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Germany 2050
a greenhouse gas-neutral Country

For our Environment

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Contents

Germany in 2050: 1 Tonne of CO_{2eq} per Person per Year

Industrial nations share a huge responsibility for the global protection of the environment, as they have attained their welfare levels by the use of fossil energy. They have depleted resources all over the world and made intensive use of the land. In other words, they are the main cause of many of the environmental problems we are facing today and of global climate change.

Climate change is already under way and within the United Nations Framework Convention on Climate Change, members of the international community are working towards the prevention of serious disruptions to the climate system and its uncontrollable consequences. In order to achieve this, the global temperature must not increase by more than 2°C compared to pre-industrial temperatures.

The climate target that has been agreed upon internationally can only be met if all countries reduce their emissions of greenhouse gases (GHG), i. e. carbon dioxide (CO_2), methane and nitrous oxide as much as they can. For today's industrial nations such as Germany, this would mean that they must become almost greenhouse gas-neutral and reduce their emissions by 80-95 % compared to 1990[I].

A greenhouse gas-neutral Germany with per-capita emissions of just one tonne of CO_{2eq} in 2050 is technically achievable and implies a reduction of emissions by 95 % compared to 1990. In order to achieve complete GHG-neutrality, the last remaining tonne per capita could be offset by reduction measures outside Germany.

The following scenario[II] describes the possibility of a greenhouse gas-neutral Germany in 2050, but does not make any predictions about the probability of such a development. It is not a forecast. We demonstrate that, in principle, it is possible for Germany to lower its greenhouse gas emissions by 95 % compared to 1990 by 2050. Our premise is that in 2050, Germany will still be a highly developed industrial country that has maintained its standard of living, with consumption and behaviour patterns similar to today's. The study does not make predictions on future developments, but describes one of a range of possibilities for a greenhouse gas-neutral Germany. It becomes increasingly clear that a there is much scope for adapting energy systems to a GHG-neutral economy, and switching energy supplies to renewables is key. Germany's energy policy turnaround and the implementation of ambitious climate goals should be seen as an opportunity to shape our future in political and social terms, eyes firmly on the results to be achieved –running the economy and our lives on a practically completely greenhouse gas-neutral basis.

Many essential steps to bring about a greenhouse gas-neutral Germany are highly interlinked with developments in the EU and require an EU policy that propagates ambitious targets in greenhouse gas abatement for the entire Union, while also supporting national policies to achieve greenhouse gas neutrality.

Scenario Analysis for a greenhouse gas-neutral Germany by 2050

For several years, the German Federal Environment Agency (UBA) has been looking at the question how the climate target of a GHG-neutral Germany can be achieved. In a multi-disciplinary project launched by the agency, the first point of call was power generation because of its high emissions. It was shown in 2010 that power generation from 100 % renewable energy is possible.[1]

Even then it was understood that a renewable energy supply alone would not be enough to completely abolish greenhouse gas emissions. Other sectors of the economy would have to follow suit and undergo major changes, relying on low-GHG technology.

Consequently, the study now submitted, "Greenhouse gas-neutral Germany 2050", includes in its research all relevant emission sources that are described in the annual National Inventory Report (NIR) on emissions and removal of greenhouse gases. Alongside complete energy supply, including heating and transport, we also look at emissions from industry, waste disposal, agriculture and forestry[2] as well as changes in land use.[3] We develop a target scenario. The transformations that lead to the target and related economic considerations or the selection of appropriate policy instruments, however, are not part of our study.

The scenario analysis is based on the assumption that in 2050, Germany will still be an exporting industrial country with an average annual growth of 0.7 % of its gross domestic product.

A greenhouse gas-neutral Germany and its European and international Context

The study shows that future greenhouse gas neutrality in Germany is technically achievable. The scenario looks at the issue merely from a national perspective and does not include interaction with other countries. The study focuses on the national GHG reduction target of 95 %.Taking into account the mentioned assumptions, this should be achievable in Germany by technical means. Accordingly, calculations are based on GHG emissions generated in Germany. However, Germany is part of worldwide trade and international contracts and thus linked to other countries, which has an effect not only on the release of greenhouse gases, but also on the scope of action for climate protection.

Not considered within the framework of this study are the emissions emanating from goods imported from abroad. By the same token, emissions from exported goods were not subtracted. Relocation of production abroad (carbon leakage), which may well be a possibility, is also not taken into account. If, for example, a big industrial installation relocates to Portugal and supplies the German market from there, its GHG emissions are no longer recorded within the German, but the Portuguese inventory. German emissions will only nominally decline, because the products of the industrial installation will still be consumed in Germany, causing additional GHG emissions in Portugal.

This study was carried out on the assumption that industry sectors that are currently based in Germany would remain there. Taking current industrial structures as a starting point, technical adaptations to industrial processes are described. However, when looking at the economic and regulatory prerequisites for a GHG-neutral Germany, the problem of carbon leakage must be discussed. Some very noticeable effects of such relocation will be highlighted in this study (cf. Conclusion/Discussion, p. 27). ►

In principle, it would be possible to underpin technical measures and behavioural changes promoting GHG-neutrality in Germany by crediting emission abatement schemes abroad. As reducing emissions is a global challenge in the face of climate change, it can make more economic sense to fund emission reduction abroad than restricting efforts to national measures only. The achieved emission reductions can be credited to the funding state. Some such instruments have already been agreed upon as part of the Kyoto Protocol and are known as Joint Implementation (JI) and Clean Development Mechanism (CDM). However, the Kyoto Protocol emphasizes that reductions should be achieved on a country's national territory and only be complemented by emission abatement abroad. The continuation of volume-based flexible instruments also depends on the final shape the new international climate agreement will take. The negotiations on this should be completed in 2015.

As a member of the European Union, Germany's environmental policy is subject to regulations of the EU and the internal EU market. It is therefore important that efforts are made not only in Germany, but also within the community to generate a regulatory framework that encourages GHG-neutrality. The EU and all its members are committed to the 2°target. Further research should address the question how a GHG-neutral Europe could be achieved and how member states could benefit from synergy effects. Again, the global perspective, in particular the danger of carbon leakage from within to outside the EU, must be addressed.

The aim of this paper is to demonstrate that transforming Germany into a greenhouse gas-neutral society by the assumed target year 2050 is technologically feasible. Furthermore, our calculations are based on the assumption that technology for avoiding greenhouse gas generation and enhancing energy efficiency will have moved on from current pilot status to widespread use in 2050. Accordingly, this scenario presupposes significant technological progress and change. Our analysis is based on the current best available technology. We do not assume the emergence of new inventions, but further development of current technology.

For the purpose of this study, no changes in behaviour, such as the development and spread of different lifestyles or consumer patterns, will be assumed, although the German Federal Environment Agency might consider such changes desirable as well as necessary from a sustainability point of view. The focus of this study has been deliberately chosen to cover technical solutions that would allow climate targets to be met, while also taking into account ecological and health aspects. However, where there is a close link between technical solutions and the reduction of GHGs through behavioural changes, this will be discussed, among other things, in the Chapters Transport, Agriculture and Waste Disposal.

Furthermore, the study is based on the assumption[III] that Germany's population of 82.5 million in 2005 will have dropped by approximately 12.5 % by 2050. Thus, approximately 72.2 million would live in Germany in 2050. The assumption is based on a more or less constant birth rate of 1.4 children per woman, a moderate increase in life expectancy and an average net immigration of 150,000 people.[4]

Alongside climate protection, there are other are other environmental goals (guard rails) to enable sustainable development in Germany[III], such as:

- decrease in the use of resources by 50 % until 2020 and by 90 % until 2050,
- preservation of soil with a decrease of newly sealed soil to 30 hectares per day by 2020 and the long-term objective of no further sealing of soil.

These guard rails will not be discussed in detail because we are aware that they must be further investigated.

What we want to deliver is a description of solutions for the various sectors and point to alternative approaches by varying parameters and techniques or scenario philosophy.

Greenhouse Gas Emissions in 2050

The term greenhouse gas-neutral, as used in this study, can be understood literally, i. e. a certain product or process will not release greenhouse gases. In this publication, however, we use the term more loosely for very low, climate-compatible emissions. Accordingly, we set an emission limit for a GHG-neutral Germany 2050 – approximately 60 million tonnes of CO_2e, which is equivalent to a reduction of 95 % compared to 1990 levels. The present level of GHG emissions per head in Germany would be reduced from roughly 11 tonnes p. a. to approximately 1 tonne. These figures only include greenhouse gas emissions generated in Germany and recorded in the National Emissions Inventory. Indirect emissions caused by goods imported from other countries are not included. In order to achieve complete GHG-neutrality, the last remaining tonne per capita could be offset by reduction measures outside Germany.

Table 1 shows how the remaining emissions would be distributed over the range of emission sources. For practical reasons, we deviated from the NIR categories and assigned all industrial processes (Sector 2 in the Common Reporting Format (CRF) for international climate reporting), solvents and other product applications (CRF Sector 3) to one single category.

Figure 1 illustrates the decrease in greenhouse gases by 95 % compared to the baseline year 1990.

Table 1

Distribution of GHG emissions in the UBA THGND* 2050 Scenario

*** German abbreviation for greenhouse gas-neutral Germany**

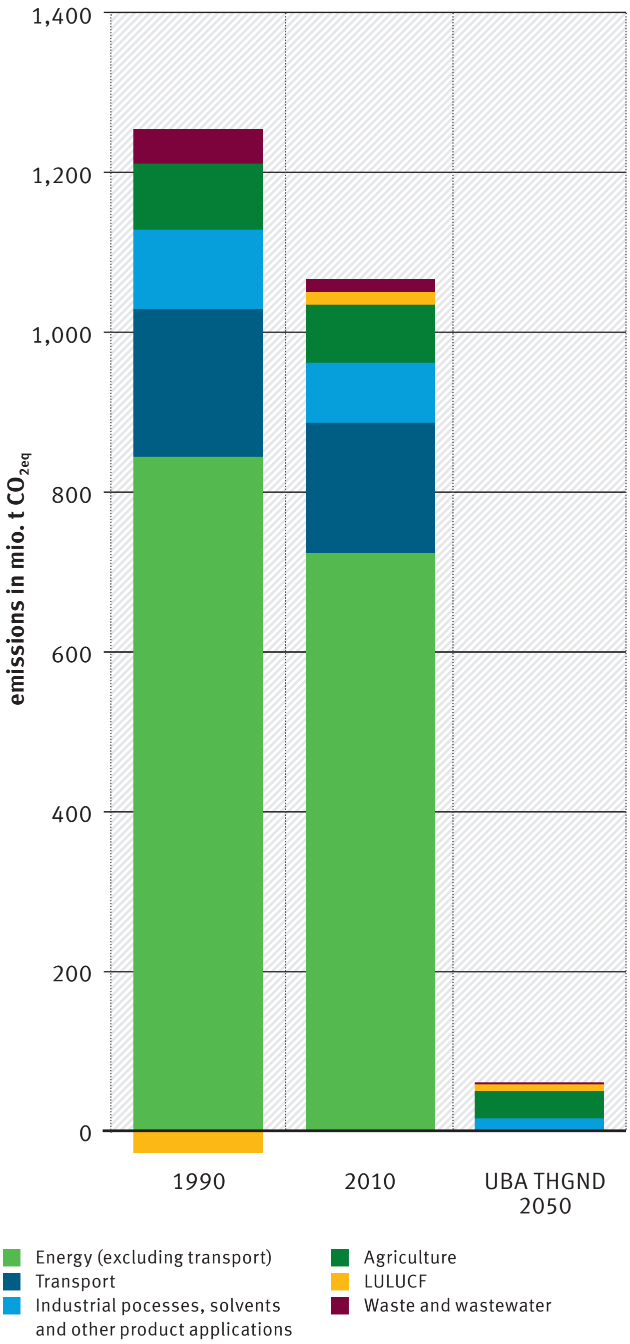
Emission Source	CO_{2eq} in million tonnes
Energy[I]	0
Industrial processes, solvents and other product applications	14
Agriculture	35
LULUCF[II]	8
Waste	3
Total	**60**

I including transport, processing industries etc.
II Land use, land use change and forestry.

Source: Umweltbundesamt

Figure 1:

Greenhouse gas emissions[I,II]



I 1990 and 2010 according to NIR.
II Transport, excluding the international share of shipping and aviation.

Source: Umweltbundesamt

Table 2

Total final energy use in 2050 in the UBA THGND 2050 Scenario

	Electricity in TWh	renewable methane in TWh	liquid renewable fuels in TWh
Private households	104.7	44.5	0
Commerce, trade and services (CTS)	90.3	62.4	18.6
Industry energy [I,II]	179.7	198.8	0
Transport	91.1	0	533.3
Total energy	**465.8**	**305.7**	**551.9**
		1,323.4	
Industry material		282	
Total energy and material		**1,605.4**	

I Excluding 15.1 TWh from internal production flows in the paper industry.
II Beyond the power requirements for the industrial processes themselves (see Section Industry), heating, lighting and IT power requirements are also included.

Source: Umweltbundesamt

Energy

Emissions from the energy sector will fall from 1,028 million tonnes of CO_{2eq} in 1990 to almost zero in 2050. This can be achieved by switching to renewable energy entirely while making extensive use of potential efficiency gains. As well as showing how electricity supply can be generated entirely from renewable sources[IV], we also explain how to ensure a complete supply of renewable fuel for heating and transport.

As a consequence, we expect to see a steep rise in electricity consumption to meet the needs of all sectors. The long-term final energy demand in a greenhouse gas-neutral Germany has been estimated to be approx. 466 TWh/a for power generation, 305 TWh/a for heating fuel, 552 TWh/a for motor fuel and 282 TWh/a for renewable inputs in the chemical industry (see Table 2 as well as Section Transport and Industry). Taking into account energy losses during the provision and distribution of final energy carriers, the net energy to be generated amounts to approximately 3,000 TWh/a.

For a sustainable energy supply, we are establishing the following guard rails:

- The German Federal Environment Agency does not deem it justifiable to grow crops as biomass for energy production, mainly because of competition for arable land and expected negative impacts on water, soil, biodiversity and wildlife.[5] The study stipulates that biomass used in 2050 comes from waste and residues (cascade use), which limits its contribution as an energy source to the entire system.
- Furthermore, the use of fossil energy carriers in CCS[V] will not be included because of the various environmental impacts and competing uses of geological formations.
- The use of nuclear energy is not an option in this study.

Instead, we assume that power is predominantly generated by wind and PV installations, depending on domestic and global capacity. Hydropower and geothermal installations contribute a smaller proportion to the general power supply.

The essential component of a completely renewable energy supply is the generation of hydrogen through the electrolysis of water, using electricity generated from renewables. Further catalytic processes can generate methane and other hydrocarbons from hydrogen. In the following the generation of hydrogen and methane based on electricity is called “power-to-gas” (PtG), the generation of liquid hydrocarbons “power-to-liquid” (PtL) respectively.

Depending on the available technology in the different sectors, the actual components of the final energy carrier mix may vary. The share of each of the three energy carriers in the final mix is limited by technical reasons. For better understanding, qualitative representation of a feasible region (solution space) and its composition is shown in Figure 2.

It is not possible to meet all energy demands with electricity from renewable sources alone. Mainly in the transport sector, and especially in aviation and shipping, electricity cannot always be used directly. However, in many other areas, such as communication technology or lighting, electricity is indispensable as a final energy carrier. In a renewable energy system, a large share of electricity as the final energy carrier seems realistic and we expect that in the long term there will be a shift towards electricity-based heat production and process heat generation. The growth of the hydrogen share in the energy carrier mix is also limited due to technological restraints, as hydrogen cannot be used on long-haul flights. At the other end of the solution space, a GHG-neutral energy supply without the use of hydrogen as energy carrier may be achievable, but a higher hydrogen share has an advantage over methane and other hydrocarbons because it can be produced with higher energy efficiency and no carbon source is required in its generation. However, more research and development in the field of hydrogen use is necessary. It would have exceeded our capacities to include a quantitative model of the use of hydrogen as fuel in our study. The use of hydrogen as fuel has not been included in our study, but some direct use of hydrogen fuel might well make sense. Further research and analysis is required.

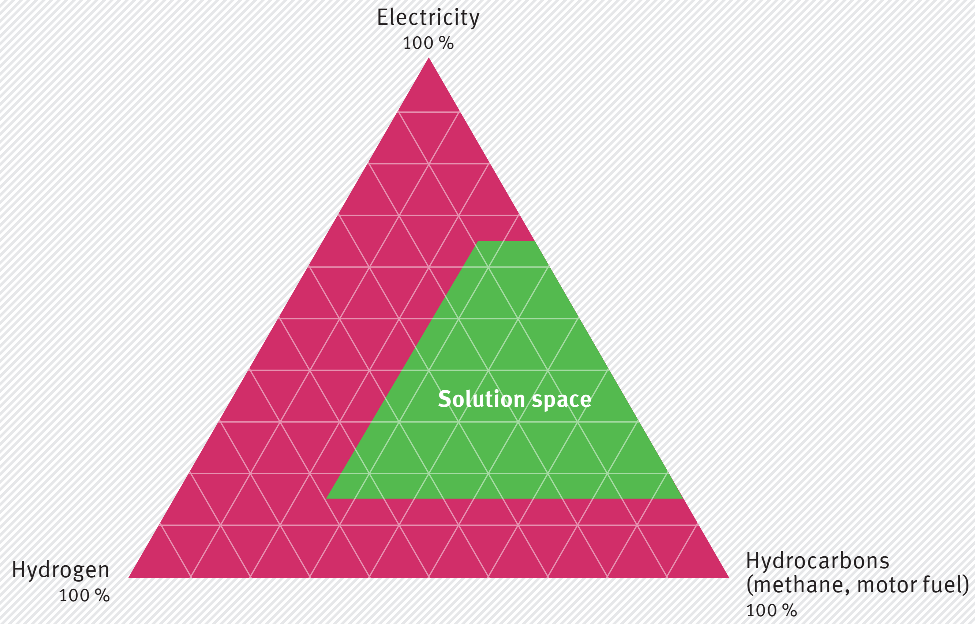
Hydrocarbon compounds generated from renewables are indispensible in a GHG-neutral energy system, whether as heating or motor fuel or in the chemical industry. They do require, however, a GHG-neutral source of carbon to sustain them.

What has to be taken into account when setting the proportions in the energy carrier mix are energy losses, efficiency, availability of resources and usability in various fields of application and further technological development.

The study demonstrates that final energy consumption can be halved by 2050 compared to 2010[VII] (see Figure 3). Private households in particular have a huge potential for reducing their consumption of heat and electricity, while in industry and the commerce, trade and services (CTS) sector, energy requirements could be reduced at least by half, according to our assumptions.

Figure 2:

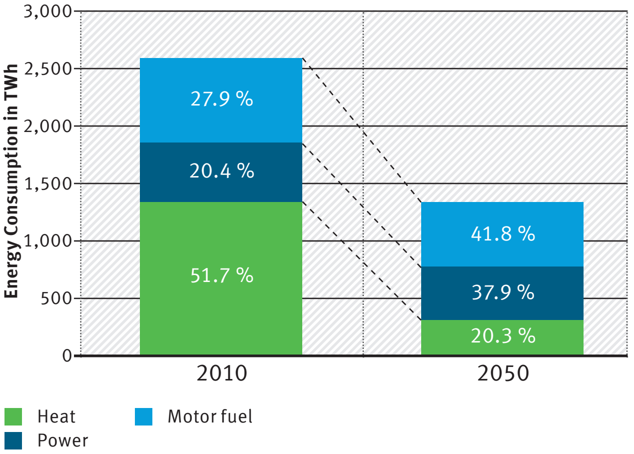
UBA THGND 2050 Scenario, qualitative representation of the final energy carrier mix in a triangle diagram.

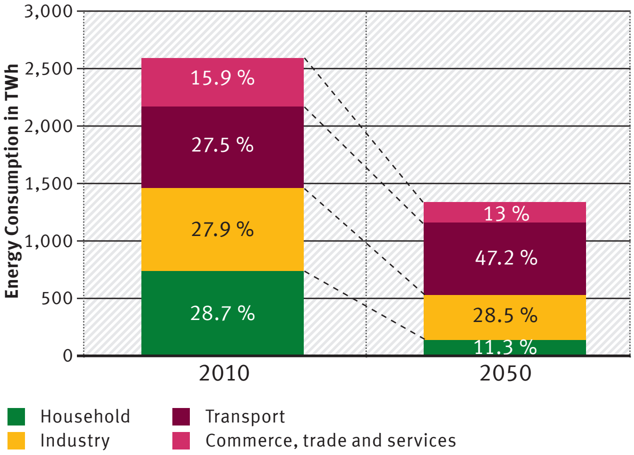


Source: Umweltbundesamt

Figure 3:

UBA THGND 2050 Scenario, comparison of final energy in 2010 and 2050 (left: sorted by purpose, right: sorted by sectors) I, II



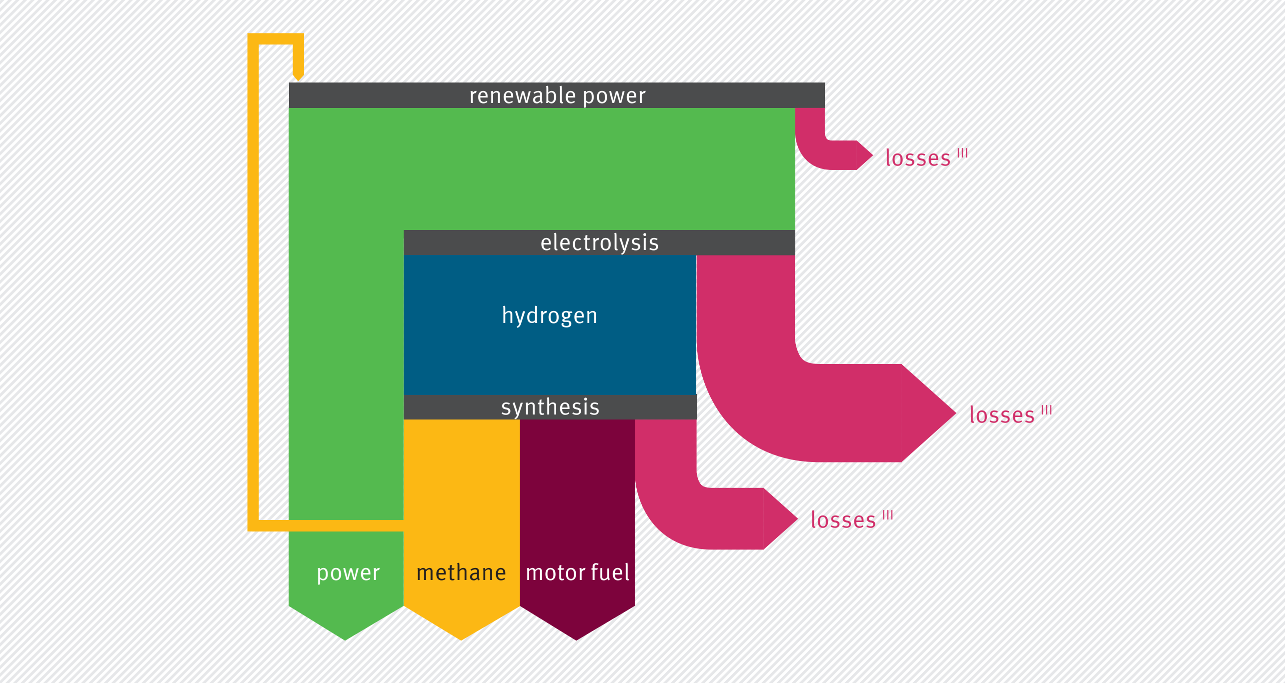


I In calculations for shipping transport, only domestic fuel stocks were included rather than the German share in international shipping. Similar rules apply to aviation calculations, which results in considerably lower figures. If the German share in international shipping and aviation is taken into account, final energy consumption will only be marginally reduced.
II Not including final energy in the shape of renewable methane as input in the chemical industry (using current calculation methods)

Final energy is predominantly provided by renewable power. The energy flow, as described above, is illustrated in qualitative terms in Figure 4 below. The figure does not show further losses during transfer when importing renewable gas and fuel. Hydrogen does not figure as a final energy carrier in our scenario (see explanations on hydrogen given above in the solution space context). To what extent hydrogen could be used should be investigated in further research projects, where the higher efficiency of hydrogen use should be weighed against the need to build a new infrastructure for this energy carrier.

Figure 4:

Qualitative representation of the energy flow in the UBA THGND 2050 Scenario I,II



I Including demand for renewable inputs for the chemical industry.
II Representations of energy flows are proportional to the energy flows required.
III Including line losses, losses from reconverting methane into power and losses from converting biomass into power

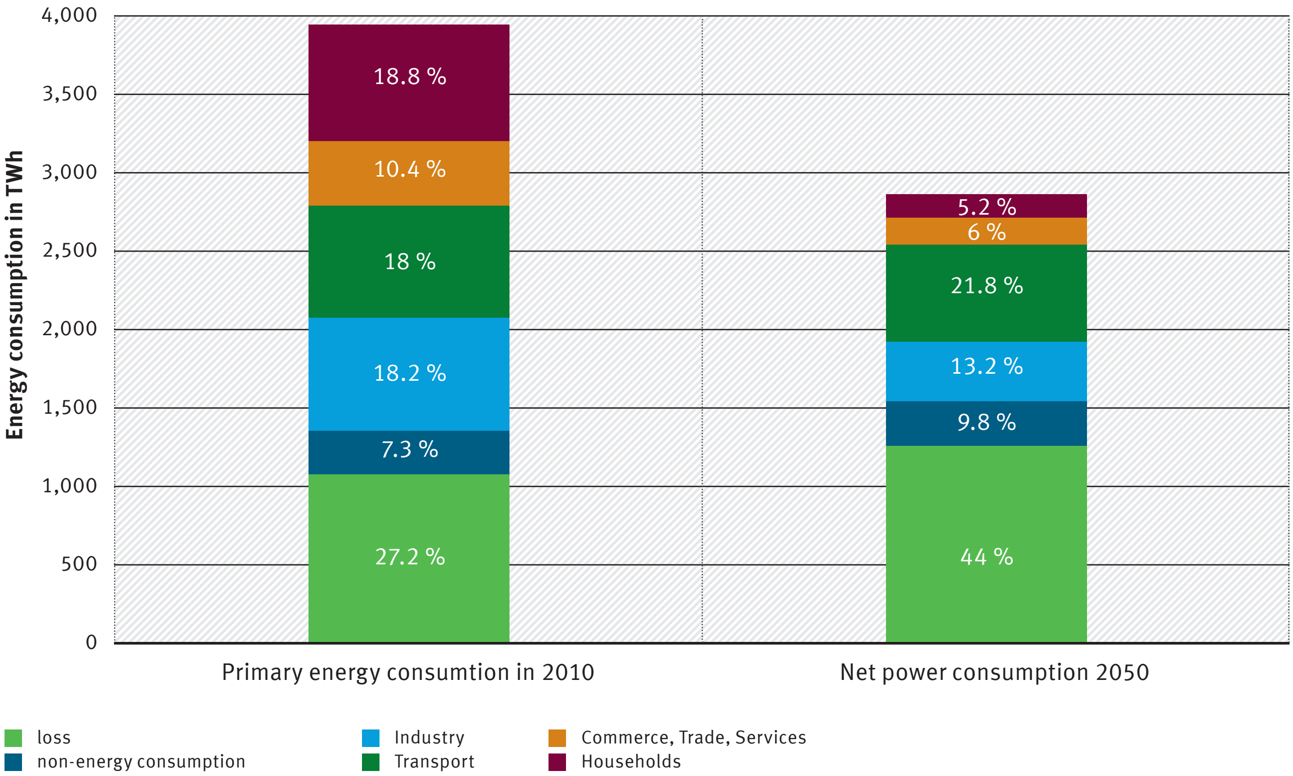
Source: Umweltbundesamt

We assume that in 2050, most of the power used as final energy (466 TWh p.a.) will be domestically generated. Germany has the necessary technical potential to generate the whole power demand (around 3,000 TWh). However, we assume that a good proportion of the renewable power will probably be generated outside Germany, by ecological reasons. And this will probably be more economical. Any transport of energy, whether power, methane or fuel, is associated with energy loss, which must be factored into the generating capacity. It is therefore realistic to assume that the quota of imported power will remain at today's levels.

Generally, it must be recognised that in a renewable energy system, the generation of fuel will lead to greater losses through conversion than in a fossil energy system. In 2010 statistics[VII] showed losses of 27 % within the existing energy system. On the assumptions made above, in a renewable energy system[VIII], such losses would reach approximately 44 %[IX] – bearing in mind, however, that we are comparing the conversion of finite fossil resources with renewable resources.

Figure 5:

Energy consumption according to sectors in 2010 and in the UBA THGND 2050 Scenario



Source: Umweltbundesamt

Transport

The transport sector could become GHG-neutral by 2050. Energy-related transport emissions can be reduced to approximately zero if the entire sector switches to renewable power. However, this would imply additional high demand for power and power-generated synthetic fuel. A drastic drop in final energy demand throughout the transport sector is therefore essential, despite the predicted rise in traffic volume.

In order to make the transport sector GHG-neutral, a whole gamut of measures must be implemented inside as well as outside the transport sector. Incentives for technological innovation must be complemented by underpinning measures encouraging traffic avoidance and modal shift, while fuel efficiency must be improved. A significant decrease in energy demand in the transport sector can only be achieved by a combination of these three approaches.

Traffic avoidance is the most straightforward route to reducing final energy demand, and avoiding the build-up of traffic does not necessarily mean reducing mobility. Finding new ways of bringing together work, shopping and leisure in our communities could help avoid unnecessary journeys, resulting in high mobility with less traffic.

Modal shift means switching from one mode of transport to a more sustainable mode. It is another essential tool to make the transport sector more energy-efficient. Motorised private traffic (MPT) could be reduced by using integrated transport schemes (cyclist/pedestrian/bus & rail/car-sharing) and freight traffic could be shifted from the roads to rail and waterways and reduce final energy demand considerably.

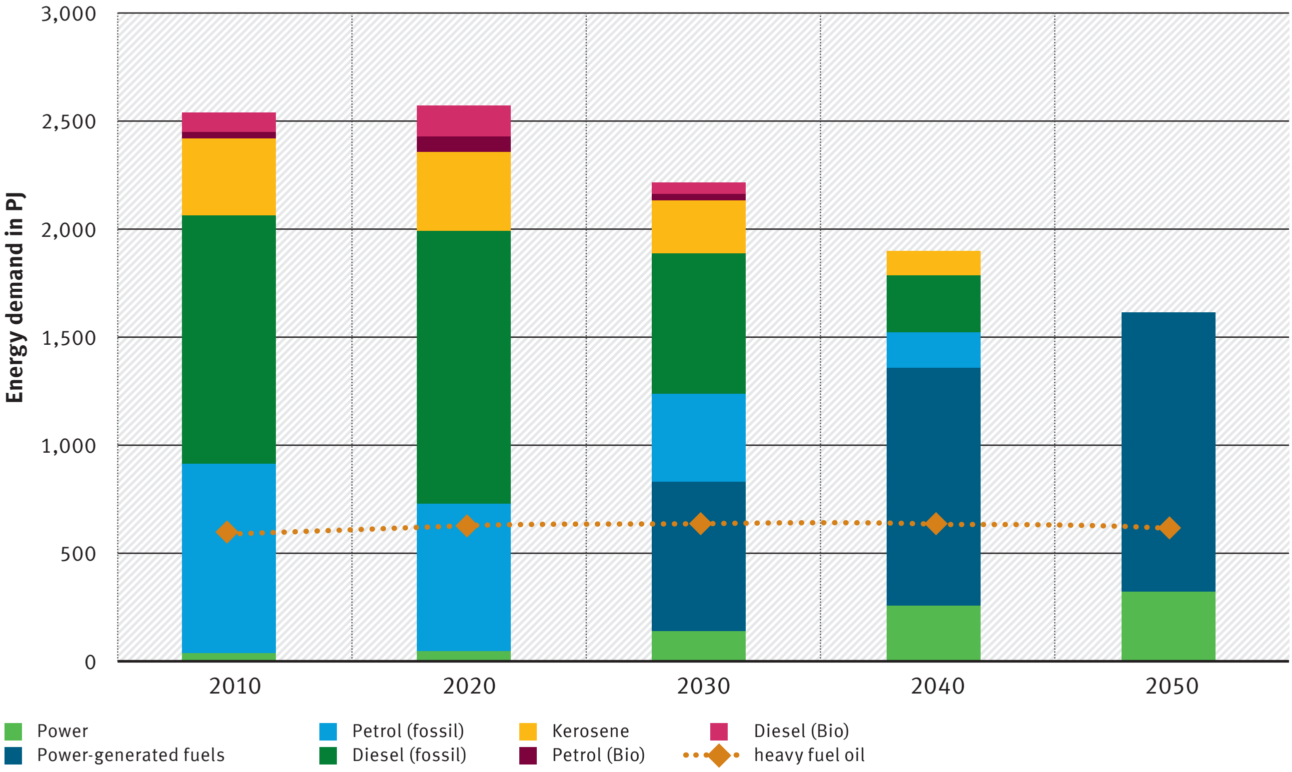
The third element is *efficiency improvement* in the vehicles used.

And there is a fourth component – the use of almost CO_2-free fuels.

Our scenario for a GHG-neutral transport sector assumes that its final energy demand will be 2.248 PJ or 624 TWh[X] (including shipping), which is approximately three quarters of the final energy demand extrapolated from current figures with no supporting

Figure 6:

Final energy demand classified by energy carriers in transport in the UBA THGND 2050 Scenario [12]



Source: Blanck et al. (2013)

measures implemented. This can be achieved not only by a slightly reduced traffic volume and modal shift, but above all by a higher proportion of electric vehicles on the roads.

In the scenario, the share of power-generated fuels is over 80 %. The power demand was calculated on the assumption that all fuels would be produced using power-to-liquid technology. It has to be emphasized, that this scenario is just one of several possible scenarios. The calculation of power demand in this scenario was chosen to show the upper limit and is for this reason an extreme point in the solution space. A comprehensive analysis is needed, whether and if so, to which extent power-generated fuels should be made available for the different energy carriers in the transport sector.

Only 20 % of power is used directly (excluding shipping, see Figure 6). This is because by 2050, although 57 % of all car journeys will use electricity, there are limitations on power use in heavy goods vehicles and the use of power-generated fuels in other modes of transport (aviation in particular) and a substantial proportion of vehicles will therefore continue to use conventional combustion engines.

Generating fuel from power, however, will entail conversion losses. These must be factored in when calculating the overall demand for power (net power generation) in the transport sector. From an energy efficiency perspective, the direct use of power in electric vehicles is highly preferable. However, this is offset by other advantages: power-generated fuels can be stored and used in those areas of the transport sector where the direct use of electricity is not an option.

The scenario with its focus on power-based fuels demonstrates that demand for electricity will rise although final energy demand will be declining. Sufficient availability of power from renewable sources is a prerequisite for a GHG-neutral transport sector.

Industry

Overall results show that a GHG-neutral and energy-efficient industry sector can be achieved in 2050, provided that the assumptions made for this study are taken into account. GHG emissions from energy sources can be avoided altogether by using renewable power, hydrogen and methane. Process-related emissions can also be significantly reduced to 14 million tonnes of CO_{2eq} by 2050. The largest emitters will be the cement industry with 6.3 million tonnes of CO_{2eq}, the lime industry with 3.5 million tonnes of CO_{2eq} and the glass industry with 0.8 million tonnes of CO_{2eq}.

In the scenario, it is assumed that the structure of the industry sector remains basically the same in 2050. The possibility of new industries developing is not part of this study.

The industries considered in this scenario were selected on the basis of their final energy consumption, as described in the UBA publication "*Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008* (Auswertung für das Jahr 2008) (Database for the assessment of energy efficiency measures 2008)."[6] The purpose of our selection was to include all industries that have a relevant impact on the final energy consumption of the sector.

As the internationally agreed NIR categories for industrial GHG emissions deviate from those reflecting the structure of the German industrial sector, data from other sources were used to determine energy consumption for the baseline year 2010. Accordingly, these energy and emission data are not compatible with the NIR. Because reliable industry data on energy consumtion in 1990 were not available, GHG reductions cannot be traced back to the usual reference year 1990 in this chapter.

In order to use renewably generated energy carriers, many industries have to make fundamental changes to their production processes and adapt technology in their installations. We therefore assume in this study that in primary steel production, basic oxygen steelmaking no longer takes place, whereas electric arc furnace steelmaking using scrap and directly reduced iron (DRI) will have been massively expanded. The energy carrier used in direct reduction will be methane, generated entirely from renewables, while electric arc furnaces and roller mill furnaces will be powered from renewable sources.

Although increases in production are expected for 2050, the study shows that the industry can reduce its final energy consumption to approximately 373 TWh/a, which is a reduction of 50 % compared to the baseline year 2010. In many industries, this is equivalent to a specific per-tonne reduction by a factor of 2 to 4. This is often achieved by optimising material and energy efficiency in the production process, using waste heat and highly efficient technology. The scenario assumes that many technological innovations will emerge over the coming four decades.

With a share of approximately 50 % (199 TWh/a) in the final energy mix of the industry sector, renewably produced methane will be the main energy carrier in 2050, followed by renewable power with a share of approximately 45 % (159 TWh/a) (See table 3). Accordingly, a significantly larger share of technologies should be powered by electricity. This way additional balancing power might become available which would increase options to balance demand and supply on the electricity market at any time.

In the chemical and steel industry sectors renewable hydrogen could also be used instead of renewable methane – both as an energy carrier as well as a reducing agent. The large scale application of hydrogen from renewable energy sources in the industry sector as a whole, however. would imply considerable changes in infrastructure (e.g. installing a pipeline system throughout Germany for hydrogen transport) plus new and further developments of process technologies in various industrial sectors. On the other hand, the use of methane from renewable energy sources would require a significantly lesser degree of technical and structural changes as an existing natural gas pipeline network could be used for transport purposes. Therefore, in our scenario we assumed the use of methane only for the industrial sector. This results in a conservative estimate for the electricity demand, as the generation of methane is more energy intensive than the generation of hydrogen.

In addition, the paper industry will generate 15 TWh/a from residual biomaterial (lignin etc) from the production process.

Furthermore, we assume that in the future, 282 TWh/a of renewably produced methane will be used as carbon source for synthetic processes by the chemical industry. This will abolish altogether process-related GHG emissions in many areas, such as ammonia production.

Table 3

Energy data for the manufacturing industry in the UBA THGND 2050 Scenario

	Total final energy demand in TWh/a	renewable methane in TWh/a	renewable power in TWh/a	use of own residual biogenic material flows in TWh/a	Changes in total final energy demand compared to 2010 in %
Steel industry [I]	104.7	66.7	38,0		-42.19
Non-ferrous metal industry	16.5	6.3	10,2		-35.29
Foundries	6.5	1	5,5		-49.31
Chemical industry [II]	81.0	up to 61.0	20,0		-55.49
Cement industry	15.4	11	4.4		-44.78
Glass industry	4.8	0	4.8		-81.31
Lime industry	4.7	4.3	0.4		-43.27
Paper and pulp industry	37.6	16.6	5.9	15.1	-48.15
Food industry	37.4	0	37.4		-32.97
Textile industry	4.3	1.8	2.5		-49.82
Other industries (not considered in the study) [III]	60.2	30.1	30.1		
Total	**373.1**	**198.8**	**159.2**[IV]	**15.1**	

Source: Umweltbundesamt

I We assume that it should be technically feasible to substitute a larger share of renewable methane by renewable hydrogen which can be generated in a less energy-consumming way.
II Methane and hydrogen are interchangeable in their use and are therefore added up to 61 TWh/a. The assumption for this sector is that at an annual reduction rate of 1.5 % for all energy carriers from now to 2050, 61 TWh of methane/hydrogen and 20 TWh of power will be required. In addition, 282 TWh of methane will be required as renewable resource or carbon source in chemical synthesis.
III For all other industries that are not included in this study, it was assumed that on average, their total final energy consumption would be reduced by 50 % compared to 2050 and the ratio of renewable methane to renewably generated power would be 50-50 in 2050.
IV without space heating and information and communications technology.

By 2050, the entire industry sector will see a reduction of process-related greenhouse gas emission to approximately 14 million tonnes p. a., which is a reduction of 75 % compared to 2010 (see table 4). Savings can be achieved by product switches – as in the cement industry – and the use of renewable raw materials in the chemical industry. Even with today's technology, it is possible to replace F-gases in many industrial areas, but the pace at which the switch is happening is unsatisfactory. If all technological measures available today were implemented by 2050, F-gas emissions could be reduced by 92 % to a minimum of 1,2 million tonnes of CO_{2eq}. Product and process-related measures, the use of solvents from renewable sources and optimised efficiency in the use of solvents could reduce emissions from NMVOCs to 0.765 million tonnes of CO_{2eq} by 2050. As regards emissions from the use of nitrous oxide, we assume that no longer using them as anaesthetics would automatically reduce emissions to 0.031 million tonnes of CO_{2eq}.

Table 4

Greenhouse gas emissions of the industry sector and the manufacturing sector in 2050 in the UBA THGND 2050 Scenario

	Greenhouse gas emissions(GHG-EM) in t CO_{2eq}/a		
	from energy supply	process-related	Change of overall emissions compared to 2010 in %
Steel industry[I]		162,000	-99.7
Non-ferrous metal industry		0	-100.0
Foundries		0	-100.0
Chemical industry[II]		500,000	-98.7
Cement industry[III]		6,330,000	-79.8
Glass industry		761,563	-94.1
Lime industry[IV]		3,530,000	-64.8
Paper and pulp industry		0	-100
Food industry		0	-100
Textile industry		0	-100
Production and use of fluorinated greenhouse gases			
Aluminium and magnesium industry		283,000	8,0
Production of fluorinated greenhouse gases		300,000	17.2
Refrigeration units-, air conditioning and heat pumps		28,000	-99.7
Production of insulation material		69,000	-89.7
Fire extinguishing agents		0	-100.0
Aerosols and solvents		100,000	-78.2
Semi-conductor production		109,000	-26.4
Electrical production equipment		65,000	-88.0
Other SF6 applications		250,000	-90.6
Emissions from solvents and other product uses			
Use of paint and varnish		255,310	-55.4
De-greasing and dry cleaning		47,785	-42.1
Production and use of chemical products		70,938	-42.4
Other applications of solvents		390,824	-51.4
Other industries (not considered in this study)	0		
Total	**0**	**13,783.420**[V]	

I CO_2 emissions are caused only by the burning of graphite electrodes in the electric arc furnace.
II Process-related GHG emissions arise only as by-products of adipic acid and nitric acid because in 2050 the only sources of carbon in use have been synthesised using renewable methane.
III Assuming that due to new production methods and products, raw material-related CO_2 emissions in cement production can be reduced by 80 %, approximately 2,500 kt CO_2 will arise from de-acidification of raw materials in 2050.
IV Raw material and hence process-related CO_2 emissions will be reduced by 30 % in 2050, due to decreased production.
V Including 31,000 tonnes of CO_{2eq} from nitrous oxide.

Source: Umweltbundesamt

Waste and Wastewater

Between 1990 and 2010, emissions in the waste management and wastewater sector have been considerably reduced and are set to decrease further by 2050 to 3 million tonnes of CO_{2eq}. This is a reduction of over 90 % compared to 1990.

More separation of recyclable material and the thermic or mechanical/biological treatment of domestic waste before it goes to landfill sites have reduced methane emissions from landfill sites considerably. Landfill emissions dropped from approximately 38 million tonnes of CO_{2eq} in 1990 to 9 million tonnes of CO_{2eq} in 2010. The trend is set to continue.

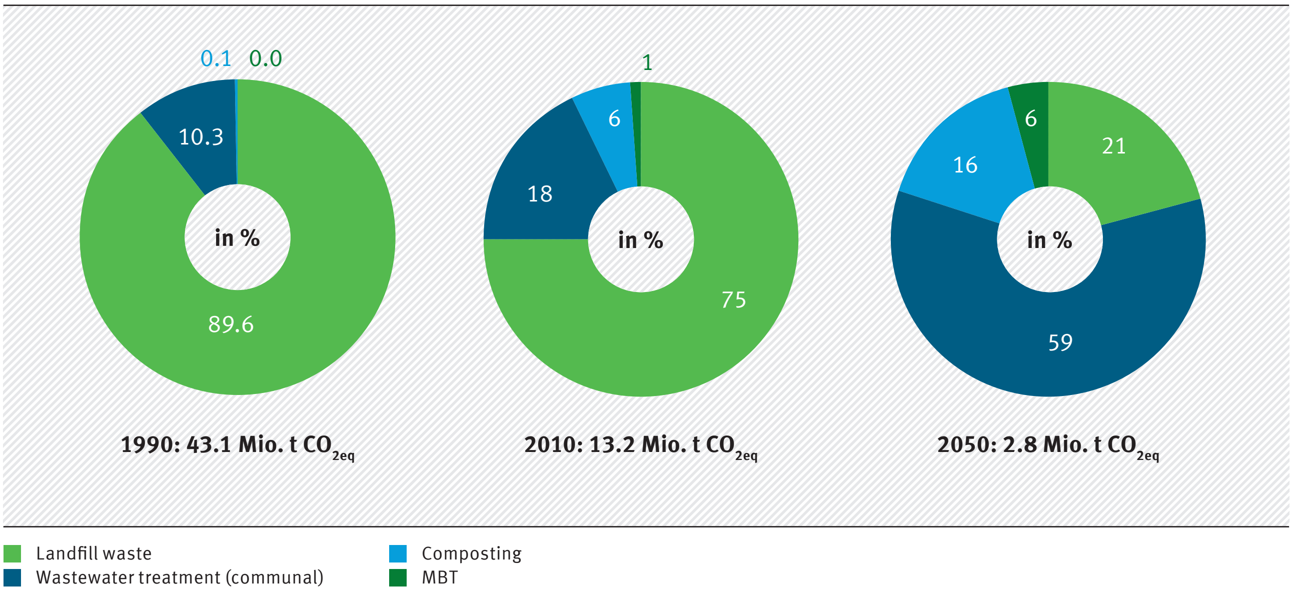
Due to the reduced volume of residual waste and the reduced formation of gas since waste treatment was introduced in 2005, the annual emissions of methane will have fallen to an estimated total of 56.000 tonnes (1.2 million tonnes of CO_{2eq}) in 2050. These estimates factor in a further reduction in landfill sites and the use of aerobic stabilisation methods. Not all methane from the landfills will be released into the atmosphere. We assume that landfill gas will be collected and undergo biological oxidation, which reduces methane emissions by a further 50 %. As a result, methane emissions from landfill sites are expected to decrease to 28,000 tonnes of methane in 2050, which would be a drop from 9 million tonnes of CO_{2eq} in 2010 to approximately 0.6 million tonnes of CO_{2eq} in 2050.

The share of methane from landfill sites, which was 90 % of the total of the waste sector, should thus drop from 90 % in 1990 to 20 % in 2050. Conversely, the share of emissions from waste water will rise from 10 % to 60 %, although in absolute figures, emissions will fall from 4.44 million tonnes of CO_{2eq} in 1990 to 1.65 million tonnes of CO_{2eq}.

The expansion of separate biowaste collection schemes will probably result in an over 30 % increase of waste to be treated in composting and fermenting installations. As greenhouse gas emissions from the running of such installations will fall, we assume

Figure 7:

Changes of greenhouse gas emissions in the waste and wastewater sector 1990-2050 in the UBA THGND 2050 Scenario, own graphics based on data from NIR 2012[7] and our own calculations



Source: Umweltbundesamt

that in spite of a rising volume in processing material, emissions from biowaste treatment will decline by one third by 2050.

We assume that waste undergoing mechanical-biological treatment (MBT) will remain constant between 2010 and 2050. By adding mechanical-biological stabilisation (MBS) equipment to existing MBT plants, a 40 % emission reduction to 100,000 tonnes of CO_{2eq} can be achieved. In addition, treatment residue material will decrease because MBS treatment will render a higher proportion of waste recyclable for heating or other purposes.

Furthermore, we assume that a large proportion of petrol-based products will have been discarded by 2050, which makes fossil carbon emissions from incinerators fall to negligible quantities.

By the same token, long-term emission reductions can also be expected in wastewater treatment. As the population will be increasingly connected to central waste water treatment and the rural proportion of the population is in decline, methane emissions from septic tanks will decrease to approximately 35,000 tonnes of CO_{2eq}.

According to our assumptions, nitrous oxide emissions from wastewater treatment will drop to just over 1.6 million tonnes of CO_{2eq}. This is only achievable if the German population drastically reduces its protein intake – i. e. eats less meat – which would be in line with the recommendations of the German Nutrition Society DGE. Under these assumptions, GHG emissions from wastewater treatment can be expected to fall to approximately 1.65 million tonnes of CO_{2eq} by 2050.

Agriculture

In the scenarios for the German agricultural sector, annual GHG emissions from this source group must be brought down to 35 million tonnes of CO_{2eq}. This could be achieved by combining technical efficiency measures, the modification of production methods and limitations on animal-rearing. Technical measures to protect the climate could drive down emissions emanating from the source group agriculture to 45 or 47 million tonnes of CO_{2eq} (a reduction of 20 – 25 %). In order to achieve this, efficiency levels in the use of nitrogen (N) have to be raised and residual fertilizers (manure, slurry) must be reused in biogas installations with leak-proof storage of fermenting residues[XI]. Further reductions of GHG emissions can only be achieved if animal farming is restricted – especially the rearing of ruminants because of their digestion-related methane emissions.

We have been considering two scenarios for the agricultural sector[XII]: one scenario is based on the continuation of existing agricultural structures (Scenario conv) and a scenario adopting the targets of the German sustainability strategy of 2002, in which it is assumed that ecological agriculture will have expanded to 20 % of the agricultural land.

In addition to the assumptions made in the introduction, the following assumptions and prerequisites apply for both scenarios:

- In 2050, no biomass will be grown in Germany for the sole purpose of energy use (see section energy). Only residual and waste products from crops and animal-rearing (such as manure, slurry, excess straw, grass and tree cuttings etc),
- Renewable resources continue to be used at the levels of 2007.
- In order to reduce GHG emissions from agricultural use, grassland areas must no longer be turned into arable land and most of the agriculturally used wetlands (approximately 6 % of existing agricultural land) must be taken out of production and returned into wetland. The remaining emissions from wetland are included in the LULUCF sector.
- Assumptions on the sealing of surfaces are laid out in the LULUCF chapter.

Table 5

Measures for GHG reduction in agriculture in the scenarios for 2050 [8]

	N_2O	CH_4	THG total	Reduction per step
	in million tonnes of CO_{2eq}			
Scenario 1: conventional agriculture (CONV)				
Baseline situation continued into 2050	37.2	22.6	59.8	
N-efficiency increased [I]	30.7	22.6	53.3	-6.5
80 % of residual fertilizers in biogas installations	29.1	18.5	47.6	-5.7
Dairy cattle replacement rate lowered (from 0.28 to 0.2), increased calf-rearing	29.0	17.9	46.9	-0.7
No suckler cows, sheep minus 50 %	28.9	14.6	43.5	-3.4
No rearing of bulls and heifers	28.5	12.7	41.2	-2.3
Dairy livestock minus 38 %	27.9	8.4	36.3	-4.9
Pig minus 55 %	27.2	7.8	35.0	-1.3
Scenario 2: organic farming on 20 % of agricultural land (Eco -20 %)				
a) Ogranic farming on 20% of the agricultural land				
Baseline situation continued into 2050	3.4	3.4	6.8	
N-efficiency increased (from 50 to 60 % efficiency)	3.4	3.4	6.8	0.0
80 % of residual manure in biogas installations	3.1	3.0	6.1	-0.7
No suckler cows, sheep minus 50 %	2.9	2.5	5.4	-0.7
No rearing of bulls and heifers	2.8	2.0	4.8	-0.6
b) … and conventional agriculture on 80 % of the agricultural land				
Baseline situation continued into 2050	31.0	18.7	49.7	
N-efficiency increased[I]	25.6	18.7	44.2	-5.4
80 % of residual manure in biogas installations	24.2	15.2	39.4	-4.8
Dairy cattle replacement rate lowered (from 0.28 to 0.2), increased calf-rearing	24.1	14.6	38.8	-0.6
No suckler cows, sheep minus 50 %	24.0	13.2	37.2	-1.5
No rearing of bulls and heifers	23.8	10.5	34.2	-3.0
Dairy livestock minus 38 %	23.5	7.0	30.5	-3.8
Pig livestock minus 11 %	23.3	6.9	30.2	-0.3

I Increased efficiency of N in mineral fertilizers from 80 % to 90 %; organic N from 26 % to 60 %; N-fixation through legumes from 20 % to 40 %.

Source: Osterburg et al (2013)

The two scenarios (1) and (2) – conventional vs. 20 % organic agriculture in Germany, differ in their productivity rate, with emissions remaining at a constant level of 35 million tonnes of CO_{2eq} per annum. The effects of international trade, however, are not taken into account.

In the CONV scenario, the cultivation has expanded despite a shrinkage of arable land, compared with baseline year 2007, as the share of cereal crops increases to over 70 %. A decline in livestock will reduce the need for growing cattle feed (maize for silage, clover and grass). Livestock will decline to 40 % of 2007 levels – especially cattle, pigs and sheep, while poultry and horses will remain at current levels. Due to an increase in performance of dairy cattle, the production of milk will not decline to the same extent as meat production.

Table 6

Production volumes for the baseline year 2007 and the scenarios for 2050[9]

	Baseline year	CONV	ECO -20 %		
	2007	2050	2050	(conv)	(öko)
	in million tonnes				
Cereal total	45.0	65.1	56.7	54.1	2.5
Wheat	23.0	41.6	34.6	33.6	0.9
Rye	3.0	3.4	3.0	2.3	0.7
Barley	11.4	12.4	11.8	11.8	0.0
Oats	0.8	0.8	0.6	0.3	0.4
Maize	4.1	4.5	4.5	4.4	0.1
Other cereal	2.2	2.4	2.1	1.8	0.4
Pulses	0.3	0.4	1.4	0.6	0.8
Oilseed rape and oil crops	5.3	6.4	6.3	6.0	0.3
Potatoes	11.0	11.2	10.5	9.1	1.5
Sugar beet	23.3	28.0	27.7	24.4	3.3
Vegetables	3.2	2.9	2.6	1.8	0.8
Fruit	1.3	1.2	1.2	0.9	0.3
Grape must	0.8	0.8	0.7	0.6	0.1
Milk	28.1	17.4	18.3	14.3	4.0
Meat total	6.4	2.9	4.8	4.6	0.2
Beef	1.1	0.3	0.3	0.3	0.1
Pork	4.0	1.4	3.3	3.2	0.1
Lamb/mutton	0.04	0.02	0.02	0.02	0.00
Poultry	1.0	1.1	1.0	0.9	0.0
Eggs	0.8	0.9	0.8	0.8	0.1

Source: Umweltbundesamt

In the ECO -20 % scenario, the use of agricultural land is similar to the CONV scenario. However, cattle and pig rearing does not have to be reduced as drastically in order to achieve the same reduction in GHG levels. On the organically maintained arable land, more rye, pulses and clover is grown, whereas wheat and oilseed rape crops are reduced. Rearing of pigs and poultry takes up only a small share in organic farming.

If animal farming is reduced, but meat consumption in Germany does not decrease in proportion, this would only reduce GHG emissions from German agriculture and suppliers from abroad would fill the gap, which would offset the climate protection effect on a global scale through livestock increases abroad. This relocation of emissions is known as carbon leakage. We therefore assume that changes in the use of agricultural land and supply of agricultural produce are underpinned by changes in eating habits. These assumptions are based on the recommendations of the German Society for Nutrition (DGE). In a nutshell, these recommendations champion a significant reduction of meat consumption and an increased use of vegetables. High meat consumption is associated with higher health risks, due to the high saturated fat and cholesterol content of meat and processing methods like smoking, frying, barbecuing and pickling. It should be mentioned, however, that diseases mentioned in a nutritional context may have multiple causes and nutrition is just one factor of many.

We also assume that food waste could be reduced by half.

The suggested changes to current consumer behaviour patterns and an end to the cultivation of energy biomass crops will result in a major decline of demand for agricultural products. The consumption of animal products in particular has a significant impact on cumulated land and energy demand and GHG emissions arising from feeding the German population.However, a reduced consumption of animal products and a reduction of food do not necessarily directly affect production in the German agricultural sector. In an open market economy, domestic consumption and nutritional habits have only a limited effect on agricultural production structures, which are largely shaped by the trade on international markets.

The other scenario where conventional agriculture is complemented by organic farming on 20 % of the agricultural land highlights some synergies that result in a less drastic reduction of agricultural production. The synergies result from the increased use of grassland for nitrogen-binding crops such as clover and other legumes. In the ECO -20 % scenario, no mineral fertilizer containing nitrogen is used on organic grassland, which reduces N2O emissions and enhances the nitrogen-binding properties of clover. The nitrogen bound in this way is then fed to cattle, turned into manure and re-used in organic farming. Thus, less agricultural land must be set aside for the cultivation of clover and other legume crops. Since livestock need not be reduced as drastically in the Eco -20 % scenario compared to the CONV scenario in order to meet GHG reduction targets, there is more scope to further reduce intensive land use and thus reduce production, by switching to organic farming.

However, according to the German Federal Environment Agency, the use of a higher proportion of agricultural land for organic farming would be desirable from an environmental perspective. Organic farming would mean that in contrast to conventional farming, no chemical, nitrogen-containing mineral fertilizers and chemical pesticides would be used. The German Federal Environment Agency would therefore favour a further expansion of organic farming beyond the 20 % target. The option of a complete switch to organic farming should be investigated – quantitatively as well as environmentally.

Land Use, Land Use Change and Forestry (LULUCF)

Given the assumptions described above, total emissions for the sector should amount to 8 million tonnes of CO_{2eq} in 2050 (see Table 7).

The LULUCF sector comprises all soil-bound carbon sources and sinks in woodland, fields, pastures, residential areas and wetlands. We are looking at the release of greenhouse gases in forestry, deforestation, tilling and binding atmospheric carbon dioxide through forestation and growth in existing woodland (sinks). The sector does not include the emissions described in the Agriculture section, such as nitrous oxide emissions from fertilizers or methane emissions from animal farming.

Table 7:

Greenhouse Gas Emissions in the UBA THGND 2050 Scenario for the LULUCF Sector

Category	Emissions in million tonnes of CO_{2eq}
Agricultural land	5,5 (adding lime: 1,5 and wetlands: 4)
Residential use	2,5
Peat extraction	0
Woodland	0
Total	8

Source: based on Osterburg et al (2013)

The forestry sector scenario does not allow for a 2050 scenario taking into account the complex ecological (natural and anthropogenic cycles, effects of climate change and conservation targets) and economic considerations (source of raw materials, services to the ecosystem).

However, looking at the WEHAM scenarios[11] (WaldEntwicklungs- und HolzAufkommensModellierung, woodland development and wood production models) of the Thünen Institute, which were developed to predict future timber harvesting rates, we would like to make the case for setting a long-term zero-net emissions target for the forestry sector. In other words, emission and sequestration should balance each other out and hover around zero. This can only be achieved by complying consistently with sustainable forestry management standards to ensure the timber harvesting rate does not exceed regrowth.

A savings potential of 37.1 million tonnes of CO_{2eq} has been identified by the Thünen Institute for Rural Studies for 1.05 million hectares of agriculturally used wetland. Of these, 633,000 hectares of grassland and 420,000 ha arable land could be set aside and restored.[12] Due to their proximity to human settlements and infrastructure or because of irreversibly damaged peat stocks, the remaining 180,000 hectares of arable land cannot be reconverted into wetland. We assume that these areas will become extensively cultured grassland and continue to release 4 million tonnes of CO_{2eq}. Together with an assumed 1.5 million tonnes of CO_2 emissions from the agricultural use of lime, total agricultural land emissions will amount to 5.5 million tonnes of CO_{2eq}. Since in 2050, no further land will be converted into arable land, there will be no emissions from the conversion of land from other use.

Further reductions of up to 2 million tonnes of CO_2 could be made by putting an end to peat extraction and widely substituting peat with alternative material such as coconut fibre or terra preta in horticulture. Banning peat extraction in Germany could lead to a simple export of emissions if not underpinned by a simultaneous import ban on peat.

No additional expansion of residential and traffic areas is anticipated for 2050. It is assumed that there will be a linear decline in land use from 80 hectares per day in 2007 to 30 hectares per day in 2020[XIII], reaching the zero target by 2050. Greenhouse gas emissions from settlement areas in 2010 are assumed to continue at the same levels, which would mean 2.5 million tonnes of CO_2 in 2050. The question whether green areas in settlements can act as carbon sinks cannot be answered because of a lack of data.

The sector land use, land use change and forestry has a very special role in comparison to other sectors, as it has the potential to act as a sink with its large natural carbon stores in the soil and in biomass that must be protected. Climate protection measures are slow to take effect and the sector is highly dependent on natural effects (such as a changing climate). In addition, action taken in the LULUCF sector will affect not only GHG emissions and GHG-binding, but also the supply of food and raw materials. Such action also happens within a global context and will not just have a national impact. These circumstances make it more difficult to assess future possibilities, potentials and developments regarding GHG emissions and GHG sinks in the LULUCF sector in general and the forestry sector in particular.

Reflections on the Interaction between Resource Productivity and Greenhouse Gas Avoidance

This study focuses on the question what a greenhouse-gas neutral Germany would look like in 2050. The German Federal Environment Agency is of the opinion that not only must GHG emissions be avoided, but the use of resources must be cut by 50 % until 2020 and by 90 % until 2050. However, resource productivity is a highly complex field and only a few examples are given within the framework of this study so that some of the interactions can be discussed here.

The use of natural resources results in various material and energy flows, consumption of water and use of land on the input side. On the output side, there is the use of ecosystem services, such the sink function of environmental media (water, soil, air) and the absorption of pollutants, including greenhouse gases. Improving resource management by a more economical and efficient use of abiotic raw materials helps directly to avoid or reduce GHG emissions. Energy-intensive products often consist of metals, are made from petroleum or industrial minerals or contain mineral raw materials such as pebbles, sand or rocks. Replacing such products by products from sustainable forestry is a valid contribution to resource protection. Such products are increasingly used in a cascade, i. e. when a product reaches the end of its lifetime it will be re-used in other products. Today, wood has become the quantitatively most significant renewable raw material in Germany's energy and material flows. It is used in many traditional ways for building, furniture, window frames, freight palettes, paper and cardboard. Traditional use could be revived and innovative products and methods for the use of wood developed, e.g. in the construction sector where supporting frames, cladding, boards, stairs and window frames could increasingly replace steel, concrete, plaster and plastic. In other words, wood should be increasingly used for high-grade purposes and then re-used wherever possible.

The expansion of photovoltaic (PV) power generation has a huge potential in terms of protecting the environment and resources, as it substitutes the use of fossil or biotic energy carriers. However, uncertainty about the availability of key resources for thin-layer photovoltaic panels, such as indium, tellurium, gallium or germanium could slow down development. They can only be extracted as by-products from mining mass metals like aluminium, zinc, lead and copper. Even small changes in demand can have a strong impact on price development. In addition, since these metals for technology are only used in very small quantities, there is a risk that they will be irretrievably lost, being dissipated in large material flows.

Although no fossil energy carriers are required to operate wind farms, raw materials are needed – as in PV modules – to build, erect and maintain wind turbines. Especially the rare earths neodym and dysprosium are among the most critical resources. As components for electromagnets in highly efficient and low-maintenance gearless wind turbines, they are sought after, but scarce. Wind farms have a high initial material input. In contrast to conventional power stations, 78 % of the total energy input for the Alpha Ventus offshore wind farm and its life cycle GHG emissions accumulate in earlier material production chains and during installation. However, within seven or nine months of operations, wind farms break even in energy production terms. Looking at the energy balance alone does not take into account the environmental impact and health risks involved in the extraction and preparation of raw materials in the countries of origin. In order to counter-balance the negative effect of mining and refining resources in the long term, wind turbines at the end of their operational life must be considered man-made reservoirs of raw material with high reuse and recycle potential.

Electromobility is expected to reduce emissions in the transport sector of the future. With batteries for intermediate storage, power from renewable sources can be used to fuel electric vehicles. It can be expected that a large proportion of future electric vehicles will rely on traction batteries based on lithium ion technology. These contain lithium or cobalt, depending on cathode types. According to Umbrella in 2011, geological reserves of lithium will cover demand for the next decades, whereas for cobalt, cumulated consumption will exceed known reserves (7.3 million tonnes) between 2040 and 2050. By the same token, supplies of neodym and dysprosium for permanent magnet motors could also become hard to obtain. The current pilot recycling schemes for these materials must therefore be extended and become the standard within the next decade.

Product design is another factor that has repercussions on the use of resources and waste generation as well as on the duration and versatility of the relevant products. Products that protect resources and avoid waste are characterised by sparing use of material and the use of secondary raw materials, while also taking into account the environmental rucksacks generated in preceding material processing chains. The lifespan of such products must be as long as possible. During their lifetime, they must be resource-efficient and at the end of their lifetime, they should be dismantable and their components reused or recycled. When looking at the protection of natural resources and the avoidance of waste, the whole life cycle of a product or scheme must be considered in order to achieve the best protection for the environment.

The industrial sector illustrates the links between climate protection and resource productivity in a striking manner: Approximately 50 % of today's industrial CO_2 emissions can be traced back to the production of five basic materials in industrial production – steel, cement, paper, plastic and aluminium. Any technical solution that reduces the use of these products will also contribute to climate protection. There are many ways of reducing the use of raw materials and energy along the value-added chain. From the German Federal Environment Agency's perspective, the long-term objective is to reduce per capita raw material use by a factor of 5 to 10 by 2050.

Conclusion/Discussion

A GHG-neutral Germany with annual per-capita emissions of 1 tonne of CO_{2eq} in 2050 is technically achievable and would be equivalent to a reduction of emissions by 95 %, compared to 1990. We are describing one possible option within a solution space.

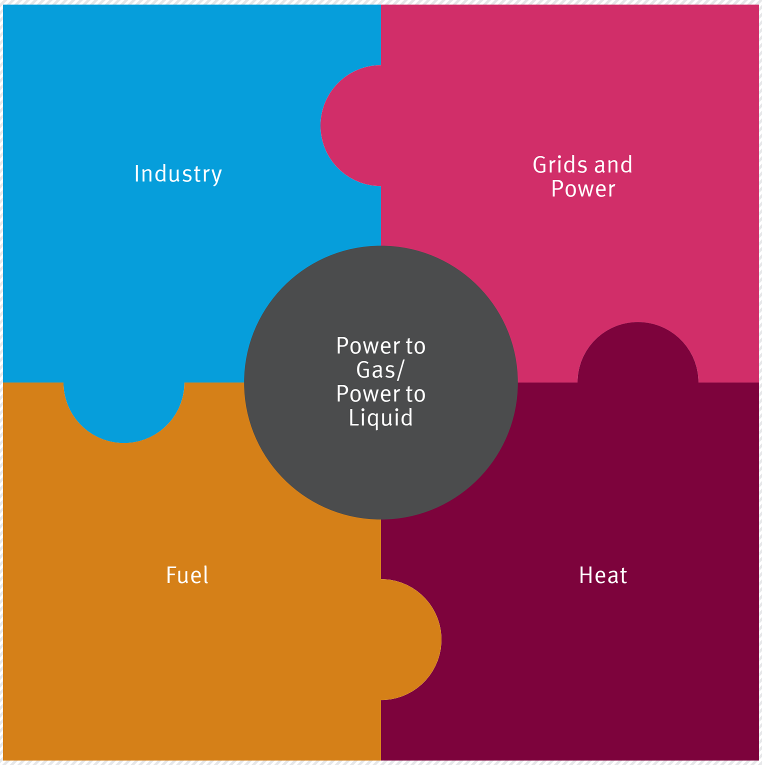
Not only the supply of power, but also of fuel can be ensured with renewable energy.

Our scenario is based on the assumption that all energy supplies have been switched to renewables and extensive use of efficiency gains is made. Thus, emissions from the energy sector would fall to near zero and other sectors could substantially reduce their emissions. In our scenario, a key element is the conversion of renewably generated power to hydrogen, methane and more complex hydrocarbons. This is the only way to meet the demand for fuel and raw materials in the industrial, transport and heating sector. The result is a major increase in power demand, far beyond what could be called excess power.

Although the technological potential to produce all power domestically is available, we assume that it could make sense for ecological and economical reasons to use this potential only partially and import the rest from abroad. PtG and PtL technology could also be used where the power is generated and fuel

Figure 8:

Overview of possible applications of Power to Gas/Power to Liquid technology in the UBA THGND 2050 Scenario



Source: Umweltbundesamt

rather than electricity would be imported. Assuming that the share of domestically generated power remains constant at 466 TWh, the share of primary energy imports[XIV] would also remain the same.

For a GHG-neutral Germany to become reality in 2050, innovations and further development of existing technology are indispensible. More research and development is needed in this field.

In our study, we were looking at the currently best available technology and assumed that applications that have so far only been tested on a small scale will become mainstream. We are aware that for our scenario to become reality, innovative technology must lead the way in the coming four decades. Power to gas and, above all, power to liquid technology are still in the very early stages of marketability. There are currently several pilot schemes operating in Germany, whereas Iceland has already its first commercially operating power to liquid installation.

Further analysis is needed to enlarge the solution space and identify suitable transformation routes. The reduction of high power consumption levels is one such research area – especially in the transport sector. We need to find out whether it would be possible to extend the use of hydrogen and power from renewables further and how more can be done to avoid and displace traffic.

Hydrogen is currently not yet used as an energy carrier for power generation and transport. Further research and development is urgently needed, as hydrogen offers many major advantages compared to methane and liquid fuels (fewer conversion losses). There are, however, also disadvantages (lower energy density).

Whether more power can be used directly in transport and whether gas such as methane or hydrogen might replace liquid fuel is the object of further research. The need for new infrastructure must be considered when looking at the use of hydrogen in more detail. Hydrogen would have the potential to reduce high conversion losses significantly, which would also reduce the demand for power[XV]. Several suggestions have been made and are currently discussed, including the installation of a grid of overhead contact wires along the motorways, complemented by a switch to hybrid heavy goods vehicles. The sesuggestions must be assessed regarding their effects on overall efficiency and cost.

We also assumed that in 2050, energy could be saved by avoiding and displacing traffic. Our assumptions are based on only moderate steps that are likely to be implemented from today's perspective. Further-reaching measures such as driving restrictions or significant changes in behaviour and lifestyle could lead to greater avoidance and displacements effects, but would require a changed mindset through public debate to be acceptable.

Our study does not include an economic cost-benefit analysis, as we are just taking a first step to indicate that a GHG-neutral Germany is technically achievable. We cannot predict what it will cost to reduce emissions by 95 % and what the economic benefit of such a transformation would be. Further research must show costs and benefits of such a development in detail. An economic and regulatory framework must be identified that would encourage the development and market diffusion of the necessary technological innovation.

However, there is always a high degree of uncertainty in long-term economic analysis. The cost of some techniques is as yet unknown, such as the cost of power to gas and power to liquid technology. Each step in the conversion from hydrogen to liquid fuel means higher energy losses in the process, increasing costs. Further research is needed here. The various fuel and motor types and their cost must be assessed (including learning curves) in order to obtain a complete picture. This has not been done within the scope of this study.

Our study does not give an answer to the question of which framework must be in place in order to introduce a certain technology. Looking at the use of methane as a carbon source for the chemical industry, it becomes clear that the oil industry will not switch to methane as long as oil is cheaper than renewable methane, which requires a major investment in technology. The necessary framework could be created by a targeted policy.

On the way of becoming greenhouse gas-neutral, Germany must take further sustainability criteria as a guideline and study in detail interdependencies between sustainability and resource productivity.

As mentioned in the introduction, the cultivation of biomass crops solely for energy generation has been excluded from our scenario for sustainability reasons. In contrast to other studies, we also do not include Carbon Capture and Storage (CCS), not least because storage capacities in Germany are limited. The use of nuclear energy is no longer an option in Germany. In our study, we were unable to draw a picture of the interactions between sustainability and resource productivity. Further research should focus on how climate protection objectives and resource efficiency can complement each other and possible clashes resolved.

The environmental impact of certain climate protection technologies must also be further investigated and evaluated.

A comprehensive assessment must take into account the displacement of emissions abroad, i.e. carbon leakage – a problem where we could do no more than scratch the surface in our study.

We only looked at domestic emissions – following the method for emissions reporting. In other words, those emissions caused abroad, but for which we are responsible because we import the goods produced, have not been included. Conversely, emissions from products manufactured in Germany that are then exported are included. There are balances for the relevant energy material flows, reflecting imports and exports. These are part of the integrated environmental and economic accounting system (SEEA) and life cycle analyses, but because of the complexity of assumptions that would have to be made for 2050, these could not be included (cf. A greenhouse gas-neutral Germany and its European and international Context, p. 5). There were, however, a few exceptions where there is an obvious connection. Thus, we assumed that there will be no imports of biofuel, as this would be associated with competition for farmland and emissions caused by indirect land use. Carbon leakage was also mentioned in the chapter on agricultural emissions. Although we have been mainly looking at technical solutions in this study, when turning to agriculture, we assume that in 2050, the population will have a healthier diet – e. g. eat less meat. This would lead to a significant decrease in livestock – the only way agricultural emissions could be reduced to satisfactory levels without massive leakage effects through meat imports.

We present this scenario in order to initiate a timely discussion on possible solution spaces for a GHG-neutral Germany and GHG-neutral industrial countries in general. Through research, development and demonstration, we will be able to create the prerequisites for political decision-making. Measures and policies that are required to bring about a GHG-neutral Germany can be discussed in time and then implemented.

Footnotes

I Within the framework of the Kyoto Protocol, Germany committed itself to lowering its greenhouse gas emissions between 2008 and 2012 by 21 % compared to 1990. In addition, the Federal German Government approved an energy concept in the autumn of 2010, which was amended in June 2011. It provides for a higher proportion of renewables in energy generation while exiting nuclear energy. Furthermore, there are more detailed targets for lowering energy consumption in a range of sectors. Additionally, concrete targets for the reduction of greenhouse gas emissions compared to 1990 have been set: 40 % by 2020, 55 % by 2030, 70 % by 2040 and 80 to 95 % by 2050.

II The figures follow variant 1 of the 11th coordinated population projection published by the Federal Statistical office in 2006.

III See also further targets in the sustainability strategy paper of the German Government „Unsere Strategie für eine nachhaltige Entwicklung“ (Our strategy for sustainable development) of 2002.

IV Cf. Study by the German Federal Environment Agency Energy Target 2050: 100 % Power from renewable Sources.

V Carbon Capture and Storage

VI The calculated proportion is 51 %. Please note that for 2050, international aviation and shipping has been included, which is not currently the case.

VII Referring to primary energy.

VIII Referring to net power supply.

IX An efficiency ratio of 50 % was assumed for the supply of motor fuel.

X of which 91.1 TWh for electromobility.

XI fermentation residues can be used as fertilizers.

XII defined in line with UNFCCC source group 4 – agriculture.

XIII Cf. further sustainability objectives defined by the German Government Unsere Strategie für eine nachhaltige Entwicklung (our strategy for sustainable development) of 2002.

XIV In our study, net power generation in 2050 equals primary energy.

XV net power demand.

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