DE 2015 Report

pathways to **deep decarbonization** *in Germany*

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SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

Wuppertal Institute
for Climate, Environment and Energy

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Deep Decarbonization Pathways Project

The Deep Decarbonization Pathways Project (DDPP), an initiative of the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), aims to demonstrate how countries can transform their energy systems by 2050 in order to achieve a low-carbon economy and significantly reduce the global risk of catastrophic climate change. Built upon a rigorous accounting of national circumstances, the DDPP defines transparent pathways supporting the decarbonization of energy systems while respecting the specifics of national political economy and the fulfillment of domestic development priorities. The project currently comprises 16 Country Research Teams, composed of leading research institutions from countries representing about 70% of global GHG emissions and at very different stages of development. These 16 countries are: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States.

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Executive summary

In order for the global community to succeed in climate change mitigation, the issue needs to be addressed at many different political levels, both internationally and nationally. Recognizing the existence of both individual national challenges and common global challenges in climate change mitigation, the Deep Decarbonization Pathways Project (DDPP) was co-founded in 2013 by the United Nations' Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI). The DDPP is a collaborative global initiative that aims to demonstrate how individual countries can transition to a low-carbon economy consistent with the internationally agreed target of limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius (°C) compared with pre-industrial times. Achieving this target will require that global net greenhouse gas (GHG) emissions approach zero by the second half of the century. This will require, more than any other factor, a profound transformation of energy systems by mid-century, through steep declines in carbon intensity in all sectors, a transition we call "deep decarbonization".

In accordance with the proceedings of the fifteen other countries' teams, this report explores what is required to achieve deep decarbonization in Germany and reach the German target of reducing domestic GHG emissions by 80% to 95% by 2050 (compared with 1990).

In past years, Germany achieved significant progress in GHG emission mitigation and also fulfilled its Kyoto target. Overall, GHG emissions have been reduced by 27% between 1990 and 2014.

However, progress on GHG emission reductions has slowed down over time. In order to reach 80% to 95% GHG emission reductions by 2050, the average annual emission abatement must amount to 3.5% from 2014 on. Thus, the task requires annual reduction rates in the same range as historically reached maximum values in Germany. The challenge is significant, since in contrast to the successful start of Germany's energy system transformation, future progress requires deeper structural changes in the energy system and the German economy.

Potential decarbonization pathways for Germany are illustrated by means of three ambitious scenarios:

- Scenario "Target" from the study "Development of Energy Markets – Energy Reference Forecast" (Schlesinger et al. 2014), here referred to as "Government Target Scenario"
- Scenario "100-II" from the study "GROKO II – German Energy Supply Scenarios Based on the EEG Draft Bill" (Nitsch 2014), here called "Renewable Electrification Scenario"
- Scenario "KS 90" from the study "Climate Protection Scenario 2050" (Repenning et al. 2014), here referred to as "90% GHG Reduction Scenario"

The level of deep decarbonization of the German energy system differs in all three scenarios, with energy-related emission reductions between 1990 and 2050 varying between 80% and more than 90%. Some of the strategies used to achieve emission reductions also vary between the scenarios. Nevertheless, three strategies that strongly contribute to GHG emission reduction are used to a significant extent in all three analyzed scenarios:

- Energy efficiency improvements (in all sectors but especially in buildings)
- Increased use of domestic renewables (with a focus on electricity generation)
- Electrification and (in two of the scenarios also) use of renewable electricity-based synthetic fuels (especially in the transport and industry sector)

These three strategies are also used extensively in other energy scenarios for Germany. It can be argued that they need to be implemented successfully to be able to reach substantial GHG emission reductions by 2050.

The scenario analysis shows that besides the three key strategies, there are other strategies used only in one or two of the three analyzed scenarios that can be regarded as more controversial:

- Final energy demand reductions through behavioral changes (modal shift in transport, changes in eating and heating habits etc.)
- Net imports of electricity from renewable sources or of bioenergy
- Use of carbon capture and storage (CCS) technology to reduce industry sector GHG emissions

Due to their comparatively low current relevance, strategies to reduce non-energy related (often non-CO_2) emissions – especially in agriculture and industry – are not always discussed in mitigation scenarios. However, these strategies will gain importance in the future, as deep decarbonization requires these emissions to also decrease considerably compared with today.

As a result of the decision to phase out nuclear energy in Germany, the deployment of nuclear power plants is not envisioned by any of the current energy scenarios for the years after 2022. There is widespread agreement in Germany that the disadvantages of nuclear power outweigh its benefits. CCS for use in power supply is also not considered in the analyzed scenarios as there is little acceptance for this technology within the German society.

The detailed quantitative analysis and comparison of the three illustrative scenarios shows that all three scenarios do not assume any drastic or sudden changes in social and economic developments. For example, they do not assume dramatic technological breakthroughs, drastic lifestyle changes or lasting economic crises.

Furthermore, final energy demand is expected to be reduced dramatically by 2050. All three scenarios assume it to be 40% to 47% lower in 2050 than in 2010. This means that faster efficiency improvements than in the past are required for Germany to be able to reach its medium- and long-term energy and climate targets. Reductions in final energy demand are expected to be achieved mainly by energy efficiency improvements and not so much through reductions in energy service demand. While the change in total final energy demand is similar in all three scenarios, there are more pronounced differences between the individual sectors.

Electricity demand varies considerably in 2050 in the three selected scenarios. In the "Government Target Scenario" electricity demand in 2050 is about 100 TWh lower than it was in 2011, while it is some 250 TWh higher in the "Renewable Electrification Scenario" (mainly due to the assumed electrification of processes and extensive hydrogen generation). In the "90% GHG Reduction Scenario" electricity demand is similar to 2011.

Regarding the future primary energy mix, the three scenarios project that renewable energy sources make up between 51% ("Government Target Scenario") and 73% ("90% GHG Reduction Scenario") in 2050 (from 11% in 2014). Biomass continues to be the most important renewable energy source, but is followed closely in all three scenarios in 2050 by wind energy. With respect to fossil fuels, the combined share of coal and lignite (today 25%) decreases to between 2% and 9%, while oil (today 35%) remains more relevant with a 2050 share of between 9% and 20%, being used mainly in the transport sector.

The three scenarios project GHG emission reductions of 80% to 90% by 2050. Thus, the German government's targeted emission reduction rate is achieved within the scenarios. It should, however, be noted that the types of GHG emissions included vary: While the "Government Target Scenario" looks only at energy-related GHG emissions and describes how these can be reduced by 80% by 2050, the "Renewable Electrification Scenario" projects an 86% decrease in energy- and process-related GHG emissions by the middle of the century. The third illustrative scenario, the "90% GHG Reduction Scenario", looks at all GHG emissions and describes a pathway that reaches – as the name suggests – emission reductions of 90% by 2050.

The analysis shows that to reach very strong GHG emission reductions of 90% or more by 2050 (compared with 1990) it is necessary to implement most or all mitigation strategies mentioned above, as is done in the most ambitious of the three scenarios analyzed here, the "90% GHG Reduction Scenario."

Besides GHG emission mitigation, the implementation of decarbonization strategies can also positively or negatively influence the attainment of other societal objectives. Beneficial non-climate impacts of mitigation measures have been named "co-benefits" by climate change researchers. Potential co-benefits for Germany include increased energy security, higher competitiveness of and global business opportunities for companies, job creation, stronger GDP growth, smaller energy bills for households and less air pollution.

In order to achieve deep decarbonization and related co-benefits in Germany, the real challenge consists not so much of developing but of actually implementing decarbonization strategies. Therefore, authorities at different political levels need to introduce appropriate policies supporting the implementation of measures linked to the long-term mitigation strategies.

As transformation processes are subject to constraints, uncertainties and path dependencies, these challenges need to be identified and addressed at an early stage. Concrete policy challenges linked to deep decarbonization in Germany exist for all of the three key strategies mentioned above. For energy efficiency improvements, they include obtaining a considerable increase in the rate of building refurbishments and the development and dissemination of low-carbon technologies for transport vehicles. With regard to an increased use of renewable energy sources for electricity generation, it is, for example, necessary to foster the development of flexibility options that help keep the electricity grid stable, to introduce a new electricity market design, to keep investment conditions stable and to ensure public acceptance for required infrastructure projects. In the currently less advanced field of electrification of processes and power-to-x, a consistent and stable policy framework needs to be established and research and development of innovative technologies should be supported.

The report at hand aims to show that although there are challenges to be overcome on the way to a fundamental transformation, deep decarbonization can be achieved in Germany by 2050. As a result of about 30 years of critical engagement with climate and energy policies in Germany, a huge amount of theoretical and practical knowledge on transformation processes has been gathered. This knowledge should be used and also expanded in order to properly deal with the challenges associated with the complex process of achieving deep decarbonization. Germany should also be open to learn from transformation processes in other countries, just as other countries should learn from Germany's experiences.

1 Introduction

With the upcoming 21st UNFCCC's Conference of the Parties in December in Paris, climate policy comes more and more into the focus of the international community. After all, it is hoped the conference will deliver new guidelines for future international efforts on climate change mitigation. As global GHG emissions continue to rise (although more slowly than in the years before), great efforts are still required to stay within the planetary (climate) boundaries. European decision makers also see the year 2020 approaching and thus the deadline for its 20-20-20 climate and energy targets.[1] While the market deployment of renewable energy is on track in the EU, progress is slower than expected especially with regard to the energy consumption reduction goal. The same is true for Germany, which is at risk of falling short on several national climate and energy objectives (e.g. on greenhouse gas (GHG) emission mitigation and energy consumption reduction) for 2020 (see Table 2).
In view of these individual national challenges and common global challenges, the Deep Decarbonization Pathways Project (DDPP) was co-founded in 2013 by the United Nations' Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI). The DDPP is a collaborative global initiative that aims to demonstrate how individual countries can transition to a low-carbon economy consistent with the internationally agreed target of limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius (°C). Achieving this target will require that global net GHG emissions approach zero by the second half of the century. This will require, more than any other factor, a profound transformation of energy systems by mid-century, through steep declines in carbon intensity in all sectors, a transition we call "deep decarbonization."
The DDPP comprises sixteen research teams composed of leading researchers and institutions from the world's largest GHG-emitting countries, including industrialized, emerging, and developing economies: Australia, Brazil, Canada, China, France, Germany India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, United Kingdom, and United States. Each team is exploring what is physically required to achieve deep decarbonization in their own country's economy while taking into account socio-economic conditions, development aspirations, infrastructure stocks, natural resource endowments, and other relevant factors. The country teams consist of independent scholars who do not necessarily reflect the positions of their national governments.
In September 2014, the DDPP presented an interim report on the first phase of its work at the invitation of Secretary General Ban Ki-moon on the occasion of the United Nations Climate Summit. The interim report includes chapters that summarize at a high level the findings of each country's team. Now, each country's team is issuing its own separate, detailed report, including additional scenarios not included in the 2014 interim report. Furthermore, a synthesis report to be published in September 2015 summarizes the current state of each country's team's findings, including analysis of aggregated results across the teams.

1 The so-called 20-20-20 goals are a 20% greenhouse gas emission reduction vs. 1990, 20% share of renewable energy sources in gross energy consumption and 20% primary energy consumption reduction vs. projections for 2020

This report looks at GHG emission reduction and the transformation of the energy system in Germany. It shows that progress has been made in the past and that ambitious future targets have been set (Chapter 2). Basing on the current situation, it describes and compares three ambitious scenarios that (partly) differ in their assumptions on how deep decarbonization and thus the German target of reducing GHG emissions by 80% or more (vs. 1990) can be realized by 2050. The key strategies followed in every scenario (increase in energy efficiency, increase in electricity from renewable energy sources, electrification of processes and power-to-x, Chapter 4) are analyzed in further detail but also additional strategies to reach deep decarbonization are identified and briefly discussed (Chapter 5). Since the implementation of decarbonization strategies also influences the achievement of other societal goals, potential co-benefits of deep decarbonization are discussed in the German context (Chapter 6). Finally, policy challenges are outlined that have to be addressed to allow for a successful transition to a low-carbon economy and the achievement of the political targets in Germany by 2050 (Chapter 7).

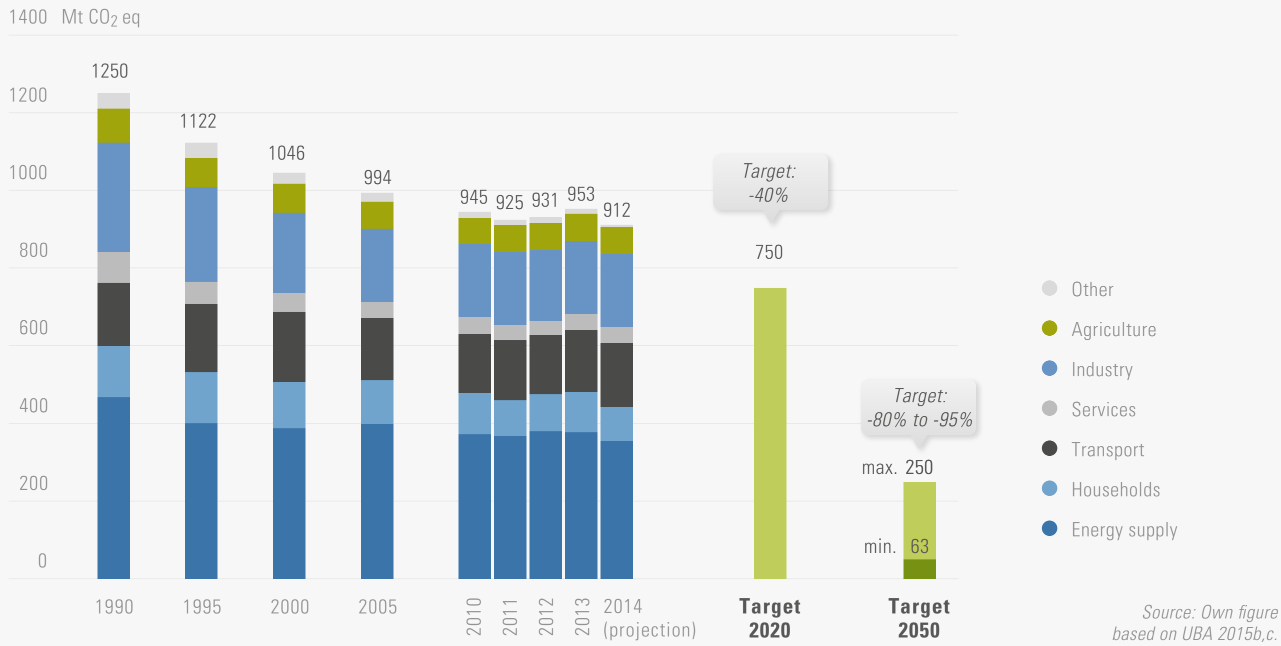
2 GHG emission reduction and transformation of the energy system in Germany

In past years, Germany was one of the countries politically emphasizing and targeting GHG emission reductions. Simultaneously, significant progress was achieved in GHG emission mitigation: From 1990 until 2000, average annual emission reductions of 1.8% were achieved (see Figure 1). In the following years emission mitigation slowed down but still amounted to an average of 0.8%/year between 2000 and 2008. Then came the financial crisis yielding record lows of GHG emissions from 2009 to 2011. Afterwards, however, emissions went up again, slightly from 2011 to 2012 and more significantly from 2012 to 2013 (an increase of 2.4%). According to recent projections by the German Federal Environment Agency, the total amount of GHG emissions in Germany in 2014 was around 4.3% lower than in 2013 (UBA 2015a). The relatively large decline is mainly attributed to a mild winter. Temperature-adjusted GHG emission reductions are estimated to have declined by 1.5% to 2% compared with 2013 (AGEB 2015a).

Overall, Figure 1 shows that GHG emissions in Germany were reduced by 27% between 1990 and 2014. Germany also fulfilled its Kyoto target of decreasing GHG emissions by an average of 21% between 2008 and 2012 (an average GHG mitigation of 23.6% was achieved (BMUB 2014a)).

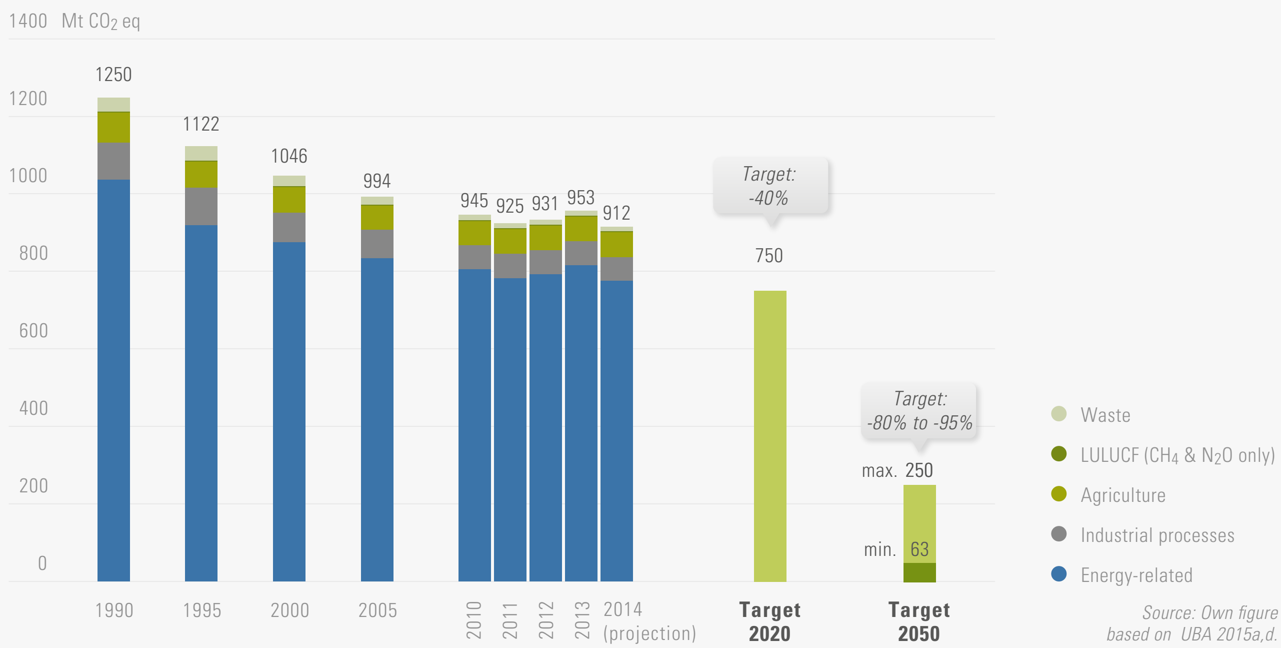
In most sectors of the economy, significant reduction rates could be achieved in this timeframe (services 53%, industry 34%, residential 33%, energy supply 24%, agriculture 21%). Only in the transport sector, the amount of GHG emissions remained at the same level (164 Mio t CO_2 equivalent in 2014 vs. 163 in 1990). It should, however, be noted that a certain amount of emission reductions can be attributed to the German reunification in 1990 and not to climate policy. Eichhammer et al. (2001) estimate that as a result of the economic breakdown in Eastern Germany following the reunification, about 105 m tons of CO_2 emissions – so-called Wallfall profits – had been avoided by 2000 (compared with a hypothetical reference value for that year). If the development of GHG emissions is displayed not by sector but by source (as in Figure 2), it can be seen that the huge majority of emissions

Figure 1: Development of GHG emissions in Germany by sector



Source: Own figure based on UBA 2015b,c.

Figure 2: Development of GHG emissions in Germany by source



Source: Own figure based on UBA 2015a,d.

originates from energy-related sources (energy supply sector, manufacturing industry, transport, small-scale furnaces and others). The major part of residual emissions is directly related to industrial processes and agriculture. Since energy-related sources are responsible for most emissions, mitigation efforts focus on this area. Reductions in GHG emissions from energy supply achieved until today largely resulted from an increasing share of renewable energy sources in the primary energy and electricity production mix (see Figure 15 in Section 4.2).

Overall, Germany already pursues a comparatively ambitious decarbonization pathway and has been successful at lowering GHG emissions in the past. However, progress on GHG mitigation has slowed down over time. In order to reach the government's targets of a 40% reduction by 2020 and an 80% to 95% reduction by 2050 (in comparison with the 1990 level), further efforts are needed to stimulate emission mitigation. Achieving the 2020 target requires GHG emissions to decrease by an average of 3.2% between 2014 and 2020. In view of the goal for 2050, the average annual emission abatement must even amount to 3.5% from 2014 on. Thus, the task is becoming rather more difficult than easier as necessary annual reduction rates are in the same range as the historical maximum values.

The future challenge becomes even more obvious when considering that the rather successful start of the transformation of the German energy system did not require substantial structural changes so far. In the past, the dynamic development of renewable energy sources and moderate efforts to enhance energy efficiency as well as a growing general awareness for the problem of climate change constituted the observed development. That's why – according to an analysis by members of the German Renewable Energy Research Association (ForschungsVerbund Erneuerbare Energien, FVEE, see e.g. Fischedick 2014, Henning et al. 2015), which represents about 80% of Germany´s non-university research capacity for renewables – this period can be denoted as the first of four phases of the energy system's transformation process (Fischedick 2014). The breakdown into four transformation phases aims to highlight that distinct kinds of challenges that result from varying characteristics and requirements need to be addressed at different points of the decarbonization process. With the share of renewable energy sources in electricity generation now reaching more than 25%, Germany can be considered to have entered the second phase of the transformation process. This second phase – which might be completed between 2025 and 2035 – already requires significantly more efforts and more interventions in the given structures. In order to achieve a successful transformation, those aspects have to be addressed with specific policies. The necessary changes can be differentiated according to the area where the changes occur: production, demand, infrastructure, market/economy and society. Table 1 shows the characteristics using the example of the electricity system.

The texture of appropriate technical and organizational structures, as well as suitable market conditions in combination with safeguarding sufficient public support, build the foundation for the subsequent phases of the transformation process. As such, this timeframe might be the most important one in determining whether the long-term transformation targets can be reached.

Following Phase 2, Phase 3 of the transformation path pursues a complete coverage of electricity demand by renewable energy sources and might last until the year 2050. In this phase, long-term storage options become important and cross-national strategies are crucial (Fischedick 2014). In a following phase (or even parallel phase), stronger decarboniza-

Table 1: Selected characteristics and requirements in the second phase of the energy system transformation process

Production	Demand	Infrastructure	Market/Economy	Society
Continued expansion of renewable energy	Significant efficiency increases in all consumer areas	Modernization and development of networks	Guarantee of stable (attractive) investment conditions	Inclusion of civil society in decision making and planning processes (participation)
Continued technical progress and exhaustion of learning curve effects	Increase in new power applications (such as electric vehicles, heat pumps)	Expansion of cross-border interconnectors	Adjustments to the electricity (energy) market design	Overcoming resistance to infrastructure expansion
Increase in contribution of renewable energy solutions to system stability	Increase in flexibility on the demand side	Use of short-term storage	Feed-in tariffs as the preferred instrument, stepwise complemented by tendering schemes	Support of the transformation process through lifestyle changes (e.g. as "shared economy")
Increase in flexibility of the power plant parks	Development of new demand side management (DSM) potentials	Testing of long-term storage options		Increase in civic engagement and user-integrated solutions (e.g. common city district solutions)
Increase in self-supply systems				

Source: Fischedick 2014

Table 2: Current political climate and energy policy targets of the German government

	Status quo	Target			
	2014	2020	2030	2040	2050
Greenhouse gas emissions					
Greenhouse gas emissions (versus 1990)	-27%	-40%	-55%	-70%	-80% to -95%
Energy efficiency/ energy savings (cross-sectoral and transformation sector)					
Primary energy consumption (versus 2008)	-9%	-20%	Not specified		-50%
Annual increase in final energy productivity	0.6% (2008-2013)	2.1% (2008-2050)			
Gross electricity consumption (versus 2008)	-6%	-10%	Not specified		-25%
Combined Heat and Power (CHP) share in thermal electricity generation	approx. 22% (2013)	25%	Not specified		
Renewable energy sources					
Share in gross electricity consumption	27%	40% to 45% (2025)	55% to 60% (2035)		At least 80%
Share in final energy consumption for heating	10%	14%	Not specified		
Share in fuel consumption	5%	10%	Not specified		
Share in gross final energy consumption	12% (2013)	18%	30%	45%	60%
Buildings					
Heat demand (no reference period defined)	n.a.	-20%	Not specified		
Primary energy demand (no reference period defined)	n.a.	Not specified			-80%
Annual rate of energy-related building refurbishment	approx. 1% (2005-2008)	2%			
Transport					
Final energy consumption (versus 2005)	+1% (2013)	-10%	Not specified		-40%
Number of electric vehicles*	approx. 24,000	1 m	6 m	Not specified	

* The government target refers to all vehicles that can be charged through a plug. Thus, this definition of electric vehicles includes battery electric vehicles and plug-in hybrid electric vehicles, but not conventional hybrid electric vehicles that cannot be charged through a plug.

Sources: BMWi and BMU 2010, EEG 2014, EEWärmeG 2008, BMWi 2015a, b, EU 2009, UBA 2015e, AGEB 2015a, b, c, Diefenbach et al. 2010, NPE 2014 tion requirements in the demand sectors might lead to higher electricity demand. This could either be triggered directly by a more intensive electrification of the sectors or by increased demand for low-carbon energy carriers or feedstocks, respectively, that need to be provided via power to gas/fuel/chemical technologies. In any case, additional renewable energy sources need to cover the growing demand, and the energy system in that last phase of the transformation process becomes more and more a purely electricity-based system.

In the face of the challenges linked to the realization of the GHG-emission-reduction goals and the efforts to mitigate climate change in general, the German government set a variety of sub-targets to be achieved at different points in time (see Table 2). Many of these targets were determined in the framework of the 2010 "Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply" (BMWi and BMU 2010), when the German government specified its vision of the "Energiewende." After the Fukushima disaster in 2011, the targets of the Energy Concept remained mostly unchanged, but it was decided the country would pursue a stepwise nuclear power phase-out strategy to be completed by 2022.

In order to obtain its political climate and energy targets and mitigate climate change as much as possible, the German government is considering, planning, adopting and implementing different policies and measures. How much particular policies and measures as well as the whole policy mix can actually contribute to GHG mitigation is, however, often highly uncertain. An instrument often used to outline possible pathways to GHG mitigation and thus deep decarbonization are scenario studies. Assuming certain input factors (such as GDP and population development, future structure of the economy, implementation of climate and energy policies), different scenarios show how GHG emissions could develop in the future.

3 Deep decarbonization pathways for Germany – A comparison of three illustrative scenarios

This chapter provides a short overview of energy scenario studies released for Germany during the past few years (Section 3.1). From these studies, three illustrative decarbonization scenarios are selected to be discussed in detail throughout this report (Section 3.2). An overview is provided on the key differences between the three scenarios with regard to their decarbonization strategies (Section 3.3). Finally, the key assumptions and energy system developments are examined briefly (Section 3.4). Chapter 4 and Chapter 5 discuss in more detail the decarbonization strategies of the respective scenarios.

3.1 Overview of decarbonization scenarios for Germany

Energy scenarios have long played an important role in German energy policy discussions. Studies looking several decades ahead and describing the potential of renewable energy sources and the possibility of phasing out the use of nuclear power plants were developed in Germany as early as the 1980s. Most of the scenario studies released in recent years focus on the challenge of achieving deep cuts in carbon emissions in the German energy system within a few decades. These scenario studies have been commissioned by many different stakeholders, including federal and regional government ministries, environmental NGOs, and industry associations. The following Table 3 shows an overview of important energy scenario studies for the German energy system released since 2011.[2]

The scenario studies have been developed by many different authors and scientific institutions, and they differ, among other things, in the time periods they analyze. Two of the studies listed in Table 3 (Matthes et al. 2013, Schlesinger et al. 2011) limit their analysis to timelines ending in the year 2030, while all other studies look at least as far ahead as 2050. While most of the scenario studies analyze only the energy sector, which today is responsible for more than 80% of Germany's total greenhouse gas emissions, three of the studies (Repenning et al. 2014, Benndorf et al. 2014, Matthes et al. 2013) also discuss possible future developments in non-energy-related greenhouse gas emissions. Each of the listed studies describes at least one climate protection scenario that assumes that various emission mitigation measures are enacted in the future. For comparison purposes, many of the studies also describe a reference scenario in which no or only few new climate and energy policies are enacted. While all mitigation scenarios that run until 2050 describe (energy-related) greenhouse gas emission reductions of 80% or more relative to 1990, there are some differences in the respective strategies the scenarios choose to realize these emission reductions, as will be discussed later in this chapter.

3.2 Choosing three illustrative scenarios

For the detailed analysis of potential decarbonization pathways for Germany in this chapter we have chosen the following three illustrative scenarios from the literature:[3]

Table 3: Important energy scenario studies for the German energy system released since 2011

Study title	Commissioned by	Date
Climate Protection Scenario 2050	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)	August 2014
GROKO II – German Energy Supply Scenarios Based on the EEG Draft Bill	German Renewable Energy Federation (BEE)	July 2014
Development of Energy Markets – Energy Reference Forecast	Federal Ministry for Economic Affairs and Energy (BMWi)	June 2014
Germany in 2050 – a greenhouse gas-neutral country	Federal Environment Agency (UBA)	April 2014
Energy System Germany 2050	Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE)	November 2013
Policy Scenarios for Climate Protection VI	Federal Environment Agency (UBA)	March 2013
Long-term scenarios and strategies for the expansion of renewable energies in Germany	German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU)	March 2012
Energy Scenarios 2011	Federal Ministry for Economic Affairs (BMWi)	July 2011

Sources: Repenning et al. 2014, Nitsch 2014, Schlesinger et al. 2014, Benndorf et al. 2014, Henning and Palzer 2013, Matthes et al. 2013, Nitsch et al. 2012, Schlesinger et al. 2011

2 It should be noted that the table only lists scenario studies covering the entire energy system. Additional scenario studies have been released which deal solely with the electricity system (e.g. SRU 2011, Kuhn 2012, Hartmann 2013).

3 It should be noted that while the scenario analysis in this and the following chapters is based largely on the data found in the three respective publications (Schlesinger et al. 2014, Nitsch 2014, Repenning et al. 2014), some additional information was kindly made available to the authors of this report by all three teams of authors. Furthermore, to a very limited extent our own assumptions were made in order to deduce certain information that was not found in the publications and could not be obtained through the authors. It should further be noted that the three scenarios do not always use the same statistical sources, statistical definitions and sectoral boundaries, limiting their comparability. In this report care has been taken in the scenario comparisons to make sure that the findings derived are robust in relation to these differences.

- *Scenario "Target"* from the study "Development of Energy Markets – Energy Reference Forecast" (Schlesinger et al. 2014)
- *Scenario "100-II"* from the study "GROKO II – German Energy Supply Scenarios Based on the EEG Draft Bill" (Nitsch 2014)
- *Scenario "KS 90"* from the study "Climate Protection Scenario 2050" (Repenning et al. 2014)

From here on, these three scenarios will be referred to as follows in order to help readers differentiate these scenarios based on their respective main characteristic:

- The scenario "Target" will be referred to as "Government Target Scenario"
- The scenario "100-II" will be referred to as "Renewable Electrification Scenario"
- The scenario "KS 90" will be referred to as "90% GHG Reduction Scenario"

Of the dozens of German energy scenarios released within the past few years, these three scenarios were chosen for the following reasons:

- All three scenarios are up to date. (The respective studies were all released in 2014.)
- All three scenarios describe energy sector developments until at least 2050.
- The studies of all three selected scenarios provide a relatively high level of numerical detail in regard to their respective assumptions and results.
- The selected scenarios are highly relevant in the German energy policy discourse, especially the two scenarios commissioned by the two government ministries responsible for energy and climate change policy.
- All three scenarios achieve the German government's target of reducing greenhouse gas emissions by 80% or more by 2050 as compared with 1990, at least with regard to energy-related emissions. At the same time it is instructive to compare these scenarios as they achieve different energy-related emission reductions (80%, 86% and 92%), in part by employing different mitigation strategies.

In the following, we will provide a brief overview of each selected illustrative scenario and its respective scenario study, before the scenarios' key assumptions and results are compared and discussed in more detail in Section 3.3.

The study "Climate Protection Scenario 2050" (Repenning et al. 2014) – which contains the "90% GHG Reduction Scenario" – was commissioned by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), which in Germany is responsible for the government's climate mitigation policies. It was prepared by Öko-Institut and Fraunhofer ISI and finished in August 2014. Key objectives of the study were to illustrate the measures and strategies required to reach the German government's medium- and long-term greenhouse gas mitigation targets and to assess the relationship between the costs and benefits of the required mitigation policies for consumers and the economy as a whole. The study is one of the few studies released in recent years that not only addresses energy-related greenhouse gas emissions but also includes in some detail the possible future development of non-energy-related emissions. The study uses a combination of different modeling instruments to develop its scenarios, including technology-rich bottom-up models for space heating demand in buildings and energy demand in the industry and service sectors. For the electricity market, investments in new renewable energy technologies are preset by the authors so as to be in line with political targets and long-term decarbonization needs, while deployment and dispatch of conventional power plants is determined through the use of an optimization model. For most types of non-energy related emissions, existing projections and reduction potentials from the literature were used. The study develops three different scenarios. In a current policy scenario, only policy measures enacted by October 2012 were taken into account. No further changes to Germany's energy and climate policy framework were assumed. In this scenario, the government's energy and climate targets are markedly missed. The scenario is supposed to highlight the gap that future climate policy measures need to overcome. A second scenario (KS 80) describes the measures and strategies required to reach the government's minimum mitigation target of minus 80% by 2050 compared with 1990. Finally, a third scenario (KS 90) investigates the measures and strategies that would be needed to achieve greenhouse gas emission reductions of 90% by 2050. This most ambitious scenario was chosen for the following scenario comparison as it is the only detailed and up-to-date scenario study that describes a possible future development that comes close to fulfilling the upper end of the government's greenhouse gas emission mitigation target of minus 80% to minus 95%. In this report we refer to the scenario as the "90% GHG Reduction Scenario".

The study "GROKO II – German Energy Supply Scenarios Based on the EEG Draft Bill"[4] (Nitsch 2014), from which the "Renewable Electrification Scenario" originates, was commissioned by the German Renewable Energy Federation (BEE) and was finished in July 2014. It was prepared by Joachim Nitsch, who has long worked in the development of energy scenarios at the German Aerospace Center (DLR). The study's key objectives were to highlight the expected consequences of a draft amendment of the Renewable Energy Sources Act (which was under political discussion in the summer of 2014) and to show ways to further increase the security of supply and renewable energy shares while reducing greenhouse gas emissions. To this end, two scenarios were developed for the study. The study does not elaborate on the methodology or specific models used, but previous similar scenario studies by the author have used electricity system models with temporal and spatial resolution to validate the feasibility of the assumed deployment of electricity generation technologies.

One of the study's two scenarios is called "GROKO-II" and aims to highlight the consequences of the EEG amendment on the further deployment of renewable energy sources in the electricity sector. In this scenario no significant additional climate and energy measures are enacted. In the "GROKO-II" scenario the government's main energy and climate targets are clearly missed. The study's other scenario is called "100-II." This scenario highlights a possible pathway to meet the government's energy and climate targets. This scenario was mostly chosen for the following scenario comparison as it represents an example of the many mitigation scenarios for Germany that focus mainly on an expanded use of renewable energy sources as well as efficiency increases. Furthermore, the scenario achieves GHG emission reductions by 2050 that are somewhat higher than the government's minimum target but lower than those of the most ambitious scenarios available. While the scenario describes developments until the year 2060, we will focus on the year 2050 in the following scenario comparison. In this report we refer to the scenario as the "Renewable Electrification Scenario."

The study "Development of Energy Markets – Energy Reference Forecast" (Schlesinger et al. 2014), which includes the "Government Target Scenario," was commissioned by the Federal Ministry for Economic Affairs and Energy

4 Our own translation of the German title of the study ("GROKO – II – Szenarien der deutschen Energieversorgung auf der Basis des EEG-Gesetzentwurfs"). "GROKO" is the German abbreviation of the term "Grand Coalition," standing for the current coalition government of Germany's two biggest parties, the Christian Union (CDU/CSU) and the Social Democrats (SPD). The term "EEG" is short for "Erneuerbare-Energien-Gesetz," German for "Renewable Energy Sources Act," the German law regulating the feed-in support for electricity generation from renewable energy sources.

(BMWi), which is responsible for energy policy within the German government. The study was finished in June 2014 and was prepared by Prognos, the Institute of Energy Economics (EWI) and the Institute of Economic Structures Research (GWS). The study uses a number of dedicated models to define inter alia the development of key drivers like population, number of households and economic output by sectors. Furthermore, it determines final energy demand by sector and developments in the energy conversion sector. For the electricity system a dynamic optimization model is used that is based on detailed technological and economic data on conventional and renewable generation technologies. The model takes into account electricity demand and supply from other European countries as well as meteorological conditions in Europe (which determine electricity generation from renewable energy technologies).

One of the objectives of the study is to describe the most likely developments in the German energy system through the year 2030 and to add a "Trend Scenario" that extrapolates these developments until 2050. In the reference forecast and trend scenario most of the government's climate and energy targets are missed. Another objective of the study is to show how developments within the energy system would need to be different from the reference forecast and trend scenario in order for the government's targets to be met. This "target scenario" was chosen for the following scenario comparison mainly because of the high relevance of this study's scenarios in the German energy policy discourse. Furthermore, the target scenario was devised to meet relatively precisely the government's key energy and climate targets. Energy-related GHG emissions are reduced by 80% by 2050 (compared with 1990), thus meeting the low end of the German government's climate target. In this report we refer to the scenario as the "Government Target Scenario."

3.3 Key decarbonization strategies used in the three illustrative scenarios

Various strategies to reduce GHG emissions over the coming decades can be differentiated in current energy scenarios for Germany. These strategies reflect the scientific, political, and social discussions in Germany over the past years and decades about appropriate, sustainable, and socially acceptable emission mitigation strategies. The construction of new nuclear power plants, for example, is not envisioned by any of the current energy scenarios as there is widespread agreement in Germany that the disadvantages of nuclear power and the risks associated with it outweigh its potential GHG reduction benefits. Likewise, CCS for use in the power sector is also not envisioned by any of the energy scenarios for Germany released within the past few years as it has become clear that there is very little acceptance for this technology within German society, especially given the low-carbon alternatives available in electricity generation.

Table 4 differentiates between eight key strategies used in German energy scenarios to reduce GHG emissions and provides a qualitative assessment of whether and how much each strategy is used in the three scenarios analyzed here. If a strategy is used to a moderate or strong extent in one of the scenarios, this is marked green. If a strategy is not used or used only to a very small extent, this is marked red. The table illustrates that some strategies are used in all three scenarios while others are used only in one or two of the three scenarios.

Table 4 indicates that in order to reach very strong reductions in GHG emissions of about 90% or more by 2050 (compared with 1990) it may be necessary to implement most or all of these mitigation strategies, as is done in the most ambitious of the three scenarios analyzed here, the "90% GHG Reduction Scenario."

In the following Section 3.4, the three selected scenarios are analyzed and compared with regard to their main assumptions and results. The various mitigation strategies differentiated in Table 4 will then be discussed in more detail (and in slightly divergent separation) in Chapters 4 and 5.

Chapter 4 will discuss the following three strategies that significantly contribute to GHG emission reductions and which are used to a significant extent in all three analyzed scenarios:

- Energy efficiency improvements
- Increased use of domestic renewables (with a focus on renewables in electricity generation)
- Electrification and use of renewables-based synthetic fuels ("power-to-x")

These strategies are also used extensively in other energy scenarios for Germany, and it can be argued that they need to be implemented successfully for Germany to be able to reach substantial GHG emission reductions by 2050. Chapter 5 will briefly discuss the other strategies that are used only in one or two of the three scenarios respectively and can be regarded as more controversial:

- Final energy demand reductions through behavioral changes
- Net imports of electricity or bioenergy
- Use of CCS technology to reduce industry sector GHG emissions

In addition, Chapter 5 will also discuss non-energy related (often non-CO_2) emission reductions in the agricultural sector as an important non-energy system strategy to cut GHG emissions.

3.4 Analysis and comparison of the three illustrative scenarios

This section analyzes and compares the three illustrative scenarios, focusing first on the key assumptions driving energy demand (Section 3.4.1). The energy system developments described by the respective scenarios are discussed with regard to final energy demand (Section 3.4.2), electric-

Table 4: Overview of the extent to which key decarbonization strategies are used in the illustrative scenarios *

	Government Target Scenario	Renewable Electrification Scenario	90% GHG Reduction Scenario
Energy demand reductions			
Final energy demand reductions through **energy efficiency**	Very strong efficiency improvements	Strong efficiency improvements	Very strong efficiency improvements
Final energy demand reductions through **behavioral changes**	Not considered	Not considered	Considered to a moderate extent
Using less CO_2-intensive energy sources/carriers			
Increased use of **domestic renewable** energy sources	Strong increase	Very strong increase	Strong increase
Substitution of fossil fuels through electricity	Moderate substitution	Strong substitution	Strong substitution
Use of renewable energy based **synthetic fuels (e.g. H_2)** as a final energy carrier	Not used to a relevant extent	Strongly used	Moderately used
Importing carbon-free energy			
Net imports of electricity	Low net imports	Considerable net imports	Moderate net imports
Net imports of bioenergy	Moderate net imports	No net imports	Considerable net imports
Using CCS			
Use of **CCS technology** to reduce **industrial** GHG emissions	Not considered	Not considered	Considered

* Section 3.4 as well as Chapters 4 and 5 will provide more detailed information about the differences between the scenarios that have led to the assessment provided by this table.

ity demand and supply (Section 3.4.3), primary energy demand and supply (Section 3.4.4), and greenhouse gas emissions (Section 3.4.5).

3.4.1 Comparison of demographic and economic assumptions of the scenarios

As is common for scenario studies of this type, all three scenarios do not assume any drastic or sudden changes in social and economic developments. For example, they do not assume dramatic technological breakthroughs, drastic lifestyle changes or lasting economic crises.

The following table provides a comparison of selected assumptions regarding the future development of key drivers of energy demand. Differences between the scenarios are relatively minor with regard to population, number of households and GDP development. The German population is expected to decline by 9% to 12% between 2010/2011 and 2050 in all three scenarios, while the number of households is assumed to remain relatively stable during the same period (-3% to +3%, see Table 5). Real GDP is expected to grow by 39% to 49% between 2010 and 2050 (see Table 5). This corresponds to average annual GDP growth rates of between 0.8% and 1.0%.

3.4.2 Final energy demand

Final energy demand is expected to be reduced dramatically by 2050. The three scenarios assume that total final energy demand will be 40% to 47% lower in 2050 than in 2010. These scenarios are in line with many other scenario studies showing that faster efficiency increases than in the past are required in the coming years and decades for Germany to be able to reach

Table 5: Overview of key demographic and economic assumptions of the illustrative scenarios

Population (in millions)						
	2010 *	2020	2030	2040	2050	Change 2050/2010
Government Target Scenario	80.2	79.4	78.2	76.1	73.1	-9%
90% GHG Reduction Scenario	81.4	80.6	79.0	76.0	71.8	-12%
Renewable Electrification Scenario	81.6	80.5	79.1	75.5	73.8	-10%
Number of households (in millions)						
	2010	2020	2030	2040	2050	Change 2050/2010
Government Target Scenario	40.0	41.0	41.0	41.0	40.0	0%
90% GHG Reduction Scenario	39.0	40.7	41.0	40.4	40.0	3%
Renewable Electrification Scenario	39.7	40.8	41.0	40.6	38.6	-3%
Real GDP (in billions USD_{2010})						
	2010	2020	2030	2040	2050	Change 2050/2010
Government Target Scenario	2911	3192	3599	3969	4340	49%
90% GHG Reduction Scenario	2725	3049	3303	3542	3794	39%
Renewable Electrification Scenario	2805	3126	3376	3678	4050	44%

* For the "Government Target Scenario" here (as well as in the following tables), the number refers to the year 2011. The considerable difference in the population figure for 2010/2011 between the "Government Target Scenario" and the other two scenarios is due to the Schlesinger et al. (2014) study being the only one of the three studies that takes into account major recent changes in the population statistics released by the Federal Statistical Office in 2013. In that year the Office reversed its estimate of the German population downward based on newly available data from a countrywide census conducted in 2011.

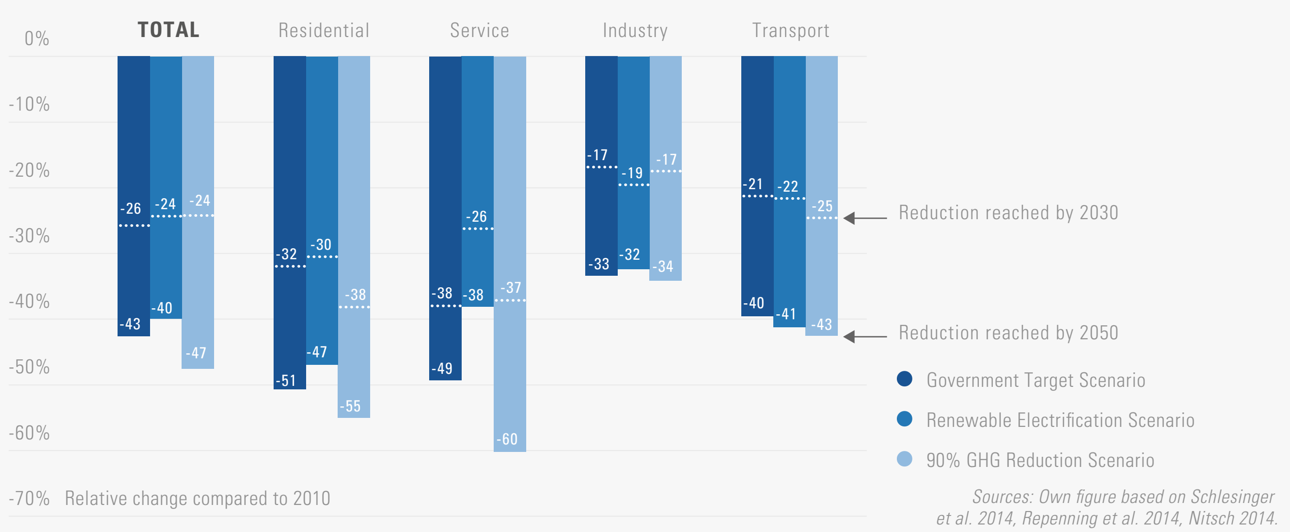
Sources: Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014, Nitsch et al. 2012 its medium- and long-term energy and climate targets. Reductions in final energy demand are expected to be achieved mainly by energy efficiency improvements.[5] To a lesser extent, reductions in energy service demand compared with a reference development also contribute to lower final energy demand, especially in the "90% GHG Reduction Scenario."

While the change in total final energy demand is similar in all three scenarios, Figure 3 shows that there are more pronounced differences between the scenarios in energy demand changes in individual sectors. Differences are greatest in the service sector. Here energy demand reductions by 2050 (compared with 2010) vary between 38% ("Renewable Electrification Scenario") and 60% ("90% GHG Reduction Scenario"). In all scenarios, energy demand reductions by 2050 are lowest in the industry sector and (with the exception of the "90% GHG Reduction Scenario") highest in the residential sector. A large part (about 50% to 60%) of the total final energy demand reductions in all three scenarios are realized by 2030, with the residential and service sectors achieving a larger share of their energy demand during this early period compared with the industry and transport sectors.

Energy demand reductions in the residential and service sectors

The strong reductions in final energy demand in both the residential sector and the service sector in all three scenarios are driven to a large extent by massive reductions in energy demand for space heating.[6] In the "Government Target Scenario" energy demand for space heating

Figure 3: Change in final energy demand compared to 2010



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

5 To some extent, the energy efficiency improvements are the result of the switch from fossil fuels to electricity for some applications. This electrification allows more efficient technologies to be used. For example, an electric engine is more efficient than a combustion engine.

6 No data on space heating is available for the "Renewable Electrification Scenario." However, since space heating makes up a large part of overall final energy demand in the residential and service sectors and this demand is reduced considerably in the scenario, it is obvious that energy demand for space heating needs to be lowered to a great extent as well. Space heating made up almost 70% of final energy demand in the residential sector and around 47% in the service sector in 2012 (AGEB 2013).

is reduced by 56% between 2011 and 2050, while it is even reduced by 71% in the "90% GHG Reduction Scenario" between 2008 and 2050. These reductions in space heating demand mainly result from the refurbishment of existing buildings and the construction of highly efficient new buildings.

For the refurbishment of existing buildings to progress as assumed in these two scenarios, the annual rate of energy-related refurbishments will need to be increased considerably compared with today's rate. It is estimated that today about 1% of the buildings in Germany are refurbished for better energy use each year. The "Government Target Scenario" assumes that this rate is increased to almost 2% by 2030 and is kept at this rate until the middle of the century, while the "90% GHG Reduction Scenario" assumes that this rate can even be increased to more than 3% after 2030. However, the scenario's authors note that further investigations are required to find out whether such high rates of refurbishments can indeed be realized by the industry. The challenges associated with increasing the rate of building refurbishments are discussed further in Section 4.1.1.

Energy demand reductions in the transport sector

In the transport sector an important energy demand reduction strategy in the investigated scenarios is a strong increase in the efficiency of conventional cars and trucks.[7] For example, in the "90% GHG Reduction Scenario," newly sold cars using gasoline engines reduce their specific energy demand by over 40% between 2010 and 2030 and light diesel-powered trucks reduce their energy demand by almost 35% over the same period (Repenning et al. 2014). Lightweight construction, improvements in aerodynamics and the use of (non-plug-in) hybrid technology are mentioned in the descriptions of both the "90% GHG Reduction Scenario" and "Government Target Scenario" as important strategies to achieve these demand reductions. At the same time both the "90% GHG Reduction Scenario" and the "Government Target Scenario" assume that electric cars gain a considerable share in overall car sales over the observed period. As electric engines are more efficient than their conventional fuel-powered alternatives, this increase in share also contributes to energy demand reductions (see also Section 4.3 on electrification strategies). The following Table 6 shows the evolution of the share of electric cars in the "Government Target Scenario" and the "90% GHG Reduction Scenario," with electric cars defined here as battery electric vehicles, plug-in hybrid electric vehicles and fuel-cell electric vehicles.

In addition to these technical changes, both the "Government Target Scenario" and the "90% GHG Reduction Scenario" also assume changes in the modal split in freight transport compared with today (see Table 7). The "90% GHG Reduction Scenario" assumes that the share of rail, which generally requires less energy per ton kilometer than road transport, increases from 17% in 2010 to 26% in 2050 while that of road transport decreases from 75% to 67% during the same period. It is assumed that this shift toward freight rail transport is achieved by political measures that increase the relative costs of freight road transport, especially higher energy taxes and a more comprehensive truck toll system with regularly increasing fees. In the "Government

7 The "Renewable Electrification Scenario" does not provide detailed (disaggregated) information about final energy demand in the transport sector (Nitsch 2014). However, as total energy demand reductions in this scenario are similar to those in the other two analyzed scenarios, we assume that the drivers of demand reduction – including more efficient conventional cars and trucks – are similar as well.

Table 6: Shares of electric cars in total car stock in two of the illustrative scenarios

	2010	2020	2030	2040	2050
Government Target Scenario	0%	2%	14%	31%	53%
90% GHG Reduction Scenario	0%	2%	24%	59%	80%

Sources: Schlesinger et al. 2014, Repenning et al. 2014

Table 7: Modal split in freight transport in two of the illustrative scenarios (based on ton kilometers travelled)

	2010/2011	2020	2030	2040	2050
Government Target Scenario					
Road	73%	73%	71%	68%	64%
Rail	18%	19%	21%	23%	26%
Inland shipping	9%	8%	8%	8%	9%
90% GHG Reduction Scenario					
Road	72%	70%	70%	69%	67%
Rail	17%	22%	23%	24%	26%
Inland shipping	11%	8%	7%	7%	7%

Sources: Schlesinger et al. 2014, Repenning et al. 2014

Table 8: Modal split in land-based motorized passenger transport in two of the illustrative scenarios (based on person kilometers travelled)

	2010/2011	2020	2030	2040	2050
Government Target Scenario					
Individual motorized transport	85%	85%	85%	86%	86%
Rail	9%	10%	10%	10%	10%
Bus	6%	5%	5%	5%	4%
90% GHG Reduction Scenario					
Individual motorized transport	83%	86%	86%	87%	88%
Rail	9%	8%	7%	6%	6%
Bus	8%	7%	7%	6%	6%

Sources: Schlesinger et al. 2014, Repenning et al. 2014

Table 9: Passenger kilometers traveled in the three illustrative scenarios (in billions)

	2010	2020	2030	2040	2050	Change 2050/2010
Government Target Scenario	1134	1143	1140	1122	1085	-4%
90% GHG Reduction Scenario	1072	938	884	915	868	-19%
Renewable Electrification Scenario	1129	1153	1147	1099	1053	-7%

Sources: Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014, Nitsch et al. 2012

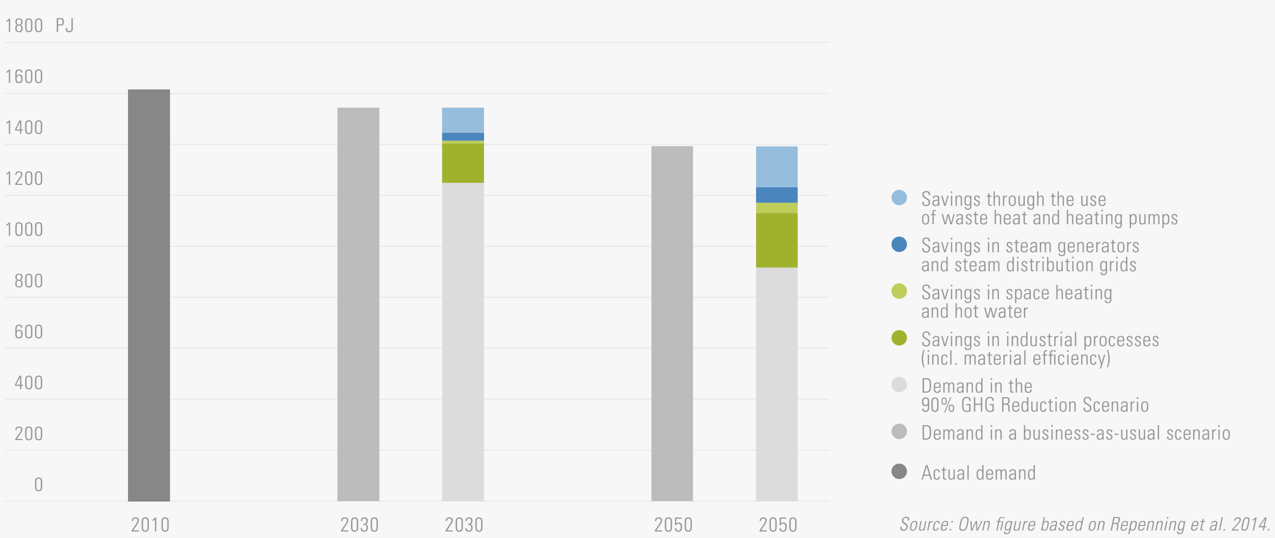
Target Scenario" the modal shift in freight transport until 2050 is similar. However, this scenario's authors argue that non-policy-related factors will lead to growth in the rail transport share: They expect long-distance freight transport to make up most of the expected additional freight transport demand until 2050 as trade among European countries is expected to continue to increase as a result of increasing intra-European division of labor. The authors also expect trade with containers to gain more and more relevance. Both of these developments favor rail transport as compared with road transport.

In passenger transport, only modest changes in the modal split are expected in both scenarios (see Table 8). The less energy-efficient individual motorized transport slightly increases in both scenarios compared with today, as it is expected that an increasing share of the population will have access to a car in the decades ahead. However, in the "90% GHG Reduction Scenario" it is assumed that *owning* a car will become less attractive and flexibility in the choice of transport modes will increase. This will lead to more and more journeys being undertaken partly or fully by bike or on foot, reducing passenger kilometers travelled by motorized transport compared with today by almost one-fifth, much more than in the other two analyzed scenarios, in which passenger kilometers travelled are reduced by a more modest 4% and 7%, respectively (see Table 9).

Energy demand reductions in the industry sector

In the industry sector energy demand reductions in the scenarios are achieved to a great extent by reducing energy demand for industrial processes, as shown in Figure 4 for the "90% GHG Reduction Scenario". These processes are diverse and differ significantly from one industrial branch to another. In the chemical industry, for example, membrane technology could be used more extensively to produce chlorine. In the production of cement clinker, the required temperatures could be reduced significantly if binders other than limestone could be used. In the production of glass, energy demand reductions can be

Figure 4: Fuel demand in the industrial sector in the 90% GHG Reduction Scenario



Source: Own figure based on Repenning et al. 2014.

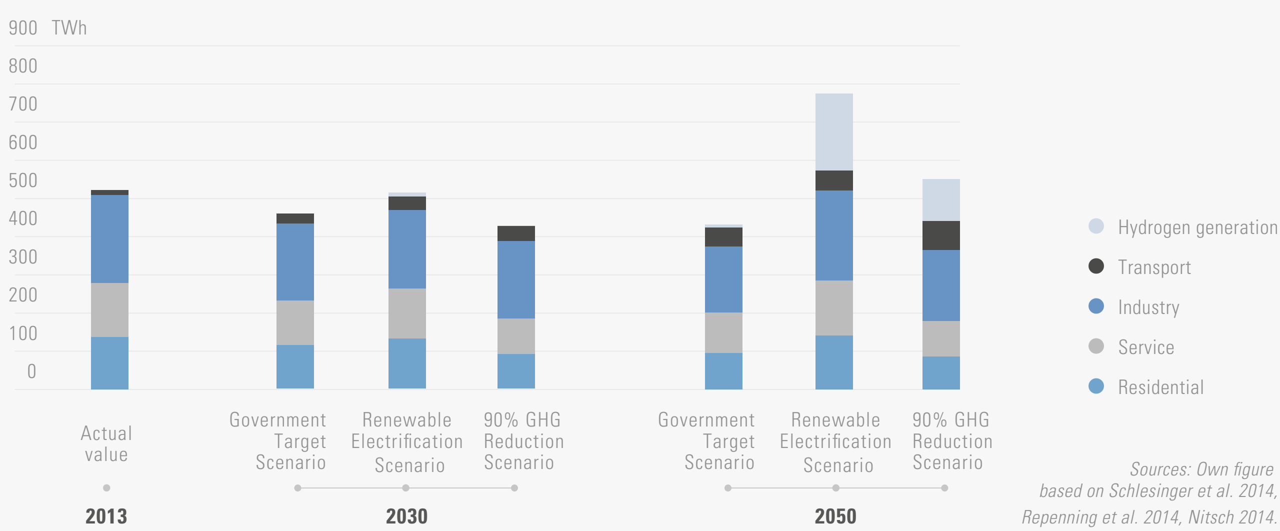
achieved through the use of innovative burner technologies and an increase in the share of glass returns. New steam-drying processes could significantly reduce energy demand in paper and pulp production. Furthermore, basic oxygen steel production could be substituted to a larger extent by the more energy-efficient electrical steel production. Both the "Government Target Scenario" and the "90% GHG Reduction Scenario" assume that such innovative process technologies are used to an increasing extent in the next few decades.[8] However, the usually higher costs compared with conventional technologies and the typically long lifetimes of existing technologies hinder the comprehensive exploitation of the technical potential of many of these innovative technologies.

Another area of significant energy reduction potential in the industry sector is the utilization of waste heat (see also Figure 4). Both scenarios assume that this potential is used to a much greater extent in the future. Optimizing the use of waste heat often requires technical components that are specifically geared to each other and may require significant changes in production processes. The "90% GHG Reduction Scenario" assumes that the waste heat can be heated to up to 140 degrees Celsius by using electric heating pumps, thus allowing this heat to be used in a wide variety of industrial processes.

3.4.3 Electricity demand and supply

As Figure 5 shows, electricity demand by sector (defined here as final energy electricity demand by sector plus electricity demand for production of hydrogen via electrolysis) varies considerably in 2050 in the three selected scenarios. In the "Government Target Scenario," electricity demand in 2050 is about 100 TWh lower than it was in 2013, while it is some 250 TWh higher

Figure 5: Electricity demand by sector (including electricity demand for hydrogen generation)



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

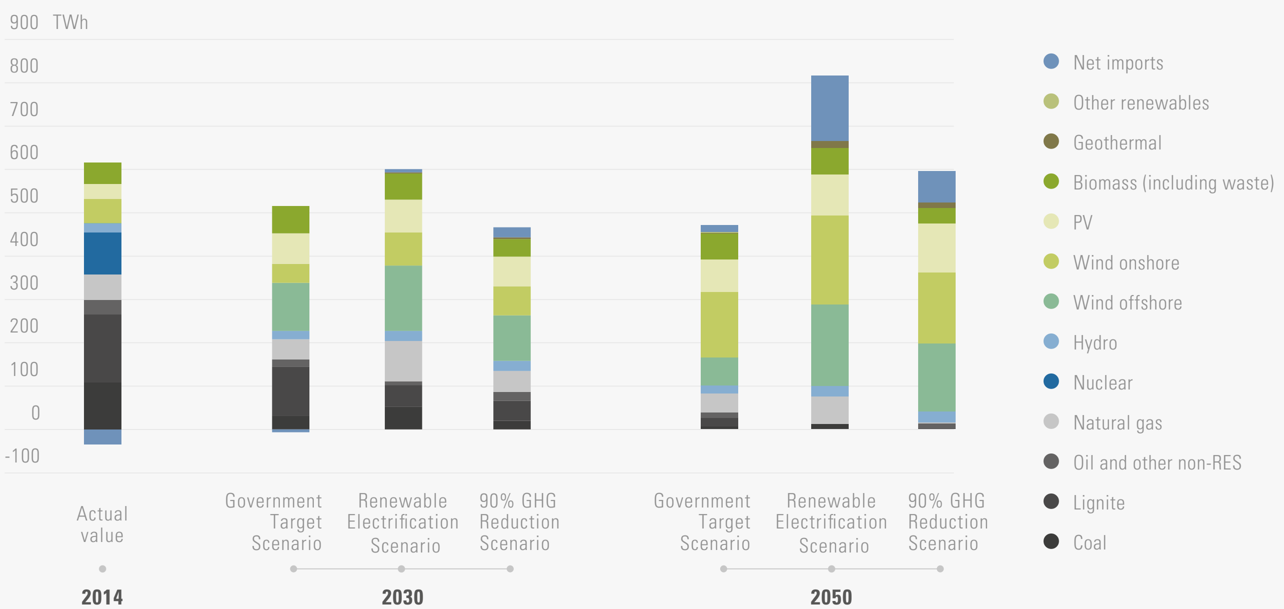
8 The "Renewable Electrification Scenario" does not provide detailed (disaggregated) information about the changes in final energy demand in the industrial sector (Nitsch 2014).

than it was in 2013 in the "Renewable Electrification Scenario." In the "90% GHG Reduction Scenario," the level of electricity demand is similar to 2013. The figure shows that two reasons for the high electricity demand in 2050 in the "Renewable Electrification Scenario" can be differentiated:

- Electricity demand in the residential, service and industry sectors is at a similar level respectively as it is today, while it is considerably lower than today in the other two scenarios. Although detailed information about electricity demand in the individual sectors is limited in the Nitsch (2014) study, it is likely that the higher electricity demand in the three mentioned sectors is due to a combination of less optimistic assumptions regarding future efficiency improvements in electric end-use applications and stronger assumptions regarding the potential to substitute fossil fuels for electricity, especially for space and process heat.
- Much more electricity is required in this scenario in 2050 to generate hydrogen than in the other two scenarios. While the "Renewable Electrification Scenario" requires 200 TWh of electricity for electrolysis, the corresponding demand in the "90% GHG Reduction Scenario" is only about 110 TWh, and in the "Government Target Scenario" less than 10 TWh.

Electricity demand in 2050 by end-use sectors is very similar in the "Government Target Scenario" and the "90% GHG Reduction Scenario," except for the transport sector, where electricity demand in the latter scenario is 25 TWh (or 50%) higher than in the "Government Target Scenario," mainly due to a higher share of electric cars in the total car stock (see Table 6 above).

Figure 6: Electricity generation by source (including net imports)



The figure refers to gross electricity generation except in the case of the 90% GHG Reduction Scenario, for which net electricity generation is shown as data for gross generation is not available.

Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014, Nitsch 2015 (personal communication, April 30, 2015), Harthan 2015 (personal communication, May 11, 2015), AGEB 2015c.

Electricity demand varies much less between the three scenarios in the year 2030, as no or only very little electricity is required for generating hydrogen until then. In the two scenarios that use significant amounts of hydrogen by 2050 ("Renewable Electrification Scenario" and "90% GHG Reduction Scenario"), the use of this energy carrier only becomes relevant after 2030. After that year the growing shares of intermittent renewable energy sources lead to growing amounts of "excess" electricity generation which lend themselves to be used for hydrogen generation. The electrification strategy in the end-use sectors, which is employed most strongly in the "Renewable Electrification Scenario," leads to stronger electricity demand in that scenario in 2030 compared with the other two scenarios, although this effect is also becoming more pronounced until 2050.

Corresponding to electricity demand, electricity supply in 2030 and 2050 is highest in the "Renewable Electrification Scenario," while it is lowest in the "Government Target Scenario," as Figure 6 shows. In all three scenarios, electricity supply is increasingly dominated by renewable energy sources. Looking only at domestic electricity generation (i.e. without net imports or exports), the share of renewables increases from 26% in 2014 to 60% in 2030 and 82% in 2050 in the "Government Target Scenario," to 66% (2030) and 89% (2050) in the "Renewable Electrification Scenario," and to 70% (2030) and 97% (2050) in the "90% GHG Reduction Scenario." Another metric to define the role of renewables in the power sector is the share of renewables in gross electricity consumption. This metric is used by the German government to express its targets. The government target for 2050 is 80%, which is almost met by the "Government Target Scenario" (79% in 2050) and exceeded by the other two scenarios.

Wind energy dominates in all three scenarios, with its share in total domestic generation reaching 30% ("Government Target Scenario") to 39% ("90% GHG Reduction Scenario") by 2030 and 47% ("Government Target Scenario") to 62% ("90% GHG Reduction Scenario") by 2050, up from 9% in 2014. While the absolute contribution of onshore wind power in 2050 is similar in all three scenarios (between 148 TWh and 186 TWh) there is disagreement among the scenarios about the future role of offshore wind power in domestic electricity generation in Germany. Its contribution by the middle of the century varies considerably, ranging from only 64 TWh/a to over 200 TWh/a. After wind, solar PV is the most important source for domestic electricity generation in 2050, with its share growing from 6% in 2014 to between 14% and 21% and its absolute contribution growing from 35 TWh in 2014 to between 75 TWh and 114 TWh.

Nuclear energy is phased out in all three scenarios by 2023 in line with the current German nuclear phase-out law. Lignite and coal, which today dominate the electricity generation mix in Germany with a combined share of 43% in 2014, play only a very minor role in the "Government Target Scenario" and "Renewable Electrification Scenario" in 2050, with shares of 6% and 2%, respectively. In the "90% GHG Reduction Scenario," electricity generation from fossil fuels is virtually phased out by 2050. The remaining fossil fuel electricity generation in the "Government Target Scenario" and "Renewable Electrification Scenario" is mostly based on natural gas, the majority of which is used in combined heat and power (CHP) plants.

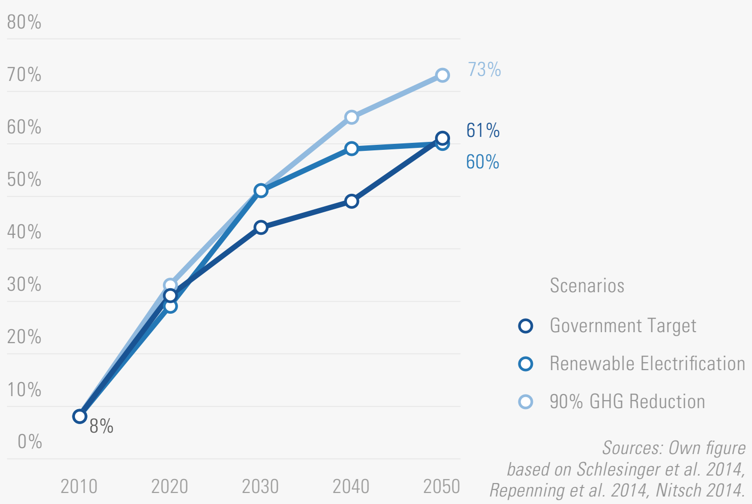
All scenarios expect Germany to become a net importer of electricity by 2050.[9] Net imports are modest in the "Government Target Scenario,"

9 Since 2003 Germany has consistently been a net exporter of electricity. In 2014 Germany net exported a record 36 TWh, or 6%, of domestic electricity generation (AGEB 2015c).

reaching 16 TWh by 2050, but are substantial in the "90% GHG Reduction Scenario" (74 TWh in 2050) and especially in the "Renewable Electrification Scenario" (146 TWh in 2050). In these two scenarios it is assumed that Germany will be able to cost-effectively import renewable-based electricity from European as well as North African countries. While none of the three analyzed scenario studies discusses in detail the exact sources of the electricity imports, other studies assume that electricity will be imported mainly from offshore wind power located in both Northern Europe and North Africa and from solar PV and solar thermal power plants located in North Africa.

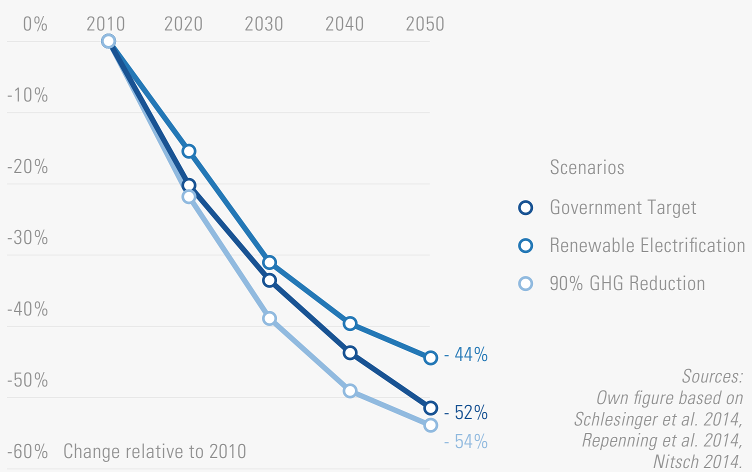
Even if it is assumed that the imported electricity will be available to Germany any time it is needed, the high reliance on wind power and solar PV in domestic electricity generation in the scenarios by 2050 leads to high shares of fluctuating renewable energy sources. While onshore wind, offshore wind, and solar PV made up 16% of Germany's electricity supply in 2014, this share grows to between 60% ("Renewable Electrification Scenario") and 73% ("90% GHG Reduction Scenario") by 2050 in the three scenarios.[10] As Figure 7 shows, the scenarios expect that by 2030, about 50% of Germany's electricity supply will be based on wind and solar PV. Section 4.2 will discuss the challenges associated with very high shares of fluctuating renewable energy sources in the electricity supply and will highlight the measures that can be taken to help maintain a stable electricity supply.

Figure 7: Share of fluctuating sources (defined as domestic solar PV, onshore and offshore wind) in total electricity supply (in %)



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

Figure 8: Change in primary energy demand relative to 2010 (in %)



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

Underlying primary energy data for the 90% GHG Reduction Scenario includes only energetic primary energy, while the data for the other two scenarios refer to total primary energy.

3.4.4 Primary energy demand and supply

Primary energy demand is reduced considerably in all three analyzed scenarios (see Figure 8). Compared with primary energy demand in 2010, demand is reduced by between 44% ("Renewable Electrification Scenario") and 54% ("90%

10 It should be noted that these shares were calculated based on primary electricity generation, which does not include secondary generation, e.g. electricity generation from pumped hydro storage plants or from electrolysis-based hydrogen. Including these adjustable sources would slightly reduce the share of intermittent sources in the total electricity supply.

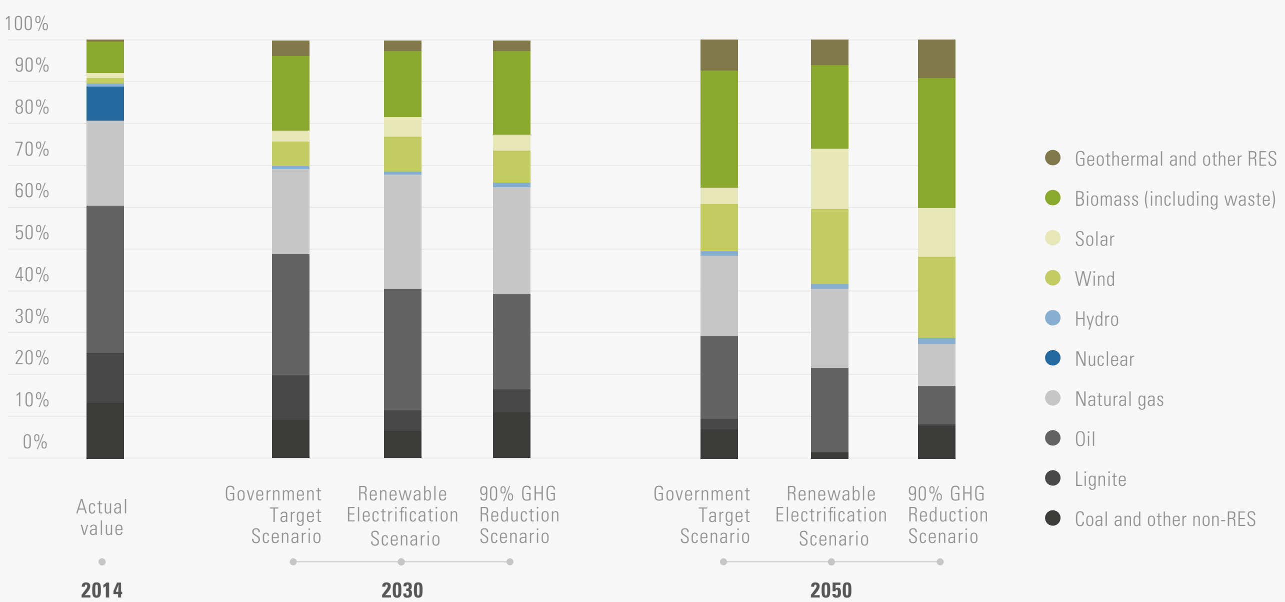
GHG Reduction Scenario") by 2050. There are several reasons for this strong reduction in primary energy demand:

- Strong improvements in energy efficiency in all end-use sectors (see Section 3.4.2 above)
- Shift from mainly thermal-based electricity generation, with its considerable conversion losses, to a mainly wind- and solar PV-based electricity generation with no conversion losses (as defined by statistics). (See Section 3.4.3 above)
- Reduction of population of about 10% between 2010 and 2050 (see Section 3.4.1 above)

Figure 9 shows the primary energy mix of 2030 and 2050 according to the scenarios. While the differences are much more pronounced in 2050 than in 2030, the figure shows that already by 2030 there is disagreement between the scenarios with regard to the role of oil, natural gas, and especially coal. This disagreement can be explained in part by the varying views about how fast the use of coal and lignite can or should be reduced, especially in electricity generation.

In all three scenarios renewable energy sources make up more than 30% of the total primary energy supply in 2030 and more than 50% in 2050, growing from 11% in 2014. In the "Government Target Scenario" the share in 2050 is 51%, in the "Renewable Electrification Scenario" it is 59%, and in the "90% GHG Reduction Scenario" the share is highest at 73%. While coal and lignite make up a combined 25% in today's primary energy supply, their combined share decreases significantly to between 2% ("Renewable Electrification Scenario") and 9% ("Government Target Scenario"). Oil remains relevant with a 2050 share of between 9% ("90% GHG Reduction Scenario") and 20% (both "Government Target Scenario" and "Renewable Electrification Scenario") and is used mainly in the transport sector, but its share is also much lower than today's (35% in 2014, AGEB 2015).

Figure 9: Primary energy mix



Underlying primary energy data for the 90% GHG Reduction Scenario includes only energetic primary energy, while the data for the other two scenarios refer to total primary energy.

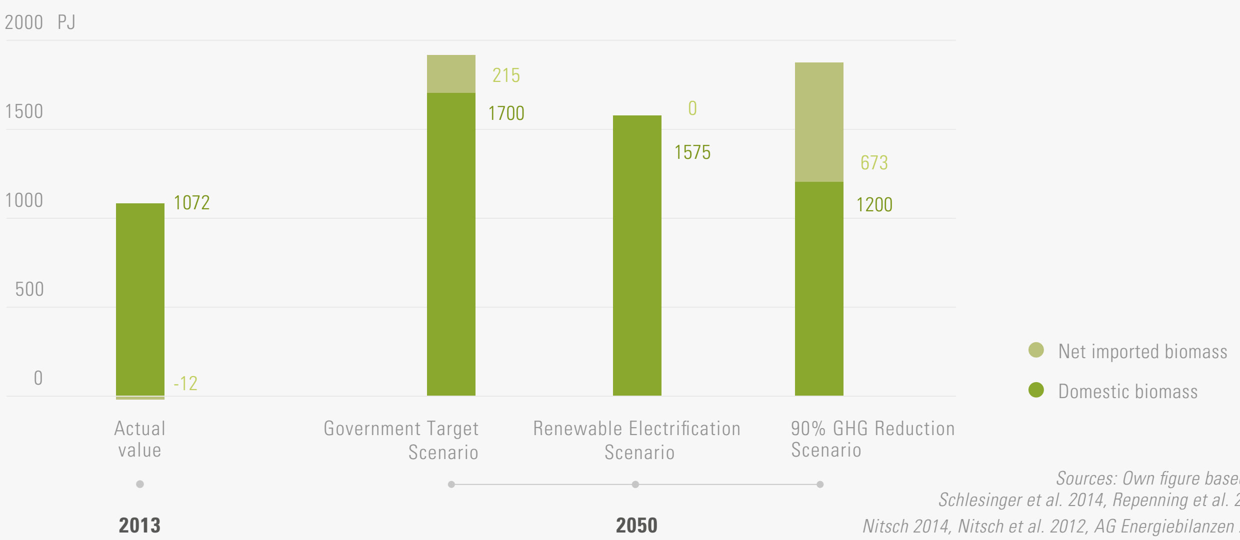
Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014 , AG Energiebilanzen 2015a.

Biomass continues to be the most important renewable energy source in the primary energy supply, but is followed closely in all three scenarios in 2050 by wind energy. Biomass use increases over today's level of 1,060 PJ (2013), growing to between 1,575 and 1,915 PJ in 2050 (see Figure 10). In all three scenarios most of this growth in biomass use takes place by 2030. However, as Figure 10 shows, there is disagreement about exactly how large the sustainable biomass potential will be in Germany by 2050, with assumptions in the three scenarios ranging from 1,200 PJ ("90% GHG Reduction Scenario") to a more optimistic 1,700 PJ ("Government Target Scenario"). Consequently, a significant amount of biomass is assumed to be imported in the "90% GHG Reduction Scenario" (about 670 PJ/a), while the amount is lower in the "Government Target Scenario" (215 PJ/a). The authors of the "90% GHG Reduction Scenario" cite studies that find higher average per-capita biomass potential in other European countries and Russia than in Germany, leading to the assumed potential for future biomass imports.[11]

3.4.5 Greenhouse gas emissions

As Figure 11 shows, energy-related GHG emissions are reduced by 56% in the "Government Target Scenario" and by 62% in the "90% GHG Reduction Scenario" between 1990 and 2030.[12] The "Renewable Electrification Scenario" only provides the sum of energy-related and process-related GHG emissions, which is reduced by 60% during the same period. Until 2050, energy-related GHG emissions are reduced by 80% in the "Government Target Scenario" and by 92% in the "90% GHG Reduction Scenario," while energy- and process-related GHG emissions in the "Renewable Electrification Scenario" are reduced by 86%. As energy-related GHG

Figure 10: Domestic and net imported primary energy supply of biomass



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014, Nitsch et al. 2012, AG Energiebilanzen 2015

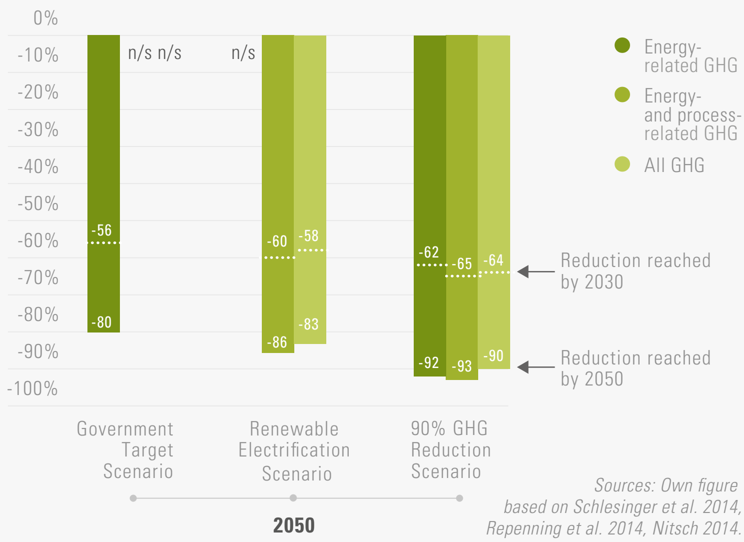
11 Overall, however, Germany's dependence on energy imports decreases significantly over the course of time in all three analyzed scenarios (cf. Section 6.1).

12 In 2014, energy-related GHG emissions in Germany were 26% below 1990 levels (UBA 2015a, d).

emissions in Germany were reported to be 26% below the 1990 level in 2014, the speed of emission reductions in all three scenarios is slightly higher until 2030 than afterwards, reflecting the growing difficulty in reducing emissions once the "low-hanging fruits" of emission reductions have been harvested.

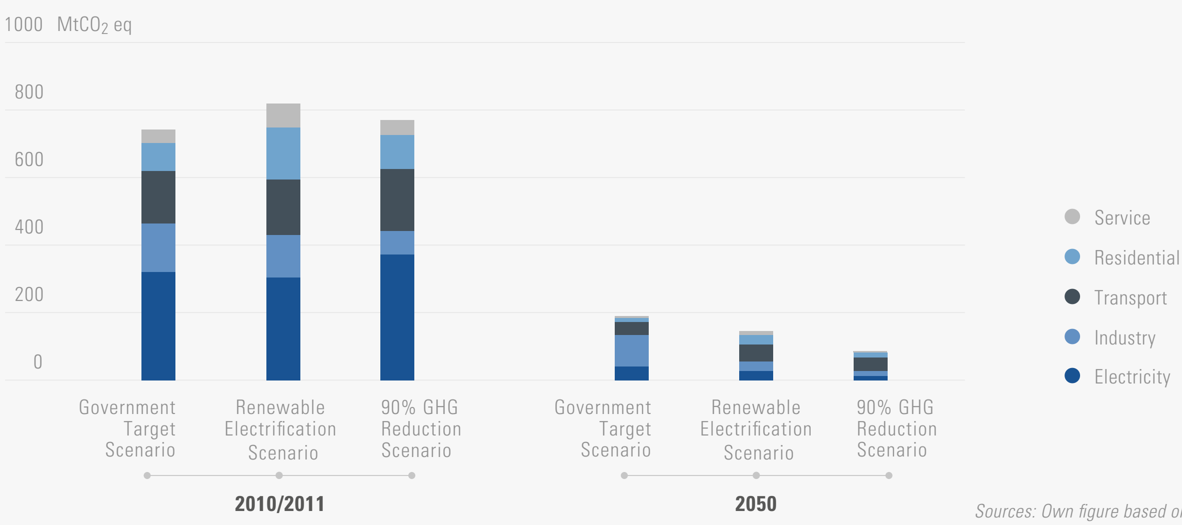
The "90% GHG Reduction Scenario" is the only one of the three analyzed scenarios that takes into account *total* GHG emissions.[13] These emissions are reduced by 90% between 1990 and 2050 in the scenario. Thus, the reduction in overall GHG emissions in this scenario is lower than the reduction in energy- and process-related emissions. This largely reflects the difficulty of achieving deep GHG emission reductions in the agricultural sector, where animal husbandry and soil cultivation lead to GHG emissions that cannot be fully avoided or captured. While the agricultural sector contributed about 7% of total GHG emissions in Germany in 2014 (UBA 2015a), its share rises substantially, to 31%, in 2050 in the "90% GHG Reduction Scenario".

Figure 11: Relative change in GHG emissions compared to 1990



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

Figure 12: Energy-related CO_2 emissions by sector



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

13 The non-energy-related GHG emissions made up 15% of total GHG emissions in Germany in 2013 and were comprised mostly of agricultural emissions and industrial process emissions (see Section 5.4). In the "90% GHG Reduction Scenario," the share of non-energy-related emissions increases to 38% by 2050.

It should be noted that the "90% GHG Reduction Scenario" only achieves such deep reductions in the sum of energy and process-related emissions by assuming that most of the process emissions remaining in 2050 as well as some energy-related emissions of the industrial sector will be captured and stored through CCS technology. Without this assumption, energy and process-related emissions would only be about 85% lower in 2050 than in 1990, similar to the "Renewable Electrification Scenario."

Figure 12 shows energy-related CO_2 emissions in the end-use sectors and in electricity generation for the three analyzed scenarios in 2010/2011, 2030 and 2050.[14] While today emissions from electricity generation are the single most important source for energy-related CO_2 emissions, these emissions can be reduced substantially over the coming decades in all three scenarios. In the medium term (until 2030) most emission reductions are expected to be realized in the power sector, followed by the residential and service sectors with their significant potential for energy savings through building refurbishments.

In 2050, transportation is the sector exhibiting the highest emissions in the "Renewable Electrification Scenario" and the "90% GHG Reduction Scenario," with the service sector emitting the least. In the "Government Target Scenario," emissions in that year are highest by far in the industry sector, followed by transportation and electricity generation. Figure 12 supports the widespread agreement that a substantial share of emission reductions required until the middle of the century will need to be realized in the power sector. The figure also suggests that the industry and transport sectors pose perhaps the greatest challenges in aiming for a deep decarbonization of the energy system.

4 In-depth analysis of key strategies

This chapter focuses on three decarbonization strategies that are relied upon in all of the illustrative scenarios. These strategies can therefore be regarded as key strategies that Germany will need to implement successfully in order to have a chance of achieving deep reductions in GHG emissions by the middle of the century. The fact that all three illustrative scenarios rely on these strategies also indicates that there is a general agreement that these strategies are technically and economically feasible and that public support for their implementation is high. The three strategies consist of energy efficiency increases (Section 4.1), increases in electricity generation from renewable energy sources (Section 4.2), and electrification of processes and power-to-x (Section 4.3).

4.1 Increase in energy efficiency

Strategies for achieving energy demand reduction can vary with regard to the expected outcome of a process: Either the outcome diminishes as well or not. Energy efficiency improvements differ from mere energy savings as it is assumed that the same output as before can be achieved, only with lower energy inputs. In the case of mere energy savings, the output is diminished as well. Thus, energy efficiency improvements represent a subset of the available opportunities for energy savings (Irrek and Thomas 2008). They further mean a decoupling of economic growth from energy consumption.

14 The differences between the three scenarios for the year 2010/2011 can largely be ascribed to differences in the definition of sectors.

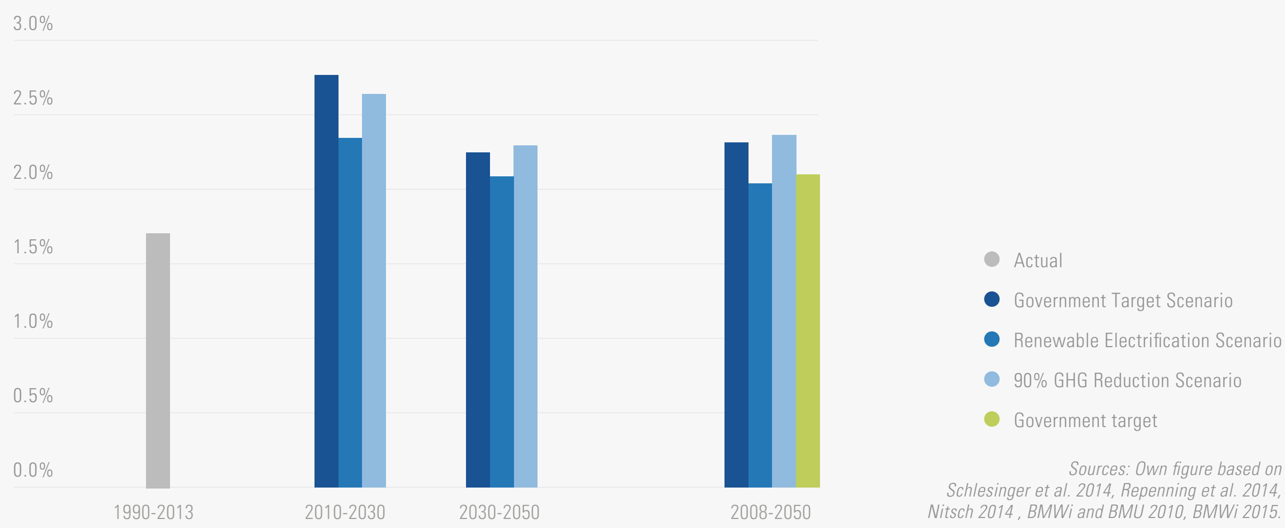
In the framework of its Energy Concept adopted in 2010 (BMWi and BMU 2010), the German government set an official target of improving final energy productivity (i.e. the ratio GDP/final energy consumption) between 2008 and 2050 by 2.1% annually (see Chapter 2 and Figure 13). Achieving this goal is expected to lead to a decrease in primary energy consumption of about 50% between 2008 and 2050 (BMWi and BMU 2010). Consequently, a 50% primary energy reduction by 2050 was also determined as an official target. Figure 13 shows that the three analyzed scenarios realize average annual improvements in final energy productivity of between 2.0% and 2.4%, roughly in line with the government target.

The figure also shows that between 1990 and 2013, final energy productivity in Germany rose by 1.7%/year (using temperature-adjusted data), mainly due to more efficient power plants and the tapping of energy-efficiency potential in the industry and residential sectors (BMUB 2014b).[15] However, productivity improvements will need to accelerate in the coming years and decades for Germany to reach its energy and climate targets, as the analyzed scenarios suggest (see Figure 13). Several recent studies estimating energy-efficiency potential for Germany suggest that the realization of the German energy-efficiency targets is feasible (Schlomann et al. 2014). Furthermore, cost-potential curves have indicated that a great majority of efficiency measures lie below the cost neutrality line, meaning that they are cost-effective even under today's economic and regulatory conditions (Schlomann et al. 2014).

Increasing the rate of refurbishment in the building sector

The implementation of energy-efficiency measures in buildings is considered crucial for the success of the “Energiewende” and should be

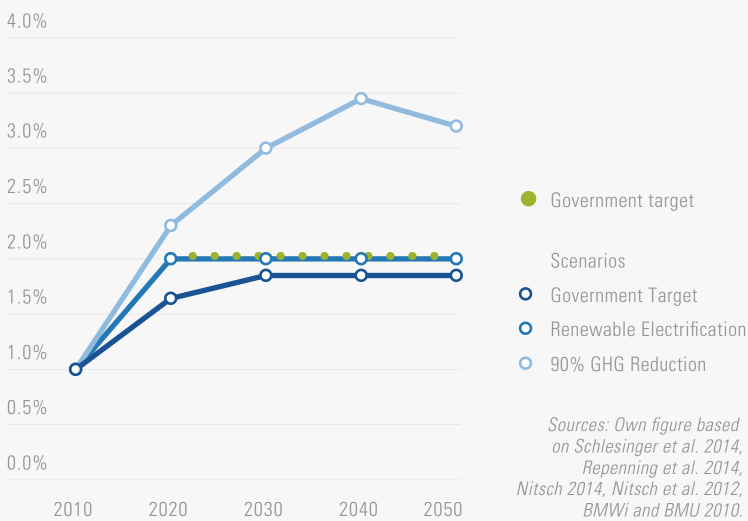
Figure 13: Average annual change in final energy productivity over various periods



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014 , BMWi and BMU 2010, BMWi 2015.

15 It should be noted that in general energy-efficiency improvements are difficult to measure on a macroeconomic scale since even temperature-adjusted indicators are influenced by factors such as structural change (e.g. change in industry production toward less energy-intensive products).

Figure 14: Annual rate of energetic refurbishments in the buildings sector



prioritized according to the commission of experts (Löschel et al. 2014).

While specific energy consumption for heating[16] has been lowered noticeably between 2002 and 2012 (i.e. by about 25%), buildings in Germany still account for about 40% of domestic final energy consumption and 33% of all CO_2 emissions (Löschel et al. 2014; BMUB 2014b). The majority of final energy consumption in buildings results from heating and cooling, hot water supply, and lighting (Kemfert et al. 2015). Hence, higher energy efficiency can mainly be obtained by improvements of the building envelope and the energy standard of equipment (Kemfert et al. 2015).

As large remaining energy-efficiency potential has been identified for this sector (BMWi 2014a), and the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety considers the building sector "a cornerstone of climate policy" (BMUB 2014b), it set several sub-targets for energy efficiency in the building sector (see Chapter 2). However, since the adoption of these targets in the framework of the German government's Energy Concept in 2010, the rate of building modernization amounted in 2011 as well as 2012 only to approximately 1% (BMWi 2014a). This is especially disadvantageous as rapid action is required due to the fact that buildings now refurbished are not expected to be renovated again before 2050 and thus entail a long capital lockup (Löschel et al. 2014). Figure 14 shows that the analyzed mitigation scenarios also see the need for a considerable increase in the annual rate of energy-related refurbishments to about 2% ("Government Target Scenario" and "Renewable Electrification Scenario") and even about 3% ("90% GHG Reduction Scenario") over the coming decades. As reasons for the rather low current rate of building modernization in Germany, several important barriers have been identified, most of which also apply to cost-effective efficiency measures in other areas (Kemfert et al. 2015). Firstly, as about half of the flats in Germany are not occupied by the owner, in many cases there is a principal-agent problem (since it is not the home owner, who usually pays for the refurbishment, but the tenant who benefits from lower energy bills) (Kemfert et al. 2015). Secondly, a high trade-off exists between lower life-cycle costs and lower upfront costs, as energy-efficiency measures in buildings mostly require relatively high upfront investments (Kemfert et al. 2015). Furthermore, due to the rising number of elderly people in Germany, there is a rising unwillingness to implement building refurbishments. Finally, uncertainty about the continuity of financial support programs like investment subsidies and loans at reduced rates of interest discourages possible investors (Kemfert et al. 2015).

16 Adjusted for fluctuations in temperature.

Raising energy efficiency in transport

The commission of experts also recommends focusing on energy efficiency in the German transport sector (Löschel et al. 2014). Germany is currently the fourth biggest passenger vehicle market in the world (behind China, the USA and Japan) and the third largest producing country (behind China and Japan) (OICA 2015a, OICA 2015b). Germany therefore has the potential to play an important role in making cars more energy-efficient. In the past, the effects of efficiency improvements in vehicles remained somewhat limited given the growth in the average mass and power of cars sold. Increasing efforts in terms of engine efficiency have been counterbalanced by additional weight for the purposes of greater safety and comfort. Moreover, sports utility vehicles have become much more common even though road space for driving and parking is severely limited in many German cities.

Many new cars are initially bought by companies that mostly do not focus on energy efficiency in their purchasing decisions. Because company-owned cars are often used as an incentive for staff, this requires fiscal measures to be changed to ensure there are sufficient incentives for energy-efficient company cars.

As Germany sells a lot of medium-size and luxury cars on international markets, German car manufacturers worry that fleet fuel economy standards may harm them more than other countries' manufacturers. These worries have resulted in efforts by German car manufacturers to water down respective political initiatives of the EU. This can be considered shortsighted because of growing awareness and image issues for cars and owners who are not up to the task concerning climate change.

There is also technical potential for improving the energy efficiency of vehicles used in freight transport, although this potential is generally thought to be more limited compared to that in road passenger transport. Generally, because energy costs make up a substantial share of the total cost of freight transport, freight transport modes have been developed toward increasing energy efficiency.

Improving energy efficiency of industrial processes

For all scenarios, efficiency improvements in the industry sector are a key aspect of GHG mitigation. Energy-efficiency improvements in the industrial sector can be achieved through the use of best available technologies for machines and production plants, including the use of more efficient motors, pumps, burners, ovens, dryers, heating and cooling systems, and insulation. These so-called cross-cutting technologies are typically applied in several different branches, leading to the potential for cross-sector learning. Examples of sector-specific efficiency strategies are improved steam crackers in the chemical industry, with better heat integration and heat transfer using naphtha as feedstock to a high extent, the optimization of grinding mills in the cement industry, or improved melting concepts for glass (Fleiter et al. 2013). A number of barriers for the diffusion of energy-efficient technologies in the industrial sector have been identified. These include a lack of information about savings potential, a lack of priority for efficiency investments compared with other investments, expectations of quick returns on investments that many efficiency measures cannot deliver, and a lack of trust in new technologies, especially when they are to be used in critical production processes (Bauernhansl et al. 2013).

Very important for many industrial branches are combined heat and power (CHP) plants.. In the "Government Target Scenario," for example, the use of heat from CHP plants increases more than twofold in the industrial sector between 2020 and 2050, from 161 PJ to 357 PJ. CHP also plays an important role in the concept of industrial symbiosis. It is based on the idea of clustering and concentrating industry at a site (industrial

parks) to reach a better interlinkage of input and output from different processes. Process heat is difficult to transport over large distances so it needs to be produced close to where it is consumed. Currently, excess heat from blast furnace slag or cement production, for example, is not always used efficiently. Heat maps for industrial clusters could help to tap this potential.
Cost-reduction potential from GHG emission mitigation measures is limited for the energy-intensive industry, as technologies required for a deep decarbonization pathway are for the most part more expensive than technologies used today, at least in the short to medium term. Additionally, energy-intensive industry has long investment cycles (20-30 years) and large sunk costs in their complex facilities (Ahman and Nilsson 2015). Interlinkages between branches could help to boost this transformation, but existing structures are to a certain extent inert to such radical changes, even more so if investment certainty is missing. Incentives for making use of waste heat are controversial and could turn out to limit the realization of waste-heat reduction potential. Policy measures should therefore focus on incentivizing the use of "unavoidable" waste heat.

Limiting the rebound effect

Energy-efficiency improvements may lead to rebound effects – i.e. a proportion of the efficiency improvement is counteracted by individuals consuming more of the product (e.g. driving more in a more fuel-efficient car) or of other products – as energy bills decrease and leave room for additional consumption.
The exact extent to which the rebound effect actually influences energy consumption remains controversial as the effect on overall energy demand is difficult to determine empirically (Löschel et al. 2014). According to the commission of experts monitoring the German "Energiewende," the overall rebound effect for the areas of motorized individual traffic and heating and cooling of private households can be assumed to be below 30% (Löschel et al. 2014). For private car traffic in Germany, however, some studies estimate the rebound effect at about 60% (Frondel, Peters and Vance 2008, Frondel, Ritter and Vance 2012).
In order to limit the occurrence of rebound effects, the expert commission on the German monitoring process recommends using instruments that increase the energy costs to consumers, as higher specific energy costs incentivize energy-efficiency improvements while working against rebound effects (Löschel et al. 2014). An example could be a tax that raises the cost for energy consumption and thereby provides financial incentives for energy savings (Löschel et al. 2014).

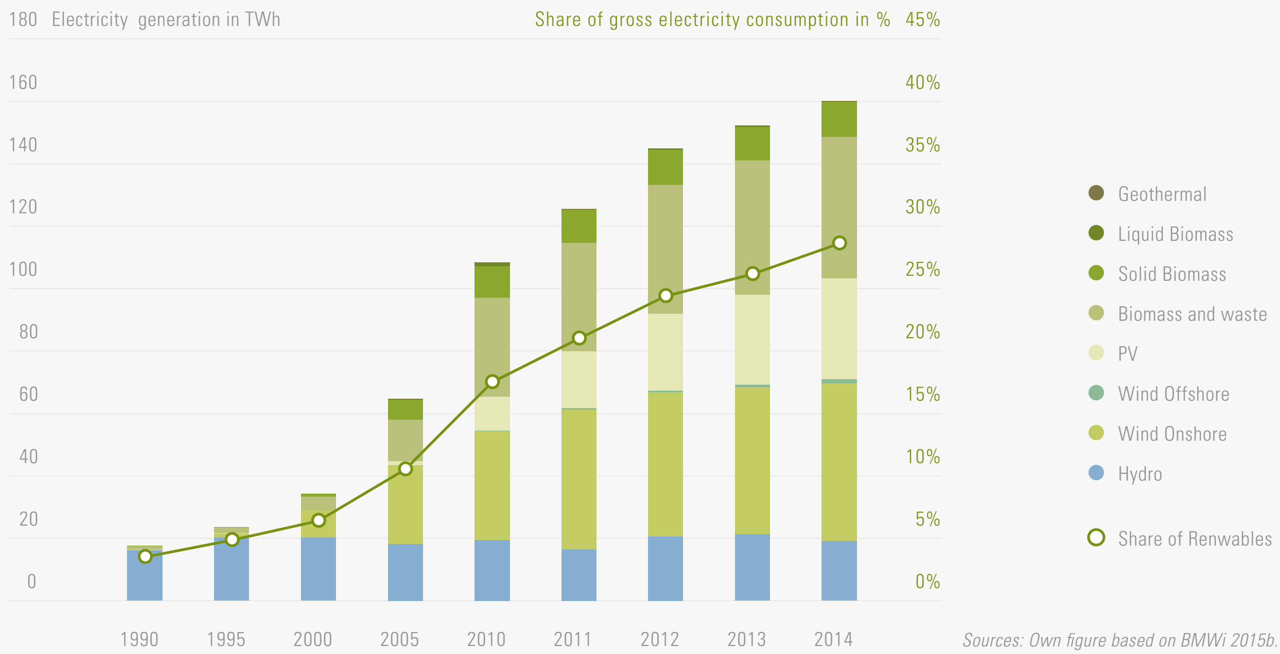
4.2 Increase in electricity generation from renewable energy sources

Besides energy efficiency, the integration of renewable energy sources in the German electricity system is one main strategy to reach a decarbonization of the energy system. According to the current political energy and climate targets set by the German government (BMWi and BMU 2010), renewable energy sources shall cover 80% of gross electricity consumption in 2050 to help achieve a reduction of greenhouse gases of 80% to 95% by 2050 compared with 1990 (see Chapter 2).
Figure 15 shows the development of renewable electricity production in the past 25 years in Germany. Until about the year 2000, renewable electricity was mainly produced from hydro energy, accounting for about 3% to 5% of the whole electricity consumption. In 2000, the German Renewable Energy Sources Act ("Erneuerbare-Energien-Gesetz", EEG) was introduced, which promoted the installation of renewable power plants by providing a fixed and technology-specific feed-in tariff. Since then the electricity production from renewables has risen to about 27% of gross electricity consumption in 2014. The main renewable energy sources used in electricity generation in

Germany today are onshore wind (9% in 2014), biomass (8%, including biogenic part of waste), and solar PV (6%) (AGEB 2015c).

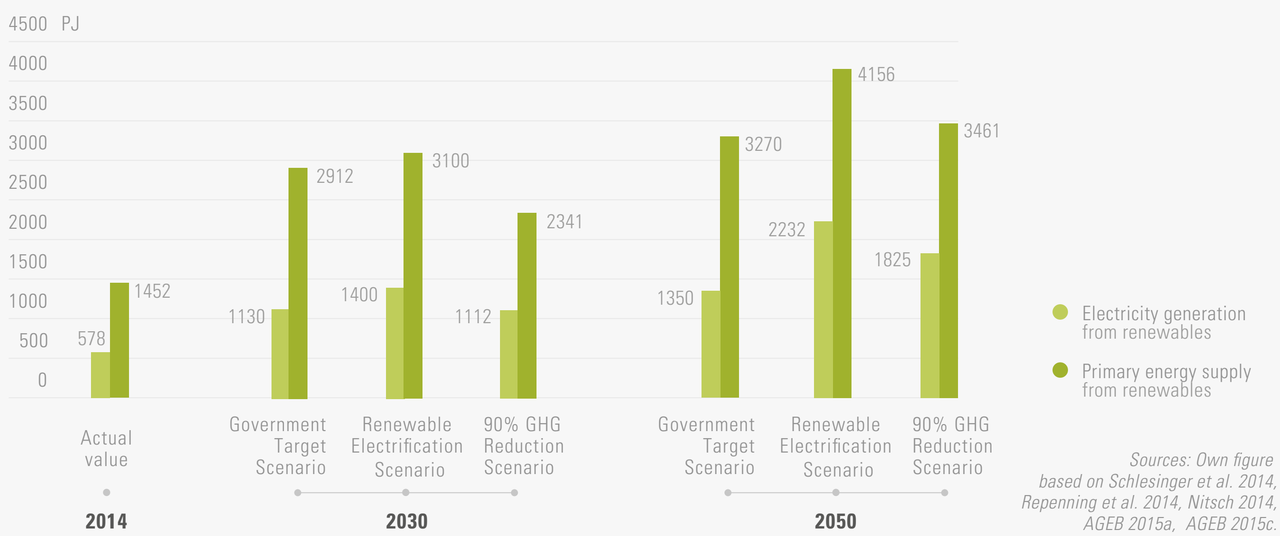
Figure 16 shows that the three analyzed scenarios expect domestic renewable electricity generation to more than double between 2014

Figure 15: Development of renewable electricity generation and share of renewables in gross electricity consumption



Sources: Own figure based on BMWi 2015b.

Figure 16: Electricity generation and primary energy supply from domestic renewable energy sources



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014, AGEB 2015a, AGEB 2015c.

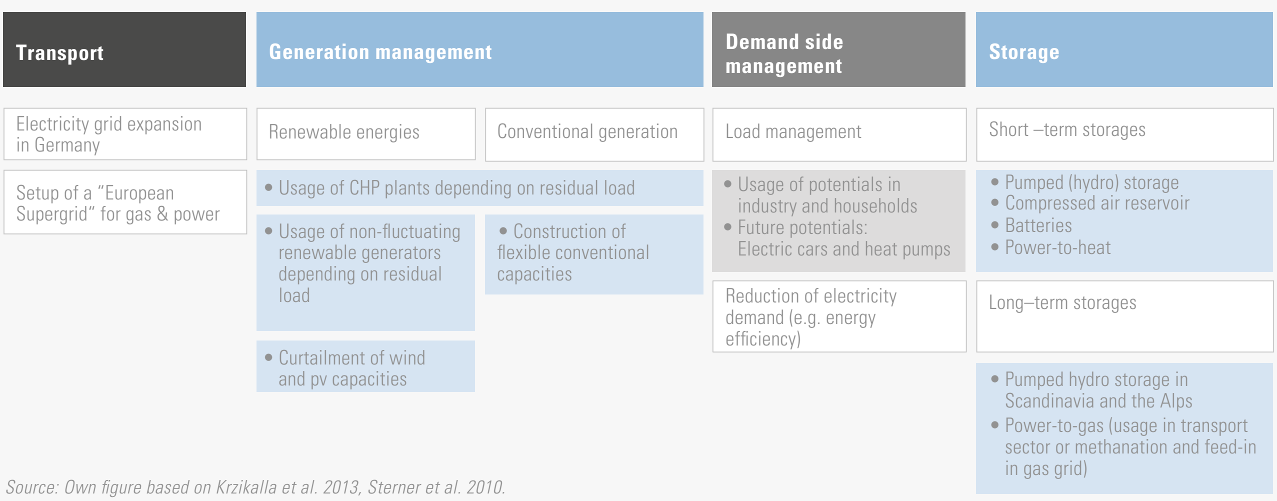
and 2050, with even growth of more than 210% ("90% GHG Reduction Scenario") and almost 290% ("Renewable Electrification Scenario") in the two more ambitious scenarios. The figure also shows that renewable electricity generation is widely expected to increase its share in the total renewable energy supply (from 40% today to between 41% and 56% in 2050).

Comparing the scenario data for 2030 and 2050, it is noticeable that the use of domestic renewable energy sources in the "Government Target Scenario" grows only modestly between 2030 and 2050. After 2030 emission reductions in this scenario are achieved to a great extent through further efficiency improvements, the use of less carbon-intensive fossil fuels (i.e. using natural gas instead of coal and lignite) and biomass imports (see Figure 21). Furthermore, the "Government Target Scenario" achieves smaller reductions in GHG emissions compared with the other two scenarios, in which the use of renewable energy sources continues to increase strongly after 2030.

In order to maintain the stability of the electricity supply, electricity generation needs to match demand at all times. In a conventional energy system, the balance is ensured by the in-time production of electricity from fossil fuels. However, renewable feed-in is less flexible than fossil generation because electricity is generated to a large extent when the wind blows and the sun shines, not necessarily when it is needed most. This means that the electricity supply loses flexibility during the course of the transition of the electricity system. In order to compensate that loss, new flexibility is needed. There are several options to achieve flexibility, which are shown in Figure 17.

The higher the share of electricity generation from fluctuating renewable energy sources, the more flexibility is needed. In the early phase of the transformation of a fossil-based electricity system to a decarbonized one, renewable electricity can be fed into the grid without requiring any additional measures. Germany has recently left this phase behind: In recent years measures to integrate the rising share of renewables and to simultaneously maintain a stable grid operation have started to be taken, such as the local curtailment of electricity production from wind power. Power-to-heat has also started to be applied in Germany in recent years: The municipal

Figure 17: Possibilities to integrate high shares of renewables in the German electricity system – an overview



Source: Own figure based on Krzikalla et al. 2013, Sterner et al. 2010.

utilities of the cities of Lemgo and Nürnberg, for example, have installed electric boilers in 2012 and 2014, respectively, to support district heating generation. The boilers are run at times when high electricity generation from renewables (especially in combination with low electricity demand) leads to low power prices (Agora Energiewende 2014a, N-ERGIE 2015, Stadtwerke Lemgo 2012).

In the long term, a higher share of renewables will only be feasible if the energy system is re-organized (see Table 1 on the characteristics of transformation Phase 2). To this end, flexibility needs to be promoted to compensate for greater fluctuation (compare Figure 17):

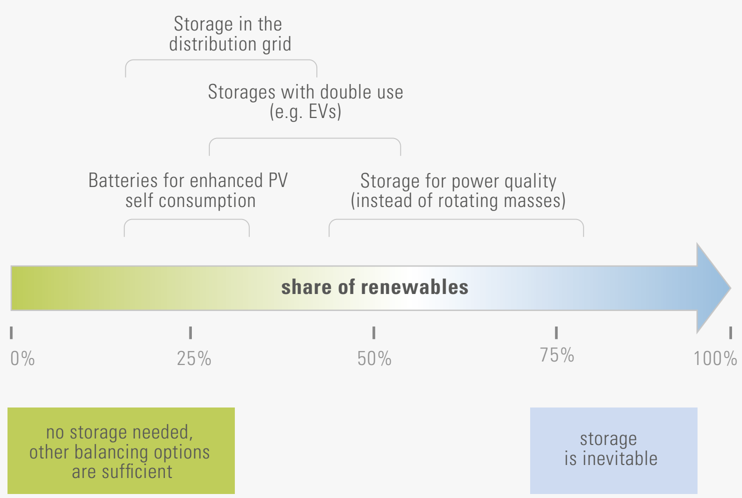
- The grid needs to be expanded in order to balance the differing local occurrence of renewable energy in-between the regions and to transfer electricity to the places where it is needed.
- Flexible conventional power plants can be operated according to the deficits that remain between the load and the electricity production from renewables and hence facilitate the integration of electricity from renewable energy sources.
- The renewables need to provide flexibility, too: In future system configurations of a decarbonized electricity system, they will need to provide control power in order to maintain system stability.
- Demand can also play a part in the transformation process: The lower the electricity demand, the easier it can be met.
- Besides reducing the demand, it is also possible to shift part of this demand to times of high renewable production. This measure is called demand-side management (DSM).
- An additional balancing option of great importance is to store electricity in times of production surpluses and to use it in times of deficits.

With growing shares of renewables in electricity supply, energy and electricity markets will need to be designed in a way to incentivize the use of the various flexibility options. At the same time, the market design should encourage competition among these options so as to ensure that the least costly options are utilized first.

There are diverse challenges to implementing these flexibility options: First, they are in most cases more costly than today's practice of providing flexibility via conventional power plants. Moreover, transformation is complicated by the inertia of the system. For example, electricity grid extension in Germany during the past few years has progressed more slowly than was originally envisioned, partly because of local opposition against new transmission lines. More generally, it needs to be taken into account that the electricity system is highly complex and that any changes are likely to influence different components of the system. System changes thus require careful implementation.

In the following we will discuss the use of storage technologies in more detail to indicate the complexity of the transformation of the electricity system. Figure 18 shows schematically the development of storage demand as the share of fluctuating renewable electricity increases.

Figure 18: Share of renewable electricity generation and resulting storage demand.



Source: Own figure based on Adamek et al. 2012, EFZN 2013, Agora Energiewende 2014 b.

With low shares of renewables, no storage is required for their integration. Instead, conventional base load power plants can be relied upon to provide the additional flexibility needed. However, even though in this first phase there is no need for additional storage from a systemic perspective, there are other drivers for storage installation. For example, home storage systems are installed by some PV plant owners to increase self-consumption of the generated electricity and to reduce the amount of electricity that needs to be purchased from the utility. As Germany exhibits relatively high utility tariffs for the residential and service sector, it is therefore likely that storage units will be installed before they are required to be installed from a system stability perspective. One of the challenges with respect to this development is to prepare those storage units to also participate in grid balancing, when needed.

The biggest challenge will be the transformation toward a fully renewable energy supply: In such a system there will be the need for both high-power storage, which can balance short-term load fluctuations, and seasonal storage, which can compensate for long-lasting periods of low renewable electricity.

As of now, there are several barriers for the large-scale implementation of energy storage: In the electricity sector, most storage applications are more expensive than alternative measures such as grid extension, which for the next five to ten

Box 1: Case study: Linking the power, heat and fuel sectors to support the integration of renewables

In order to reach a fully renewable electricity system, a coupling of the different energy sectors' electricity, heat, and fuel is necessary. This is due to two reasons:

On the one hand, decarbonizing electricity is easier than decarbonizing other forms of energy. This is because renewable electricity can be produced from multiple sources and can easily be distributed even over great distances. In contrast, renewable heat production from solar power does not temporally correlate well with heat demand, and geothermal heat is spatially restricted. In the transport sector, renewable energy can be provided either by electricity or biofuels (or by wind energy in a few applications). Since the potential for sustainably produced biofuels is restricted due to limited arable land, electricity will likely be the main energy source for decarbonized transport.

On the other hand, linking the sectors offers new flexibility to the electricity sector: In the heat, gas and fuel sector there are inherent buffer capacities as well as storage options that are usually easier and cheaper to implement than electricity storage.

One approach to link electricity and heat is to use heat pumps. These pumps use geothermal energy to meet heat demand at low temperatures. Heat pumps are driven either by electricity or by natural gas. With the help of thermal storage – a mature technology that can be realized at low costs – these pumps' operation can be made more flexible and can hence support the integration of high shares of fluctuating renewables. Thermal storage can either be small and supply a single household, or it can be used in much larger applications, for example as seasonal storage for an entire district. The larger the thermal storage, the bigger the time frame within which the electricity consumption of the heat pumps can be shifted.

Another possibility to link electricity and heat is to produce both simultaneously in so-called combined heat and power (CHP) plants. Up to now, these plants have mainly been run at times when there is need for heat. In order to contribute to the stability of the electricity system, the CHP plants could in the future be driven by electricity demand: In times of electricity surplus, production can be curbed; in times of deficits it can run at its maximum capacity, with the heat going into thermal storage.

Another option for linkage is the power-to-gas approach. Here, the surplus electricity is used to produce hydrogen via electrolysis. The hydrogen can be used directly in the transport sector; can be fed into the gas grid up to a certain share; can be used to produce heat and electricity in fuel cells; or can be stored in either small decentralized storage units or in large caverns for later use. Alternatively, it can be converted into methane by adding carbon in a process called methanation. This methane can then be used like natural gas: It can be stored in existing gas storage, distributed using the existing gas grid, and used to fire natural gas applications in heating, power production or transport. This opens the possibility of storing the surplus electricity for a long time in the form of gas and to either reconvert it to electricity at suitable times or use it in other energy sectors.

In a decarbonized system, the electricity and transport sectors can also be linked in a stronger way than today: Transport that is today driven by gasoline or other fossil fuels could be electrified in the future. The batteries of the vehicles can then, if they are connected to the electricity grid while the vehicles are not in use, relax the stability difficulties: The batteries can be charged in times of generation surplus and can even be discharged in times of generation deficits – as long as the owner will not be restricted in his or her travel plans.

The barriers for sectoral coupling are diverse: For many technologies (e.g. CHP or heat pumps), there are established conventional alternatives (e.g. boilers). Moreover, purchasing costs are higher (e.g. for electric vehicles) while the additional system benefits offered by these technologies are not recompensed. Finally, especially in the case of power-to-gas, conversion losses are significant.

years will likely be sufficient. Furthermore, the legal framework regarding energy storage needs to be adapted and harmonized in order to promote the deployment of storage options.

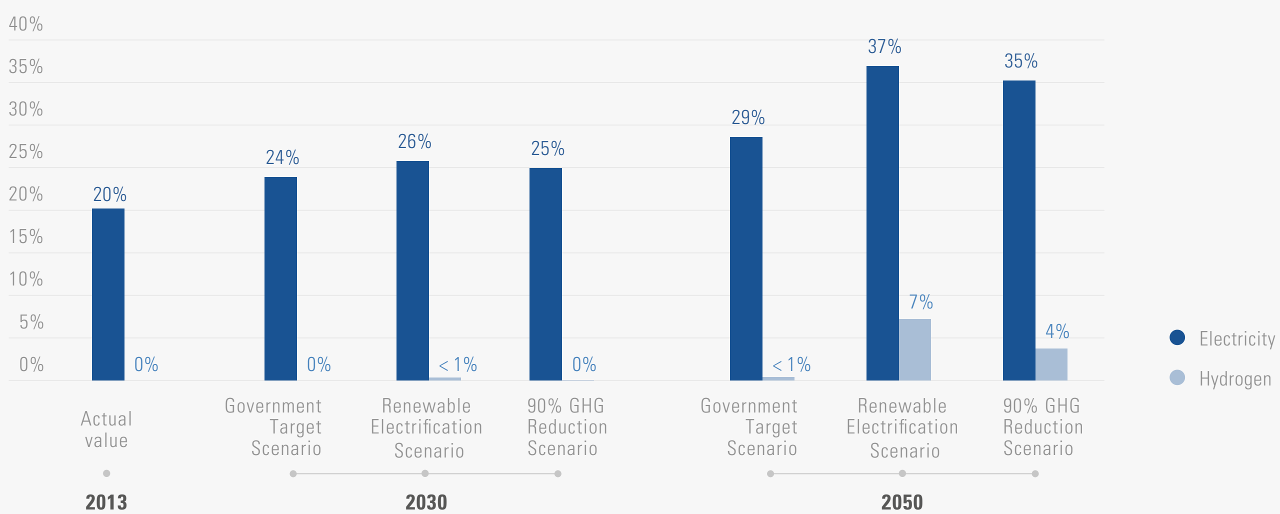
4.3 Electrification of processes and power-to-x

Electrification of processes and power-to-x ("x" standing in for for heat, hydrogen or synthetic fuels in general) are considered important in most available deep decarbonization scenarios (see Figure 19), especially as means to reduce GHG emissions in transport and industry in the long-term. Both, electrification of processes and power-to-x will gain importance as the share of renewable energy sources in electricity production increases. If electricity was not produced sustainably, true decarbonization by means of this strategy would hardly be possible because it results in relatively high amounts of electricity demand and involves large conversion losses.

Figure 19 shows that electricity as a final energy source is expected to play a much larger role in decarbonization scenarios than it does today. Its share grows from 20% in 2013 to between 29% ("Government Target Scenario") and 37% ("Renewable Electrification Scenario") in 2050. Hydrogen will also become a relevant final energy source according to two of the three scenarios, mainly in the transport sector. The "Government Target Scenario," on the other hand, does not foresee a relevant role for hydrogen. The authors of that scenario point to the high costs and the energy losses of generating hydrogen from electricity and water.[18]

As most electrification and power-to-x technologies are still in the early phases of development, they have barely been considered by the German government in their target setting. The exception is electric vehicles, for which a goal of 6 million vehicles (incl. plug-in hybrid electric vehicles) by 2030 is set as a target (see Table 2; there is no target for 2050).

Figure 19: Shares of electricity and hydrogen in total final energy demand



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014 , Nitsch 2015 (personal communication, April 30, 2015), AGEB 2015d.

18 It should be pointed out that it is easier for the "Government Target Scenario" to relinquish the option of replacing fossil fuel with hydrogen, as this scenario is the least ambitious one with regard to GHG emission reductions.

Today, the electrification of processes and power-to-x is still not used prevalently. By the end of 2014, about 24,000 electric vehicles (i.e. battery electric vehicles and plug-in hybrid electric vehicles) were registered in Germany (NPE 2014). Electricity demand for the production of hydrogen is currently negligible (Schlesinger et al. 2014). However, the use of power-to-heat technology has been on the rise in recent years (see also Section 4.2).

Electrification and use of synthetic fuels in the industrial sector

A future switch to much higher shares of renewable electricity, renewable-based hydrogen and even gaseous or liquid synthetic fuels offers significant GHG mitigation potential for the industrial sector (Nitsch 2014, Benndorf et al. 2014). More electricity instead of fossil fuels could be used to provide process heat and power other industrial processes. Hydrogen or further processed synthetic methane or fuels based on electricity from renewable sources could also be used for many industrial processes or for industrial feedstock.

However, technological breakthroughs in some very low-carbon technologies are needed to achieve significant GHG emission reductions in many energy-intensive processes. Existing decarbonization scenarios make different assumptions about the future availability of many of these low-carbon technologies, as the uncertainties about their technological availability and economic feasibility are currently large.

The introduction of such breakthrough technologies could provide a strong impact in many different branches. An example for increased electricity use in the glass industry is the intensification of electro-chemical processes such as electric melting. In the paper industry, drying is the most energy-intensive process and could be electrified. In the steel industry, hydrogen or methane could be used as a reducing agent instead of coal or coke in Direct Reduced Iron (DRI) processes. DRI would then be processed in electric arc furnaces (Benndorf et al. 2014). Furthermore, the feedstock for the chemical industry might be shifted completely to renewably produced methane and hydrogen (Benndorf et al. 2014).

Electrification and power-to-x can only be used to mitigate GHG emissions in industry if the further increase in renewable electricity production is promoted in the framework of the German "Energiewende." Additionally, large infrastructure for electrolyzers is a pre-requisite to produce the necessary amounts of hydrogen and synthesized fuels, especially methane. Currently, stakeholders from the industrial sector are not very keen on switching to electrification, not least because of the higher costs currently associated with such technologies. Furthermore, as of now significant uncertainties are linked to the future availability and economics of the relevant technologies.

It should also be noted that the electricity-based production of methane and other synthetic fuels requires the addition of CO_2. Sources of CO_2 may be increasingly hard to find as the economy shifts toward decarbonization. CO_2 emissions from burning biomass and perhaps a limited amount of "unavoidable" industrial CO_2 emissions may in the long-term be the only CO_2 source for generating synthetic fuels.

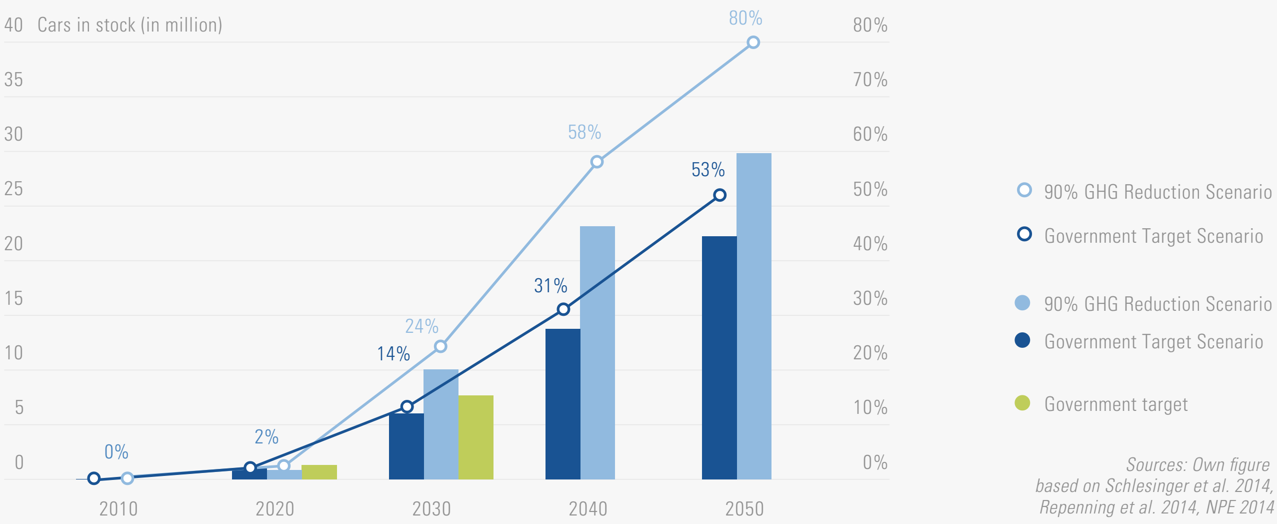
Electrification and use of hydrogen in the transport sector

Tethered modes of transport in Germany will benefit from an increasing share in renewable energy sources in the German power system by receiving electricity with a steadily shrinking GHG intensity. However, companies operating these modes might take dedicated measures to increase the speed of that transformation (e.g. in order to be perceived favorably by the public) by creating additional demand for electricity from renewables.

As explained in Section 4.2, the increase in fluctuating renewable energy sources requires growing buffer capacities for electricity to keep the grid stable. This is where a combination of electricity production from renewable sources and new electric drive trains for road vehicles might be able to achieve multiple benefits in both sectors. Cross-sector systemic effects are vital here. While the electric drive train can be the common denominator of such propulsion systems, it makes sense to be active in both battery electric and hydrogen fuel cell concepts and to bring both to the market. Figure 20 shows the number of electric passenger vehicles in use in Germany in 2010 and in the coming decades according to two of the analyzed scenarios.[19] Electric cars here include not only battery electric vehicles but also plug-in hybrid vehicles and hydrogen-powered fuel cell vehicles. While negligible in 2010, the scenarios expect the number of electric cars to reach 6 million to 10 million by 2030, reaching or exceeding the government's current target of 6 million electric vehicles by 2030. By 2050, this number increases in the two scenarios to about 22 million and 30 million, respectively, and in the same year the share of electric passenger vehicles in total passenger vehicles reaches 53% and 80%, respectively.

Given Germany's current role in car production and use it has the potential to be a forerunner in the introduction of such carbon-neutral propulsion systems. However, other regions like California appear to be more conducive to such a development given the success of Tesla Motors, for example. California's strict emission targets and probably some pioneer spirit on the demand side create an economically viable market niche. Even though there is no need for imitating regulations and attitudes that foster the Californian market, there needs to be a framework that sufficiently promotes the introduction of new carbon-neutral propulsion systems. Ambitious EU fleet fuel-economy standards would be conducive in this regard.

Figure 20: Number of electric passenger vehicles in stock (including hydrogen-fueled vehicles, left axis) and their share in total passenger vehicles (in %, right axis)



Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, NPE 2014

19 The third scenario analyzed (the "Renewable Electrification Scenario") does not provide information about the number of electric passenger vehicles.

5 Additional strategies to achieve deep decarbonization

This chapter will briefly discuss additional GHG reduction strategies that are not adopted in all mitigation scenarios and can be regarded as more controversial:

- Energy demand reductions through behavioral changes
- Net imports of electricity or bioenergy
- Use of CCS technology to reduce industry sector GHG emissions

In addition, this chapter will also discuss non-energy related (often non-CO_2) emission reductions in the agricultural sector as perhaps the most important non-energy system strategy to cut GHG emissions.

It should be noted that the strategies discussed in Chapter 4 and in this chapter have been chosen because of their apparent relevance for deep decarbonization pathways and their visibility in energy scenarios. However, these strategies are not necessarily exhaustive. For example, the following additional strategies could also be differentiated:

- Increasing product-service efficiency (e.g. through car sharing, greater building occupancy)
- Increasing material efficiency (e.g. through reducing yield losses in manufacturing)
- Radical product innovations (e.g. alternatives to cement)
- Radical process innovations that help reduce industrial process emissions (e.g. substituting clinker in cement production)

5.1 Energy demand reductions through behavioral changes

Generally, GHG emission reductions in the energy system can be realized not only through energy efficiency improvements and the use of non- or lower-emitting energy sources or conversion technologies, but also through behavioral changes. There are various ways through which changes in behavior can lead to energy demand reductions. People could opt to reduce their consumption of goods or services (e.g. doing less travel) or they could opt to switch to less energy- or emission-intensive goods or services (e.g. using the train instead of the plane). Conscious behavior can also help reduce the rebound effect (see Section 4.1.4) by not increasing the consumption of energy-intensive goods or services when cost savings are realized through energy-efficiency improvements.

Typically, energy scenario studies do not assume significant changes in people's behavior.[20] Instead, they tend to focus on efficiency improvements and the decarbonization of energy supply to reduce GHG emissions. This may be due to the belief that changes in people's behavior are difficult to achieve, or it may be due to the assumption that voters do not agree that policymakers should attempt to change people's behavior or preferences.[21] However, it can be argued that many of the changes in behavior leading to lower energy demand and GHG emissions would also lead

20 At least they do not do so explicitly. It can be argued that many energy scenarios may implicitly assume that people consciously avoid rebound effects. That is, they do not increase their consumption of goods and services despite potential costs savings realized through the efficiency improvements assumed in the scenarios.

21 Another possible explanation is the difficulty of integrating behavioral changes into the technologically focused models that are typically used to develop scenarios.

to co-benefits (like health improvements) that may not always be fully taken into account by people's individual decisions.

While in recent years there has been increased research to better understand the potential for reducing energy demand and GHG emissions by changing behavior and lifestyles (see e.g. Schäfer 2012, Brischke 2014, EEA 2013, Faber et al. 2012), many developers of energy scenarios still appear to be reluctant to incorporate in their climate mitigation scenarios substantial changes in the demand for goods and services compared with a business-as-usual development. As Table 4 in Section 3.3 shows, two of the three energy scenarios analyzed in this report do not explicitly assume any significant behavioral changes. However, the most ambitious mitigation scenario ("90% GHG Reduction Scenario") does assume that people will modify their behavior to some extent, notably:

- Some modal shift from car use to public transportation
- Slight reduction in average room temperatures in winter
- Reduction in meat consumption
- Slower diffusion of electric appliances

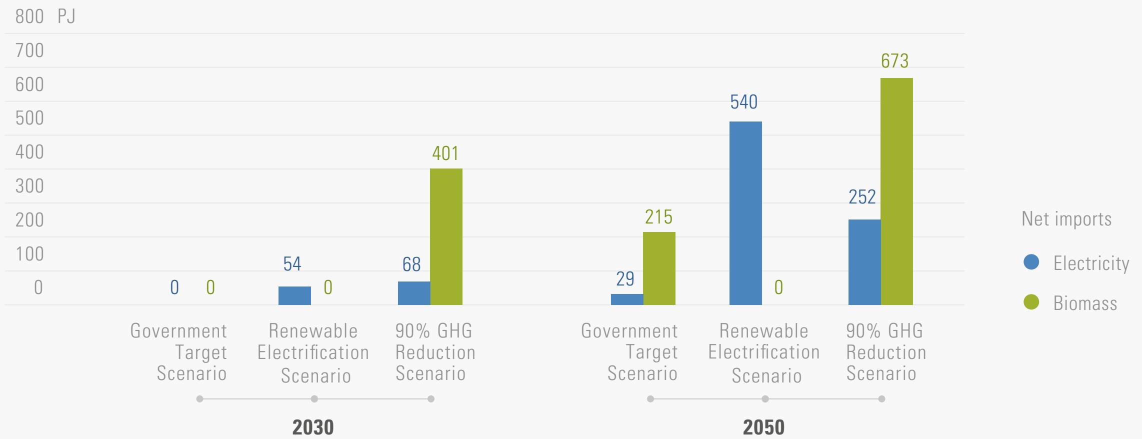
According to the authors of the "90% GHG Reduction Scenario" changes in behavior would make it easier to achieve an 80% GHG reduction by 2050 and are even indispensable if a 90% reduction is to be reached.

More research on the energy demand and GHG reduction potential as well on promising policy measures for fostering the desirable behavioral and lifestyle changes appears to be needed. Both national as well as regional and global energy scenario studies should also be more active in trying to incorporate the impacts of potential future reductions or modifications in the demand for goods and services in some of their scenarios.

5.2 *Import of low-carbon energy sources*

Importing low-carbon energy sources from abroad enables a country to reduce its consumption of carbon-intensive energy sources. Importing such sources may be reasonable if the domestic potential for low-carbon energy sources is limited or if exploiting these sources were to be (much) more expensive than abroad. At the same time a climate mitigation benefit is only ensured if the countries of origin could not use these low-carbon sources themselves to reduce their GHG emissions. In principle, low-carbon energy sources can be imported in the form of biomass or in the form of low-carbon based electricity, hydrogen or other synthetic gases or fuels. In Europe and Germany in particular, renewable-based electricity from abroad, mainly from North Africa (solar and wind power) is frequently discussed as an option for the coming decades (see e.g. Pitz-Paal et al. 2013, Zickfeld and Wieland 2012). While it is undisputed that the technical potential to exploit renewable energy sources for electricity generation in North Africa is much higher than current and future electricity demand in this region, it is disputed whether Germany should pursue an energy strategy that relies heavily on future imports. Critics point to the political instability of the North African region, potential problems associated with the dependency on electricity imports, and potential social and political opposition to the construction of the infrastructure that would be required. The three scenarios analyzed in this publication all foresee electricity and/or biomass imports in the decades ahead. Figure 21 shows the respective amount of imports in the years 2030 and 2050. The highest low-carbon energy imports are described in the "90% GHG Reduction Scenario." Here about 400 PJ of biomass and 68 PJ of electricity are imported already in the year 2030, and these imports grow to 673 PJ of biomass and

Figure 21: Net electricity imports based on renewable energy sources and net biomass imports



Note: 50% of the 2050 net electricity imports in the Government Target Scenario are assumed here to be based on renewable energy sources

Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

around 250 PJ of electricity until 2050. The "Renewable Electrification Scenario" foresees higher electricity imports of 540 PJ in 2050 but no biomass imports, while in the "Government Target Scenario" only some biomass (215 PJ) is imported by the middle of the century, but no electricity.

As the data for 2030 shows, net electricity imports are not expected to play a major role until after 2030. This mirrors the development of electricity demand (see Figure 5), which is relatively low in all scenarios until 2030 but grows considerably between 2030 and 2050 in the two scenarios ("Renewable Electrification Scenario" and "90% GHG Reduction Scenario") that also assume high net electricity imports by 2050. The growth in demand is due to the electrification strategy and hydrogen generation, the latter of which becomes relevant after 2030 in the two scenarios. It can also be argued that it takes time for the necessary grid infrastructure and the required renewable energy power plant capacity abroad to be built, so that it would be difficult to realize significant net renewable electricity imports within the next 10 to 15 years.

In order to illustrate the relevance of low-carbon energy imports in the scenarios in 2050 we can assume for simplicity that the 673 PJ of biomass imports in the "90% GHG Reduction Scenario" would be substituted by 673 PJ of natural gas if biomass imports were not available. CO_2 emissions would then be some 37 Mt higher, and the scenario would only reach GHG emission reductions of around 87% by 2050 (compared with 1990). Assuming likewise that the scenario's 252 PJ of electricity imports would – in a non-importing scenario – be generated by natural gas using power plants with an efficiency of 60%, additional CO_2 emissions of 23 Mt would accrue. This analysis indicates the relevance of low- or non-CO_2 energy imports for ambitious decarbonization scenarios. Deep decarbonization in Germany may depend on such imports due to the country's limited renewable energy potential (compared with some other regions of the world), its relatively high energy demand, its high population density, and its decision to phase out nuclear power.

This conclusion is supported by the aforementioned study "Germany 2050 – A Greenhouse Gas-Neutral Country" (Benndorf et al. 2014) developed by the German Environment Agency. In this very ambitious scenario, which reaches GHG emission reductions of 95%, some 7,200 PJ (2,000 TWh) of renewables-based electricity are assumed to be imported to Germany by 2050 – either directly via the electricity grid or indirectly through the import of electricity-based synthetic gases or fuels.

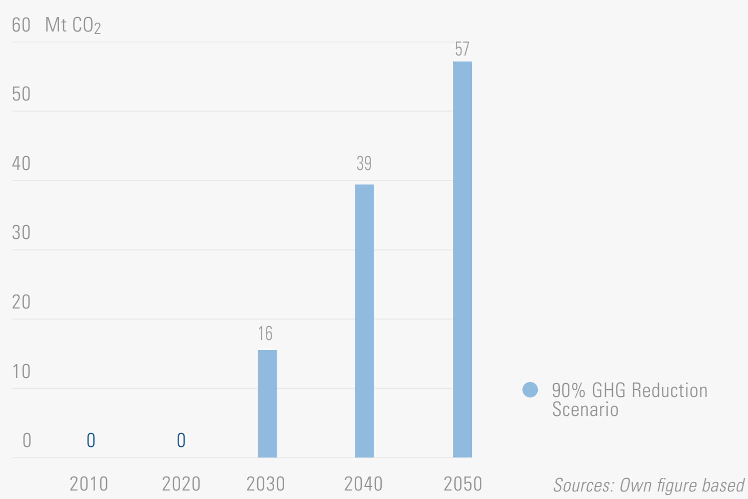
It should be noted, however, that importing low-carbon energy sources in a sustainable way not only requires other countries to have sufficient access to such sources beyond their own needs but also requires these sources to be exploited responsibly. This is especially relevant with regard to biomass imports.[22] From a climate change mitigation perspective, it needs to be ensured that biomass production and transportation really leads to significantly lower GHG emissions compared with alternative (fossil) fuels. It should also be ensured that importing biomass does not lead to social or ecological problems in exporting countries, like lack of cultivation area for food, excessive monocultures, or the harmful destruction of subsistence farming.

5.3 Use of CCS to reduce industrial sector CO_2 emissions

Carbon capture and storage (CCS) technology is regarded by some to be a promising option to significantly reduce the GHG intensity of fossil fuel use, enabling societies to continue to use fossil fuel sources even in a highly decarbonized future. Electricity generation with its large-scale coal, lignite, and natural gas power plants is typically considered to be a suitable application for CCS technology. However, in recent years a consensus appears to have formed among energy system researchers that it is unlike that CCS technology will be used in the German power sector, not only but mainly because of a lack of public acceptance and political support. However, some researchers argue that CCS technology could well play a role in reducing emissions in the industrial sector. It is argued that unlike in the electricity sector, where there is significant potential to reduce emissions by increasing the use of renewable energy sources, it is much more difficult to imagine technological solutions to radically reduce energy- and process-related emissions in the industrial sector.

The use of carbon capture and storage could thus be a solution to achieve very deep GHG emission cuts in the industrial sector, provided a number of challenges associated with this technology can be overcome in the years to come.[23] Figure 22 shows that one of the three analyzed scenari-

Figure 22: Annual amount of captured and sequestered energy- and process-related CO_2 emissions from the industrial sector in the 90% GHG Reduction Scenario



Sources: Own figure based on Repenning et al. 2014.

22 The authors or the "90% GHG Reduction Scenario" refer to two scientific studies (EEA 2006, WBGU 2008) that have evaluated the sustainable biomass potential in Europe and Russia. The scenario's authors conclude that an equal per capita distribution of this potential would allow Germany to import up to 900 PJ of biomass by 2050.

23 These challenges include the need for technological and cost-related improvements, the need for sufficient and safe CO_2 storage sites, and the need to convince the public to accept the related CO_2 transport infrastructure and storage sites.

os, the most ambitious "90% GHG Reduction Scenario," assumes that CCS technology will be used to reduce industrial sector CO_2 emissions. Specifically, in this scenario 16 Mt CO_2 are captured and sequestered in 2030, growing to 57 Mt in 2050. Both energy- and process-related emissions are assumed to be reduced by CCS. Most emissions are captured in the iron and steel industry and the cement industry, followed by the production of ammonia and limestone.

The sector's GHG emissions are reduced by 65% by 2050 through the use of carbon capture technology, and without its use overall GHG emissions in the scenario would be reduced by only about 85% by 2050 (compared with 1990) instead of 90%. CCS can thus be regarded as a potential key technology for Germany to reach very deep GHG emission reductions. Without a doubt the main advantage of a CCS-related strategy in the energy-intensive industry is the fact that structural changes in the production processes can be avoided due to the "end of pipe" characteristic of CCS technology. However, the authors of the aforementioned study "Germany 2050 – A Greenhouse Gas-Neutral Country" (Benndorf et al. 2014) argue that a combination of highly efficient ("breakthrough") technologies and the substitution of fossil fuels through electricity and electricity-based synthetic fuels can eliminate the sector's energy-related GHG emissions and reduce its process-related emissions to well below 20 Mt CO_2-eq.

5.4 Decrease in non-energy-related agricultural GHG emissions

In relative terms, the amount of non-energy-related GHG emissions in Germany is comparatively small. In 2014 non-energy-related GHG emissions were responsible for 15.3% of all GHG emissions (CO_2 equivalents). These emissions are mainly comprised of agricultural emissions (7.1% of overall GHG emissions) and industrial process emissions (6.8%) (UBA 2015e).

Due to the relatively small share of non-energy-related GHG emissions in overall GHG emissions, current German climate policy discussions and measures focus on energy-related CO_2 emission reductions. For the same reason, non-energy-related (often non-CO_2) GHG emissions are only rarely considered in scenario studies (see Chapter 3). However, if the German government's targets concerning the reduction of energy-related emissions are achieved, the share of non-energy-related emissions in total GHG emissions will rise significantly in the coming decades. As a result, measures to mitigate non-energy-related emissions will likely become very relevant for achieving truly deep decarbonization. This section focuses on potential strategies to reduce GHG emissions in the agricultural sector, because of the high relevance of this sector in total non-energy-related GHG emissions.[24]

Increasing resource efficiency in agriculture

Animal husbandry and the use of fertilizers are mainly responsible for the non-energy-related GHG emissions in the agricultural sector (Benndorf et al. 2014). GHG emissions from fertilization can on the one hand be lowered by an optimization of the fertilizer, the amount used, and its time of application, as well by an improvement of fertilizing technologies (Benndorf et al. 2014). On the other hand, there are residual fertilizers of animalistic origin that emit methane and nitrous oxide. These fertilizers (as well as other agricultural residual materials) can be used for the pro-

24 While industrial process emissions are similarly relevant, one possible solution to reduce these emissions has already been discussed above, because CCS can address both energy-related and non-energy-related CO_2 emissions from the industrial sector. Various breakthrough technology innovations that could also reduce process emissions in the industrial sector and are very specific to the various industrial branches are not discussed in detail in this report.

duction of biogas. Thus, GHG emissions can be reduced through a reduction of open-air storage of residual fertilizers. Furthermore, biogas installations replace fossil energy sources and energy crops such as maize and thereby lead to additional GHG mitigation. According to Benndorf et al. (2014), in Germany the use of residual fertilizers in biogas production has a huge potential that has not been completely exploited yet.

Regarding animal husbandry, a productivity increase of dairy cows can lead to a GHG reduction per kg milk. However, aspects of animal welfare have to be considered. Additionally, if the cows' lifespans are prolonged, their annual replacement rate can be lowered, so that fewer GHG emissions occur as the number of required cow offspring diminishes (Benndorf et al. 2014). In the period from 1990 to 2010, for example, the productivity of a dairy cow increased by 48% while the GHG emissions per cow rose only by 23% (Benndorf et al. 2014).

Increasing the share of ecological agriculture

Currently, about 50% of the German land area is used for agricultural production, but only 6.4% of the agricultural area was ecologically managed in 2013 (Benndorf et al. 2014). According to the German government's sustainability strategy, this number should increase to 20% within the coming years (there is no exact target year) (Federal German Government 2015). Reaching this goal is (among other reasons) desirable because studies show that in comparison with conventional agriculture, in ecological agriculture there are fewer GHG emissions per hectare (i.e. a median of 0.92 instead of 2.67 t CO_2-eq per hectare (Flessa et al. 2012), although analyzed agricultural enterprises are comparable only to a certain extent) (Benndorf et al. 2014). This is mainly due to an eschewal of mineral fertilization and of pesticide use in crop farming (Benndorf et al. 2014). With regard to animal farming, the amount of product-related emissions heavily depends on the productivity of the ecologically managed farm. Therefore, studies comparing GHG emissions of ecological and conventional animal farming show even higher deviations than those analyzing crop farming (Benndorf et al. 2014). Nevertheless, in general GHG emission reductions can be achieved by increasing the share of ecological agriculture.

Reducing domestic demand for agricultural products by limiting grocery waste

Other things being equal, reduced demand for agricultural products could lead to lower production and thus lower GHG emission (although not necessarily in Germany if agricultural exports increased). Measures aiming at this goal would not directly target the agricultural sector but other sectors such as industry, services and residential. One obvious way to achieve this goal is the avoidance of grocery waste. Grocery waste is caused at several steps along the value chain, i.e. in manufacturing (17%) and trade (5%), by large-scale consumers (17%) and especially by private households (61%) (Kranert et al. 2012). In total, grocery waste in Germany is estimated at almost 11 Mt per year (Kranert et al. 2012). According to Benndorf et al. (2014), half of it can be avoided.

Of the 61% of grocery waste from private households, about 2/3 are regarded as avoidable or partly avoidable (Benndorf et al. 2014). It can e.g. result from improper storage, mismanagement of stock, expiry of best-before dates, or it can comprise special ingredients only used for certain products. With respect to private households, an important step toward waste reduction is by increasing awareness of the efficient use of groceries (Benndorf et al. 2014).

Adopting a more climate-friendly diet

A more climate-friendly diet can lead to a further reduction of demand for agricultural products. Especially products of animal origin and those requiring a high degree of manufacturing cause high GHG emissions along their production chain. Lowering the consumption of these products not only mitigates GHG emissions but is also in line with recommendations of the German Society for Nutrition (DGE). In particular, the average per capita consumption of meat in Germany is significantly higher than recommended. Hence, there is a significant potential to reduce both meat consumption as well as the associated GHG emissions (Benndorf et al. 2014). The "90% GHG Reduction Scenario" assumes that the stock of cattle and pigs can be reduced by 30% by 2050 compared with 2010. In the aforementioned scenario "Germany 2050 – A Greenhouse Gas-Neutral Country" (Benndorf et al. 2014) it is also assumed that meat consumption is reduced until in line with the recommendations and that food waste will be reduced by half compared with the current amount of waste.

6 Co-benefits from a German perspective

Primarily, all strategies analyzed in the previous chapters constitute important instruments for GHG emission mitigation. At the same time, implementation of these strategies can positively or negatively influence the attainment of other societal objectives — e.g. those linked to human health, food security, biodiversity, local environmental quality, energy access, livelihoods, and equitable sustainable development (IPCC 2014). Therefore, policy makers often deliberately implement measures that aim at obtaining different objectives at the same time (e.g. GHG emission reduction and increase in energy security) or at least do not lead to significant negative impacts (e.g. GHG emission reduction and land use changes). Targeting several objectives by means of one policy implies the opportunity to enhance support for the policy as well as its cost-effectiveness (Höhne et al. 2015).

Intentionally targeted beneficial non-climate impacts of mitigation measures have been named "co-benefits" by climate change researchers (IPCC 2001).[25] The importance of additional impacts of climate policies varies between countries. In the case of Germany, co-benefits are mainly discussed in the areas depicted in Figure 23 and described in further detail in the following subsections. If the scenarios analyzed in the framework of this study provide quantitative information on the possible impact of "Energiewende" measures on co-benefits, it is outlined below. Obviously, there are also risks, uncertainties and adverse side effects linked to the implementation of "Energiewende" measures (see for example Section 4.2 on the growing challenge of maintaining power system stability as the share of fluctuating renewables increases) that need to be addressed adequately and in time. However, this chapter focuses on potential additional *benefits* besides GHG emission mitigation that can be obtained by means of climate policy.

6.1 Energy security effects

Energy security is defined by the International Energy Agency (IEA) as "the uninterrupted availability of energy sources at an affordable price" (IEA 2015). It thus comprises the whole energy supply chain from the provision of primary energy to energy usage by consumers (Anders et al. 2014). In the case of Germany, one im-

25 Such co-benefits as well as potential adverse side effects from climate policy are analyzed for each sector in the framework of the Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC 2014).

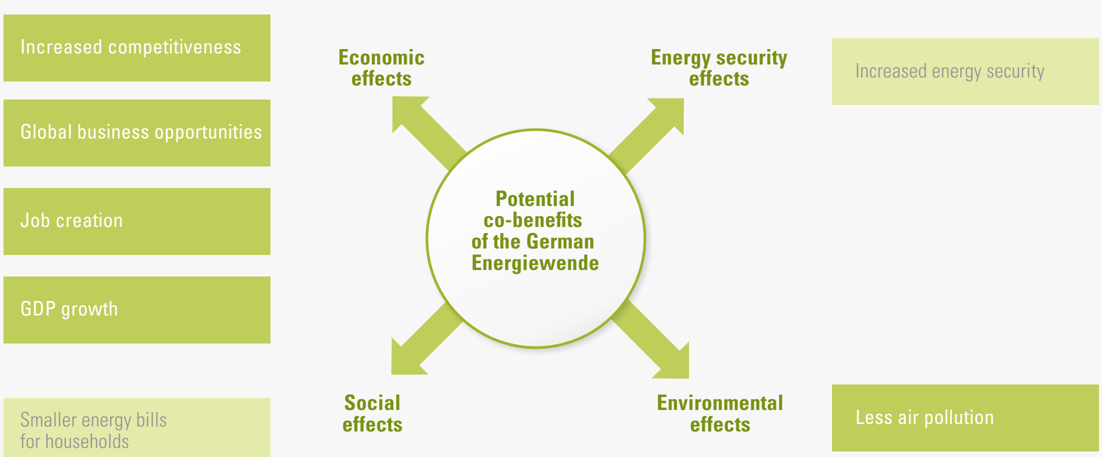
portant aspect of energy security that could be positively influenced by climate policy is import dependence.

Like many European countries, Germany imports the majority of the primary energy consumed domestically. In order to decrease its import dependence, it aims at lowering its overall energy demand and/or produce more energy on its own. This can be of high importance since countries without a diversified energy supply are vulnerable to the suspension of energy production by supplying countries and exposed to volatile international energy prices. Energy deliveries can be interrupted, for example, by natural disasters or unstable political situations in supplier and transit countries. Thus, if Germany minimizes its energy imports and diversifies its energy portfolio, it simultaneously strengthens its stance in bilateral negotiations. This is because a lower share of energy imports decreases the exporting country's opportunity to use high energy dependence as leverage.

In 2013, Germany imported 98% of oil consumed domestically, 88% of gas, and 87% of coal, as well as the uranium required for producing nuclear energy (AGEB 2015d). Lignite as well as the major share of renewable energy sources originated from inside Germany. Overall, Germany's primary energy import dependency was 71% in 2013. By 2050, the scenarios analyzed expect it to decrease to between 39% ("90% GHG Reduction Scenario") and 50% ("Government Target Scenario") (see Figure 24). The absolute amount of primary energy imports decreases even more, as overall primary energy demand is reduced significantly. Both in relative as well as in absolute terms oil and hard coal lose significantly in relevance among the imported energy sources, while biomass imports and/or electricity imports become relevant imported energy sources by 2050, according to the scenarios.

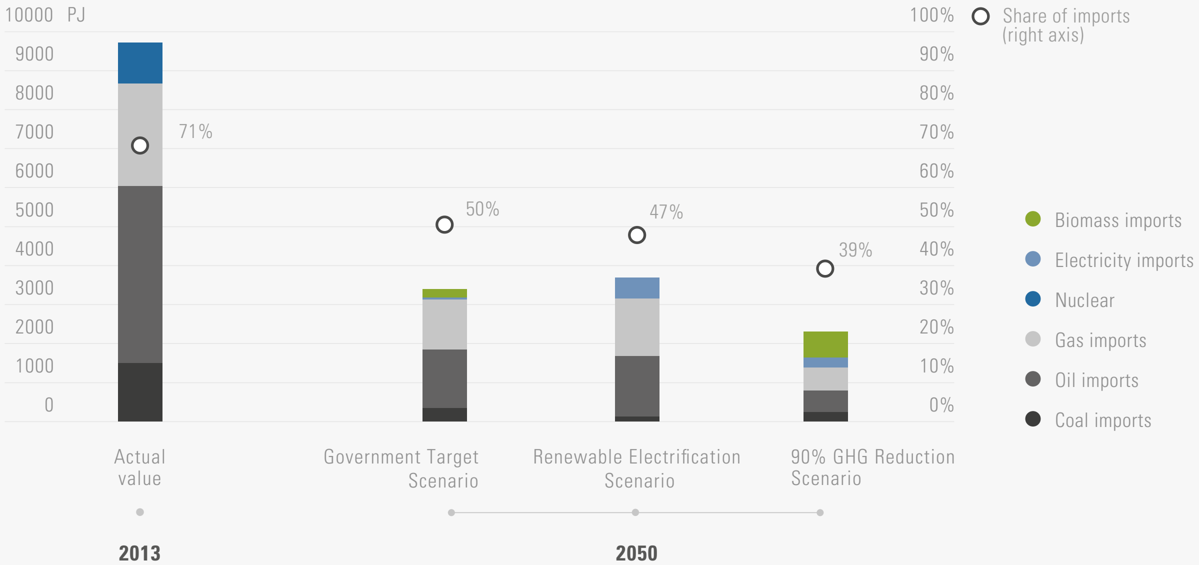
Hence, the implementation of climate protection measures in Germany not only reduces GHG emissions but at the same time increases national energy security by lowering import dependence. Nevertheless, the expert commission on the German "Energiewende" argues that diminishing energy imports should not be an ob-

Figure 23: Potential co-benefits of the German 'Energiewende'



Source: Own Figure

Figure 24: Primary energy imports by source (in PJ, left axis) and share of imports in total primary energy supply (in %, right axis)



As no information about fossil fuel imports are provided for the 90% GHG Reduction Scenario, it is assumed here that 100% of the fossil fuels used in 2050 are imported in the scenario.

Sources: Own figure based on Schlesinger et al. 2014, Repenning et al. 2014, Nitsch 2014.

jective in itself (Löschel et al. 2014). Instead, for a risk assessment of import dependence, different aspects – such as concentration on few suppliers, mutual dependencies, and political stability in export regions – should be taken into account (Löschel et al. 2014).

6.2 Economic effects

Moreover, the implementation of climate policies can also have positive effects on different economic aspects.

For companies, climate policy measures that lead to energy savings can be of great significance. Since energy savings bring lower energy bills, they may allow firms to produce at lower cost. If energy savings over time are greater than the required investments or if they are achieved merely by behavioral changes (energy-conscious consumption), companies can offer the same product for a lower price and thereby increase their competitiveness on the global market (EC 2013).

In order to determine the extent to which German energy policies actually influence domestic companies' international competitiveness, the expert commission on the "Energiewende" suggests comparing the aggregated annual consumer expenditure for electricity, heat, and fuels with similar data from Germany's main trading partners (Löschel et al. 2014). In general, it can be noted that higher future electricity prices resulting from climate policies could increase production costs for German enterprises. This would be a disadvantage if other countries did not implement similar regulation, and it could increase the risk of carbon-intensive industrial production moving from Germany to another country (so-called carbon leakage). However, many electricity-intensive companies in Germany are protected from price increases resulting from "Energiewende" measures by a policy trying to prevent market distortions. Generally, a study on decarbonization of the German state of North-Rhine Westphalia (NRW, where many energy-intensive companies are located) recommends closely monitoring energy price developments (which, of course, also depend on many other factors) and their impact on the local economy to avoid negative effects of climate policy (Anders et al. 2014).

Additionally, companies that develop and sell innovative energy technologies or services can benefit from a widespread implementation of climate protection measures. If a firm is among the first companies entering a market (first mover) or if its products are superior to its competitors', it may be able to exploit global business opportunities.

In the past, European companies had a temporal advantage in learning to deal with innovative energy technology because environmental regulation had been adopted relatively early in Europe. Many companies managed to realize the green innovation potential, so that a home market for advanced energy technology was created. Currently, for example, German companies offering technologies for electricity and heat generation as well as for increasing energy efficiency sell internationally competitive products. In several cases, they are even market leaders (BMWi 2014a). However, market leadership can change rather quickly, as several German producers of photovoltaic modules have painfully experienced in recent years. Since they could not compete in price with (mainly) Chinese PV manufacturers, companies declared insolvency and had to lay off many employees.

Besides leadership in new markets, another indicator of innovativeness is patents. Those filed for innovations in renewable energy technology in Germany have been showing dynamic development since 2007, with only a slight decrease in 2013 (Renewable Energies Agency 2015). More than 75% of these patent registrations were filed by companies from the solar and wind power industry. Furthermore, Germany was the second largest exporter of potential climate products (products with climate or environmental protection as main purpose), with a 13% share, behind China (20%) in 2011 (BMUB 2014b).

However, the expert commission on the "Energiewende" remarks that the use of single indicators for the exploitation of global business opportunities in a certain field is flawed (in the case of patents, for example, there is no comparison to non-green patents, not all innovations are registered as patents, and there is no causal link to "Energiewende" measures) (Löschel et al. 2014). In order to be able to determine the impact of the "Energiewende" on innovation as well as on German energy innovations in the international environment more accurately, the commission suggests developing a system of indicators (Löschel et al. 2014).

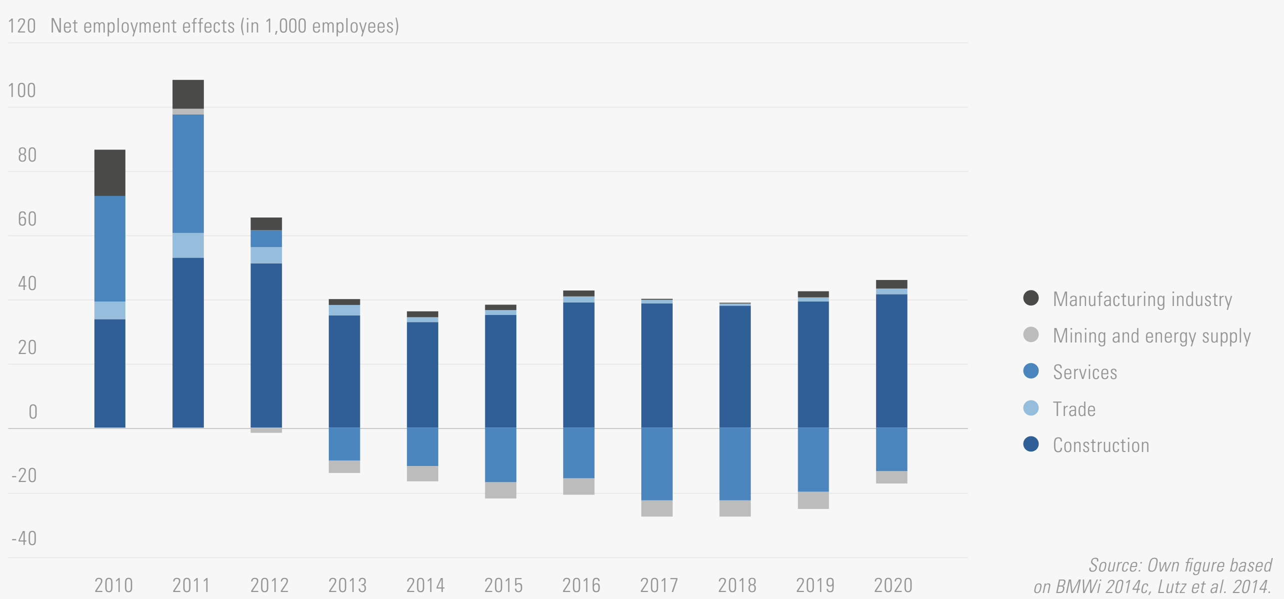
Increased competitiveness and the exploitation of global business opportunities often involve the creation of new jobs. As market size increases, the number of people working in the production of innovative energy technology as well as at service companies supporting their implementation might surge. Provided a certain share of the products is installed domestically, there is also a positive jobs effect for craftspeople needed for assembly. Other companies and sectors that are indirectly intertwined can also benefit from job creation. Altogether, the fact that the market for energy technologies and services has a primary local character implies positive employment effects for the respective region (BMWi and BMU 2012). In Germany, this potential especially exists in the construction sector, which could benefit if an increase in the rate of building refurbishment was achieved.

With respect to the overall net employment effect of climate and energy policies, two studies have recently been released for Germany. One study by Lutz et al. (2014) modeled the net employment effect of "Energiewende" measures from 2010 to 2020 (in comparison with a reference scenario without "Energiewende" policies from 2010 on) and found overall positive job effects for all years (more than 80,000 jobs created in 2010 and just under 30,000 in 2020) (see Figure 25). The shrinking positive net employment effect is ascribed to increasing prices and wages as well as lower investments (Lutz et al. 2014). Another study by Lehr et al. (2015) modeled the net employment effects of renewable energy deployment in Germany since 1995. Compared with a reference scenario with no renewables deployment after 1995, it finds a net increase in the labor force on the order of 50,000 employees for 2015, growing to 110,000 in 2030, and 232,000 in 2050. The higher number of jobs in the renewable energy deployment scenario is due to the higher domestic gross value added of renewable energy technologies compared with fossil fuel alternatives and – after 2030 – also to the effects of the lower system costs of renewables.

With respect to different sectors of the renewable energy industry, developments vary: For example, while in 2013 the number of employees in the photovoltaic industry in Germany decreased significantly due to strong international competition (from 113,900 in 2012 to 68,500 in 2013), new jobs were created in the wind power industry (from 121,800 to 137,800) (BMWi 2014c).

The scenario study in which the "Government Target Scenario" is described (Schlesinger et al. 2014) projects a job increase of 0.3% for its target scenario versus its reference scenario in 2050. Compared to the reference scenario, positive employment effects are estimated for the construction industry (approx. +20,000 employees), parts of the manufacturing industry (approx. +15,000), and related services (approx. +70,000), but lower consumption of energy and gas is expected to result in job losses

Figure 25: Net employment effects of "Energiewende" measures compared to a reference scenario



Source: Own figure based on BMWi 2014c, Lutz et al. 2014.

in the mining and the power supply industries (together approx. -5,000). The "90% GHG Reduction Scenario" (Repenning et al. 2014) expects a positive development on the job market but does not state specific numbers for overall employment in its ambitious decarbonization scenario for 2050, neither does the "Renewable Electrification Scenario" (Nitsch 2014). Positive employment effects can be reinforced if a fair and well-organized transition for workers from the conventional power sector into new jobs is ensured (for example by providing social protection, securing rights, offering advanced training, and fostering social dialogue) (Höhne 2015).

The various expected economic effects of climate protection measures can in sum have a positive impact on the economy and lead to additional GDP growth. While factors such as a higher level of investment (in renewables and energy efficiency, for example) usually raise gross national value added, other factors such as an increase in electricity prices (lowering the competitiveness of the industry) and in the level of net electricity imports (diminishing domestic turnover, especially in the energy supply sector) potentially dampen it (Anders et al. 2014). For 2050, the "Government Target Scenario" (Schlesinger et al. 2014) expects a GDP of 3,692 billion EUR, equivalent to an average economic growth of 1.06% between 2011 and 2050. Compared with the reference scenario, this means an overall difference in GDP of about 1% (or 37.1 billion EUR in absolute numbers).

Generally, it should, however, be noted that there is a large degree of uncertainty associated with long-term projections of future economic effects. This is because models used to assess future economic impacts are usually rather short-term oriented and optimized to project the effect of incremental developments instead of long-term transitions involving substantial structural change as in the case of the "Energiewende."

6.3 Social effects

Final energy consumers can e.g. directly benefit from GHG reduction measures if those result in energy savings and thus lower energy bills. The scope of the benefit, however, depends on the amount of upfront investment required for the implementation of the measure.

If energy savings result from simple behavioral changes (e.g. avoidance of unnecessary energy consumption for heating or lighting) that do not induce any cost, consumers might receive the whole price difference as a premium. This changes if energy savings are due to investments in energy efficiency technologies and measures. While in the case of low investments (e.g. in programmable thermostats) economic benefits can be obtained within a short period of time, significant investments (e.g. in energy-efficient combined refrigerator-freezers or even building insulation) might amortize only after several years or even decades. There may also be measures leading to energy savings which are not recommendable from an economic point of view.

If consumers implement measures which lead to energy savings and at some point in time also generate financial benefits, they are then able to spend the money elsewhere. Especially with respect to low-income households, lower energy bills can help improve living conditions markedly as the money saved constitutes a greater share of their income compared with wealthier households. However, as those consumers very often do not have the means to invest in energy-efficient technologies by themselves, specific policy measures might be necessary to set appropriate incentives.

In recent years, saving energy has become increasingly important for end users in Germany as energy prices have been rising for some time (e.g. electricity costs have risen about 5.4%/year for households between 2000 and 2014 (BDEW 2015)). However, many barriers and obstacles (e.g. knowledge gap, long payback periods) hamper the implementation of energy efficiency measures.

Considering future electricity prices, the "Government Target Scenario" (Schlesinger et al. 2014) expects rising real electricity prices for households until 2025. Household electricity prices reach 323 EUR_{2011}/MWh in that year, compared to 259 EUR_{2011}/MWh in 2011. The price rise mainly results from increasing reallocation charges in the framework of the Renewable Energy Sources Act. In the following years, wholesale prices for electricity continue to increase, but a decreasing reallocation charge overcompensates for this increase and leads to falling household electricity prices until 2050. In 2050, these prices are projected to be only slightly higher than in 2011 (272 instead of 259 EUR_{2011}/MWh) and are almost identical to the 2050 prices in the reference scenario (268 EUR_{2011}/MWh). The "90% GHG Reduction Scenario" (Repenning et al. 2014) and the "Renewable Electrification Scenario" (Nitsch 2014) do not provide specific information on electricity prices for households, but the "90% GHG Reduction Scenario" also states that electricity prices (at the energy-only market) will peak around 2030. Thus, German energy policies linked to the "Energiewende" are expected to make electricity slightly more costly compared with a business-as-usual case. However, according to the expert commission on the "Energiewende," by now a broad majority of the German population accepts that transforming the energy system does not come at zero cost (Löschel et al. 2014). Nevertheless, the German government as well as experts emphasize that electricity costs for end consumers need to remain within reasonable bounds (Löschel et al. 2014). The expert commission recommends constantly monitoring the situation of poorer households and also general social impacts to allow for prompt reactions to undesirable developments (Löschel et al. 2014).

6.4 Environmental effects

Besides GHG emissions, climate policies often simultaneously reduce environmental degradation. Many measures targeting GHG emission mitigation, for example, also reduce the amount of harmful substances emitted into the air because both types of emissions frequently originate from the same sources, such as power plants, factories and cars (Höhne et al. 2015). As a result, air pollution (especially in the form of nitrogen oxides, sulfur dioxides, and dusts) generally declines as GHG emissions are reduced. Profiting from better air quality are people living near (former) pollution sources; they will suffer from less illnesses caused by air pollution. In turn, government expenditure can be decreased as fewer people become ill owing to environmental pollution. Money can be saved because medical treatment for those people is rendered unnecessary and they are able to work instead of staying at home. Thus, employee productivity can be increased.

The scenario studies do not provide data showing how much air pollution could be reduced by means of climate policy measures. However, studies such as Pozzer et al. (2012) show that in a reference case without further efforts, air pollution in Germany would keep on rising until 2050. A study on the German state of North-Rhine Westphalia states that the implementation of planned climate protection measures (especially the abandonment of energy carriers emitting air pollutants such as lignite) would result in significant air quality improvements (Anders et al. 2014).

7 Resulting policy challenges

In order to achieve deep decarbonization and related co-benefits in Germany, different strategies can be implemented (see Chapters 4 and 5). The real challenge is not in developing but actually implementing these strategies. In order to successfully carry out this task, authorities need to introduce appropriate policies that support the implementation of measures linked to the strategies. Furthermore, ways have to be found to overcome barriers and obstacles still in place. In this context, not only do current measures need to be considered but so does the realization of future measures. All measures need to be part of a consistent long-term strategy and must be prepared in time. It must also be considered that transformation processes are subject to constraints and path dependencies that need to be identified at an early stage and overcome. The whole task is especially difficult as – depending on the particular technology, societal development, etc. – all future developments are to varying extents subject to uncertainty. Although possible developments can be depicted, for example in forms of scenarios, given the complexity of the system and the high number of significant variables, actual developments can still differ considerably from these projections.

Besides, an additional challenge for policy makers lies in the fact that the German "Energiewende" is not centrally organized but influenced and regulated by different levels of governance (EU, national level, federal states, regions and municipalities). While different tasks need to be carried out on each of these levels, successfully managing climate and energy policy from a multi-level perspective constitutes a challenge in itself.

Subsequently, this chapter will explore the challenges policy makers in Germany will face in pursuing deep decarbonization. The focus is laid on those policy challenges that enjoy a high priority and should be met comparatively soon to create a sufficient implementation velocity. Thereby, policy challenges are classified as priority because a belated consideration creates lock-in effects and/or because they are required for the implementation of one of the three key strategies identified in Chapter 3 and analyzed more closely in Chapter 4. Since these key strategies are – although to different extents – used to decarbonize the German economy in each of the illustrative scenarios (and also almost any other scenario on the future development of the German energy sector), their realization can be regarded as inevitable. Thus, dealing early with policy challenges that will otherwise arise in the future can help clarify the picture in terms of required future action.

7.1 Increase in energy efficiency

On the one hand, supporting energy efficiency measures through policies enjoys priority because it is an important strategy in each ambitious scenario study on the future German energy system. On the other hand, efficiency measures should be implemented in the short-term because technologies and measures to achieve efficiency improvements are available, often cost-effective, and comparatively easy to implement. Furthermore, in areas with long investment cycles (e.g. buildings), lock-in effects can be created if energy efficiency measures are not implemented soon. If energy efficiency improvements can be obtained (and overall activity levels do not rise so much that they annihilate achieved energy consumption reductions), it also reduces the necessity for future decarbonization measures, for example, on the supply side.

Generally, the German government's energy efficiency policies follow the philosophy of "requirements and incentives." Thus, the existing policy mix mainly combines legal standards with information campaigns and financial or fiscal stimuli (BMWi 2014a).

There are several important documents and current policies that directly target energy efficiency improvements in Germany, mainly:

- The German government's "Energy Concept" (BMWi and BMU 2010, see Chapter 2), which describes the envisaged transition of the national energy system toward a sustainable energy system and forms the basis for many energy policy changes of recent years. The document, which was adopted in 2010, states concrete reduction targets for primary energy (-50% by 2050 vs. 2008, see Table 2) and gross electricity consumption reduction (-25% by 2050 vs. 2008) and mentions measures to be turned into laws.
- The EDL-G, or "Gesetz über Energiedienstleistungen und andere Energieeffizienzmaßnahmen," represents the transposition of the EU's Energy Services Directive (ESD, Directive 2006/32/EC) into German law. The EDL-G's main goals are to provide a suitable framework for the implementation of efficiency-enhancing measures, to remove barriers to energy efficiency and to promote the development of a market for energy services and further energy efficiency measures. The EDL-G is currently being revised as it should also accommodate new regulation from the ESD's successor, the EU's "Directive 2012/27/EU on energy efficiency" (EED). This EED contains additional policies that should help realize further energy saving potential and reach the EU's energy saving targets.
- Further crucial policies are German laws corresponding to EU policies such as the Ecodesign Directive (a framework for designing standards for energy-related products, e.g. refrigerators), the Labelling Directive (on information standards for energy-related products, e.g. TVs), as well as the EPBD (Energy Performance of Buildings Directive on requests for new buildings).
- Moreover, the "Ökologische Steuerreform" (Ecological tax reform) was initiated in 1999. By gradually raising electricity and energy taxes, the German government aimed to increase energy prices in order to encourage energy savings and investments in improved energy efficiency.

However, although the importance of energy efficiency has often been stressed, improvements lag behind expectations (for example, primary energy consumption should be reduced by 20% by 2020 (compared with 2008), but in 2014 only a 9% reduction could be achieved, see Table 2). The general challenge is that as efficiency improvements can be obtained in many different areas, there is also a variety of barriers hindering their realization. Hence, different policies addressing particular barriers (e.g. financial support for homeowners to achieve building refurbishment, regulation to make companies carry out energy audits, support for the further development of the energy services market etc.) are required in order to increase energy efficiency rates. This is especially important in the buildings and transport sector, where the highest energy efficiency potential in Germany exists (see case study on energy efficiency policies in the building sector in Box 2).

In order to achieve progress, the German government adopted the new "Nationaler Aktionsplan Energieeffizienz" (NAPE, National action plan for energy efficiency, not to be confused with the National Energy Efficiency Action Plan (NEEAP), which has to be submitted regularly to the EU Commission) in December 2014. The Plan defines energy efficiency measures to be implemented immediately as well as further work processes for the current legislative period. Important urgent measures include an increase in funding for building refurbishment and the creation of energy efficiency networks together with industry (for an exchange of experiences on energy efficiency measures) (BMWi 2014b).

The NAPE is one of several measures enacted in the framework of the "Aktionsprogramm Klimaschutz 2020" (Climate Action Programme 2020, BMUB 2014c), which the German government adopted in December 2014. By imple-

Box 2: Case study: Energy efficiency policies in the building sector

Improving energy efficiency in buildings is urgently required for mainly two reasons. First, the building sector comprises the highest energy efficiency potential in Germany, so it could contribute a great share to GHG emission reductions. In the "Government Target Scenario," for example, energy demand for space heating is reduced from 2,556 PJ in 2011 to 1,348 PJ in 2050 and thus constitutes by far the energy service with the highest final energy demand reduction potential (Schlesinger et al. 2014). Additionally, investment cycles in the building sector are quite long. If a homeowner today invests in building refurbishment, it is rather unlikely that he or she will do so again soon. Hence, in order to allow for an achievement of the ambitious building refurbishment targets, it is necessary to start modernizing buildings in accordance with modern energetic standards today.

Policy challenges regarding building efficiency are immense. The rate of energy-related building refurbishment needs to increase two- to threefold compared with today to allow for the achievement of the government's GHG emission reduction targets, according to the analyzed scenarios (see Section 4.1.1).

In order to increase efforts for energy efficiency in buildings, the EU as well as the German government have enacted policies that aim to overcome the barriers. In the building sector, energy efficiency policies (Kemfert et al. 2015) mainly consist of:

- legal provisions
  (e.g. in the framework of the Energieeinsparverordnung (EnEV, Energy Saving Ordinance, transposition of EU Energy Performance of Buildings Directive in German law) and the EDL-G, which include minimum standards for the energy performance of new and existing buildings and their energy equipment)
- financial support measures
  (e.g. funding schemes by the state-owned Kreditanstalt für Wiederaufbau (KfW) bank to support building owners with loans and subsidies and thus diminish their liquidity constraints)
- information and advice
  (e.g. information campaigns or labelling schemes such as energy performance certificates, which indicate possible energy savings linked to excellent performance standards)

According to the DIW, existing policies in the building sector are effectively applied in the case of new buildings, as compliance with standards can be ensured by means of construction licensing procedures (Kemfert et al. 2015). However, it is more challenging to boost energy efficiency of existing buildings because home owners cannot be forced to invest in and implement efficiency measures. Furthermore, building refurbishments might achieve lower-than-expected efficiency improvements (Kemfert et al. 2015). Today many existing buildings undergo renovation for maintenance or beautification only. These opportunities should be better harnessed in the future to improve energy efficiency by adding thermal insulation or shading and using more energy-efficient windows, heating, and cooling systems, instead of just replacing paint, tiles, or windows as they were before.

In order to overcome this challenge, the commission of experts monitoring the "Energiewende" as well as the DIW suggest a further tightening of regulation for new as well as existing buildings (especially of the EnEV) (Löschel et al. 2014). Mandatory minimum energy performance standards (MEPS) for existing buildings undergoing major renovation (e.g., more than 10% or 20% of the building shell or of the walls, windows, or roofs) as well as for building components and heating and cooling systems could constitute an important policy for energy efficiency in existing buildings.

However, experts (Kemfert et al. 2015, Löschel et al. 2014) argue that minimum energy performance standards at time of renovation need to be combined with measures offering economic incentives to obtain energy efficiency improvements in a sufficient amount of buildings. Possible forms of economic incentives could be a combination of financial support programs and negative incentives like energy taxes, income tax deductions for a share of refurbishment costs, or an energy-based structure of the real estate tax (Kemfert et al. 2015).

A first step on the way to better policies resulting in increased energy efficiency of buildings is the National Action Plan on Energy Efficiency (NAPE) adopted in December 2014. It includes additional economic incentives for building refurbishment (especially for non-residential buildings) (BMWi 2014b) and states the intention of developing a general energy efficiency strategy for buildings (BMWi 2014b).

menting measures stated in the programme, the government aims at reaching its objective of a 40% GHG reduction by 2020 (compared with 1990). Besides the NAPE, the Climate Action Programme contains further measures targeting energy efficiency, for example in transport.

Besides national government, authorities on other policy levels can also contribute to increases in energy efficiency. For example, regarding the transport sector, room for action is limited for national governments (Löschel et al. 2014). Instead, vehicle parameters making car manufacturers develop and deploy more efficient propulsion technologies, for example, are set by EU legislation. Thus, energy efficiency improvements on the national level increase with the ambitiousness of EU policies.[26]

26 It should be noted that the German government has considerable influence on EU legislation and can thus help shape energy and climate policy on the EU level. However, in the past Germany has not always used its weight to drive forward ambitious EU energy and climate regulation. In 2013, for example, it was reported that the German government attempted to delay and weaken regulation limiting specific CO_2 emissions of new cars (The Guardian 2013).

Due to their closeness to citizens, municipalities are in a position to implement information and education policies. This can be accomplished by explaining existing higher level policies (e.g. regulations, support programs) as well as technological possibilities for energy efficiency improvements to its citizens and entrepreneurs. Efficiency-enhancing measures can especially be fostered by low-threshold and affordable energy consultants and through outreach by municipalities and their public utilities (Landsberg 2015). Furthermore, municipalities can help remove the lack of transparency regarding existing support schemes available for local actors by establishing objective consulting systems (Schüle et al. 2011).

7.2 Increase in electricity generation from renewable energy sources

A focus on the dissemination of renewable energy sources is especially important as investment cycles in the energy supply sector are usually long. If investment flows today are not directed toward renewable energy supply but rather toward fossil-fueled power plants, a future lock-in effect will be created (Kemfert et al. 2015). Additionally, the increase in electricity from renewable energy sources is a main pillar of the German "Energiewende" and considered in every scenario. It also constitutes an important precondition for a widespread electrification of processes and implementation of power-to-x processes on a renewables basis or appropriate flexibility options in general. Achieving the GHG emission reduction target is impossible without a successful dissemination of renewable energy sources.

Important documents and current policies on the dissemination of renewable energy sources for electricity production in Germany include:

- The 'Energy Concept' (BMWi and BMU 2010), which was adopted in 2010 and paves the way for a sustainable energy system, also includes many important policies targeting the dissemination of renewable energy sources. It further contains specific objectives for the share of renewables in gross electricity consumption (at least 80% by 2050, see Table 2) and in gross final energy consumption (at least 60% by 2050) and asserts measures that should be turned into laws.
- The "Erneuerbare-Energien-Gesetz" (EEG, Renewable Energy Sources Act) governs financial support for the operation of renewable energy production plants. It was first enacted in 2000 and has been revised regularly since then.[27] Providing fixed feed-in tariffs for the production of "green" electricity, the EEG is credited with being an important factor for the widespread dissemination of renewable energy sources in Germany from 2000 until today. The EEG also incorporates requirements on electricity generation from renewables determined in the EU's "Renewables Directive" (2009/28/EC). The Directive targets an average 20% share of renewable energy sources in the EU's gross final energy consumption by 2020 and therefore mandates specific shares of low-carbon energy production from each member state (e.g. 18% in Germany).
- Furthermore, several legislative documents determine the regulatory framework of German electricity supply, for example regarding the general provision of electricity and gas as well as the regulation of supply grids ("Energiewirtschaftsgesetz," EnWG, Energy Industry Law) or the expansion of electricity grids (Netzausbaubeschleunigungsgesetzt, NABEG, Law on the Acceleration of Grid Development and Bundesbedarfsplangesetz, BBPlG, Law on the Federal Requirement Plan) (BMWi 2014a).

In order to keep investments in renewable energy sources flowing, the government must ensure that investment conditions are stable. Of high importance for the increase of renewable energy sources in electricity production are also major changes of the overall system, especially regarding technological flexibility for system stability. This requires policies supporting the identification and promotion of suitable technologies (e.g. storage systems, demand-side management). Moreover, the way to reform the electricity market must be determined and implemented (see case study on a new design of the German electricity market in Box 3). Furthermore, grid construction needs to be accelerated, especially if the focus is on more centralized electricity production (e.g. in form of offshore wind farms). Particularly in this case (and with respect to windmills), government must successfully deal with public opposition against new energy infrastructure projects (see case study on public participation in Box 4).

Recent policy initiatives by the German government on renewables in electricity generation include a revision of the EEG in 2014 which was strongly influenced by EU legislation. In April 2014, the European Commission adopted new rules on public support for environmental protection and energy for the years 2014 to 2020 (EC 2014). They strongly affect financial support for renewable energy in Germany because feed-in tariffs – such as the German ones – should be gradually replaced by market-based feed-in premiums. Furthermore, the allocation of public support should be implemented more and more by means of competitive bidding processes (EC 2014). As a consequence, public support for newly installed renewable energy sources should be more cost-effective, and market distortions limited (EC 2014). The new rules on public support for environmental protection and energy were taken into account for the EEG revision. However, whether this EU policy is an adequate instrument to foster the continuous dissemination of renewable energy sources at the lowest cost in Germany cannot yet be assessed. Critics argue, for example, that the abolishment of feed-in tariffs reduces security of investment, which could lower investments in renewables, especially by private households and energy cooperatives (Grashof and Weber 2014). Moreover, they claim that feed-in premiums remove the priority feed-in of electricity from renewable energy sources and thus reduce incentives to shut down coal-fired and nuclear power plants (Grashof and Weber 2014).

Besides the EEG revision, important recent actions include the 2015 publication of the White Paper on a new electricity market design (BMWi 2015c, see case study in Box 3).

A dissemination of renewable energy sources can also be influenced by authorities on other political levels.

Policy challenges at the EU level strongly affecting Germany mainly result from the form which financial support for new renewable energy sources takes (see information on the EU's new rules on public support for environmental protection and energy for the years 2014 to 2020, above).

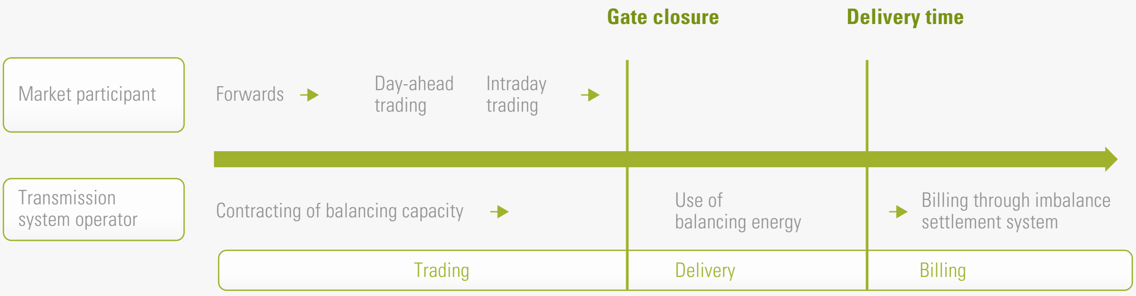
Similar to energy efficiency, municipal consulting on regulation and support programs as well as technological possibilities for the installation of renewable energy sources could foster their actual implementation. Purposeful urban development and urban land-use planning could facilitate the installation of renewable energy sources by municipal corporations (e.g. public energy utilities) as well as other investors.

27 Already in 1991, Germany enacted the Grid Feed-In Law (German: Stromeinspeisungsgesetz, StromEinspG) that obligated energy companies to purchase electricity from renewable energy sources at minimum prices. Compared to the later EEG, the Grid Feed-In Law provided less differentiated remuneration (not allowing PV plants to be operated economically, for example) and set a limit for the financial support for renewables, negatively affecting investment security.

Box 3: Case study: New design of the German electricity market

As stated in Chapter 2, Germany is currently facing a tipping point because until recently renewable electricity had been fed into the electricity grid with priority access and without endangering system stability. Now renewable energy sources lose this priority access and need to increasingly assume system responsibility. Because of the interaction between different energy sources, energy demand and balancing or flexibility measures (e.g. storage or demand-side management) need to be coordinated by a form of market or another controlling instance. A new market design will have to be adopted soon. Currently, a number of submarkets constitute the German electricity market (BMWi 2014d, see Figure 26). These submarkets produce a pricing signal to which electricity generation and consumption adjust. If any unexpected differences occur, the transmission system operators compensate for them with balancing capacities. Synchronization is checked by the system of balancing groups and imbalance settlement. The interplay between them makes the electricity market provide remuneration for energy and capacity. In order to correct for bottlenecks in the grid, transmission system operators extend and advance the power grid and transitionally use redispatch measures (BMWi 2014d).
Regarding the future, it is not yet predictable how a decarbonized energy system will be organized. How will the transition take place? Which elements will come into the market, when, and how? Which features of energy supply will become valuable? Like the answers to those questions, the specific requirements for a new electricity market will only become clear bit by bit when moving toward a decarbonized energy supply.
In July 2015, the German Federal Ministry for Economic Affairs and Energy published a White Paper called "An Electricity Market for Germany's Energy Transition" (BMWi 2015c), which describes a new electricity market design to be implemented in the coming years in order to ensure a safe electricity supply as the share of (fluctuating) renewable energy sources increases.[28] The following paragraphs depict the findings stated in the White Paper.
According to the Ministry, specific support for flexibility options will not be necessary because pricing signals from electricity markets automatically provide incentives for the most cost-efficient option. However, due to a number of barriers, some producers and consumers of electricity face distorted price signals, i.e. fixed components of electricity prices in the electricity sector and the interface to the heating and transport sector. Therefore, it will be necessary to examine and address these barriers to flexibility. Pricing signals should further ensure that market players provide an appropriate and efficient technology mix of flexible producers and consumers and make timely investments in new capacities. New renewable energy facilities will need to accept the same responsibility for the overall system as conventional power plants. In order to strengthen the pricing signal flexibility, the electricity market should be widened toward a European market. A shift from hourly trading products to quarter-hour products could leverage additional potential for flexibility.
Despite the policy preferences presented in the ministry's White Paper, debates continue about whether the market design adjustments envisioned in the White Paper will suffice or whether a capacity market will be needed sooner or later to ensure security of supply. Generally, two different kinds of capacity markets are discussed. In a centralized capacity market, the state directly determines how much capacity is held available, whereas in a decentralized capacity market, the state only controls the level of capacity indirectly by changing the penalties to be paid.
Which form of market should be introduced or in which way the market design should be altered is still an object of intense research.

Figure 26: Submarkets of the electricity market in Germany, chronological representation



Source: Own figure based on BMWI 2014d.

28 The White Paper follows a Green Paper by the ministry from October 2014 that was publicly consulted until March 2015.

Box 4: Case study: Public participation in the transformation process

After Germany experienced strong opposition against nuclear power plants in the past, today the generally welcomed energy transition is – on a micro level – also facing opposition, particularly against wind power and new transmission lines. The arguments citizens raise are mainly aesthetic and health-related. Furthermore, some citizens suspect profit interests as a hidden agenda, with most decisions on the "Energiewende" being made behind closed doors, and with interests not being transparent.

Although such public conflicts exist, a joint federal initiative to increase acceptance through participation has long been lacking in Germany.[29] However, the number of public participation projects has increased sharply in recent years as decision makers realized that participation can be a suitable instrument when communicating information is not enough. Rather, concerns need to be integrated, local knowledge needs to be gathered, conflicts need to be resolved, and shared recommendations need to be produced. Participation does not produce acceptance but it enables citizens to become the owner of a process and fosters at least tolerance.

For example, a broad participatory process was conducted by the state of North Rhine-Westphalia (NRW)[30], the German state with the most fossil-fired power plants and energy-intensive industries. The process was based on NRW's climate protection law (Climate Protection Act), where concrete GHG emission mitigation goals have been fixed for 2020 (-25% vs. 1990) and 2050 (-80%). The output of the participation process constitutes the basis for the so-called "Klimaschutzplan" (Climate Protection Plan), the road map containing strategies and measures for achieving NRW's mitigation targets.

In an effort to develop inputs for the "Klimaschutzplan," politicians engaged in discussions with more than 400 different stakeholders along six sectoral working groups (see Figure 27). They debated in a systematic process over a period of two years on issues including appropriate technologies to reach decarbonization targets, the integration of these technologies into consistent pathways, possible impacts of the pathways, and appropriate policy instruments supporting the process.

With the participation process, the NRW government decided to intensively engage relevant stakeholders already in the development of the "Klimaschutzplan." After two years, several added values could be detected:

- Specification of relevant stakeholders for ambitious climate protection policy in NRW
- Significantly improved knowledge about mitigation potentials and scenarios in NRW
- Stakeholder assessment of mitigation measures
- Buildup of highly productive discussion culture among stakeholders
- Increased awareness for different perspectives among stakeholders
- Confidence building between stakeholders and ministries
- Better chance to implement mitigation measures due to joint development with stakeholders
- Starting point for further dialogue structures with stakeholders (e.g. dialogue with industry)

Generally, evaluations of participation processes tend to show that although not all projects are successful in terms of implementing a specific infrastructure (e.g. a windmill), they do reach important goals such as enlightenment, conflict resolution, etc. – and often enough also a decision on implementing infrastructures with changes.

Figure 27: Schematic description of the NRW Climate Protection Plan process

Source: IFOK 2013 (personal communication, July 13, 2015).

29 The German government has now initiated a participation process aiming at generating inputs for a national Climate Protection Plan. Similar to the process in North-Rhine Westphalia, it should constitute a roadmap to achieve GHG mitigation targets.

30 For more information see https://www.klimaschutz.nrw.de/english/

7.3 Electrification of processes and power-to-x

The electrification of processes and power-to-x, especially in transport and industry, are considered important strategies for deep decarbonization in many energy scenarios for Germany, including the "Renewable Electrification Scenario" and the "90% GHG Reduction Scenario." However, electrification as well as the conversion of electricity into gas or fuel results in relatively high electricity demand and – in the case of electricity conversion – involves large conversion losses. In order to allow for a sustainable electrification of processes and conversion of electricity, it is thus important to first focus on the decarbonization of the electricity system.

Besides, several obstacles still have to be overcome to allow for the use of a greater amount of electricity from renewable energy sources (see also Chapter 4.2). First, further renewable energy sources must be installed to match additional electricity demand. Moreover, technologies are required that allow for a better storage of energy produced from fluctuating renewable sources. Such technologies could comprise better storage batteries as well as power-to-x technologies transforming electricity, for example, into forms of gas or fuel. One reason why such technologies are envisaged to be employed rather in the long term is that they are not yet available (e.g. breakthrough technologies for industrial production processes, CCS). Since the electrification of processes and power-to-x plays an important role in many scenarios, current policy making can already try to prepare a successful future implementation of these strategies.

As the energy policy focus in Germany has so far been on expanding the use of renewable energy sources, the policy framework regarding electrification and power-to-x is not yet well developed. Important existing documents and policies include:

- Financial support schemes by the German government for research and development of energy storage technologies, e.g. the "Förderinitiative Energiespeicher für stationäre und mobile Anwendungen" (Funding Initiative Energy Storage for Stationary and Mobile Applications) (dena n.y.)
- The government's "Nationaler Entwicklungsplan Elektromobilität" (National Development Plan for Electric Mobility, Federal German Government 2009), which initiated measures to support the use of electricity in transport and was published in 2009. Since then, further steps to specifically foster electrification in transport were determined, e.g. in the 2011 "Regierungsprogramm Elektromobilität" (Government Programme Electric Mobility). Current efforts focus on the electrification of cars, two-wheelers, light transport vehicles, and city buses (BMVBS 2013).
- For the general transformation of the transport sector, the German government launched a "Mobilitäts- und Kraftstoffstrategie" (Mobility and Fuel Strategy, BMVBS 2013) in 2013 which informs about future fuel and propulsion technologies and notes a growing importance of gas and renewable methane as well as electricity and hydrogen. In the future more concrete information on how to implement the "Energiewende" in transport should be added to the strategy (BMVBS 2013).
- The policy framework for power-to-gas has mainly been developed since 2011, when two important laws were amended. According to the revision of the EnWG (Energy Industry Law), hydrogen and synthetic gases produced to at least 80% from renewable energy sources are considered biogas. Therefore, its supplier enjoys the same legal privileges as biogas producers (unlike suppliers of conventional gas). The use of hydrogen and synthetic gases was taken into account in the EEG (Renewable Energy Sources Act) amendment. It now in-

cludes that a feed-in tariff is paid for electricity produced from synthetic gas or hydrogen that originates from renewable energy sources and has been fed into the grid at an earlier point in time (and is thus considered storage gas).

With regard to the future electrification of processes and usage of power-to-x, a consistent and stable policy framework needs to be established. In addition, it is important to introduce policies that foster research and development activities in areas where further technological progress is required (e.g. storage solutions). This mainly relates to financial support but also, for example, to measures promoting cooperation between companies and researchers as well as among companies in pre-competitive research projects. Additionally, policy measures are necessary to ensure the broader market introduction of technologies that could already contribute to decarbonization, such as hydrogen and methane from renewable energy sources.

The further electrification of processes and deployment of power-to-x technologies in Germany can happen faster and with increased success, if the EU keeps promoting it as well. Currently, the EU does so, for instance, in the form of its "Strategic Energy Technology Plan" (SET Plan), which aims to accelerate the development and deployment of cost-effective low-carbon technologies such as energy storage technologies.

Box 5: Case study: Reform of the EU Emissions trading scheme (ETS)

The ETS is designed to allocate CO_2 emission allowances to those emitters who value them most. It is the EU's key tool for reducing industrial greenhouse gas emissions cost-effectively and should promote investment in clean, low-carbon technologies by energy suppliers and energy-intensive industry (EC 2015a). Hence, by putting a price on CO_2 emissions, the ETS sets an incentive for industrial companies to electrify processes on the basis of low-carbon electricity and/or to employ power-to-x technologies.

Generally, a functioning ETS is of high importance for decarbonization in Germany because the ETS covers energy suppliers and energy-intensive companies, which together emit almost 50% of national GHG emissions (Löschel et al. 2014). However, ETS allowance prices have been decreasing since summer 2008 due to an oversupply of certificates and low demand following the economic and financial crisis (BMUB 2014b). Allowance prices were as low as 5 EUR or less throughout most of 2013 and have fluctuated between 5 and 8 EUR since the middle of 2014 (EEX 2012). These allowance prices are much lower than originally anticipated (EC 2008) and do not provide sufficient incentive to invest in low-carbon technologies. Besides the missing incentive for low-carbon investments by energy suppliers and the energy-intensive industry, low certificate prices also hinder governmental financial support for climate protection measures. Since the German government established an Energy and Climate Fund, which is mainly financed by revenues from emissions trading auctions, less funding is available for climate protection measures than initially expected (Löschel et al. 2014). Hence, the reform of the ETS is an important policy challenge to be overcome by the EU.

The EU has recently agreed to introduce a so-called "market stability reserve" to the ETS from 2019 on. This reserve will automatically take a portion of ETS allowances off the market when there is a high surplus of emission certificates. Conversely, allowances are automatically returned to the market when the surplus is low. The introduction of the reserve is intended to increase certificate prices and reduce future price fluctuations. The actual effects of the introduction of the market stability reserve are difficult to foresee, so it remains to be seen whether allowance prices will indeed increase significantly and become less volatile (Acworth 2014). In July 2015, the European Commission proposed a further change to the ETS system, suggesting a reduction of the overall number of emission allowances of 2.2% each year from 2021 onwards, compared with a current annual reduction of 1.74%, in order to allow the EU to reach its target of reducing its domestic GHG emissions by at least 40% by 2030 compared with 1990 (EC 2015b).

8 Next steps

The previous chapters showed that although there are challenges to be overcome on the way to a fundamental transformation, deep decarbonization can be achieved in Germany by 2050. Important parts of the basis for a successful future transformation have already been established in the past.

As a result of about 30 years of critical engagement with climate and energy policies in Germany, a huge amount of theoretical and practical knowledge on transformation processes has been gathered. Important concrete decisions have been made and policies implemented, from the national parliament's first commission of inquiry on "Preventive Measures to Protect the Earth's Atmosphere" in 1987 to the ratification of the Kyoto Protocol in 2002 and the decision on the nuclear phase-out in 2011. Many researchers and scientists supported transformation processes with their work, whether with specific technologies or policy measures. The analysis done in the framework of Germany's DDPP country study could be conducted on the basis of already existing scenario studies by researchers from different institutions and based on the long experience of thinking in alternative energy pathways.

Thus, there is a broad knowledge base on transformation processes in Germany. With regard to future challenges and given the increasing complexity of the sector and the target system, it should, however, be expanded. Germany should also be open to learning from transformation processes in other countries, just as other countries should learn from Germany's experiences.

Focusing on Germany, further steps implemented in the framework of the DDPP could include:

- Modeling exercises of more ambitious mitigation scenarios for Germany, which target a complete decarbonization, analyze interdependencies between different sectors in detail, and further elaborate on path dependencies and major sector as well as cross-sector challenges
- Further consideration of opportunities and challenges arising from multi-level governance and implementation of decarbonization measures (EU – national level – federal states – regions – municipalities as well as companies – end users)
- Scenario modelling approaches involving stakeholder participation
- Analysis of interdependencies between national decarbonization pathways in the framework of an EU-wide decarbonization strategy.

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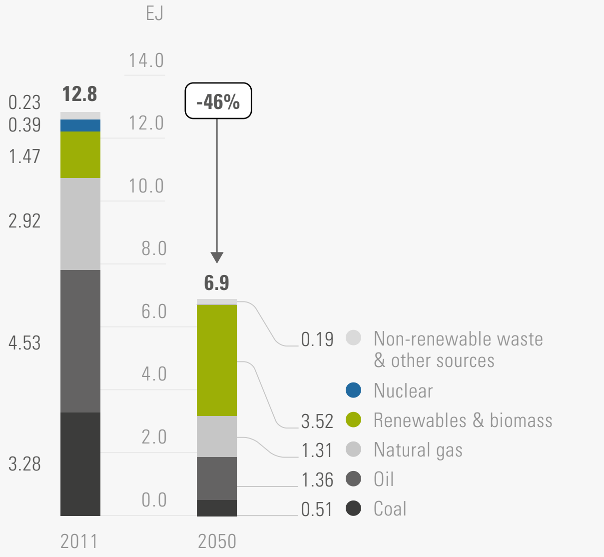
Standardized DDPP graphics for German scenarios

DE - Government Target
DE - Renewable Electrification
DE - 90% GHG Reduction

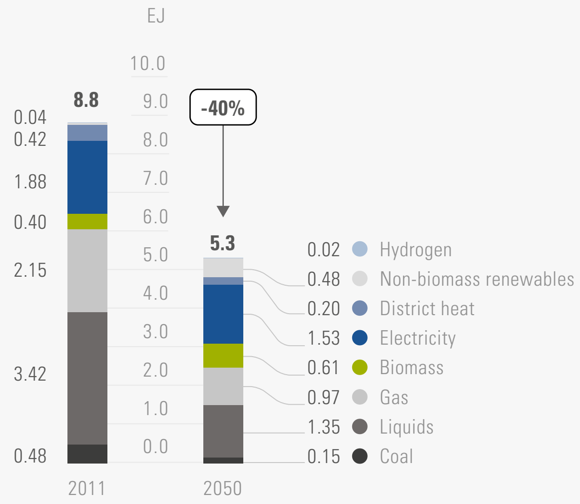
DE - Government Target

Energy Pathways, Primary Energy by Source



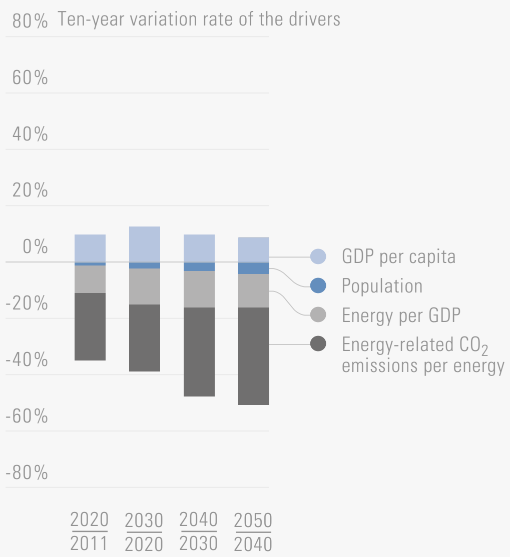
This figure relates to electrical energy output that is generated in the nuclear power plant, and does not include heat energy/steam generated.

Energy Pathways, Final Energy by Source

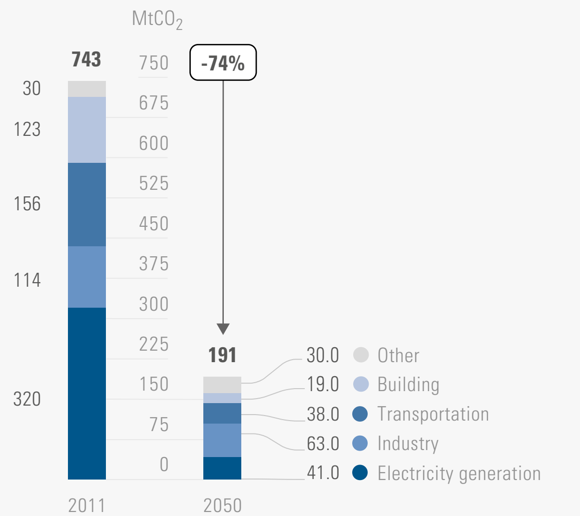


Biofuels are included among "liquids".

Energy-related CO_2 Emissions Drivers, 2010 to 2050



Energy-related CO_2 Emissions Pathway, by Sector



Some of the data used for this figure was kindly provided by the authors of the original scenario study.

The Pillars of Decarbonization

Final energy efficiency

Energy intensity of GDP, MJ/$2010

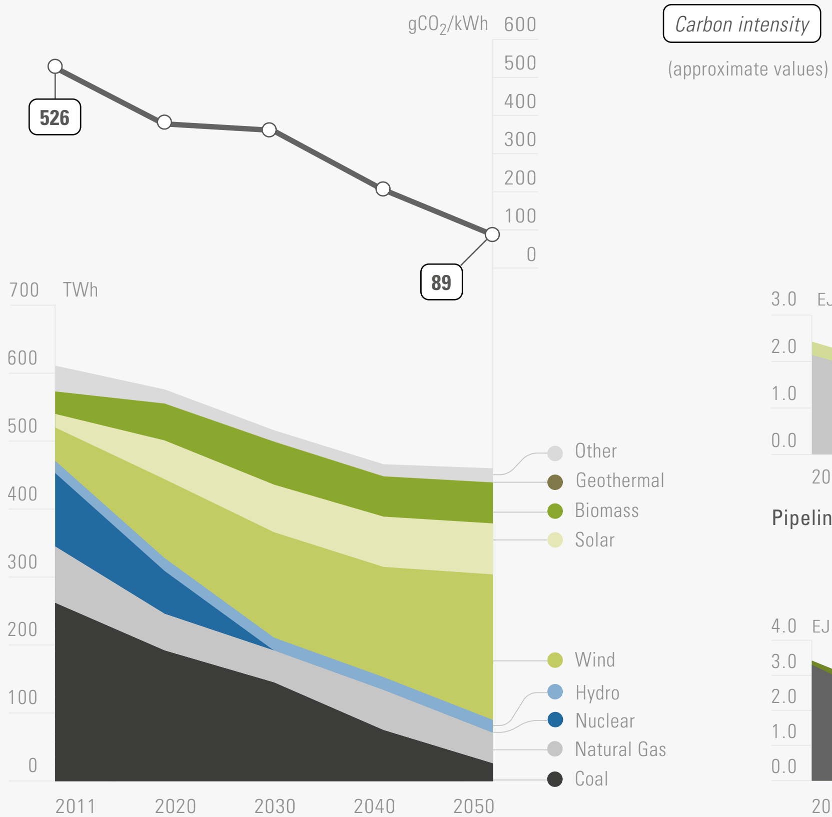
Decarbonization of electricity (approximate values)*

Electricity emissions intensity, gCO_2/kWh

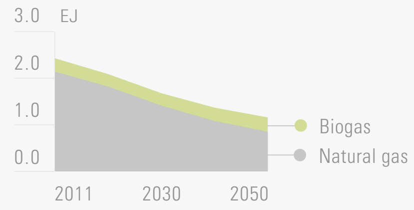
Electrification of end-uses (approximate values)*

Share of electricity in total final energy, %

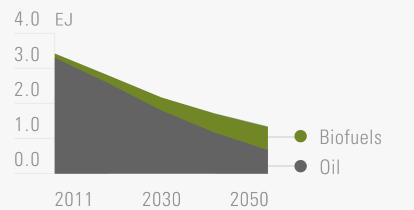
Energy Supply Pathways, by Resource



Electricity

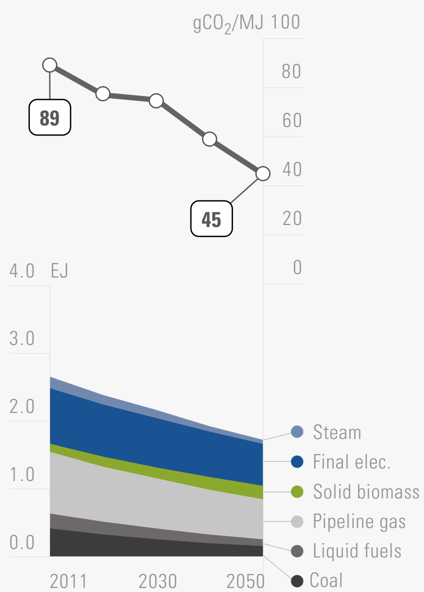


Pipeline Gas in final energy demand

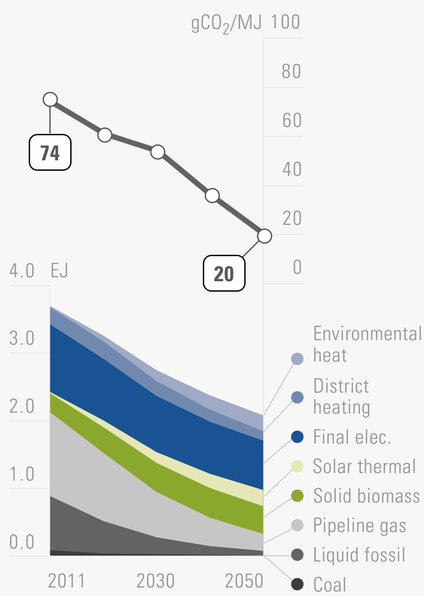


Liquid Fuels in final energy demand

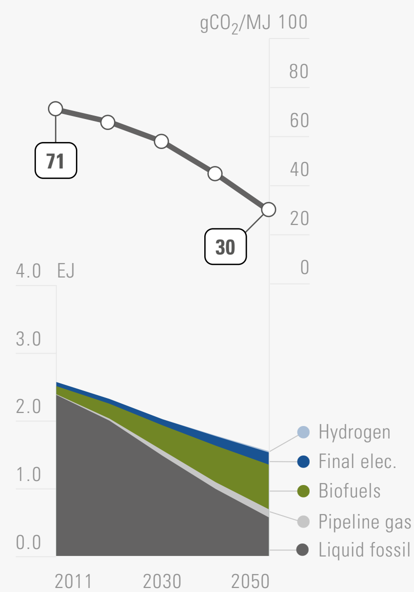
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry



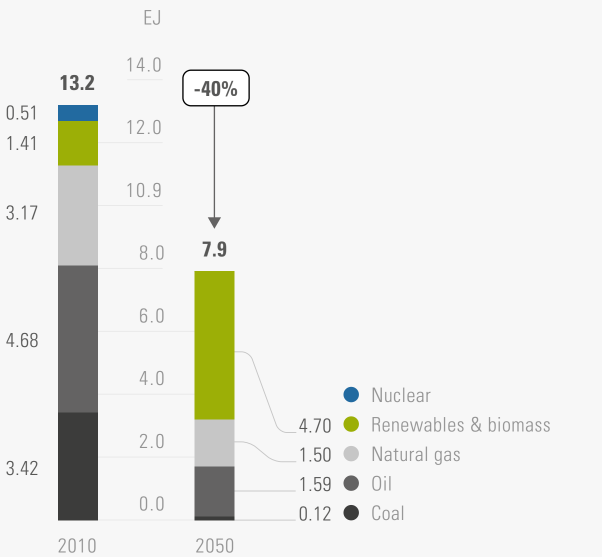
Buildings



Transportation

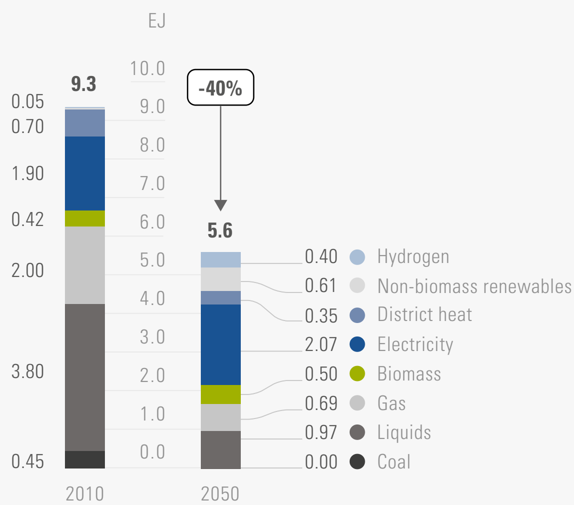
DE - Renewable Electrification

Energy Pathways, Primary Energy by Source



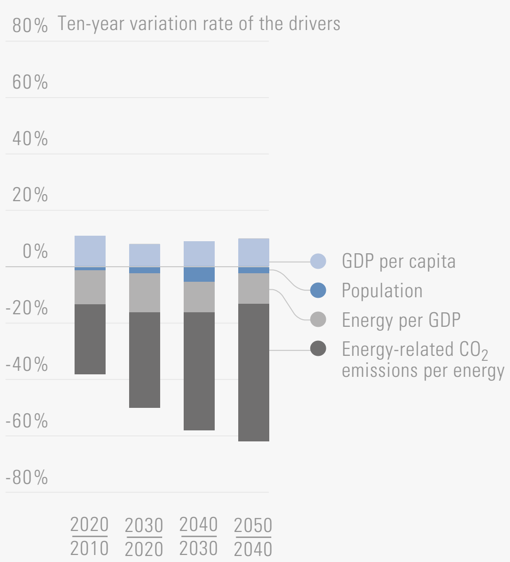
This figure relates to electrical energy output that is generated in the nuclear power plant, and does not include heat energy/steam generated.

Energy Pathways, Final Energy by Source



Biofuels are included among "liquids".

Energy-related CO_2 Emissions Drivers, 2010 to 2050



The Pillars of Decarbonization

Final energy efficiency

Energy intensity of GDP, MJ/\$2010

Decarbonization of electricity

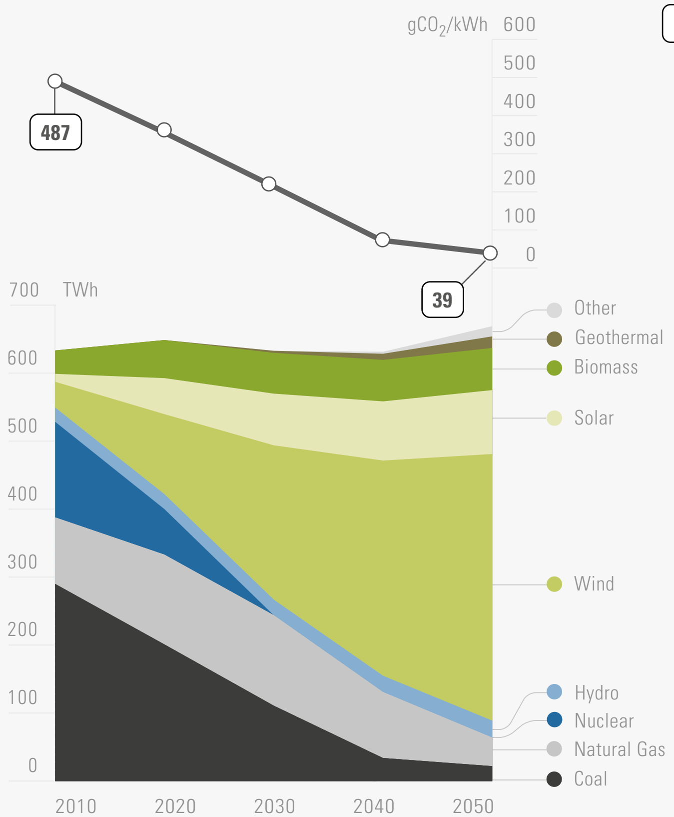
Electricity emissions intensity, gCO_2/kWh

Electrification of end-uses

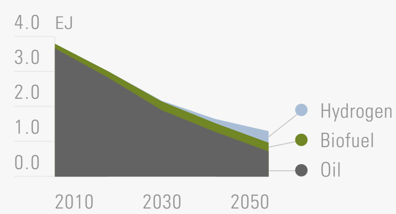
Share of electricity in total final energy, %

Energy Supply Pathways, by Resource

Carbon intensity



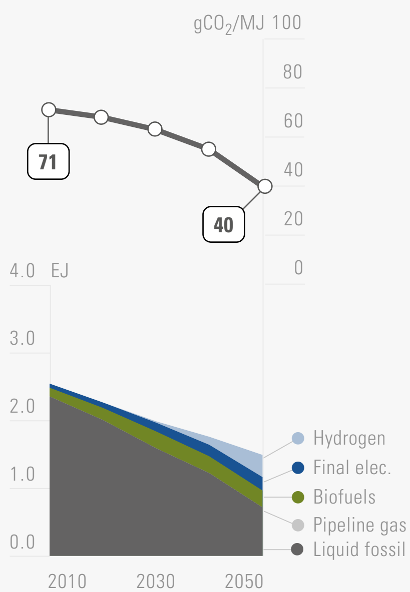
Electricity *(Data refers to domestic electricity generation)*



Liquid Fuels in final energy demand

Some of the data used for this figure was kindly provided by the authors of the original scenario study.

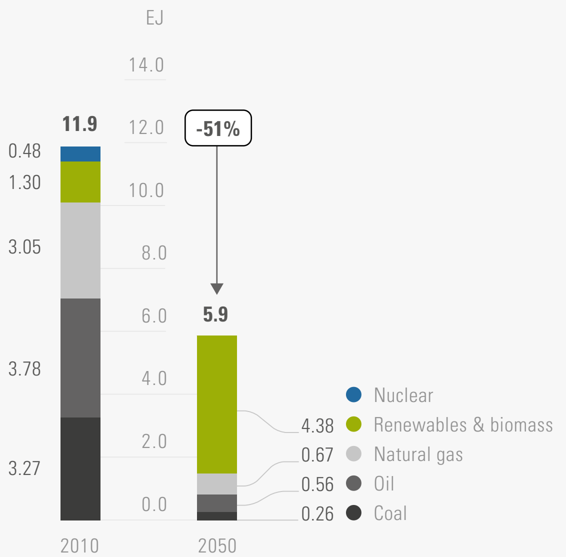
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Transportation *Some of the data used for this figure was kindly provided by the authors*

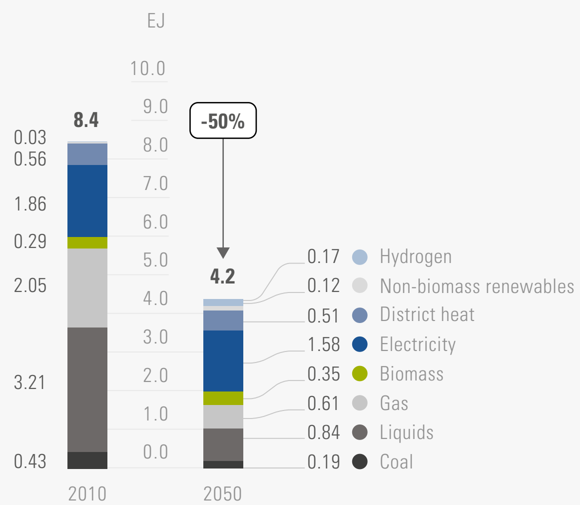
DE - 90% GHG Reduction

Energy Pathways, Primary Energy by Source



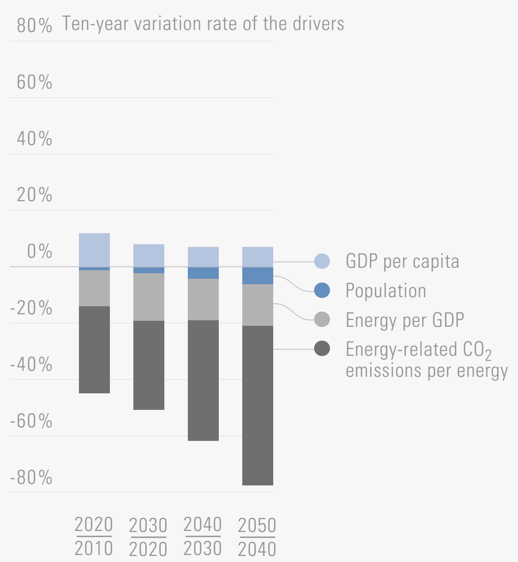
This figure relates to electrical energy output that is generated in the nuclear power plant, and does not include heat energy/steam generated.

Energy Pathways, Final Energy by Source

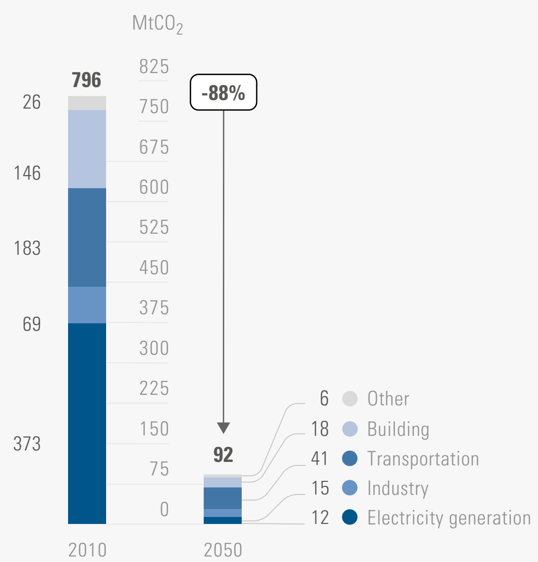


Biofuels are included among "liquids".

Energy-related CO_2 Emissions Drivers, 2010 to 2050



Energy-related CO_2 Emissions Pathway, by Sector

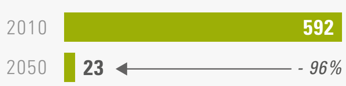


The Pillars of Decarbonization

Final energy efficiency

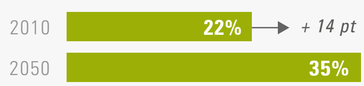
Energy intensity of GDP, MJ/$2010

Decarbonization of electricity



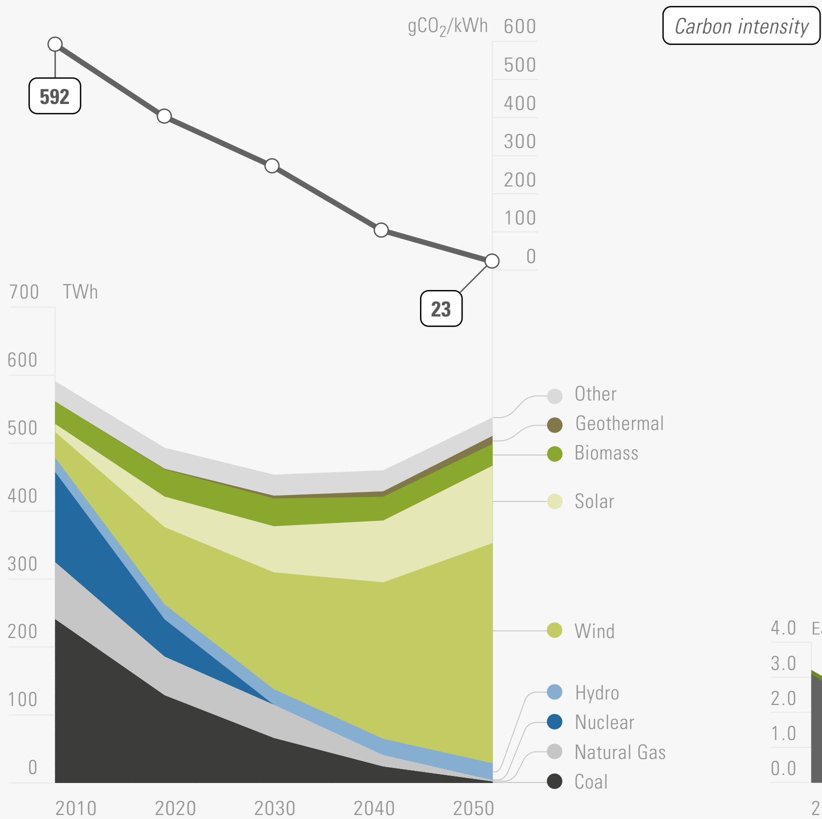
Electricity emissions intensity, gCO_2/kWh

Electrification of end-uses

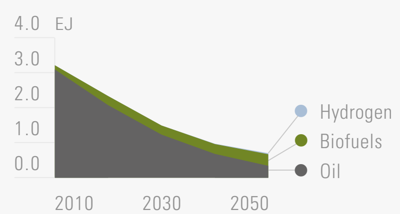


Share of electricity in total final energy, %

Energy Supply Pathways, by Resource

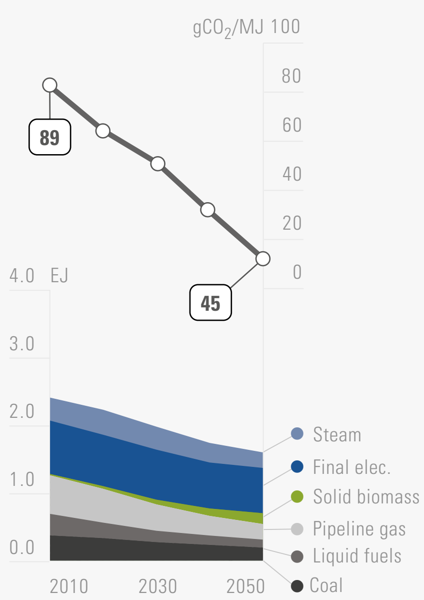


Electricity *(Data refers to domestic electricity generation)*

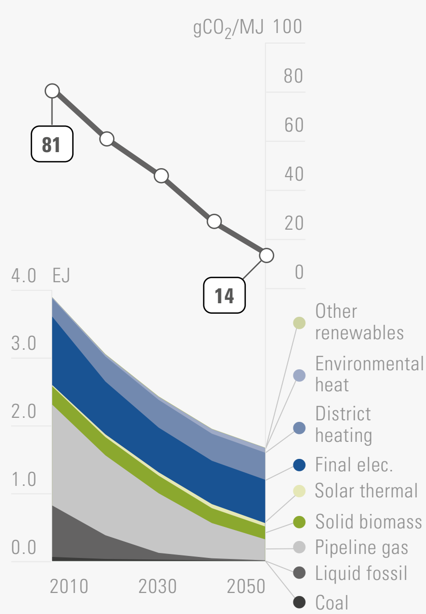


Liquid Fuels in final energy demand

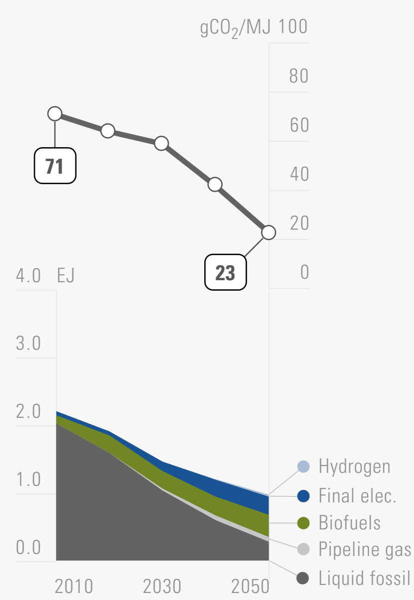
Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050



Industry



Buildings



Transportation