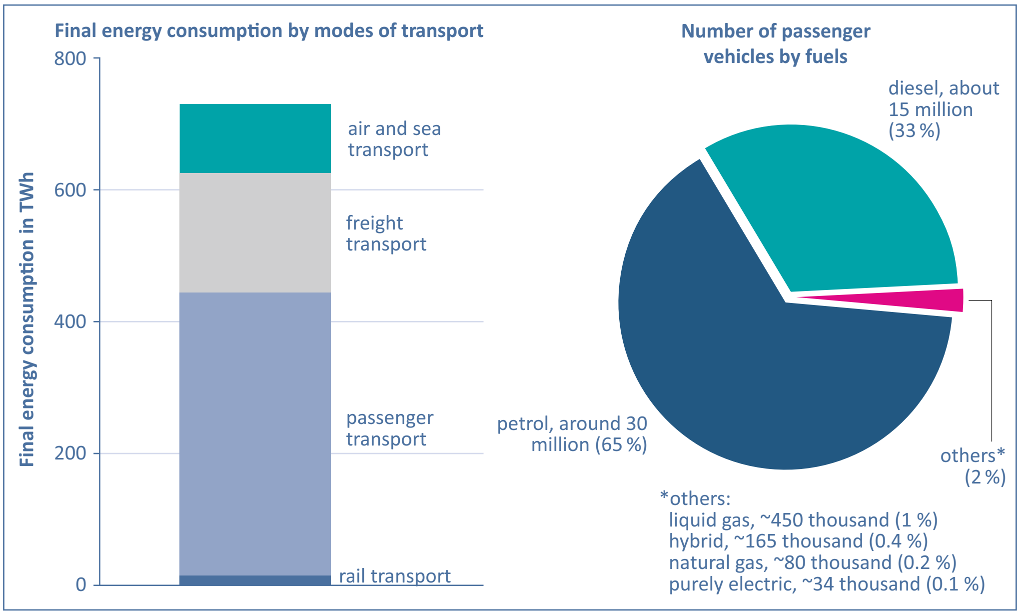

Figure 4: Composition of the final energy demand in the transport sector in 2015 and of the passenger vehicles sector by fuels.*

*Own calculation based on AGEB 2017-1 and Kraftfahrt-Bundesamt 2017.

were replaced by battery-powered electric vehicles, the final energy demand in passenger transport by road could be reduced from around 400 terawatt hours (cf. Figure 4) to some 150 terawatt hours.[31] Currently, electric vehicles account for only a very small share of new car purchases.[32] This is mainly due to the currently high initial costs, the limited range and a still patchy charging infrastructure. With a view to the current figures, it seems highly unlikely that the Federal Government‘s target of one million electric vehicles by 2020 will be achieved: Only about 95,000 of the almost 46 million passenger cars currently registered in Germany are electric vehicles.[33,34]

At the same time, the evolution of battery cells and systems for electric mobility is globally progressing at a very dynamic pace, resulting in higher power density as well as significant cost reductions. Moreover, **hybrid vehicles** commanding both an electric motor with a high-performance battery and a combustion engine, have higher ranges. Plug-in hybrids[35] and vehicles with a combustion engine as a range extender could also be used in the longer term, since they combine the advantages of electric cars with the long range of conventional vehicles.

Fuel cell vehicles generate electricity from hydrogen while driving, thus powering the electric motor. They are likewise quiet and locally emission-free. Compared to battery electric cars they have the advantages of a higher range and fast refuelling. However, since losses occur both in the conversion of power into hydrogen and in its reconversion into power in the vehicle, fuel cell vehicles require more energy for the same mileage than battery electric vehicles (cf. Figure 5). In addition, the purchase prices for fuel cell vehicles currently exceed those for battery-powered cars.

Natural gas vehicles can be operated both with natural gas and biomethane (biogas upgraded to natural gas quality)[36] as well as with synthetic methane. Compared to petrol- or diesel-fuelled vehicles, they cause less harmful emissions and have a lower carbon emissions rate.[37] If synthetic methane is used (produced from power from renewable sources), the complex overall energy conversion chain entails a higher energy amount for the same vehicle performance than for the two previously described drive mechanisms (cf. Figure 5).

Synthetic liquid fuels have essentially the same properties as petrol and diesel. There would hence be no need to exchange the vehicle fleet, and the existing network of petrol stations could remain in use. Incidentally, it is possible to generate

31 The efficiency of about 30 percent assumed for combustion engines corresponds to the average value of modern engines (on the road). For the electric motor, an average efficiency of about 80 percent is assumed.

32 In several other countries, the market share of electric cars is much higher. In Norway, for instance, electric vehicles (battery-powered electric cars and plug-in hybrids) accounted for some 42 percent of the registrations of new vehicles in mid-2017 (Manager Magazin 2017). The purchase of an electric vehicle in Norway is exempted both from the VAT and the so-called purchase tax. Thus, they tend to be cheaper than conventional cars. To this are added further incentives, such as the free use of toll roads and bus lanes, free parking spaces and, in some places, free charging stations.

33 The figure was calculated by the National Platform for Electric Mobility (NPE 2017), based on figures from the Federal Motor Transport Authority (Kraftfahrt Bundesamt). It includes all battery-powered electric vehicles, plug-in hybrids and electric vehicles with range extenders; Last update: May 31, 2017.

34 Meanwhile, even the Federal Government is questioning whether this goal can be achieved. German Chancellor Angela Merkel said in May 2017: “As things stand at the moment, we will not reach this goal” (Handelsblatt 2017).

35 Classic plug-in hybrids work along the same lines as so-called full hybrids, with the battery charged via the braking energy and the combustion engine. In certain driving situations, for example at low speeds, they can drive with electricity only. Unlike battery-powered electric vehicles, however, they cannot cover major distances in this way. Plug-in hybrids can also be charged with a plug on the power grid.

36 Biomethane is methane produced from biogas. Biogas contains between 50 and 75 per cent methane, along with other gases such as CO_2, nitrogen and hydrogen. Before the methane is fed into the gas grid, it is separated from the remaining gases.

37 According to a test report by the German automobile club ADAC, the VW VII Golf 1.2 TSI (petrol, 77 kW output) generates 148 grammes of CO_2 per kilometre, while the natural gas-powered VW Golf 1.4 TGI BlueMotion emits only 98 grammes of CO_2 per kilometre (ADAC 2016, ADAC 2014).

fuels without any toxic additives and produce virtually no soot during combustion (often referred to as “designer fuels”). These include, for instance, dimethyl ether (DME) or polyoxymethylene dimethyl ether (OME). Vehicles with conventional diesel engines would only need to be slightly modified to drive with OME. The major drawback of synthetic liquid fuels consists in the high conversion losses occurring along the entire chain from hydrogen production to its further conversion to fuels to the use in combustion engines.

2.2.2 Heavy goods, air and sea transport

In the logistics sector, purely battery electric vehicles are an option, particularly for short distances and in city centres. This, however, does not apply to long-distance transportation, since the batteries required for such uses are too heavy.[38] As in long-distance passenger transport, hybrid solutions are conceivable, too. Trolley trucks constitute an alternative based on direct electricity. However, their use only makes sense with an overhead contact line grid extending well across Europe. Since such grids cannot cover all road sections from end to end, the lorries would have to be equipped with additional batteries or hybrid drives to ensure that, for example, the logistics centres are reached. Another possibility, which has so far been little discussed, is wireless (inductive) charging.

Fuel cell drives and synthetic fuels constitute long-term alternatives for long-distance freight transport, the advantage of the higher range compared to battery electric vehicles being of much more consequence here than in passenger transportation.

Should prognoses predicting a sharp increase in the **air and sea transport** volumes to more than double the current volumes by 2050 turn out to be correct,[39] these transport sectors will become even more important for the overall energy and climate footprint. As regards aviation, purely electric solutions are rather unlikely, considering the amount of energy required between two charging processes, the weight of batteries and the low energy density of hydrogen.[40] Liquid fuels therefore remain difficult to replace. The same applies to sea transportation, although this sector has launched first studies on the use of hydrogen or methane.[41]

2.2.3 Efficiency and carbon emissions of the different drive types

Whether power-based hydrogen and synthetic fuels actually save carbon emissions depends on how the necessary power is generated. Fuel cell cars, for instance, would only produce less emissions than comparable conventional vehicles if the necessary power is generated without emitting more than about 300 g of carbon dioxide/kWh.[42] In the case of synthetic fuels, the value is significantly lower still. By comparison, Germany’s 2016 power mix was much higher, reaching 527 g of carbon dioxide/kWh.[43] If grid power is used for the production of the respective energy sources, it is only in the long term that these technologies can contribute to reaching the climate goals in the transport sector. However, if hydrogen and synthetic fuels are produced with surplus power that would otherwise be curtailed, the carbon balance would already be positive today. Efficient battery-powered electric vehicles, on the other hand, already generate less

38 UBA 2015 and UBA 2016-3.

39 UBA 2016-3.

40 UBA 2015; UBA 2016-3.

41 In 2015, the first ship under German flag powered with Liquefied Natural Gas (LNG) went into operation (Hochhaus Schiffsbetriebstechnik 2017). A hybrid electric pusher craft with a battery and fuel cell is currently under development (Bizz-energy 2016). The strict emission regulations for the North and Baltic Seas are an additional incentive for the use of alternative fuels.

42 For the sake of comparison, a Toyota Mirai with a gauged fuel consumption of 1 kgH_2 / 100 km (ADAC 2017) was compared with a VW Golf 1.2 TSI BMT with a petrol engine and an output of 77 kW (ADAC 2016). The power required for the electrolysis was assumed to be 4.3 kWh/m³ (Ausfelder et al. 2015).

43 UBA 2017-2.

carbon emissions than comparable petrol or diesel cars, even with today's average power mix.[44]

Figure 5 compares the typical efficiencies of the conversion chains of battery-powered vehicles, fuel cell vehicles and vehicles with combustion engines powered by synthetic fuel. It was assumed that all conversion chains are based entirely on electricity from renewable sources. In order to cover a given distance, a fuel cell car consumes about two and a half times more power than a battery electric vehicle, and a car powered by synthetic fuels even five times as much.[45] However, this does not mean that battery electric vehicles are invariably the best option, as technical efficiency is only one of many evaluation criteria. Further essential points for an overall assessment are, for instance, the transportability of the energy sources, which includes the issue of their range, the costs and the resource efficiency.

2.2.4 Conclusion

In addition to using renewable energies and more efficient drive systems, the transport sector can also save significant amounts of energy and greenhouse gases by **avoiding and shifting traffic** (for instance in urban passenger transport by switching from the car to walking, biking

44 This statement refers to the current power mix and its average carbon emissions. Ausfelder et al. 2017, chapter 3.6. discusses these values at greater length with a view to the European emissions trading system.

45 The exact ratio depends on the driving behaviour. Thus, the efficiency advantage of the electric motor is less obvious over long distances than on shorter drives.

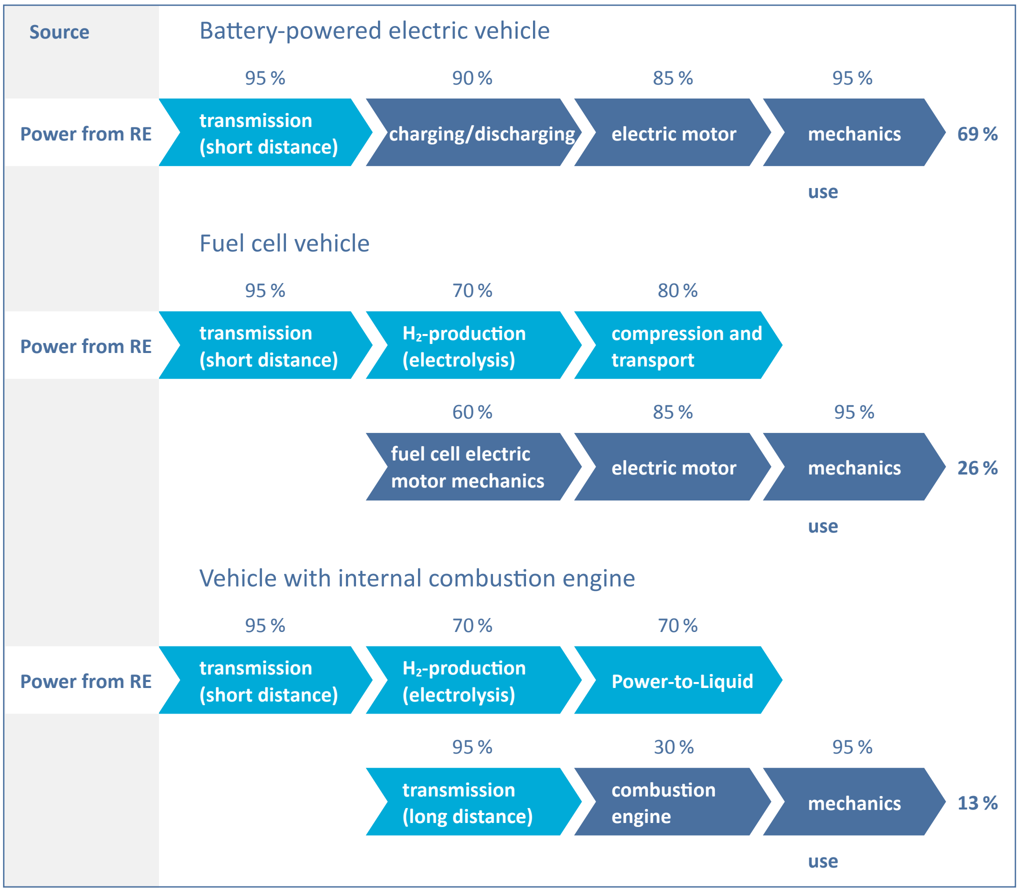

Figure 5: Overall energy efficiency of cars with different drive concepts, all based on renewable energy sources (RE) (exemplary values).*

*Ausfelder et al. 2017.

or public transport[46] or from road to rail in the freight transport sector). While these options were not amongst the subjects researched in the analysis, their importance should not be overlooked.

In addition to this option of reducing consumption, we have different drive technologies with lower specific emissions at our disposal in order to reach the climate protection targets in the transport sector. None of these technologies imaginable from today‘s point of view will alone suffice to achieve the goal.

From a systemic and economic point of view, battery electric vehicles constitute a comparatively cost-effective option for reducing carbon emissions in the transport sector: If we resort to electric mobility solutions, much less energy will be required than for the alternatives, hydrogen and synthetic fuels; hence, a noticeably lower level of expansion of wind and solar systems would be necessary. This is also borne out by the model calculations: The more ambitious the carbon reduction targets, the more electric vehicles are used if pure cost optimisation is the aim.[47] Apart from the electric rail transport, the direct use of power therefore seems to be particularly expedient where electric mobility can be introduced with moderate effort. Against this background, all activities geared towards expanding the possible areas of application of electric mobility are worthwhile. This includes the further development of batteries along the entire value chain as well as the establishment of charging infrastructures. However, even in the medium and long term, there are likely to be key areas of transportation in which the direct use of electricity is difficult to implement. From today‘s point of view, therefore, all remaining technical options

46 Development paths for urban traffic are discussed in detail in Fischedick/Grunwald 2017.

47 The cost optimisation takes costs both for the different vehicle concepts and for the necessary infrastructure into account, for instance costs for charging or refuelling infrastructure.

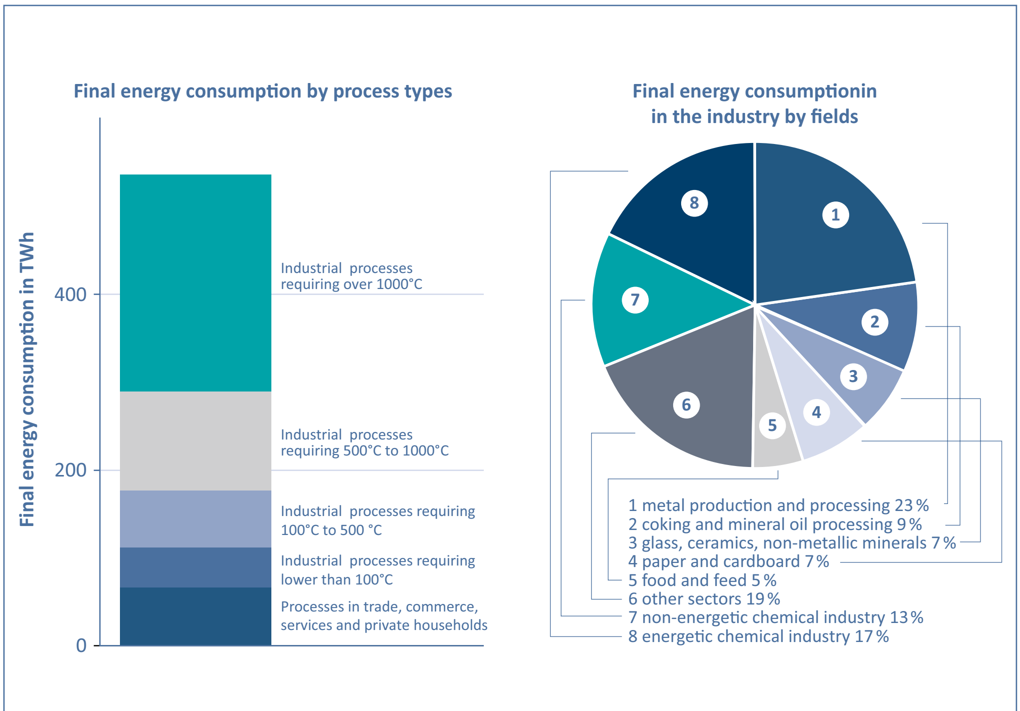

Figure 6: Final energy consumption for process heat in the industry (2015) by process types (left) and fields (right).*
*Own calculations based on BMWi 2017-1.

should also be pursued, i.e. hydrogen drive systems and highly efficient combustion-based drive systems for the relevant areas of transport (heavy goods traffic, sea and air transport, non-electrified rail transport). This requires the development of technologies and concepts for the production of hydrogen and liquid fuels based on power from renewable sources (cf. Section 2.7).

2.3 Industrial processes

The industrial sector accounts for about 30 percent of Germany's final energy consumption.[48] Two-thirds thereof are required for **process heat**, which equates to some 20 percent of the final energy consumption in Germany. Different energy sources are used to cover this demand, above all, however, natural gas. The largest share of process heat – about 75 percent – is used by the energy-intensive primary industries (the chemical sector, metal production, coking and mineral oil processing, glass production, ceramics, non-metallic minerals, paper and cardboard) (Figure 6).

Measures discussed in connexion with the reduction of greenhouse gases in industrial processes include, on the one hand, increasing the efficiency of industrial processes and, on the other hand, switching to renewable energy sources. The following aspects are essential:

1. The requirements for the energy sources vary according to the processes and are generally higher than for the generation of space heating or hot water. On the one hand, some processes require very high temperatures, in some cases over 1,500 degrees Celsius. On the other hand, the energy sources also have other functions in addition to the supply of heat. Coke, for instance, is a main reducing agent and, due to its mechanical stability, ensures stable stratification in the blast furnace process. Renewable energy sources must be able to meet these additional requirements in order to be integrated into existing industrial processes.

2. In many processes, the bulk of the energy from process heat is needed for chemical conversions and physical phase transformations. It thus becomes a direct part of the material (product) and is thermodynamically necessary. The energy is required to produce, for instance, glass or ceramics from sand and minerals, or to obtain the monomers for plastic production from oil. Since this use of energy is indispensable, efficiency measures can only help to minimise energy losses. Incidentally, the processes in the primary industry having been continuously optimised in recent decades, and the remaining efficiency potential is relatively low.

3. In addition to energy-related emissions, some processes produce carbon dioxide as a direct by-product of chemical reactions. An example of such process-related emissions is the calcination of lime in cement production. By the splitting-off of carbon dioxide, the limestone is converted into calcium oxide (quicklime). These emissions can only be avoided by switching to an altogether different manufacturing process.[49] An alternative solution would be the separation of carbon dioxide from the exhaust gas by capture technologies and (optionally) its further use in subsequent processes, for instance for the production of synthetic energy sources based on hydrogen (Carbon Capture and Storage (CCS) or Carbon Capture and Utilisation (CCU)).

2.3.1 Using electricity for industrial processes

In some industrial processes, fossil fuels could be replaced by electricity. Whether this would actually avoid carbon emissions depends on the efficiency of the power-based process compared to the conventional one and on how the power used is generated. Ammonia synthesis is a specific example: Conventional ammonia production uses hydrogen, which is

48 BMWi 2017-1.

49 The Karlsruhe Institute of Technology has developed a possible method to reduce carbon emissions during cement production: Although the binding agent "Celitement" is produced with the same basic materials as conventional cement, it requires less binding agents during application, and the manufacturing process requires significantly lower temperatures (Celitement GmbH 2017). This can reduce both energy consumption and carbon emissions. The process is currently still under development. A large-scale application is not yet conceivable.

currently obtained by steam reformation[50] of natural gas. In this process, some two tonnes of carbon dioxide are generated per tonne of ammonia. Alternatively, the hydrogen could be obtained from water by means of power-based electrolysis. In addition, nitrogen, conventionally generated by the removal of oxygen from the air during combustion, would have to be recovered by breaking down air into its elements. However, since both electrolysis and the production of nitrogen are highly energy-intensive,[51] these processes would only lead to lower carbon emissions if the emissions from power generation were reduced to less than one third of their current amount (electricity mix),[52,53] i.e. 180 g CO_2/kWh (electricity mix today[54]: 527 g CO_2/kWh).

Whether purely electrical or based on synthetically generated hydrogen – power-based processes will hence only lead to a net emissions reduction if the power is generated without significant greenhouse gas emissions. The additional power demand would require a corresponding expansion of renewable energy plants. The power-based production of the current amount of ammonia alone would entail additional electricity requirements of around 26 terawatt hours. This equates to about 5 percent of today's net power demand and one third of the current wind power generation.[55]

Achieving the necessary temperatures with power-based processes is a particular challenge. High-temperature industrial processes account for the bulk of the final energy consumption for process heat (cf. Figure 6). Heat pumps, for instance, cannot be employed for processes above 200 degrees Celsius. Today, efficient combined heat and power plants, using natural gas as fuel and usually heat driven, provide a large part of the auxiliary thermal energy, for example, for the treatment of raw materials, mechanical processing and transportation, or moulding. Electrode boilers are an alternative to processes operated with steam without, however, the efficiency of heat pumps. Like ammonia synthesis, they would only result in lower carbon emissions if the carbon emissions from power generation were reduced to about one third of today's amount. Processes requiring high temperatures of over 500 degrees Celsius are generally difficult to operate with direct electric heat.[56]

In some cases, industrial processes are also intended to contribute to a more flexible power consumption (demand response) in order to respond to the fluctuating power supply from wind and photovoltaic systems. This constitutes a further challenge for the electrification of these processes. Today, industrial processes are usually run with a constant power supply and optimal technical and economic operating parameters. Greater flexibility would come at the price of deviations from the best possible operating conditions. This could reduce

50 During steam reforming from natural gas, the natural gas (methane: CH_4) is converted into hydrogen (H_2) and CO_2 by adding water and oxygen to the process. Currently, about 96 percent of global hydrogen demand is covered by means of steam reforming and related processes.

51 The process chain requires around 11.1 megawatt hours per tonne of ammonia (Bazzanella et al. 2017).

52 This value is calculated as follows: The chemical conversion to ammonia corresponds to: $2N_2 + 3H_2 \rightarrow 2NH_3$. Together with the energy requirement of hydrogen electrolysis at standard pressure (4.3 kWh/m^3, cf. Ausfelder et al. 2015), an energy requirement of 8,959 kWh ensues for the production of hydrogen. To this we must add 1,737 kWh for the air separation and compression of hydrogen (Bazzanella et al. 2017). Taking the specific amount of carbon emissions of the current power mix (527 g CO_2/kWh), 5.7 tonnes of carbon dioxide are produced per tonne of ammonia. Conventional production generates only 1.83 tonnes of carbon dioxide per tonne of ammonia, viz. one-third of that amount.

53 It must also be noted that a significant amount of the ammonia is further processed into urea. This process requires 1.3 tonnes of carbon dioxide per tonne of ammonia. According to the current procedure, the carbon dioxide is separated during the process of steam reforming and used for urea synthesis. In principle, other CO_2 sources could likewise be used, in which case, however, an additional energy requirement would have to be taken into account for the provision of the carbon dioxide. This would increase the energy requirements for the urea synthesis.

54 UBA 2017-3.

55 BMWi 2017-1.

56 For a detailed discussion cf. e.g. Nägler et al. 2016, Nägler et al. 2015 and Gruber et al. 2015.

the energy efficiency of the processes. This problem might be overcome with hybrid systems using both electricity and, for instance, gas. The gas would be used in the event of an insufficient power supply. However, such processes often require large investments, such as the purchase of an electrode boiler or the establishment of a double infrastructure (for gas and electricity).

2.3.2 Recycling processes and waste heat recovery

Increasing the **recycling rate** is a promising option to reduce the energy requirements of the raw materials industry: As a rule, recycling is much less energy-intensive than the production of the primary substance. Glass, paper, plastic, aluminium or steel are cases in point. However, the potential contribution of recycling depends on the further development of consumption, the durability of the products concerned and the recovery rate. Even supposing a complete recovery, the quantity of substances contained in the end-of-life products cannot suffice to cover an increasing demand, because products are always recycled at the end of their life cycle, which can range from a few days to several decades.[57] Also, according to current technical standards, not all materials can be recycled to the same quality as the primary products without undue effort.

Frequently, **waste heat** is already being integrated into existing industrial processes. Depending on the process, however, large amounts of rather low-temperature heat are generated, for which there is no use in the process. They can, however, be used for space heating and hot water supply, which is, indeed, often done in companies. However, industrial waste heat is being generated throughout the year, while space heating is needed, especially in cold seasons, a part of the energy often remains unused. In order to use the waste heat as efficiently as possible, it could be fed into the heating grid. So far, however, there are hardly any incentives for district heating companies to include external heat sources, since they have natural monopolies and use their own power plants to supply the grids.[58] For industrial companies, in turn, these potentials are often difficult to predict, or they shirk the financial and organisational efforts and binding delivery obligations involved.

2.3.3 Conclusion

The analysis shows that, unlike in the transport sector or in the case of heat provision in the building sector, there are no overarching concepts in the field of industrial processes that could provide a perspective for a significant reduction of energy- and process-related carbon emissions in this sector. At the same time, the calculation examples show that where power or power-based energy sources could serve as a substitute for the fossil fuels used today, the power provided would need to have a very low specific emissions rate to achieve positive climate effects. Hence, it is important to identify and develop individual solutions for the various industrial processes in the coming years. They should be available at a high degree of technical maturity once easier ways to reduce carbon emissions have been implemented in the other sectors (transport and low temperature heat in buildings).

57 Angerer et al. 2016, pp. 95–98.

58 Thus, the German competition authority (Bundeskartellamt) concludes that with a view to the dominant position of the heating grid operators, who are simultaneously heat providers, there is "evidence of possible abusive behaviour," which includes "refusing or impeding access to the district heating grid for heat producers wishing to pass through their heat" (Bundeskartellamt 2012, p. 184). The Consumer Rights Protection Centre Hamburg likewise accuses the operator of the Hamburg district heating grid of abusing its monopoly position by favouring subsidiaries of the corporation in the procurement of heat while denying other heat suppliers access to the grid (VZHH 2012).

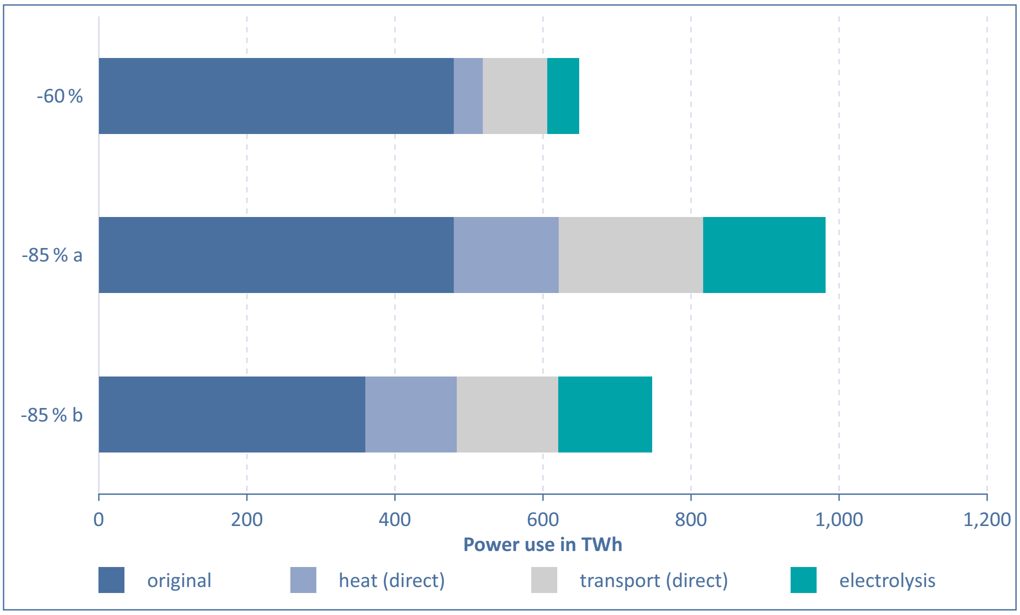

Figure 7: Power use in 2050 in three selected model calculations. Top (-60%): free optimisation of the energy system, subject to a reduction of energy-related carbon emissions by 60 percent; middle (-85% a): free optimisation, reduction by 85 percent; bottom (-85% b): model calculation with different assumptions greatly facilitating the achievement of the reduction targets, reduction by 85 percent.

2.4 Expansion of renewable energies for power generation

An increasing use of power in the areas of application outlined above – in other words: an increasing coupling of the energy sectors – will (inevitably) entail considerable growth in future power demand. This fact is broadly acknowledged in the discussion on the development of our energy system. The direct use of power for the supply of heat and in the transport sector is complemented by the use of power from renewable sources for the production of chemical energy carriers such as hydrogen and synthetic energy carriers based on hydrocarbons (cf. Section 2.7). The extent to which the power demand will increase moreover depends in particular on how the original application areas for power will develop – i.e. all the applications that are currently mainly powered with electricity, such as artificial lighting, stationary drives, information and communication technology, refrigeration, etc.

Figure 7 presents the power use in 2050 for three exemplary model calculations. The illustration shows that with more stringent climate protection goals, the power requirements increase significantly. While a reduction of energy-related carbon emissions by 60 percent entails an additional power demand of around 170 terawatt hours, a reduction by 85 percent – under otherwise equal conditions – would come with additional power requirements of more than 500 terawatt hours, in which case the power demand would be doubled. The direct use of power in the transport sector accounts for 39 percent of this additional requirement, the production of hydrogen for 33 percent and direct use of power for the provision of low-temperature heat in buildings for 28 percent. In the third case presented in Figure 7, viz. a reduction by 85 percent, but with various assumptions making it considerably easier to achieve the reduction targets[59] – an increase of some 390 terawatt hours would ensue.

59 The most important assumptions in this context are: stipulation of a phase-out of lignite- and hard coal-based power generation; reduction of the original power demand by 25 percent by 2050; an annual decrease in the energy demand for industrial processes by 0.5 percent; a doubling of the capacity of the interconnectors along borders for the exchange of power with neighbouring countries.

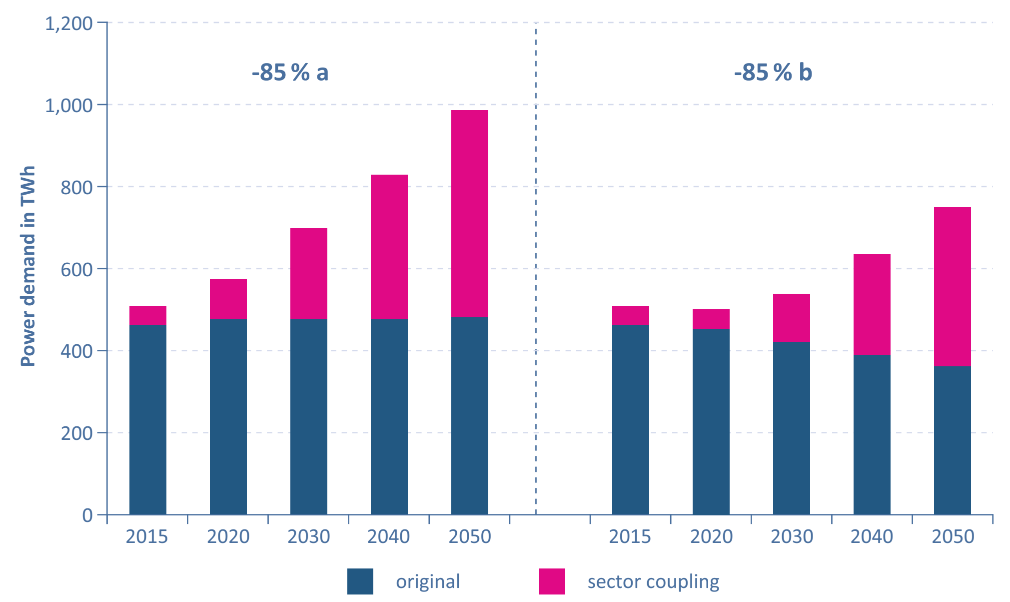

Figure 8: Development of the power demand in the model calculations with a reduction of energy-related carbon emissions by 85 percent. The illustration differentiates between power requirements for original power applications and the use of power for heat provision and in transportation (coupling of the energy sectors). Left (-85 % a): free optimisation, reduction by 85 percent; right (-85% b): model calculation with different assumptions greatly facilitating the achievement of the reduction targets/reduction by 85 percent.

Figure 8 shows how in the two model calculations, assuming a reduction of energy-related carbon emissions by 85 percent, the power requirements develop from today until 2050. In 2015, 509 terawatt hours of electricity were used as final energy, some 47 terawatt hours of which were used in the transport sector and for the provision of heat.[60] Even with optimistic assumptions making it significantly easier to achieve the reduction targets, the power demand will rise considerably, albeit delayed compared to less optimistic estimates regarding possible reductions in consumption.[61] In order to cover this growing power demand while steadily reducing carbon emissions, the continuous expansion of renewable energy plants is necessary. Figure 9 shows the development corridor for the total installed capacity of volatile renewable energy plants (sun and wind). The figure shows that even with very optimistic assumptions, which greatly facilitate the achievement of the reduction targets, an additional 350 gigawatts worth of wind turbines and photovoltaic plants would be necessary. To achieve the same reduction target without such favourable assumptions would require a total installed capacity of close to 500 gigawatts in 2050. The current installed capacity of these plants amounts to just under 95 gigawatts, consisting of 48 gigawatts from onshore wind turbines, just under 5 gigawatts from offshore wind turbines and close on 42 gigawatts worth of photovoltaics. It follows that an average annual construction rate of around 8 to 12 gigawatts will be necessary – depending on the boundary conditions and, obviously, on the respective shares of photovoltaics and onshore and offshore wind power plants.

2.4.1 Conclusion

The transformation of the energy system is essentially based on the technologies for generating power from the renewable energy sources sun and wind. The analysis shows that, depending on the boundary

60 Based on: BMWi 2017-3.

61 In the scenarios compared in Ausfelder et al. 2017, chapter 4, for example, the range of gross power generation ranges from around 450 to about 800 terawatt hours. The scenario “Germany as a greenhouse gas-neutral country” (UBA 2013) is an exception: Including the power used to produce methane and fuels from renewable sources, the necessary gross power generation amounts to some 3,000 terawatt hours, with a high proportion of regeneratively produced energy sources being imported.

conditions, an average annual expansion of 8 to 12 gigawatts is required. While this is not impossible, as proven by the photovoltaic expansion of 22 gigawatts between 2009 and 2012, it does constitute a major challenge – technically, as well as for the energy sector and society. An installed capacity of several hundred gigawatts of renewables does not only require space, but will also cause changes in the landscape. A lack of acceptance for such changes could jeopardise the expansion scheme.

A rapid expansion of renewable energies requires a corresponding expansion of power grids at all voltage levels.[62] A reasonable placement of renewable energy plants (close to the consumer and with good wind and solar potentials) and of new large consumers (at favourable locations along the transmission grid), can reduce the grid expansion requirements. Thus, photovoltaic systems could, for instance, be set up in urban neighbourhoods (as opposed to rural areas) or electrolysers near wind farms in the north of Germany. Expansion targets for renewable energies and power grids should therefore be coordinated with the increasing coupling of the energy sectors indispensable for achieving the climate protection goals.

2.5 Dispatchable power plants and energy storage systems

The consequences of a blackout are serious enough today; they will become worse as electrification progresses. In the future, this will increasingly affect the mobility sector. Also, in the event of lengthy periods without a sufficient power supply from renewable sources (so-called "dark and windless periods"), which tend to occur in cold seasons, the supply of space heating and hot water might no longer be ensured. With power (from renewable sources) becoming the dominant energy source, the question of supply security in the field of power generation increasingly affects the entire energy system.

Demand-side technologies that use power directly can only compensate for fluctuations in power generation to a very limited extent. Devices such as heat pumps with a hot water tank or batteries in electric vehicles can help to offset fluctuations for short periods of a few hours at most – provided they are equipped with the required control technologies (smart meter, smart grid, smart home). In these cases, demand response technologies and concepts play an important role. This implies moving away from the basic principle of the current power supply system, where electricity generation is strictly regulated according to the electricity load, towards a more complex interaction of generation and loads, which includes the operation of some of the loads dependent on the available power. However, if these technologies are not operated in accordance with the system requirements, they risk putting an additional strain on the system during peak load periods: This can, for instance, occur if the bulk of electric vehicles is charged at the same time of day. More particularly, however, these technologies cannot contribute to bridging longer periods without adequate supply. If during such a "cold, dark and windless period" a large part of the necessary heating has to be covered electrically, this will burden the power system even more heavily.

62 With a reduction target of 85 percent by 2050, the model calculations assume almost twice as many wind power and photovoltaic plants to be used between 2030 and 2035 as the scenarios of the Network Development Plan (NEP). This is due to a more extensive use of heat pumps and electric vehicles, which increases power consumption by 30 to 50 percent compared to the NEP scenarios (BNetzA 2016).

In order to ensure a stable power supply with high supply security even in view of the changing conditions, storage systems and dispatchable reserve power plants are indispensable. In combination with solar and wind energy plants, power storage devices – particularly pumped-storage power plants and stationary battery storage systems – can increase the availability of volatile renewable energies for short periods (a few hours).

However, the capacity of pumped-storage power plants can hardly be expanded. As regards battery storage systems, they will not be operable at a sufficient scale and profitability (even if the costs continue their sharp decline) to keep up the entire energy supply with a divergence of several days or even weeks between charging and discharging times. Therefore, a reserve capacity for power generation will remain a necessity to ensure a secure power supply during longer periods without sufficient feed-in from renewable sources.

2.5.1 Flexible reserve capacity for power generation

In order to provide dispatchable reserve power, we can basically resort to all technologies using storable chemical energy carriers at various power ranges. This includes combined heat and power plants in buildings or heating grids, gas turbines and fuel cells, as well as large-scale combined cycle power plants. The important point is that a highly dynamic and flexible operation is possible, in interaction with the power generation in solar and wind energy plants. Fossil energy sources, biomass or synthetic gases (hydrogen or methane) produced with electricity and stored accordingly can be used as fuel.

How the reserve capacity is composed is ultimately determined by operation hours the different power plants can achieve to offset a positive residual load. Due to their high performance-related investment costs, **combined cycle power plants** with high efficiencies over 60 percent require a correspondingly high utilisation rate. Highly flexible and rapidly reacting gas turbines with relatively low specific investment costs, on the other hand,

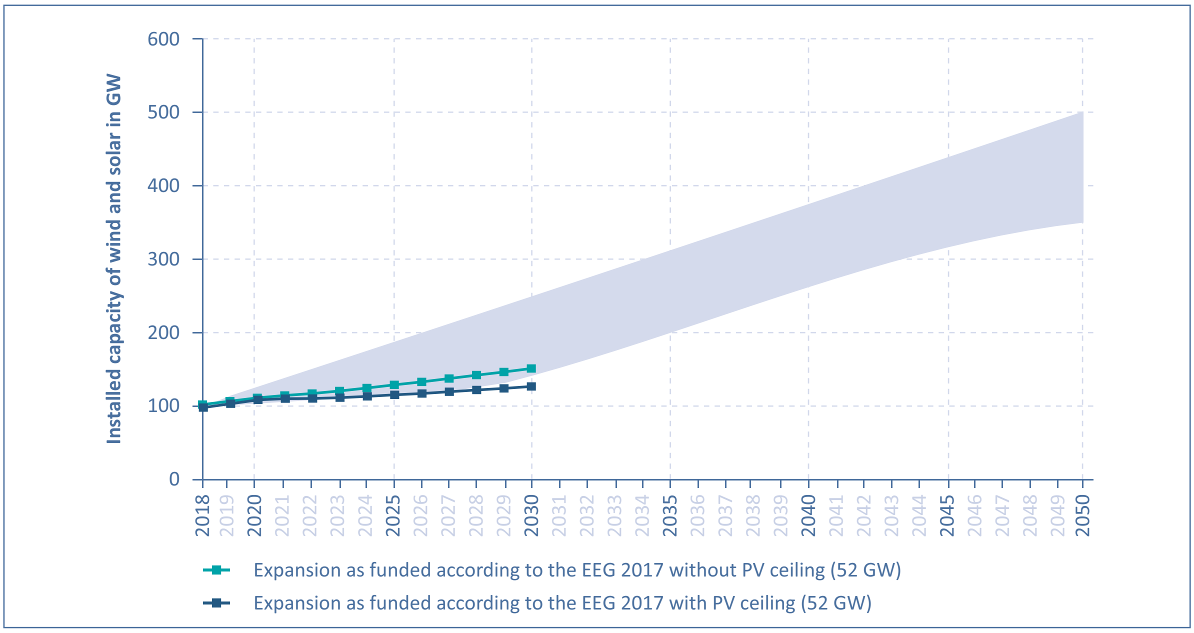

Figure 9: Corridor for the development of the total installed capacity of volatile renewable energy plants (sun and wind). The presentation is based on the model calculations featuring an 85 per cent reduction in energy-related carbon emissions. The lower limit of the shaded area results from the model calculation with various assumptions greatly facilitating the achievement of the reduction targets, and the upper limit from the calculation without such assumptions. In addition, the figure shows the expansion of the installed capacity for photovoltaic and wind power plants according to the EEG 2017 promotion scheme for renewable energies* (teal: without limitation of the photovoltaic power to 52 gigawatts, blue: with limitation of the photovoltaic power to 52 gigawatts).

*EEG 2017; BMWi 2017-4.

are more suitable for providing secure reserve power even in the case of only a few full-load hours per annum. **Biomass power plants**, which today are usually run around the clock, will likewise be operated more flexibly in the future. If they are primarily used as reserve power plants, less biomass would be needed per plant. This would enable us to expand the number of biomass power plants to further secure the power supply without consuming altogether more biomass.

Combined heat and power plants can constitute another important element of supply security, with natural gas and biogas serving as main fuels. In contrast to the currently used heat-led mode, which means that the plant is (often exclusively) operated according to the heat requirement, the future mode of operation will rather be based on the power demand. In all above-mentioned plants, the mode of operation will have to change as a result of the energy system transforming towards an ever-increasing share of power generation from volatile sources. However, since such a modified mode of operation makes it almost impossible to run a plant profitably under current market conditions, a new regulatory framework is indicated. This must, on the one hand, incentivise an optimal combination of the installed capacities of the individual technologies – both in terms of cost and supply. On the other hand, it needs to encourage an operation in accordance with the systemic requirements.

Depending on the boundary conditions, the required **reserve capacity** in the model calculations amounts to between 60 and 100 gigawatts. It does not depend to a very significant degree on the climate targets. By comparison: Today about 100 gigawatts worth of conventional power plants are installed. This means that even in the future, a power plant park of the same dimensions will be required. However, it could be differently composed: In the case of high carbon reduction targets, CHP plants, combined cycle power plants and gas turbines will prevail. In that scenario, the most important fuel for power generation is natural gas, with a share of at least 75 percent. Assuming a carbon reduction target of 85 percent, the calculations show an increase in the total installed power generation capacity, from currently about 200 gigawatts to some 600 gigawatts, including the approximately 500 gigawatts of renewable energy. It would, in other words, be more than tripled.

However, reserve power plants will be operated at rather low utilisation rates in the future, with operating conditions constantly changing over the course of the energy transition. The model calculations present the following picture for 2050: CHP plants will run 2,000 to 4,000 full load hours per annum, combined cycle power plants about 1,000 to 2,000, and gas turbines well under 1,000.

2.5.2 Short-term storage systems

Combined with solar and wind power plants, short-term power storage systems – especially the above-mentioned pumped storage power plants and stationary battery storage systems – can increase the availability of volatile renewable energies. However, the contribution the existing pumped storage power plants can make is relatively small: Assuming that all the pumped storage power plants in Germany are filled, they can provide some 6.4 gigawatts of power for about six hours.[63] If we further take the projects that are currently in planning into account, an additional capacity of around 8 gigawatts would result.[64] However, at peak load times the demand in Germany currently amounts to about

63 BNetzA 2017.

64 The data is taken from Wikipedia 2017. The projects are at different stages of the planning process, with a question mark over the future of some projects; cf. also "Successfully designing the energy transition: The role of pumped storage power plants" (Voith 2014).

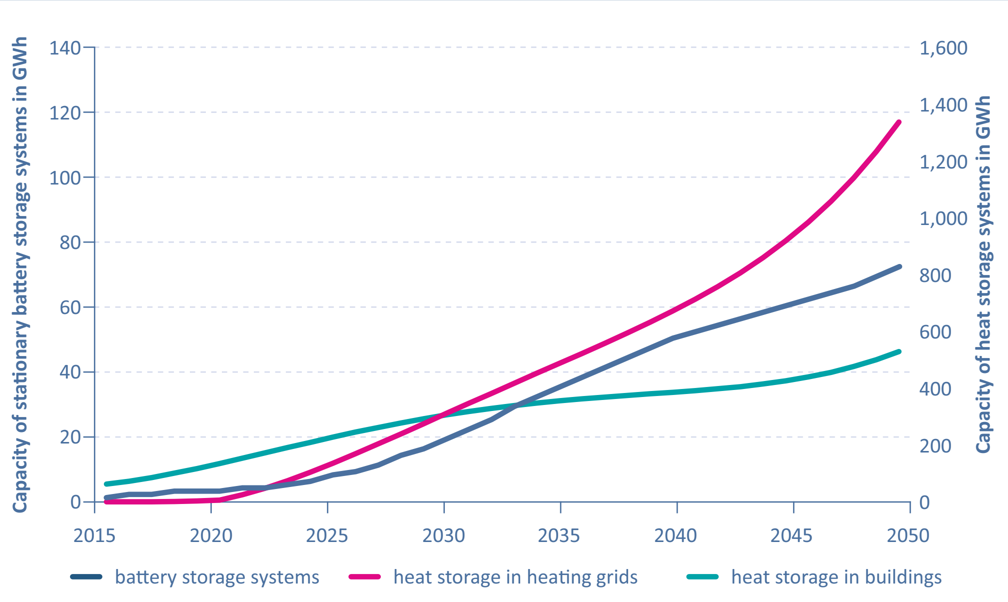

Figure 10: Expansion over time of the installed capacity of stationary battery storage systems (left axis) and heat storage systems in individual buildings and in heating grids (right axis). The presentation is based on the model calculation assuming a reduction of energy-related carbon emissions by 85 percent without any other restrictions.

80 gigawatts.[65] In the future, stationary battery storage systems can be significant as a means to temporarily store power from renewable sources and release it at a later moment in time. In combination with photovoltaic systems, they are particularly suited to balance the day-night disparities. A corresponding market is already developing for this application. In the future, storage systems of various sizes are conceivable: from small-scale storage units in residential buildings to district storage systems in neighbourhoods to large-capacity multi-megawatt storage facilities in wind or photovoltaic power plants. In addition to a demand-based provision of power, battery storage systems can be used in combination with components of power electronics to assume important system functions in the power system (voltage and frequency stability, provision of the regulating reserve).

Figure 10 shows how, according to the model calculation assuming a reduction of energy-related carbon emissions by 85 percent without any other restrictions, stationary battery storage systems are expanded over time. The substantial expansion will take place after 2025, resulting in an installed capacity of around 75 gigawatt hours in 2050.[66] Since the discharge capacity of most battery storage systems allows for a full discharge (or more) within an hour, this capacity would, in theory, suffice to cover the maximum power requirement for one hour. In the model calculation, these battery storage facilities pass through around 200 full cycles per annum, thus essentially acting as day-night storage systems.

65 Information taken from the homepage of the Federal Government 2017.

66 75 gigawatt hours equates to 15 million 5 kWh battery storage units, for example in buildings, or else 7,500 10 MWh battery storage units in solar or wind power plants.

Thermal storage systems (hot water storage tanks) for heating grids and individual buildings constitute a further flexibility option to cushion a fluctuating power feed-in at an hourly or daily level. They also form an interface between the heat and electricity sectors. Figure 10 shows the expansion over time of the installed capacity of heat storage systems in individual buildings and heating grids, based on the model calculation assuming a reduction of energy-related carbon emissions by 85 percent without any other restrictions. Heat storage in individual buildings expands virtually continuously to close on 600 gigawatt hours[67] in 2050, heat storage systems in heating grids to almost 1,400 gigawatt hours.[68] In the model calculation, these heat storage units pass through around 50 (storage in heating grids) or indeed 200 (storage in individual buildings) full cycles per annum. The former thus rather serve for storage at a daily or weekly level, while the latter are better suited as day-night storage facilities.

2.5.3 Conclusion

A continued, significant expansion of renewable energy sources for power generation does not mean that we can dispense with reserve capacities at a similar level to our current total conventional power generation: Even if a substantial number of short-term storage units is installed, renewable energy sources still have but a very low guaranteed generation capacity. The most important requirement for the provided reserve capacity is high flexibility, including the possibility of a highly dynamic operation. Despite this necessary reserve capacity, the short-term storage of both electricity and heat plays an important role: It contributes to temporarily decoupling the generation of volatile renewable energies from their consumption, to increasing their availability and thus to extending the share of these energies in the total power generation. For the coming years, therefore, all current and future technologies for energy storage and for the provision of flexible and dynamically available power generation on the basis of chemical (fossil, biogenic, synthetic) energy sources should be further developed. However, if these technologies are to be expanded and operated in accordance with systemic requirements, this must be complemented by a modification of the basic market conditions towards a corresponding incentive structure.

2.6 Biomass

Biomass is currently the most important renewable energy source[69] and will continue play a significant role in the future energy system: Biogenic energy sources can be used in all sectors and can replace fossil combustibles and fuels where chemical energy sources are required.

However, biomass-based energy sources are varied and of different provenances. For energetic use, crop biomass and residual and waste materials are the most important sources. Heating is mostly effected with wood, while biofuels are nowadays produced from starch and oil crops such as maize, rapeseed and palm oil. Bioethanol is partly imported, as the demand determined by the mandated blending could otherwise not be met.[70] This crop biomass comes with comparatively high risks to the environment and to food safety.[71] The according risks of residual and waste materials such as forest residues,

67 600 gigawatt hours correspond to approximately 13 million 1 m³ water-based heat storage units in individual buildings.

68 1,400 gigawatt hours equate to 800 heat reservoirs, which are integrated into heating grids and each boast a water storage volume of 50,000 m³.

69 In 2015, biomass (including sewage treatment plant gas, waste and landfill gas) covered just over 8 percent of Germany's primary energy demand, or about two thirds of the primary energy contribution of renewable energies. Based on: BMWi 2017-4.

70 Weidner/Elsner 2016.

71 In its study on alternative fuels for the transport sector, the Federal Environment Agency categorically excludes the use of cultivated biomass due to the possible competition with food production (UBA 2015).

straw, slurry, manure and residues from food processing, on the other hand, are low. At the same time, social acceptance for their use is high. However, the production of biofuels from these materials requires different processes than the processing of the starch and oil plants used today. Technically, suitable methods are already well developed, but under current conditions, they are usually unable to compete with fossil alternatives.[72]

While the estimates regarding the potential for biomass expansion in Germany vary, they do tend to lie well below a doubling of the current energy use of just under 300 terawatt hours.[73,74] The cultivation of energy crops is limited, in particular, by land usage, competition with food production and the ecological consequences of water consumption and the use of fertilisers and other agrochemicals. The production of bioenergy can thus entail significant greenhouse gas emissions[75] and other environmental damages, such as the loss of biodiversity, soil damage and water pollution.[76] This could, for instance, be counteracted by (internationally determined) land use policies. However, since such regulations are not foreseeable, it is difficult to estimate the sustainably usable potential of cultivated biomass.

72 Weidner/Elsner 2016.

73 Sewage treatment plant gas, landfill gas and waste are included. Based on: BMWi 2017-4.

74 Various studies assume that in 2050, between 5 and 25 percent of the final energy demand in Germany could be covered by bioenergy. Cf. Szarka et al. 2017.

75 The greenhouse gas emissions ensuing from biomass production and its use for energy purposes vary widely from case to case. They depend on factors such as the type of vegetation previously growing on the land used for cultivation (land use change). The conversion of forests and permanent pastures into arable land, for instance, releases CO_2. The use of nitrogen fertiliser produces nitrous oxide, a powerful greenhouse gas. The fossil fuels powering agricultural vehicles used for sowing and harvesting also generate carbon emissions (acatech/Leopoldina/Akademienunion 2017, pp. 62-63).

76 Measures to reduce the environmental impact of the expansion of bioenergy are discussed in the position paper *Raw materials for the energy transition. Securing a reliable and sustainable supply* (acatech/Leopoldina/Akademienunion 2017).

The potential of technically usable residual and waste biomass, on the other hand, is easy to quantify: Currently, we accumulate about 275 terawatt hours' worth of residual and waste materials per annum, only half of which is used.[77] If the entire potential were exhausted, it would suffice to cover some 7 percent of Germany's current primary energy requirements.

2.6.1 Conclusion

Today, 64 percent of biomass-based energy sources are used for the supply of heat, 22 percent for power generation and 14 percent as fuels.[78] For the future use of biomass in the context of the energy transition and with a view to a systemic optimisation of the energy system, the following changes are conceivable:

- In the long term, there will probably be no or very little direct combustion of biomass-based energy sources for the provision of low-temperature heat for space heating and hot water. This is due to the fact that better use should be made of the great advantages of biomass-based energy sources, viz. that they can provide renewable energy on demand and are suitable for use in different sectors. This statement is also robustly supported by the results of the model calculations. In commercial and industrial processes requiring high temperatures, on the other hand, biomass utilisation may play a more important role in the future.

77 Brosowski et al. 2016.

78 Based on: BMWi 2017-4.

- The relevance of biomass for the provision of transport fuels will also increase considerably. In this respect, processes for the customised production of fuels on the basis of different biogenic raw materials are gaining in significance. Those processes that are deemed relevant from today's point of view should therefore be further developed and tested in pilot plants in order to enable a wider use of biomass in the fuel sector.

- Today, biogas-powered combined heat and power plants operate largely around the clock, aiming for a high utilisation rate. As in the case of fossil fuel power plants, this should change in the medium term. From a systemic perspective, power generation in times of a high power feed-in from wind and solar power plants does not make sense. Here, too, it will be important to develop framework conditions[79] that will incentivise a demand-based operation.

2.7 Synthetic combustibles and fuels

The first three sections of this chapter have shown that, for a variety of reasons on the application side, a full transition to the direct use of electric energy is hardly realistic in either of the three sectors of consumption (heat for buildings, transport and industrial processes). This applies in particular to heavy goods traffic and air transport as well as to a number of industrial processes requiring specific energy sources. It is owing to these circumstances that we require alternative energy carriers, the production and use of which should come, if not with zero greenhouse gas emissions, at least with significantly lower emissions rates compared to current fossil energy sources. Besides biomass, which was discussed in detail in the previous section, hydrogen and synthetic combustibles and fuels are the primary technical options.

A future relevance of hydrogen and/or synthetic energy carriers is not only indicated for reasons on the application side; there are two further aspects arising from an overall systemic consideration:

1. As a consequence of the continuous expansion of power generation facilities using volatile sources – sun and wind – we will increasingly be facing periods when power generation will exceed the total momentary power consumption. Short-term storage systems such as pumped storage power plants and battery storage units can help to partially offset such surpluses. Nevertheless, an installation of sufficient short-term storage facilities to store the power from longer periods of high sun and wind production is completely unrealistic and would not be affordable even if the costs for battery storage were to decrease sharply. Such amounts of electricity can, however, be converted into hydrogen in electrolysis plants. The resulting hydrogen can either be put to various direct uses or can be further converted into gaseous or liquid hydrocarbons. Hydrogen and synthetic combustibles and fuels serve in this respect as *long-term systemic storage facilities*.[80]

79 With regard to the expected very high proportion of volatile sources, the future power or energy market will presumably need to offer business models supporting more flexibility both on the demand side (demand side management) and on the producer side (highly flexible power plants, storage systems).

80 In the case of pure energy storage devices using the same form of energy in the charging and discharging processes (e.g. battery storage systems), a first approximation shows the manufacturing costs to scale with the size, i.e. the amount of energy that can be stored. In converters for the production of synthetic energy sources (electrolysers, methanisers, etc.), a first approximation shows the manufacturing costs to scale with the rated power of the converter, while the actual storage devices are reservoirs or tanks, which often have very low production costs compared to the converters. This is one of the reasons that even with greatly reduced costs, battery storage is not a systemic option for long-term storage.

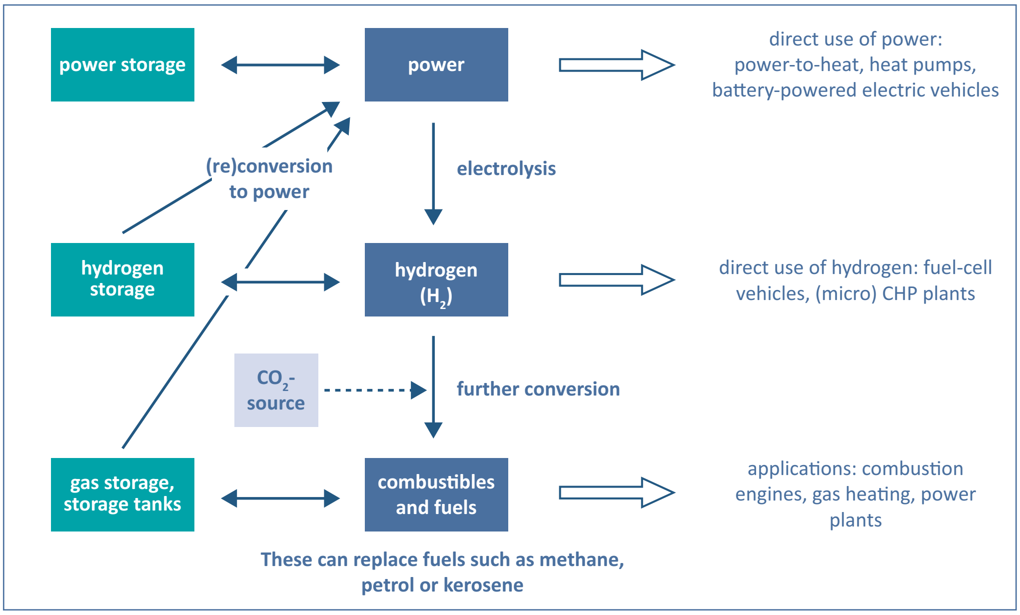

Figure 11: Fields of application for electricity in combination with processes for the production of hydrogen and synthetic energy sources

2. As described above, a significant power generation reserve capacity is required to bridge longer periods of low electricity feed-in from volatile renewable energy sources. To this end, we will, in the long term, likewise require energy carriers that can be used without producing any or any significant greenhouse gas emissions.

2.7.1 Production and storage

All processes currently under discussion for the production of synthetic combustibles and fuels from renewable power include the production of hydrogen by electrolysis as the first step. The hydrogen could be used directly, for example to generate electricity in fuel cells for vehicle drives or in reserve power plants. Other uses include a further conversion to various liquid or gaseous hydrocarbons with a very high energy density. This can be achieved through a variety of different processes, which usually require CO_2 as a carbon source. These synthetically produced combustibles and fuels can be produced so as to directly replace fossil fuels such as natural gas, petrol, diesel or kerosene. Basically, they can also be reconverted into electricity in thermal power plants or CHP plants[81] or be used as fuel in heating systems. The processes are presented schematically in Figure 11.

Synthetically generated methane can be fed into the natural gas grid. Together with the corresponding cavern and pore storage systems, the grid can store methane with a heating value of about 250 terawatt hours.[82] This equates to almost one third of the current annual energy requirement for space heating and hot water. In addition, further natural gas storage facilities with a capacity of about 150 terawatt hours are already being planned or are under construction.[83] Thus, synthetic methane can, not least, mitigate the necessity to expand the power grids compared to a supply system based largely on direct power consumption.[84]

81 The reconversion of hydrogen has the lowest conversion losses, since no conversion steps into other energy sources are required. Currently, the conversion of electricity into hydrogen and back can be realised with an overall efficiency of about 40 percent (Ausfelder et al. 2015).

82 Krzikalla et al. 2013, p. 72; Regional Authority for Mining, Energy and Geology 2017.

83 Hartmann et al. 2012.

84 Cf. for instance Ausfelder et al. 2015.

In a future energy system, methane could, for instance, be used to fuel vehicles over long-distances; in times of simultaneous high power consumption and heating demand, hybrid heat pumps could provide space heating and hot water to compensate for peak loads; and during prolonged periods of little wind and solar radiation, methane could be used for power generation in gas-fired power plants. Modern plants could generate close on 250 terawatt hours of electricity from the 400 terawatt hours of stored energy. This would be equivalent to about one-eighth of the future final energy demand per annum (provided we succeed in reducing the latter from today's well over 2,500 terawatt hours to 2,000 terawatt hours or less – a feat achieved in almost all scenarios in the model calculations featured in this paper).

By blending it with methane, hydrogen can already be fed into the natural gas grid today. For technical reasons, however, the hydrogen content is currently limited to 10 percent. A more extensive use of hydrogen in the energy supply would require significant modifications to the existing infrastructure or indeed the creation of an altogether new infrastructure. The ideal solution would be to combine the further use of the existing natural gas grid with access to pure hydrogen (e.g. for fuel cells). An "elegant" way to meet that challenge would consist of transporting a mixture of hydrogen and methane into the gas grid and separating the gases at the extraction point. Such methods could represent an alternative to establishing an independent hydrogen grid. [85]

If carbon dioxide from industrial processes or conventional power plants is used as a carbon source in the production of synthetic energy carriers from renewable power, fossil combustibles and fuels can be saved and carbon emissions reduced. Developing this notion further leads to the desirable utopia of a carbon-neutral energy supply despite the use of carbon-containing combustibles and fuels. However, this vision can only be realised if the primary energies used are invariably generated from renewable sources and if all of the carbon emissions are completely recycled, viz. the carbon cycle is completely closed.

Obviously, this can only succeed if carbon dioxide is extracted from biomass or from the air, i.e. if the carbon cycle via the air is closed. However, biomass is only available in limited quantities, while the processes for extracting carbon dioxide from the air are highly energy-intensive and expensive. In any case, as long as fossil-fuelled power plants and industrial processes continue to emit carbon dioxide into the atmosphere, it is reasonable to capture and recycle the carbon dioxide from the emissions.[86]

2.7.2 Results from the model calculations

The model calculations carried out in the analysis support the statement that the production of hydrogen and its use in various applications is useful or even necessary to ensure a secure energy supply despite a continuously decreasing use of fossil fuels. Even if we assume significantly lower reduction targets for energy-related carbon emissions than we have set ourselves – i.e. a reduction of only 60 percent – electrolysis on the basis of power from renewable sources is of importance. However, it also becomes clear that the technologies for the production of hydrogen and other synthetic energy carriers will not play a significant role until a later phase of the energy transition (assuming that the transformation process will be subject to cost optimisation efforts). However, the calculations also show that the more ambitious the reduction targets are, the sooner the expansion should begin.

85 Such methods are already the subject of first research projects; cf. for instance, TU Wien 2016.

86 Unavoidable, process-related carbon emissions from industry could be used in the long term even if CCS technology is ruled out (cf. Chapter 2.3).

Figure 12 depicts the mixture of all chemical energy carriers in 2050 according to three selected model calculations, which differ with regard to the reduction targets for energy-related carbon emissions, but are otherwise not subject to any restrictions. In addition, we see the composition of Germany‘s chemical energy carriers in 2016. It is particularly remarkable that in the model calculations with ambitious climate protection targets, the total amount of chemical energy carriers drops significantly from its current value of over 3,000 terawatt hours to some 1,000 terawatt hours. In all model results, crude oil and especially coal are no longer of much importance. Fossil natural gas, on the other hand, remains the most important source of chemical energy even if energy-related carbon emissions are reduced by 90 percent. Hydrogen plays a similarly important role, regarding both its direct use and its further conversion to synthetic hydrocarbons. In the model calculations, depending on the boundary conditions, between 50 and 200 terawatt hours of hydrogen are generated, different shares of which are used for a further conversion to synthetic fuels. Hence, the quantity of hydrogen produced exceeds the value shown in the figure, since the illustration only depicts the amount of synthetic fuel.

Hence, in the medium and long term, our energy industry will require a new branch: large, multi-megawatt factories for the production of hydrogen from renewable power and, possibly, for the further conversion of this hydrogen to carbon-based synthetic energy carriers. Today, large-scale plants in the chemical industry are run, if possible, around the clock in order to ensure a high utilisation rate of the installed systems and thus a cost-effective operation. From a systemic point of view, however, hydrogen plants should be exclusively operated with power from renewable sources and not from power plants using fossil fuels, biomass or synthetic energy carriers. However, system simulations realised on the basis of hourly values show that it is systemically favour-

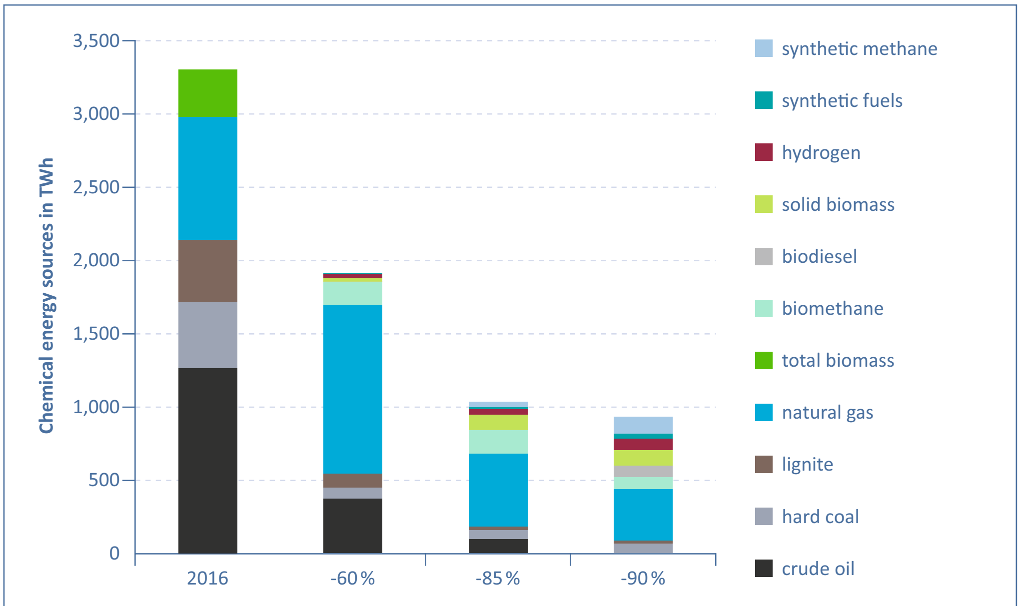

Figure 12: Mixture of chemical energy carriers (including biomass) in 2050 according to the model calculations. The illustration shows the results of three selected model calculations with different target values of energy-related carbon emissions (three right-hand bars) and the mixture in 2016* (left bar).

*Based on: Energy data – facts and figures, BMWi 2017-3. The figure shows the primary energy values for 2016. For biomass, the indicated energy content refers to the basic materials, whereas the model calculations use the energy content of the energy carriers produced.

able if electrolysis systems are not limited to the direct use of power from wind and solar plants, but can also resort to power from short-term storage systems (battery storage units and pumped storage power plants). Depending on the other assumptions and boundary conditions, electrolysers will thus run for 2,000 to 4,000 full-load hours per annum. As in the case of reserve power plants, appropriate market conditions are necessary here too in order to enable the profitable operation of these electrolysis systems. However, it will be important to plan the necessary infrastructure at an early stage and to create a sales potential for the generated products. At the same time, market integration must be realised, taking into account not least the existing dependencies in the energy sector.

Facilities for the further conversion of hydrogen and carbon dioxide into gaseous or liquid synthetic energy carriers can achieve an even higher utilisation rate, since hydrogen is comparatively easy to store. Against this background, locations with such geological conditions as will allow for the underground storage of hydrogen seem particularly convenient for the construction and operation of the corresponding facilities.

2.7.3 Import of synthetic combustibles and fuels

The results presented above are based on the assumption that the climate protection targets Germany has set for itself will be achieved primarily by resorting to renewable energy sources that can be used in Germany. Globally, there are many locations with considerably more favourable meteorological conditions for the use of renewable energies – i.e. significantly higher solar radiation or much higher average wind speeds. At such locations, plants for the production of hydrogen and synthetic chemical energy carriers could be operated at considerably higher utilisation rates. In principle, the production costs could thus be significantly reduced.[87]

However, such a solution involves considerable political uncertainties. A high share of imports could, for instance, create new dependencies – especially on countries that might be eligible as producers, but must, at the same time, be considered as politically rather unstable.[88] In this context it should be borne in mind that Germany still imports around 70 percent of its primary energy – in some cases from unstable countries (data from 2016).[89] The production and logistics infrastructure for new import goods would have to be coordinated and developed with the producer countries. However, such a supply can entail new trade flows and thus lead to closer trade relations between Germany and the respective countries.

2.7.4 Conclusion

Today, fossil energy sources constitute the main pillar of our energy system. Even if we succeed in switching a number of applications that currently run off of fossil energy sources to a direct use of power, chemical energy carriers will remain important in many areas. Given their limited potential, biomass-based energy sources will not be sufficient. Insofar, synthetic energy carriers produced with electricity from renewable sources will be an indispensable element of a future climate-friendly energy supply – in Germany and worldwide. Here, the electrolytic production of hydrogen plays a key role, since it is also the first step of all conceivable further processes for the production of fuels on the basis of hydrocarbons.[90] Our aim must therefore be to establish the

87 Ausfelder et al. 2017, chapter 5.3.6.

88 In the raw materials industry, the so-called weighted country risk is used to assess the delivery risk for raw materials. Such estimates could likewise be helpful in assessing the risk in this case. Cf. DERA 2016.

89 Evaluation tables for the energy balance in Germany (AGEB 2017-2).

90 The 2017 publication by Emonts et al. 2017, for example, presents the role of hydrogen as a flexible energy storage medium and a fuel.

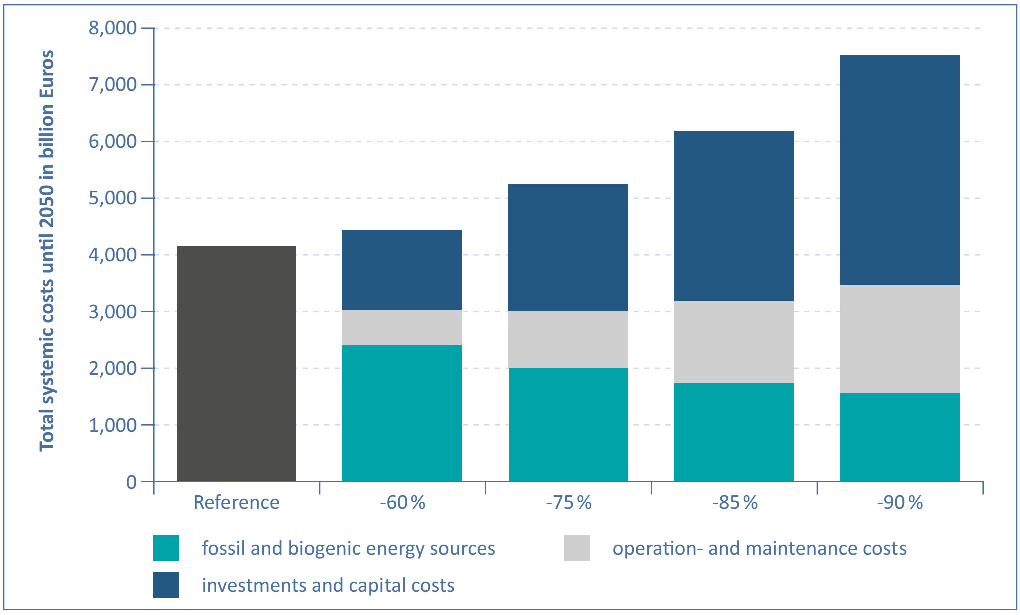

Figure 13: Total systemic costs until 2050 for different systemic developments differing with respect to the target values for the reduction of energy-related carbon emissions

technological basis as soon as possible and develop the processes that are relevant from today's perspective. Their subsequent application in pilot plants should then allow for the rapid achievement of a high level of maturity. In addition, the framework conditions should be adapted as soon as possible so as to make the production of hydrogen and synthetic energy carriers compatible with system requirements and be economically profitable.

2.8 Costs of the energy transition

The costs are one of the central issues in the discussion of the pros and cons of the energy transition. Determining the „right" cost dimension is by no means easy, since many different cost definitions are conceivable. The model calculations carried out for this analysis attempt to sum up the total systemic costs for the energy transition. They include all expenses for the maintenance, or indeed transformation, and operation of the energy system from today until 2050[91]: investments in new plants and replacement of old plants, financing costs for investments, costs for fossil and biogenic energy sources and other operational and maintenance costs for all plants. The costs for important efficiency measures such as the energetic refurbishment of buildings are likewise considered. On the other hand, external costs, i.e. costs that are not reflected in the price the end customer pays for energy, but that are borne by society as a whole, were deliberately excluded. The same goes for taxes. By comparing such summary costs with a reference development featuring no climate protection goals, we can determine a cost difference that is due to our efforts to implement the climate protection goals. Therefore, a reference scenario was chosen in which energy-related carbon emissions are reduced by 40 percent by 2030, and then remain at that level until 2050.[92]

Figure 13 shows the total systemic costs for several model calculations differing with respect to the target values for the reduction of energy-related carbon emissions. The total systemic costs are strongly dependent on the permissible amount

91 2050 was used as target year, since it coincides with the target year the Federal Government has set for the achievement of the climate protection goals.

92 Further information on the assumptions can be found in Ausfelder et al. 2017.

of carbon emissions. While a reduction of 60 percent entails an increase in the total costs of 7 percent, an additional 2 trillion euros would be necessary to reach climate protection targets (85 percent) by 2050. This corresponds to an increase of 50 percent. The value equates to an average of some 60 billion euros per annum over the next 33 years, which corresponds to just under **2 percent of the German GDP** in 2016.

However, if 90 percent of energy-related carbon emissions are to be saved, the additional costs could amount to more than 3 trillion euros compared to the reference development. Such disproportionate climate protection efforts could become necessary if the energy sector has to compensate for lacking reduction potential in other areas, for example in the agricultural sector, in order to achieve the political target of reducing the total greenhouse gas emissions in Germany by 80 to 90 percent.

Since it is unclear how the costs for the different technologies will develop until 2050, estimates as to the total costs are always fraught with uncertainty. The prices for fossil energy sources also play a role, especially for the comparison with the reference system. Here it was assumed that the prices would remain at the current, very low level until 2050.[93] Nevertheless, the figures presented above leave no doubt that with the energy transition, society is facing an encompassing large-scale project, the economic dimensions of which rival the German reunification.[94] This makes it all the more important to steer the implementation by means of judicious framework conditions and to ensure a maximum of economic efficiency in order to avoid unnecessary additional costs.

In the model calculations with 85 and 90 percent reduction of energy-related carbon emissions, the following instances account for more than half of the additional costs: investments in wind power and photovoltaic systems, storage facilities, energy conversion systems such as electrolysers, grids, new consumer devices such as electric vehicles and heat pumps, and the refurbishment of buildings. Once the transformation of the energy system is completed, this large investment volume will decrease and hence be limited to the replacement of facilities that have reached the end of their service life. Beyond 2050, the costs of a transformed energy system, in which renewable sources account for the bulk of the energy supply, will insofar be significantly lower than during the transformation phase.

The represented costs do not take account of economic aspects such as local value added, employment effects and export opportunities. Since the required technologies are likely to gain in significance around the world, technological expertise in this field is of major importance for a high-tech country like Germany, whose economy relies heavily on technology exports and therefore a great asset.

2.9 Phases of the energy transition

Quantitatively, the extent to which the energy sectors are coupled can be defined by the share of direct power used in the heat and transport sectors and for the generation of hydrogen (for use as final energy or for further conversion to synthetic fuels). The model calculations show that the direct use of power – for instance in electric vehicles and heat pumps – will play an important role in the near future (cf. Figure 14). As of 2030, the production of synthetic energy carriers from electricity will likewise gain in importance.

93 How the prices for oil, natural gas and coal develop depends not least on the success of international climate protection: A limitation of permissible carbon emissions would tend to devalue these energy sources and push their prices down. It might therefore be necessary to reduce the costs of fossil fuels in all scenarios, which would increase the differences between the reference and the reduction scenarios.

94 In the context of the 25th anniversary of the German reunification, similar “cost” values of 2 trillion euros were specified (cf. e.g. Hansen 2014).

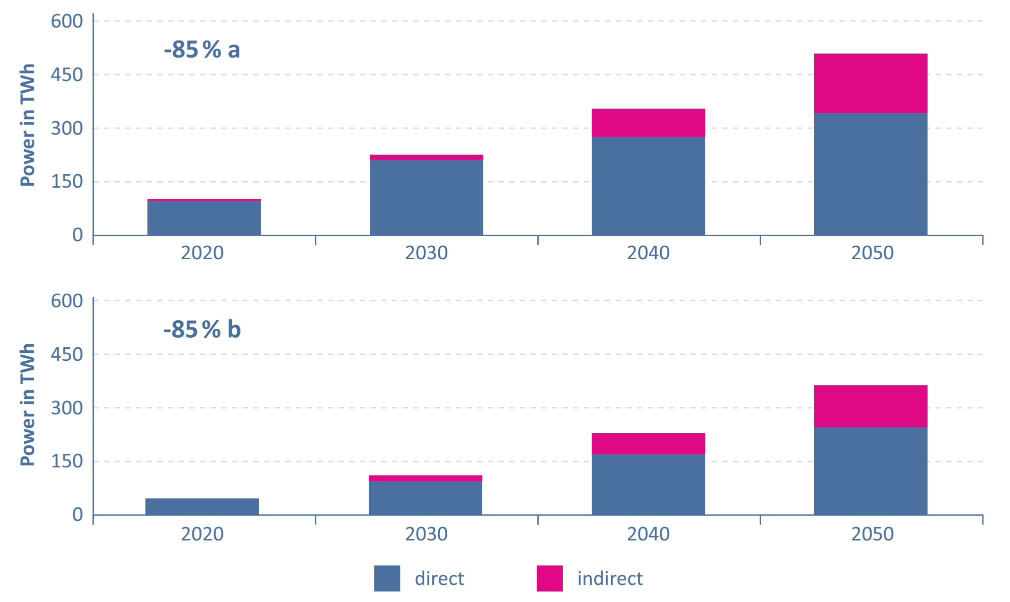

Figure 14: Development of the power demand for "the coupling of the energy sectors" in the model calculations, with a reduction of energy-related carbon emissions by 85 percent. A distinction is made between the power demand for direct power use in the transport and heating sectors and for indirect power use for the production of synthetic energy sources. Above (-85% a): free optimisation, reduction by 85 percent; below (-85% b): Model calculation with different assumptions that greatly facilitate the achievement of the reduction targets/reduction by 85 percent.

Overall, the analysis of possible pathways for a transformation of the energy system under the conditions of the (politically determined) climate protection targets results in the identification of four essential structural phases. Each phase has specific requirements and characteristics (cf. Figure 15).

Phase I, which is largely completed today, covers the past 25 to 30 years. It was characterised by substantial technological developments in the field of photovoltaics and wind energy use, as well as in biomass technologies or components of energy-efficient construction. For all of these technologies, the developments led to substantial cost reductions – in some cases on a very large scale –[95] thus creating the conditions necessary for a transformation of the energy supply towards a system based predominantly on renewable energy sources and the efficient use of energy. At the same time, a significant expansion of renewable energy sources for power generation was launched. It is obvious that a continued expansion of these power generation plants will require a comprehensive systemic integration.

In the upcoming **phase II** of systemic integration, technologies for the direct use of power, such as heat pumps and electric mobility, are beginning to gain in importance. The same goes for short-term storage systems for electricity (batteries) and heat. At the same time, both the electricity generation in power plants and the energy consumption must increasingly be adapted to a volatile power supply. In all application areas and sectors, potentials for the flexible use of power must be developed and incentives created for the operation of plants and appliances according to systemic requirements. In addition, the increasingly complex energy market must be reorganised to include a considerably higher number of participants, not least on the producer and supplier side, while continuing to be run safely and reliably. In addition to an adapted market framework, this also requires the development of according technologies and standards for successful market management.

95 REN21 2014.

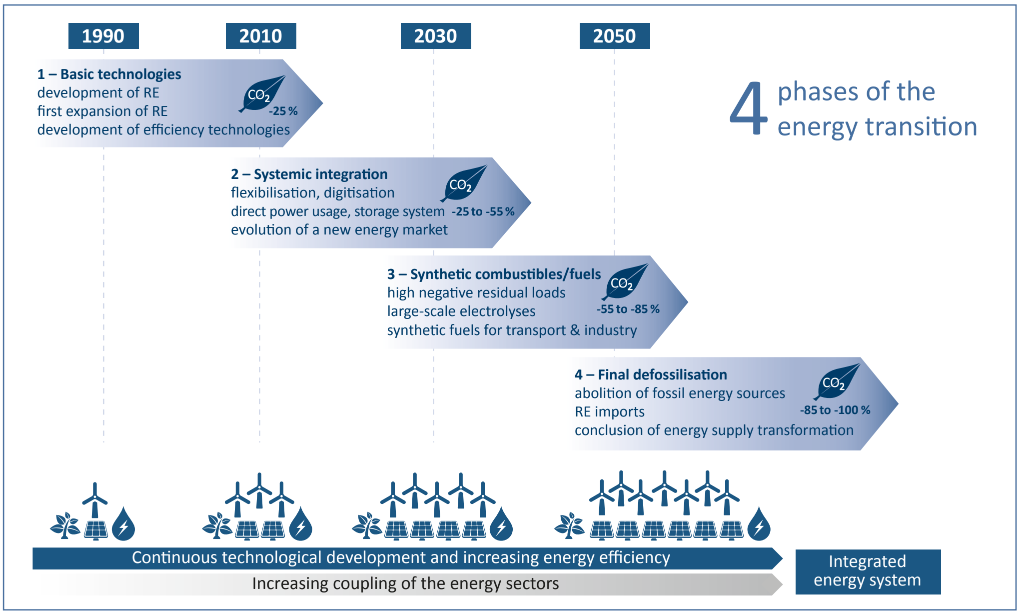

Figure 15: The four phases of the energy transition

Phase III of the energy transition is characterised by the large-scale production of hydrogen and its use in the energy system. This is necessary for two main reasons: On the one hand, not in all applications is a direct use of power easily realisable. On the other hand, the further expansion of fluctuating renewable energy sources increasingly brings about periods during which such large amounts of electricity are generated that short-term storage and load management are insufficient to utilise them. By expediting the development and trialling of the eligible technology options in research and pilot projects today, we can ensure their availability when their large-scale application is required.

In **phase IV**, fossil fuels will finally be eliminated from the system for good. From today‘s perspective, it may be questioned whether Germany is likely to achieve a completely self-sufficient energy supply from renewable sources. The importation of power or chemical energy carriers produced with renewable energies from countries with a greater potential for solar and wind energy could not only reduce the costs of the energy transition; more specifically, it could contribute to limiting the expansion of wind power to a socially acceptable level. Obviously, the phases described cannot be separated very clearly, since the transition from one to the next is gradual. Above all, continuous progress is necessary if the desired goals are to be achieved – regarding the expansion of renewable energies as well as measures to reduce energy consumption, such as energetic refurbishment of buildings.

3 Political framework conditions and regulatory elements

With the integration of energy from renewable sources into all sectors, the energy transition in Germany is entering into a new phase. In order to ensure that scarce climate-friendly energy sources are indeed used where they are most expedient and economically efficient, the political framework conditions must be adapted.

Against the backdrop of the politically set climate protection goals, the previous chapter enumerated such elements of the transformation of the energy system as seem important according to an overall systemic and cost optimisation aspect. This applies, for example, to the use of power-based supply systems on the user side, the use of short-term storage devices or other measures for a more flexible use of power. Without a market framework that encourages an expedited implementation of these supply measures, it will be difficult to enter this next phase of the energy transition in the necessary scope. With a view to the increasing interaction between and merging of the different sectors of the energy system, it appears both logical and necessary to determine a common price signal for carbon emissions in all sectors. This would allow for energy sources and technologies currently subjected to very different market environments to compete under equal conditions. Where this is insufficient, additional measures may be required, for instance in the field of technology promotion and infrastructure development. In specific areas, regulatory provisions might likewise be considered.

Today, the energy markets are subject to very different laws and regulations: The levies, duties and taxes on electricity are much higher than on petrol, diesel, natural gas and heating oil.[96] However, different regulations and pricing systems hamper the necessary increased coupling of the energy sectors and hence the closer interlinking of the power, heat and fuel markets. Together with other obstacles, this impedes a greater use of power in the heating and transport sectors.[97]

An appropriate market design is a crucial, overarching element to make the development of the energy system along the path defined by the climate protection goals as cost-effective as possible. Such a market design must allow for competition between the different energy sources and technologies (including their respective climate-damaging effect) under the same conditions (level playing field). This would require a consistent carbon price signal for all sectors, if possible throughout Europe. Since such a policy would uniformly increase the price for fossil fuels, technologies using energy from renewable sources would reach competitiveness more quickly

96 Since Germany levies no carbon tax, the actual pricing of the carbon emissions produced by different energy sources can only be compared implicitly. In the study *"New price structures for the energy transition"* (Agora Energiewende 2017-1), Agora Energiewende refers, for instance, to the following figures: Due to the EEG levy and the power tax, the implicit price for carbon emissions from electricity amounts to €185/t, while the eco-tax results in an implicit price of €58/t for diesel, €65/t for petrol, €19/t for natural gas and €8/t for heating oil.

97 The expert commission on the Federal Government's monitoring process "Energy of the Future" concludes that the current promotion of renewable energies is incompatible with endeavours to couple the energy sectors, since it makes power less attractive than fossil energy sources (Expert Commission on the monitoring process "Energy of the Future" 2016, p. Z-6).

and would be used in those fields (sectors) where they can achieve the greatest possible impact in terms of carbon emissions reduction at the lowest possible cost.

Such a **technology-neutral approach** has the advantage that the most cost-effective emission abatement technologies are chosen. The methods for the emissions reduction are numerous and varied.[98] Technology-neutral regulatory instruments will also react flexibly to unexpected new technologies, enabling the latter to compete with the established technologies in the markets. If, on the other hand, the "order of use" of emission abatement technologies is determined by technology-specific regulations, the legislator would need to know in advance at what time which abatement technology will be most cost-effective. Since this would make it more difficult to react to unforeseen developments such as technology leaps, it would imply the risk of higher economic costs than necessary. A multitude of fragmented, technology-specific regulations, such as we currently have, therefore obliges the legislator to constantly adjust various different points in order to compensate for distortions. Such compensation is often encumbered by the fact that a measure once introduced is difficult to abolish. Experience shows that fragmented or frequently modified regulations will also diminish the readiness to undertake long-term investments in infrastructure or complex technological developments.

In order for the carbon price to incentivise investments in climate-friendly technologies, it is crucial that the political decisions with regard to climate protection targets can be relied upon.[99] For the stakeholders of the energy system will not invest unless they have planning security regarding the permanence of the carbon prices. It is therefore essential for the political echelons to firmly commit to climate protection and for the stakeholders to trust in the binding nature of the climate protection goals.

98 Whereas, for instance, an efficiency standard for passenger cars merely aims at increasing the emissions efficiency of combustion engines, a carbon price signal in the transport sector incentivises the emissions efficiency of drive systems as well as a less frequent use and the switch to modes of transport with lower emission rates (electric vehicles, public transport, etc.) (Flachsland 2011).

99 Cross-sectoral climate protection instruments should therefore not least be provided with a sufficiently strong institutional basis. The EU ETS, for example, is incorporated into the European Union Treaties. The fact that the exit of an EU member state would entail complex renegotiations of the European treaties provides the EU ETS with a comparatively stable institutional base.

However, a uniform carbon price is not a magic bullet. For numerous investments and purchasing decisions, the energy price is not the only pivotal factor. The energy industry therefore requires **complementary instruments** to address distributional impacts or market failures and to avoid lock-in effects.[100] Additional policy measures may also be induced by endeavours to preserve or create added value in Germany and Europe. For instance, problematic distributional effects could occur for low-income households, were the heat supply to become very expensive due to an adjustment of the charges on diesel and (the chemically equivalent light) fuel oil at a high level. **Market failures** could occur for several reasons. These include a disparity between the market participants regarding their knowledge of relevant regulations (information deficits and asymmetries),[101] disparities between long-term economic benefits and short-term amortisation prospects for companies and households, or inadequate private incentives for the expansion of infrastructures or investments in research and development. In addition, supplementary instruments can also take external costs such as local environmental impacts and/or pollutant emissions into account.

The complementary instruments include technology promotion, a government-controlled and possibly co-funded infrastructure development and regulatory provisions (such as limits for energy consumption or admissible emissions, or the harmonisation of technical standards). However, a consistent carbon price should nevertheless be the primary instrument of climate policy and double regulations should, if possible, be avoided. Hence, additional tools are subject to a scrutiny reserve: Their necessity, effectiveness and cost-benefit-ratio should be subject to a constant evaluation. Also, the instruments should be designed so as to allow for readjustments.

Overall, the legislator faces the task of weighing technology neutrality against the risk of lock-in effects jeopardising climate protection goals. In addition, a redesign of the measures should bear a variety of other aspects in mind: These include possible effects in the fields of social policies and employment, the necessity of well-balanced adjustments to tax regulations affected by energy policy measures, or the aim to achieve more reliability and longer-term predictability with the revised regulatory system. In this context, we require not least a constant dialogue with the public in order to assess how political goals can be achieved. Such a discourse needs to be actively organised. Economic efficiency, although the focal point in the present paper, is hence not the only criterion to be considered in this process.

3.1 Options for the establishment of a consistent price signal

There are different ways to realise a consistent carbon price signal. An obvious solution would be to take the European Emissions Trading System (EU ETS) further, since it already provides a pricing system for carbon emissions. Alternatively, a carbon tax could be considered – raised either at the EU level or, in addition to the European emissions trading scheme, at the national level.

A carbon tax will fix the price of emissions; however, it is left to the market to determine their quantity. Compared to emissions trading, this reduces the price

100 Lock-in effects are barriers that make it difficult to leave a path once taken. They may arise, for instance, if, due to an underestimation of the future development of the carbon price, further investments are made in technologies based on fossil fuels. Once an investment has been made, the respective facility will remain in operation, if possible until the end of its technical life – even if subsequent developments prove that another, lower-emission alternative would have been more profitable. If the carbon price rises above a certain level, facilities resulting from these bad investments might be switched off at additional economic costs.

101 A possible example is homeowners who, not being sufficiently informed about the future price development of fossil fuels, decide to invest in a heating system that will become expensive in the long term.

risk for companies, but entails the risk of missing the reduction target altogether. The situation in Canada illustrates that such a decision can be controversial: Whereas some Canadian provinces have decided to introduce an emissions trading scheme, others have opted for a carbon tax.[102]

However, even with an extension of the EU ETS or the introduction of a national carbon tax, the objective of a level playing field would only be achieved if, at the same time, the existing tax system were subjected to a comprehensive reform. This would particularly concern the heterogeneous carbon pricing of fossil energy sources found in different areas of application and sectors (cf. reform of the eco- and electricity tax) and the promotion of renewable energies, for example via the German Renewable Energy Sources Act (EEG). Today, electricity is fraught with a multitude of taxes, duties, levies and charges: In 2016, they accounted for well over three-quarters of the final electricity price. As a result, the implicit carbon pricing for different fossil fuels varies widely in the different sectors.[103] As a consequence, the regulatory effectiveness of the climate and energy policy instruments used is controversial.[104]

How high the carbon price should be in order to serve as an effective climate policy instrument was not examined in the present study. In its 2017 report, the “High-Level Commission on Carbon Prices” analyses what carbon price would be required globally to achieve the goals of the Paris Climate Agreement while simultaneously fostering economic growth and development according to the “Sustainable Development Goals” (SDGs).[105] The expert group concluded that a price of at least 40 to 80 US dollars per tonne of CO_2-equivalent (equating to about 35 to 70 euros per tonne) would be necessary by 2020, which would increase to at least 50 to 100 US dollars per tonne (equivalent to about 40 to 85 euros per tonne) by 2030.[106]

The authors emphasise that the success of such an instrument crucially depends on a highly reliable political framework, transparency and a high degree of predictability. Nevertheless, the price should be adjustable, so that future developments such as learning effects or technological evolutions can be taken into account. Such adjustments would have to be comprehensible and transparent. Policies should be “predictably flexible”.

102 Government of Canada 2017.

103 A reform of the existing tax system could also take into account that the use of fossil fuels can generate external costs that would not be covered by carbon prices (local pollution, congestion, cf. e.g. Parry/Vollbergh 2017) and that low carbon technologies likewise incur costs for society, for example due to infrastructure requirements (roads) or environmental impacts (particulate matter).

104 A detailed discussion can be found in Ausfelder et al. 2017; cf. also: Haucap 2017.

105 CPLC 2017.

106 In the model calculations presented in this paper, the carbon prices that would be required for the chosen reduction paths were not calculated directly. On the basis of the systemic costs and the avoided amounts of carbon emissions, it is, however, possible to estimate the emission abatement costs for the entire period until 2050 for the different reduction paths (cf. Ausfelder et al. 2017, chapter 5.3.4). The abatement costs range from around 60 euros per tonne (in the model calculation with an 85 percent reduction of energy-related carbon emissions and various assumptions facilitating the achievement of the reduction targets) (cf. also Section 2.4), and 400 euros per tonne (in the model calculation with a 90 percent reduction of energy-related carbon emissions and without assumptions facilitating the achievement of the reduction targets). Hence, if lower climate protection targets are assumed, the values range at a similar level as the carbon prices determined by the expert group; with more ambitious climate protection targets, however, they are significantly higher. An important aspect in this context is that the model calculations focus exclusively on Germany: As a rule, predominantly national solutions come at higher costs than internationally coordinated solutions. By international standards, moreover, Germany does not have the best local conditions for renewable energies. In general, it should be noted that due to the many assumptions used in the calculations, the absolute values are fraught with uncertainties. The relative comparison between those model calculations with similar assumptions, on the other hand, is more robust.

3.1.1 Expansion of the European Emissions Trading System

With the European Emissions Trading System, we have already implemented an instrument for carbon emissions pricing across Europe. However, it is, at present, limited to larger industrial facilities: power plants with a combustion performance of 20 megawatts or more and a few industrial sectors. This covers only about 45 percent of the greenhouse gas emissions in the energy sector in Europe.[107] The emissions from the transport sector (with the exception of air traffic), and the bulk of heat generation are not included. In order to send an effective price signal for the coupling of the energy sectors, the EU ETS would have to be extended to include all emissions generated by the energy sector.

In principle, emissions trading hits the ecological mark very accurately compared to other mechanisms: The amount of emissions allowances is specified, and their market price determined according to supply and demand. It is therefore assured from the outset that a predetermined amount of carbon emissions is not exceeded. Empirical studies indicate that in Europe, companies participating in emissions trading have not only reduced their emissions compared to control groups and reference scenarios, but have partly even switched to lower emission technologies.[108] How far the originally issued amount of emissions allowances is compatible with national climate protection targets is unclear, since the number of certificates is fixed according to political compromises.

Economically, moreover, a coordinated European approach is particularly efficient, since emissions reductions can be realised across national borders wherever they are most cost-effective.[109] To that extent, the improvement and extension of the EU ETS would be an obvious solution. However, redesigning or expanding the EU ETS would require better coordination between the national and European levels.

If the EU ETS is currently under fire, this is mainly due to the very low allowance price of less than 5 euros per tonne. On the one hand, the system has succeeded in cost-efficiently fulfilling its central task, i.e. keeping the emissions of industrial facilities subject to emissions trading beneath the specified limit.[110] On the other hand, the amount of emissions allowances issued in recent years exceeds the present demand by far, resulting in a “surplus” of some 1.5 billion certificates (this almost equals the number of certificates issued throughout Europe in one year).[111] The large amount of these “surplus” certificates and the ensuing low price are not least a consequence of the expansion of renewable energies and the lacklustre economic development in many EU countries. Whether the low certificate price provides sufficient signals for the long-term transformation of the energy system is, however, unclear. If early investments in abatement technologies and research and development are to be stimulated, the signalling effect of the EU ETS would probably have to be significantly stronger.

Whether the market stability reserve, which the EU has planned as of 2019 in order to reduce the existing certificate surpluses will, in the short term, lead to a substantial price increase is controversial. Very likely, the market players have long

107 EC 2016.

108 These studies are discussed more closely in Ausfelder et al. 2017, chapter 6.

109 In the medium term, the EU ETS could moreover be linked with emissions trading systems in other countries and regions. At present, 35 countries have emissions trading systems at different administrative levels (ICAP 2017). The introduction of the national emissions trading scheme in China in 2017 will create the world‘s largest market for emissions allowances.

110 Statement of the Expert Commission on the Monitoring Process “Energy of the Future” 2016, p. 25.

111 The companies can use any certificates they do not employ immediately in later years. Due to this so-called “banking”, the issue of certificates does not necessarily coincide with their use.

anticipated the planned temporary withdrawal of certificates and included it in their price structure.[112] Therefore, further, complementary measures are being discussed or have, in some instances, already been adopted:

- A further increase in the annual reduction factor[113] to expedite the reduction of available allowances.
- The permanent withdrawal of the 900 million certificates held back between 2014 and 2016.[114] The transfer of these allowances into the market stability reserve de facto fulfils this requirement[115] – as long as the reserve remains intact.
- An expansion of emissions trading to all sectors and carbon emissions; this would not least endorse the increasingly necessary coupling of the energy sectors by means of a cross-sectoral price signal. When deciding on the amount of allowances that would have to also be provided for the newly integrated sectors, the existing certificate surplus could be taken into account.
- The introduction of a price corridor consisting of a minimum and a maximum price for emission certificates.[116] While the introduction of the market stability reserve will also serve to reduce price fluctuations, a fixed price ceiling and floor is not scheduled.

The first three approaches are purely quantitative, resorting only to the amount of allowances to adjust the system. A price corridor, on the other hand, would combine the benefits of quantitative control and price control: While emissions trading would continue to set the annual limit for emissions, a minimum price, for example in the form of a mark-up, could guarantee a basic incentive for emissions reductions. A price ceiling, on the other hand, would protect companies against price peaks. The price corridor could thus reduce uncertainties with regard to price development until 2050 and give companies higher planning security.[117]

Once a comprehensive reform has been completed, further readjustments should be weighed against the risk of creating more uncertainties for the companies subjected to the ETS. In order to achieve long-term predictability, the climate goals for the subsequent trading periods until 2050 could be institutionalised more strongly with reference to the overall Europe-wide reduction target for 2050 (80 to 95 percent against 1990).

Currently, certificate trading revolves around the emitters: Around 11,000 power generation plants and manufacturing facilities are subject to compulsory emissions trading.[118] An inclusion of the heat and transport sectors[119] into the EU ETS would entail a dramatic increase in the number of emitters subject to emissions trading. After all, the number of passenger cars registered in Europe in 2015 alone amounted to 252 million.[120,121] A system obliging every owner or operator of a heating boiler or

112 acatech/Leopoldina/Akademienunion 2015; Euro-Case 2014.

113 The reduction factor reduces the total amount of allowances issued per annum. An increase in the annual reduction factor to 2.2 percent is already planned for the fourth trading period (2021 to 2030). This would contribute to meeting the pan-European reduction target for 2030 (40 percent compared to 1990) and reduce the emissions covered by the EU ETS by 43 percent compared to 2005 (EC 2017-1).

114 EC 2017-2; Andor et al. 2015.

115 EC 2017-2.

116 acatech/Leopoldina/Akademienunion 2015.

117 To ensure that the price corridor does not distort the quantity-based pricing (and does not lead to inefficiencies in the overall system), the price limits must be carefully set.

118 acatech/Leopoldina/Akademienunion 2015.

119 The inclusion of the agricultural sector in the emissions trading system is also discussed. This, however, is not the subject of the present policy paper.

120 To this we must add the operators of aircraft on long-distance flights.

121 ACEA 2017.

vehicle to participate in emissions trading would not only be hugely expensive, but barely administrable. A possible solution would be to convert the EU ETS into a so-called upstream system. This would transfer the responsibility to the producers and importers of fossil energy sources. In that case, only some 1,000 stakeholders – such as refineries and oil importers – would be required to hold the emissions allowances.[122] The costs would then be, as far as possible, passed on along the customer chain to the end consumer in order to incentivise according behavioural or production adjustments at that level.

While emissions trading is expanded, sector-specific instruments such as the German Renewable Energy Sources Act (EEG) and energy taxes (for example the eco-tax), which also aim at reducing carbon emissions, could be phased out. The ensuing drop in government revenues would have to be compensated otherwise, unless the according sums are covered by other levies. Moreover, energy taxes have other functions in addition to the reduction of carbon emissions: Besides the eco-tax share, the energy tax on petrol and diesel, for instance, contains a purely fiscal component raised to cover the costs of road construction and maintenance. If the eco-tax were abolished, such costs might be passed on to all vehicles regardless of the drive system – including electric vehicles.

In part, the inclusion of other sectors into the EU ETS is even supported by stakeholders from the sectors in question.[123] With a view to the anticipated price increases, however, we must also expect resistance, especially from the energy-intensive industry. To what extent the effects of emissions trading should be reduced for companies in order to prevent their migration or to mitigate serious competitive disadvantages, is controversial. Currently, companies are extensively compensated for these burdens via the free allocation of allowances. Indeed, surveys show that in some cases, overcompensation occurs or that industrial sectors receive free allocations despite an extremely low migration risk.[124]

A reallocation of the free emissions allowances centring on actually affected companies is therefore an option to overcome resistance and prevent distortions in the effect of the EU ETS. Alternatively, a level playing field could be created by imposing a tax on particularly emission-intensive imports (border tax adjustments).[125] However, such a procedure would need to be compatible with international trade agreements.

At the political level, an expansion of emissions trading is likewise expected to meet with opposition, particularly from Eastern European EU member states fearing economic disadvantages. However, acceptance of an extension of the EU ETS could be increased by redistributing revenues from the auctioning of emission certificates.[126]

It must also be examined to what extent low-income households would be additionally burdened. Revenues the EU ETS generates by selling emissions allowances could be specifically used both to support structural change in particularly affected countries and to mitigate additional burdens on low-income households.

122 SRU 2008; Flachsland et al. 2011.

123 The German Association of the Automotive Industry, for instance, advocates the integration of the transport sector into the EU ETS (VDA 2017).

124 Martin et al. 2014.

125 Border adjustment taxes tax goods in the country of consumption (destination principle) in order to offset competitive inequalities (due to different tax burdens).

126 Whereas several experts consider a reorganisation of the EU ETS unlikely, owing to the divergent interests of individual countries in Europe (cf., for example, the Expert Commission on the Monitoring Process “Energy of the Future” 2016), other committees underline that an agreement in Europe could be achieved by means of transfer payments (SVR 2016).

Such a realignment of the current climate protection policy would have the particular benefit of reducing economic inefficiencies. The government could, for instance, use the resulting financial margin for investments in infrastructure projects. It is also vital that not only the costs, but in particular the various benefits of climate-friendly technologies (environmental protection, possible positive social and economic effects) are empirically processed, made transparent and actively communicated.

3.1.2 Introduction of a carbon tax

A possible alternative to extending emissions trading could be the introduction of a carbon tax. This could either be realised at the European level as a substitute for or supplement to the EU ETS, or else in addition to the EU ETS at the national level.[127] As in the case of emissions trading, a European carbon tax would be preferable to national solutions. However, since the EU has already opted for the emissions trading system, the introduction of such a tax at the European level is unlikely. The fact that the Council of the European Union must decide unanimously on tax issues is a further impediment.[128] Complementing emissions trading with national measures (such as have already been discussed or indeed introduced in some European countries),[129] therefore seems to be the more realistic option.

A carbon tax has the particular advantage of allowing for greater planning security with regard to the development of the carbon price. For even in a cross-sectoral emissions trading system (without a price floor) we would still be facing a double risk: a) that low certificate prices might be insufficient to incentivise investments in energy efficiency, renewable energies and technologies for the coupling of the energy sectors; and b) that a relatively high degree of uncertainty about the development of certificate prices would ensue. The clearly predictable price development a tax (or a reformed EU ETS with a price corridor) could ensure, on the other hand, would send a positive signal to the industry to engage in the (further) development of green technologies early on. A possible disadvantage might be that carbon taxes do not react to economic fluctuations: Even during a recession, they remain a stable cost factor for a company. Allowance markets, on the other hand, react to changes in the economic situation. In times of recession, the demand for certificates and thus the carbon price will drop accordingly, which reduces the burden on the companies.

Revenues from carbon taxes are more predictable for the government, too. This gives political decision makers a certain range to reduce inefficient energy and climate policies and thus promote a gradual simplification and harmonisation of climate regulations. Elements of such a tax reform could include the abolition of the electricity tax and a reform of the energy tax – similar to the measures an expansion of the EU ETS could involve. Such a reform package might likewise include the abolition or further reform of the promotion of renewable energy solutions. A main objective of the EEG, i.e. changing the relative prices in favour of renewable energies, would also be achieved by means of a carbon tax. In addition, carbon taxes, like emissions trading, precisely record the carbon content of various fossil energy sources and thus provide efficient incentives for reducing emissions.

127 This is recommended, for instance, by the Expert Commission monitoring the energy transition (Expert Commission on the monitoring process "Energy of the Future" 2016) and other experts (cf. e.g. WWF 2014, Schultz project consult 2017, BEE 2017).

128 EU 2017.

129 Whereas in the United Kingdom, for instance, fossil fuel power generation is sanctioned with a surcharge on the energy tax, the Netherlands subjects the use of fossil energy sources to taxes (Energy Tax) corresponding to their CO_2 content (FOES 2014). Sweden, too, has been raising a carbon tax since the 1990s.

Even if the tax reform were to be revenue-neutral, it would ease the burden on the economy, since the costs of emissions reduction would be distributed more efficiently. There would naturally still be winners and losers compared to the current situation. Nevertheless, considerable resistance against the additional tax burdens would have to be expected from parts of the industry. When Sweden introduced a general carbon tax in 1991, this resistance was countered by substantial tax rebates for the industry.[130] This, in turn, mitigated the efficient distribution of the costs of emissions reductions, severely limiting the equalising effect of the tax. A carbon tax aiming to combine short-term economic viability and social acceptance with the achievement of long-term climate targets would need to be progressively developed over time. As in the case of an extension of the EU ETS, disadvantages in international competition could possibly be compensated by a taxation of particularly high-emission imports (border tax adjustments).

Acceptance could be increased by the fact that the distributional effects of a carbon tax are lower than under the EEG.[131] However, as in the case of an extension of the emissions trading scheme, it would have to be carefully examined whether and to what extent the additional burdens a carbon tax would imply for low-income households could be compensated by accompanying measures. Without compensatory measures, an increase in the consumer prices for natural gas and oil, which, in 2017, still accounted for 70 percent of the space heating in German households,[132] could lead to unacceptable additional costs for the economically weakest households and at the same time undermine the acceptance of the energy transition.

Since the introduction of a European carbon tax is not to be expected, a consistent **national carbon tax** would be an option. Such a tax would have a direct impact on emissions in Germany in the sectors not yet covered by the EU ETS (heat and transport sector) and thus also on the European carbon emissions rate. However, to what extent such a supplement to emissions trading would be of economic and ecological use in the sectors already covered by the EU ETS, critically depends on its design. For this, there are various different possibilities with corresponding advantages and disadvantages:

1. A national carbon tax could be imposed only on emissions that are not covered by the EU ETS. Tax rates could be linked to the prices of the EU emissions allowances and their development. This would allow for a standardisation of the carbon price in all sectors (EU ETS and non-EU ETS) and thus create a level playing field (disadvantages: the uncertainty regarding the development of allowance prices would be reflected in the development of the tax rates; and as long as allowance prices are low, the tax rates and thus emissions prevention would likewise be so).[133]

2. Alternatively, a tax could be levied on all sectors, designed so as to reach at least the level of the certificate price and differentiating between ETS and non-ETS sectors. This would mean that in the ETS sectors, both the tax and the allowance prices would have to be paid. However, the tax could, in those cases, be reduced by the allowance price, so that the prices in all sectors would be levelled (advantages: level playing field, predictable taxation; the

130 Åkerfeldt/Hammar 2015.

131 The regressive EEG levy burdens poorer households more than a pricing based on carbon consumption (assessment by the Expert Commission on the monitoring process “Energy of the Future” 2016).

132 BMWi 2017-3.

133 If the coupling with the emissions allowance prices were abandoned, an accordingly higher taxation would be possible. While this would be easier for the companies to anticipate, no level playing field would be created.

tax might exceed the certificate prices, triggering additional emissions reductions in the non-ETS sectors; disadvantage: higher burden in the ETS sectors without additional emissions reduction at the European level).[134]

3. A carbon tax could also be levied without distinction in all sectors. In this form, it would amount to a minimum price for carbon emissions in Germany, which the sectors covered by EU emissions trading would have to pay on top of the allowance prices (advantage: minimum incentives for emissions reductions in all sectors; disadvantage: no level playing field, higher burdens in the ETS sectors without additional emissions reduction at the European level in these sectors).

In order for a carbon tax levied in the ETS sectors to have an additional climate protection effect in these sectors (this applies to alternatives 2 and 3), the additional emissions reductions achieved in Germany with the tax could be coupled with the acquisition and permanent withdrawal of certificates.

3.1.3 Reform of the funding structures of the expansion of renewable energies

As long as there are no changes in the status quo, i.e. no carbon tax is levied, the carbon price in the EU ETS remains at its present low level and the current legislation continues to apply, the expansion of renewable energies will fall short of what, according to the model calculations, is necessary to achieve national climate goals (cf. Chapter 2.4). In this case, a better promotion system for the expansion of renewable energies seems inevitable. While such a project could be realised within the framework of the EEG, this is not a necessity. A gradual transition to a European promotion system for renewables, for instance, is likewise conceivable.[135] To be sure, with a view to the overlap with the EU ETS, an increase in renewable energy sources will not trigger any additional emissions reductions in the electricity sector in Europe; however, the coupling of the energy sectors can certainly reduce greenhouse gas emissions if power from renewable sources is used in non-ETS sectors.

However, by increasing the price of electricity compared to other sources of energy, the EEG levy reduces the economic incentives to resort to technologies to couple the energy sectors. This holds especially true for areas where the present energy tax rates are relatively low, for instance the heat sector. Accordingly, calls to reform the funding structure of the promotion of renewable energies have become more insistent in recent years. In view of prognoses predicting a further increase in the EEG levy by 2023,[136] this discussion revolves not only around the exemptions for energy-intensive companies and the private consumption of solar power, but also includes the calculation and distribution of the EEG levy. Although a comprehensive presentation of alternative solutions is beyond the scope of this policy paper, we will at least point out approaches for an alternative funding structure of the promotion of renewable energies.[137] A cost-efficient funding of renewables is a central lever for the reduction of the costs and the amount of the EEG levy and thus for a coupling of the energy sectors. This has already been discussed in various studies.[138] The following section is dedicated to approaches that aim at restructuring the distribution of the costs of levies and charges. The approaches are complementary.

134 Since the emissions in the ETS sectors are determined by the cap, they would not be reduced by an additional price.

135 acatech/Leopoldina/Akademienunion 2015.

136 Agora Energiewende 2017-2.

137 For a more comprehensive discussion of the exemptions, cf., for example, SRU 2016. Raue LLP 2013 presents a detailed overview of possible options for a reform of the concession fee.

138 acatech/Leopoldina/Akademienunion 2015; SVR 2016.

Suggestions for an alternative design of the EEG funding pursue three main objectives: adequate relief for companies that have to face up to international competition and might migrate,[139] the reduction of the distributional effects of the EEG (so far, low-income earners were disproportionately burdened) and the improvement of conditions for the coupling of the energy sectors. Depending on the specifications of the alternative options, these goals have been achieved to varying degrees. Two main categories of proposals can be distinguished:

1. Funding of the EEG directly from the public budget, i.e. from the general tax revenue.[140]

2. Funding via an extended EEG levy on the use of fossil fuels in the power, heat and transport sectors.

There are several different variations of each proposal. The basic challenge consists in finding a trade-off between economic efficiency, effects on international competitiveness, acceptance and distribution effects.

Tax-financed promotion of renewable energies

Variant (1) is mainly based on the rationale that the expansion of renewable energies is an encompassing project for society as a whole, the costs of which should not be borne by the power consumers alone. The most far-reaching solution would be a complete state-funding of the expansion of renewable energies, which would allow for the complete abolition of the EEG levy.[141] Whether such a solution would be compatible with European law would have to be verified. Alternatively, the public share could be confined to the promotion of the necessary technologies. From a macroeconomic point of view, such an allocation would make sense if the benefits of such a funding of technological developments were reaped not only by the plant operators, but by the whole economy (for instance, in the form of learning effects or by the prevention of carbon emissions in the non-ETS sectors, e.g. by the use of power from renewable sources for electric vehicles). However, the share of funding attributable to this purpose is unlikely to account for more than a small part of the total costs of the EEG.[142] Both proposed models share the positive aspect that electricity costs would decrease compared to the costs of fossil technologies. A problematic point, however, is that the costs of power generation would at least partially be lost among the general public expenditure, which would lessen the social pressure to make the expansion of renewable energies cost-effective. The lower energy prices would also provide less incentives for energy savings and would not reflect the economic costs of energy generation.

Extended EEG levy

Variant (2) would also imply a change in relative prices in favour of electricity. The distribution of the EEG costs could be based on the carbon intensity of the energy sources, so that carbon-intensive coal, for instance, would be more heavily burdened than natural gas. Several variations of this model are under discussion. They differ depending on

139 Energy-intensive companies are currently benefiting both from the low stock market prices and from exemptions from the EEG levy.

140 Besides a direct financing from public funds, a further option is discussed, viz. a pre-financing of the costs of the EEG via a fund solution. In that case, the EEG levy would be frozen at a certain level. Deficits in the EEG account resulting from further expansion would then be funded via loans to be redeemed once the EEG levy falls below the stipulated level. However, the estimations in different studies as to the volume of the resulting fund and the respective interest costs vary considerably (cf. Pittel/Weissbart 2016; Matthes et al. 2014). Besides, considering the ensuing expansion of public debt and the respective burdens on future generations, such a solution is problematic.

141 A variant of this proposal could be that the government bears the future expansion costs (VCI 2017). In this case, the EEG levy would decrease over time, as the subsidies for end-of-life facilities cease.

142 Many of the overall EEG costs are a consequence of disproportionately high profit margins investors achieved in the past, as technology prices tended to fall faster than expected while the compensation rates were often adjusted too slowly and too slightly.

the share of fossil fuels in the heating and transport sector taken into account, which implies different levels of additional costs for the consumers (distributional effect).[143] A double charge on emissions via the EU ETS and the EEG levy could be avoided by provisions in the EEG levy.

From a macroeconomic point of view, a positive aspect would be that spreading the EEG levy to all energy-related carbon emissions would implicitly amount to the introduction of a more comprehensive carbon price. The level of this price would, however, depend on the funding rate for renewable energies. It would therefore have to be analysed continuously during the process whether this solution would lead to an appropriate pricing of carbon emissions. Confining the levy to certain carbon emissions, for instance from space heating, while at the same time maintaining the eco-tax in the transport sector, would, on the other hand, lead to different levels of burdens for the same energy sources and thus mitigate the equalising effect of the newly designed EEG levy. A compensation for low-income households for the higher costs could be designed so as not to jeopardise the steering effect of the EEG levy.

143 The options discussed range from including all energy-related carbon emissions to limiting the expansion to space heating, since, due to the eco-tax, traffic emissions are already subject to greater burdens than emissions from the generation and use of heat. According to calculations by the Bavarian Chamber of Industry and Commerce, the first case would entail a negligible additional burden for private households (on average no more than 23 euros/annum) while it would reduce the energy costs for the industry by almost 8 percent (IHK Bayern 2016). If only space heating were considered, households would face an additional burden of up to 87 euros/annum, while the discharge for the industry would rise to just under 15 percent (IHK Bayern 2016; Gährs et al. 2016).

3.2 Challenges, obstacles and complementary measures

A sufficiently high, uniform pricing of carbon emissions in all sectors is a central overarching measure to incentivise investments in technologies and the use of lower-carbon energy sources. It will, as a rule, strengthen the position of low-emission technologies and energy sources in the competition with conventional technologies and fossil fuels – without further state subsidies being necessary. Nevertheless, there can be major impediments to a sufficiently expeditious market introduction or to the necessary, rapidly increasing use of climate-friendly key technologies and energy sources, such as

- technologies that are still at an early stage of development and require further research and development to bring them within the reach of market maturity,
- the necessity of high infrastructure investments (such as transport networks) coming with complex and lengthy licensing procedures, to enable the extensive use of the new technologies (there are often few incentives for private companies to invest in public goods such as the infrastructure),
- the situation that, despite a carbon price signal, information deficits prevent market players from taking the economically most viable decision,[144] or that due to other priorities, market players consider the carbon price to be of secondary importance,

144 For example, homeowners or purchasers of vehicles may not be aware of the evolution the costs of fossil fuels are likely to undergo due to the long-term development of the carbon price or the impact of new regulations.

- geopolitical or industrial policy measures aiming at securing the future of the German or European economy (for example, supply of critical raw materials, conversion of vehicle drives or battery production in Germany),

- projects which do have a long-term (economic) benefit, but are, from a corporate or budgetary perspective, not profitable in the short term, for instance because the long payback periods clash with the stakeholders' short-term expectations,

- the risk of lock-in effects or technological and psychological path dependencies that prevent or hamper the achievement of long-term climate protection goals. For example, in view of the currently very low allowance price, stakeholders might not expect any relevant rise in the carbon price and accordingly make long-term investments in technologies that come with high greenhouse gas emissions.

Moreover, there may be objectives such as the reduction in harmful emissions that are not addressed by a carbon price signal and therefore require other instruments. For such cases, we have a choice of other policy instruments and complementary accompanying measures at our disposal, the most important of which will be briefly mentioned in the following:

- Subsidies, investment grants, special taxes or tax reductions and other monetary incentives are **technology- or application-specific instruments** apt to shift the relative prices of the different energy sources into a new balance. Like the extension of the EU ETS or the introduction of a carbon tax, such instruments are based on the price. However, they generally lead to distortions in the market and possibly to inefficiencies with regard to an optimised allocation of financial resources. This complicates the introduction of a level playing field. Hence, they should only be considered as accompanying measures if inaction would rapidly lead to lock-in effects or if socio-political considerations speak against a consistent carbon price (e.g. soaring prices for the heat supply) that cannot be compensated by other measures. If introduced, these instruments should have a time limitation and should be regularly reviewed with regard to their control effect.

- **Market incentive programmes** can expedite the introduction of new technologies. However, this instrument should be used with caution. It should also be limited in time to prevent deadweight and misguided subsidies, as well as unduly high economic costs for the promotion of a selected new technology.

- **Possible regulatory requirements** could comprise the statutory specification of limit values or the harmonisation of technical standards. Specific examples include a limitation of carbon emissions from heating technologies or vehicles (such as the emission standards set by the EU for passenger vehicles), provisions for energy standards for buildings (both for new constructions and renovations), as well as the banning of technologies. Regulatory provisions can help to avoid wrong decisions that consumers might otherwise take due to a lack of information regarding the carbon price development or the costs of technological alternatives. They can likewise contribute to overcoming lock-in effects. However, they may also, at least temporarily, result in higher economic costs. It is important that regulatory requirements are kept as technology-neutral as possible, since statements as to the development of specific technologies are fraught with uncertainties.

- **Promoting research and development** as well as demonstration projects is a further important aspect. It can significantly foster the pursuit of future technology options and support the development of new, economically still risky technologies from their early stages until market maturity. Likewise, specific programmes promoting innovation can contribute to bringing new technologies to the market. These could be programmes assisting the creation of start-ups or supporting innovations in small and medium-sized enterprises.

Political decision-making bodies can also **use public funds directly**, for example to (co-)finance infrastructures such as power grids or overhead contact line systems for lorries. Local examples include programmes for climate-friendly urban planning, featuring, for instance, a well-developed public transport system, free parking spaces and traffic lanes for electric cars, and more cycle paths. **Further measures** public bodies could take or subsidise include offering, extending and promoting **information and consultancy services** in order to overcome information gaps and to ensure that price structures or developments are transparent, comprehensible and accessible. This could be achieved by means of information brochures, online tools, specialised information campaigns, etc.

- Amongst the **measures initiated or supported by the public sector**, we likewise find training programmes for qualified professionals, which can be crucial for accelerating the development of certain technologies (e.g. heat pumps, electric vehicles).

- Further instruments include not least **initiatives, methods and concepts for the participation of citizens and consumers** in the processes. The aim is to involve those affected right from the beginning, for example in long-term energy policy decisions at the national and local level or in decisions regarding the expansion of infrastructures such as power grids or wind turbines. Participation processes or concepts such as citizens‘ associations are typical examples.[145]

Not only do the basic conditions tend to vary considerably between the sectors, but also the dynamic they develop on the path towards a climate-compatible energy supply. This may be due to several reasons: The stakeholders may display different behaviours and preferences (not always focussed on environmental issues, for instance in passenger transport), or else the regulations, laws and other boundary conditions may vary widely. While options seem clear enough in some sectors – e.g. the building sector – it is more complex to determine the most promising solutions in other areas such as the heavy transport sector. In many instances, a high carbon price can provide good and important impulses; nevertheless, complementary measures may be necessary, but they must be tailored to sector-specific conditions and problems.

We will now attempt to assess the impact of a consistent carbon price signal in the five crucial areas “Heat in buildings”, “Transport”, “Industrial processes “, “Power” and “Synthetic combustibles and fuels”, and identify major obstacles that a uniform carbon price would probably not, or not sufficiently, address. The presentation of potential impediments does not claim to be encompassing and exhaustive and the overview of possible instruments does so even less. Rather, they attempt to briefly sketch major problematic areas and to provide food for thought as to where possible solutions might lie.

145 Cf. for instance Renn 2015.

3.2.1 Heat in buildings

When a heating system is replaced, the selection of the new heating technology hinges on several criteria, importantly including the energy price of the respective energy source and the resulting operating costs. To that extent, a carbon price signal pushing up the price of fossil fuels would have the effect of increasing the market share of lower-carbon heating technologies such as heat pumps or solar thermal systems. If the price for electricity is lower than the price for natural gas and heating oil, this would also provide an incentive for electric heat pumps. Hence, we can assume that a carbon-dependent price signal would be effective; how great this effect would be naturally depends on the level of the price. However, there are several obstacles which such an instrument does not address:

- The „tenant/landlord dilemma“, i.e. the ownership structures in rental buildings (residential and non-residential), are a case in point. They counteract the motivation to install technologies that are expensive to buy, but more efficient and cheaper to operate.

- Another hurdle, occurring above all in the context of energetic refurbishment measures related to the building envelope, consists in the long payback periods for such measures, which often have a range of many decades. As a result of such investments, many homeowners living in their residential buildings do not enjoy the full benefit of reduced operating costs. The same applies to many company-owned commercial buildings, where the economic advantages of energetic refurbishment measures do not fully come to bear until well beyond the company‘s planning period.

- Many owners of buildings are not least greatly confused by the legal requirements and funding opportunities as well as by the advantages and disadvantages of the various technical possibilities for structural thermal insulation and systems technology, including the use of renewable energies. At the same time, the realisation of energetic refurbishment measures confronts the owners with a considerable challenge regarding the communication with a wide variety of stakeholders: It must be ensured that no aspect is omitted, from funding to implementation to warranty issues to the later operation.

The first two impediments primarily call for legal measures in tenancy and tax law. The third barrier, on the other hand, can be addressed above all by competent and comprehensive consultancy services, possibly even including new business models, e.g. companies offering to take over complete renovation projects from end to end. Since the concept of individual refurbishment plans appears to be the adequate means to address the diversity of buildings and boundary conditions, a governmental framework for such concepts would be expedient. In more general terms, the realisation of many building measures requires the involvement and participation of millions of owners and residents. The measures should be designed so as to enable a widespread and thorough implementation in the relatively short time until 2050.

The focus of research and development funding should on the one hand be on developments fostering the increased use of electric heat pumps in areas of the building sector that are currently still difficult to access (the presentation in Section 2.1 provides an according basis). On the other hand, the remaining technologies that can contribute to the achievement of climate protection goals in buildings should also be pursued. These include efficient technologies for the use of fuels, such as gas heat pumps and fuel cells, or the use of deep geothermal energy in large urban heating grids.

3.2.2 The transport sector

In the transport sector, the uncertainty as to whether and to what extent a carbon price signal can be an effective or even sufficient means to incentivise the switch to climate-friendly drive concepts and means of transport is probably the greatest. Motor fuels are already rather heavily burdened with levies and taxes (compared, for instance, to heating fuels). In the past we have repeatedly experienced periods of high fuel prices (due to according oil prices on the international oil markets), none of which was followed by any significant impulse towards more fuel-efficient vehicles. At the same time, the discussion on new drive concepts and electric mobility has several dimensions: Besides the issue of a climate-friendly transport sector, it currently revolves around the question of pollutant emissions, especially in urban areas. This, in turn, is closely linked to the future of the diesel engine. And finally, consideration is not least given to the issue of Germany as a business location and to the important role of the automotive industry in this context.

Against this background, a carbon price signal seems to be only one of several elements determining the future direction of the transport sector. As regards the expansion of electric mobility, development progress in the field of battery technology naturally plays a key role; here, we particularly require political steps for a coordinated promotion of research and development. The development of a comprehensive national charging infrastructure is a further prerequisite that likewise necessitates an appropriate political and legal framework. At the local level, cities and municipalities have different opportunities to stimulate traffic prevention. They can also incentivise the switch to traffic concepts with lower greenhouse gas emissions by means of municipal climate action plans.

3.2.3 Industrial processes

In the industrial and commercial sector, investment decisions are based to a much higher degree on economic considerations than in the building and transport sectors. To that extent, we can assume that a price signal, resulting from a stronger grading of the prices of energy carriers according to their respective carbon emissions rate, will have a steering effect. In addition, two aspects in particular seem to be of importance in this context.

- Whereas the potential for efficiency measures is largely exhausted in the energy-intensive industry – at least as far as they are economically viable – there is still considerable efficiency potential in many sectors where energy is not a primary cost factor. Frequently, this is the consequence of a lack of knowledge regarding the savings potential, paired with an underestimation of the potential economic benefits. In this instance, the establishment of a moderated process in which companies can exchange best practice experiences could be an appropriate solution. The Energy Efficiency Networks co-initiated by the Federal Ministry for Economic Affairs and Energy can be cited as an example of a successful initiative for addressing such obstacles.[146]

- With regard to the future options for reducing carbon emissions in a variety of production processes (cf. Section 2.3) – for instance by switching the powering systems from fossil fuels to electricity – significant research is still required to estimate the feasibility of such processes and reduce the costs while ensuring the high quality of the products. Here, sufficient funding must be provided for research and development projects to enable the

146 Cf. for instance: Fraunhofer ISI/LEEN GMBH 2014.

identification of individual solutions for the various industrial processes in the coming years, and to develop them to a level of technical maturity allowing for their economic implementation.

3.2.4 Power generation and use

In the field of power generation, a carbon-dependent price signal is very likely to have a potent steering effect and to shift power generation towards a higher share of natural gas and renewable energy sources. In view of the current marginal costs of power generation,[147] a carbon price of 30 euros per tonne would in all probability suffice to trigger a gradual substitution of lignite-fired power plants with highly efficient gas-fired power plants.[148] However, even with higher prices for carbon emissions, this instrument will probably not be sufficient to create the appropriate long-term framework for the establishment of an energy supply system based largely on power from volatile renewable sources and its use in different consumption sectors. Without claiming to be exhaustive, the following enumeration lists several important aspects:

- One of the most important requirements for the future power system is more flexibility to balance generation from solar and wind energy plants – on the supply side, as well as on the consumption side. Both the flexible operation of applications according to the availability of power from renewable sources (demand response) and the operation of storage units are based on temporarily varying electricity prices. Therefore, the operation of these components can only be aligned if the price difference (spread) between electricity generated at low marginal costs, and electricity generated at high marginal costs, is passed on to the users. On the one hand, it is up to the power suppliers to provide variable tariff structures; on the other hand, the political echelons are called upon to make use of the existing policy options. For instance, levies such as grid charges or the electricity tax could be made more dynamic in order to stimulate flexibility in the system. In addition, an appropriate market framework, including legislatively underpinned technical standards, is required to establish and ensure quality standards in the relevant markets.

- Next to the EEG levy, grid charges constitute the largest share of the household electricity price levied for regulatory purposes (2016: EEG levy 22.1 percent, grid charges: 24.3 percent).[149] While it generally[150] makes sense to burden the power used for the coupling of the energy sectors with all the costs incurred for its provision, including the expenses for the maintenance and construction of grids, an inefficient design of the grid charges may unnecessarily increase the power price and thus limit its steering function.

- The need for an expansion of the transmission grids in order to enable the further expansion of renewable energies, especially for offshore wind and wind energy in northern Germany, is largely undisputed. This necessary expansion requires decisions at the political level and a government-controlled or at least monitored implementation.

147 Cf. for instance: Agora Energiewende 2017-3. According to their evaluation, the marginal costs for new CCGTs using natural gas as energy source averaged €27,60/MWh in 2016, and those for old lignite-fired power plants €12,40/MWh.

148 A carbon emissions price of 30 euros per tonne would increase the costs of power generation in old lignite-fired power plants by 3 eurocents per kWh, those incurred by standard gas-fired power plants by about 1.50 eurocents and those of modern, highly efficient CCGT power plants by just under 1 eurocent.

149 BDEW 2016.

150 In certain cases, deviations from this principle may make sense, for example when power-to-X systems are operated close to large wind turbines or photovoltaic systems in order to smooth out production peaks and avoid curtailments.

- In the medium and long term, we will, in all probability require a reserve capacity for power generation on a similar scale to the capacity provided by the current conventional power plant park (cf. Chapter 2.4). However, in view of the continuous expansion of power generation from renewable sources, the number of hours these reserve power plants will run at full load will steadily decrease. It will hence be increasingly difficult to refinance these facilities merely by selling the electricity. Even if in the future high power prices could be achieved when the power feed-in from volatile renewable energy sources is low, sufficient reserve capacity could nevertheless not be ensured, as investments in these power plants would probably still be too risky. Therefore, we will sooner or later be obliged to modify the power market by introducing a compensation system for the provision of reserve capacity.

3.2.5 Synthetic combustibles and fuels

From today's point of view, a broad use of synthetic combustibles and fuels is only realistic at a very high carbon price signal. This is due to the high production costs resulting both from the complex production processes and from the fact that the technology is still at a relatively early stage of development. However, given that the electrolytic production of hydrogen with power from renewable sources is very likely to become necessary in the near future, the further development and testing of the necessary technologies should be ambitiously pursued (this, of course, assumes the continuous progress of the energy transition and the steady reduction of climate-damaging carbon emissions in the energy sector). In addition to electrolysis, this encompasses all conceivable options for the future use of hydrogen in the energy sector and the industry. This includes processes in the chemical industry, the use of hydrogen in fuel cells for power and heat supply and in the mobility sector, or its further conversion into hydrocarbon-based energy carriers. In order to develop early markets and promising niche markets for these energy carriers, tax reductions, the omission of, for example, grid charges (if power generation and conversion take place at the same location), or other monetary measures could be of support during the market introduction phase. Not least with a view to the global relevance these technologies are expected to have, especially at sunny and windy locations, it appears reasonable to continue to support the respective development efforts and pilot projects of companies and research institutions by means of significant and targeted public funding schemes.

4 Conclusion

In order to realise the German climate protection goals, a very ambitious conversion of the energy supply system will have to be implemented within a few decades. Solutions require a systemic approach with an integrated holistic view of the energy system and its future development. In none of the sectors transport, heat for buildings and heat for industrial processes can the targets set out in the Climate Action Plan 2050[151] be achieved without a far-reaching coupling with the power generation sector. At the same time, a much wider use of unpredictable volatile renewable energy sources such as sun and wind will necessarily require new options to consume power that provide dispatchable loads. An analysis of possible systemic developments based on the different options for a coupling of the energy sectors – direct power use, the production and direct use of hydrogen as final energy or its further conversion to different hydrocarbons for use as chemical raw materials and fuels – yields some robust results regarding the development of the system:

- A massive expansion of solar and wind power plants is imperative. However, in light of social acceptance, land use and nature conservation issues, it seems advisable to opt for system developments that will keep this expansion as low as possible.
- Reducing consumption can contribute significantly to achieving the climate protection goals with a limited number of renewable energy plants. Such reductions can be achieved through changed user behaviour or higher efficiency on the consumption side, for instance by means of the energetic refurbishment of buildings or more efficient technologies for electricity use, such as LED lighting systems.
- An increased use of "alternative" renewable energy sources such as solar thermal energy, geothermal energy and biomass likewise contributes to limiting the required expansion of wind and photovoltaic systems.
- Wherever it is possible without undue effort, the direct use of power should be the method of choice, since it comes with more efficient conversion chains, which reduces the need for renewable energy plants and lowers the systemic costs. This applies in particular to heat pumps for the heating of buildings, the direct use of power for industrial processes and, in the transport sector, electric vehicles with battery storage units.
- Once a certain expansion level of renewables is reached, the generation of hydrogen by means of electrolysis with power from renewable sources is an expedient means to use surplus electricity that would otherwise have to be discarded. By equally allowing for the use of power from short-term storage systems such as pumped storage power plants or batteries, the utilisation rate of electrolysis systems can be increased.

151 The "Climate Action Plan 2050 – Germany's long-term emission development strategy" (Klimaschutzplan 2050) was adopted by the German government in November 2016. It represents a long-term low greenhouse gas emission strategy according to the Paris Climate Agreement. The Climate Action plan sets specific goals for the reduction of greenhouse gas emissions in all relevant sectors.

- Hydrogen can be put to various uses in the energy system: It can be employed directly in industrial processes such as steel production or can power fuel cell vehicles; it can be reconverted to electricity in fuel cells or gas turbines or further converted into liquid or gaseous hydrocarbon-based fuels. The latter option requires the availability of suitable carbon sources, such as CO_2 from the exhaust gases of power plants powered with fossil or biogenic fuels. From today's perspective, all conceivable options may play a role, either in Germany or, as export technologies, in other regions. Accordingly, their further development should invariably be promoted.

- Despite the expansion of renewable energies for power generation, the construction of short-term storage systems and the use of intelligent load management, a second power plant park is required to ensure a secure supply at all times, including during dark and windless periods.

- An analysis of the possible transformation paths suggests that the energy transition progresses in four main development phases, each characterised by essential structural features. After a first, largely completed phase, characterised by the development of basic technologies as well as a massive expansion of renewable energy systems for power generation, we are now entering a phase of comprehensive systemic integration, in which the coupling of the energy sectors will play a significant role. This will be followed by a third phase, featuring the large-scale expansion of plants for the production and use of hydrogen. A fourth phase, characterised by the complete of abolition of fossil fuels, would, from today's point of view, only make sense for Germany if it could resort to energy carriers or power from sunny and windy climate zones.

The energy transition is not an automatic process, and will, at least in the conversion phase, entail considerable additional costs compared to a supply system that remains based on the use of fossil fuels in the longer term. Despite all the uncertainties inherent in such extensive and far-reaching developments, our studies, which are summarised in the German analysis *"Coupling the different energy sectors: Analyses and considerations for the development of an integrated energy system"*, suggest that the cumulative additional costs by 2050 will range between 1 and 2 trillion euros, depending on the level of the carbon reduction target (70 to 85 percent). This corresponds to an annual amount of 30 to 60 billion euros over the next 33 years, which equates to about 1 to 2 percent of the German GDP in 2016. While we deem it necessary to communicate such figures, we consider it equally important to place them in the context of the energy transition project in its full dimension:

- Investments in the transformation of the energy supply at all levels and in all consumption sectors account for a significant proportion of the additional costs. Once the transformation is largely concluded, investments will, as today, be limited to replacements.

- The energy transition is a large-scale project for society as a whole, pursuing objectives prioritised in a specific order – *i.e.* the reduction of climate-damaging trace gas emissions without detrimental effects on the supply security and at the lowest possible additional costs. In its dimensions, it is comparable to German reunification, for which similar „cost" values of 2 trillion euros were specified in the context of its 25th anniversary.

- The values reflect the additional costs for the overall system. They do not take external costs or economic effects such as the creation of local value added and employment effects into account. These two aspects, while likewise of major importance, are beyond the scope of our present study. They would, however, be worth examining in a separate Working Group.

- Besides mentioning the costs, it is equally important to see and realise the opportunities the large-scale project energy transition offers. Especially for a high-tech country like Germany, with an economy strongly relying on technology exports, it is, in our opinion, essential to assume a leading role in the development of technologies that are likely to gain in importance around the world.

The costs mentioned, combined with the high priority given to the goal of a climate-friendly energy supply, suggest that carbon emissions – *i.e.* the disposal of carbon dioxide into the atmosphere, which today is virtually free of charge – should be priced. This price signal should uniformly cover all sectors and energy carriers, as it is irrelevant where carbon emissions occur. However, a high price signal limited to Germany would be of little use, since it would merely lead to the migration of energy-intensive processes. Therefore, an international, or at least European, solution should be the goal. Extending the European Emissions Trading System to all sectors would be a desirable option. It could be realised with a reasonable transactional effort via the primary suppliers of fossil energy sources. A national carbon tax, replacing other taxes on energy carriers, is a second option. It could be levied in addition to the EU ETS or alternatively, should an expansion of the ETS prove politically impossible to realise in the near future. We consider the establishment of a consistent price signal for carbon emissions to be the most important overarching individual measure towards a future market framework, as it is technology-neutral and uniformly affects the energy system as a whole.

However, a consistent carbon price is not a magic bullet. The energy industry therefore requires complementary instruments to address distributional impacts or market failures and to avoid possible lock-in effects. Market failures could, for instance, occur due to information deficits or disparities between long-term economic benefits and short-term amortisation prospects for companies and households. In addition, supplementary instruments can also take external costs such as local environmental impacts or other pollutant emissions into account. The complementary instruments include technology promotion, infrastructural developments and regulatory provisions (such as limit values or the harmonisation of technical standards). Additional tools should therefore be subject to a scrutiny reserve: Their necessity, effectiveness and cost-benefit-ratio should be subjected to a constant evaluation. Also, the instruments should be designed so as to allow for readjustments.

Annex

Technology	Electrical direct heating	Electrical heat pump	Hybrid heat pump	Natural gas heat pump	Cogeneration in individual buildings (apartment block cogeneration)	Solar thermal energy
Technical description	Electrical resistance heating	Use of ambient heat based on electricity	Use of ambient heat based on electricity; peak load boiler	Use of ambient heat based on fuel	Coupled production of electricity and heat (via motor, fuel cells)	Direct heat production from solar radiation energy
Interactive power supply grid	High	High	Medium	None	High	None
Investment costs	Low	High	High	High	High	Medium
Market availability	High	High	Medium	Low	Medium	High
Development potential	Low	Medium	Medium	High	Medium (fuel cells in particular)	Low
Possibility for flexible electricity usage	Connectable load	Connectable load in connection with storage	Connectable load ("Fuel-Switch")	Only in connection with synthetic energy sources or biomass	Residual electricity production possible	None
Other	Only advisable as a last option for peak power generation	Developments necessary in the area of coolants (Freon gas regulation) and adapted solutions for various buildings and restoration standards	Interesting option, particularly for buildings with connections to natural gas grid	Technology for use in combustion with higher efficiency than boiler; particularly interesting as bridging technology	Increasingly electricity-driven usage; storage necessary to secure coupled production; economical primarily in large-scale buildings	Proportionate coverage for low-temperature heat demand, particularly in summer and proportionate transitional phase times; always use in combination with other systems

Table 1: Technical options for heat supply in individual buildings with lower specific CO_2 emissions than today's boiler with fossil fuels

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The Academies' Project

With the initiative "Energy Systems of the Future", acatech – National Academy of Science and Engineering, the German National Academy of Sciences Leopoldina and the Union of the German Academies of Sciences and Humanities provide impulses for the debate on the challenges and opportunities of the German energy transition. In interdisciplinary working groups, some 100 experts from science and research develop policy options for the implementation of a secure, affordable and sustainable energy supply.

The working group »Coupling the Sectors«

The working group dealt with the issue of how the different sectors electricity, heat and transport could be interlinked with one another in a future energy system. It investigated how energy savings, an increase in overall efficiency, and a massive expansion in renewable energies impact the coupling of the sectors. While developing different courses of action, the working group aspired to achieve the optimisation of the overall system by means of systemic approaches.

The interdisciplinary working group investigated, over a span of two years, the existing as well as future coupling of the sectors within the German energy system. For this purpose, they analysed the status quo, observed potential individual technologies and designed their own model calculations for the future energy system up to 2050. Interim results were discussed at a technical discussion with a group of experts and during the three-way energy discussion with stakeholders.

The results from the working group were prepared in three formats:

1. The position paper "»Coupling of the Sectors« – Options for the next phase of the energy transition" presents the synthesis of the results in a generally understandable form and focuses on the courses of action for the development of future energy systems.

2. The German analysis "»Coupling of the Sectors« – Investigations and consideration of an integrated energy system" combines the results into a comprehensive form.

3. The German materials for the description of the modelling of the energy system document the work approach. They are available at http://energiesysteme-zukunft.de/publikationen/

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Expert discussion

On 9 May 2017, a draft of the position paper was made available for discussion at the technical discussion "Coupling the Sectors – Connecting the concepts of electricity, heat and transport". The feedback expressed there was included in subsequent text production. In addition to members of the working group, the following individuals took part:

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