CLIMATE CHANGE
07/2014

Germany in 2050 – a greenhouse gas-neutral country

Für Mensch & Umwelt

Umwelt Bundesamt

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Imprint

Publisher:
Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
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Fax: +49 340-2103-2285
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Internet: www.umweltbundesamt.de

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Study performed by:
Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau

Study completed in:
April 2014

Edited by:
Section I.2.2 Energy Strategies and Scenarios
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Translation by:
Carol Finch, Renate FitzRoy, Kay McBurney, Ros Mendy and
Kim Sanderson

Proofreading:
Marion Greenway, Lynda Hepburn

Publication as pdf:
http://www.umweltbundesamt.de/publikationen/germany-in-2050-a-greenhouse-gas-neutral-country

ISSN 1862-4359

Dessau-Roßlau, April 2014

Foreword

The Federal Environment Agency (UBA) has for several years been researching appropriate, effective ways of implementing the targets set by the international community on stemming climate change in a highly industrialised and developed nation like Germany. The findings of the Intergovernmental Panel on Climate Change (IPCC) show beyond doubt that industrial nations in particular will need to work towards ambitious climate targets by the middle of this century if they are to fulfil their global responsibility. This provides an opportunity for Germany to take on a trailblazing role, setting the bar high and working towards the 'greenhouse gas-neutral country' climate target.

The UBA has launched an interdisciplinary process in order to discover how a greenhouse gas-neutral Germany might look in 2050. The process began with an investigation of electricity generation, because this involves high emissions; the UBA showed that it is in fact possible to generate 100% of our electricity from renewable sources.

From the outset, it was clear that a sustainable supply of energy from renewables would not on its own be sufficient to avoid almost all greenhouse gas (GHG) emissions. Other sectors of the economy would also need to make major changes and increase their use of low-GHG technologies.

The present study, 'Greenhouse gas-neutral Germany 2050' therefore investigates all the relevant sources of emissions that are described in the German National Inventory Report (NIR) on greenhouse gases. Thus besides energy supply — including the heat and transport sectors — we also consider greenhouse gas emissions from industry, waste management, agriculture and forestry and changes in land use. We then present a target scenario. Our study does not cover the routes towards this transformation, any associated economic assessments, or the selection of suitable policy instruments.

Instead, we aim to demonstrate that a greenhouse gas-neutral Germany can largely be achieved using technical measures. We hope to provoke discussion about our sustainable, greenhouse gas-neutral future. Further study will be required, for example into the extent to which lifestyle changes can help make our greenhouse gas-neutral target easier to achieve.

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Abbreviations

AEL	Alkaline electrolysis
AL	Agricultural Land
AMI	Agrarmarkt Informations-Gesellschaft mbH (Agricultural Market Information Company), Bonn
BAU	Business as Usual
BBD	Best Before Date
BDI	Bundesverband der Deutschen Industrie (Federation of German Industries)
BMELV	Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz (Federal Ministry for Food, Agriculture and Consumer Protection)
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety)
BMVBS	Bundesministerium für Verkehr, Bau und Stadtentwicklung (Federal Ministry of Transport, Building and Urban Development)
bn	Billion
BMWi	Bundesministerium für Wirtschaft (Federal Ministry for Economic Affairs and Energy)
BÖLW	Bund ökologische Lebensmittelwirtschaft (Organic Food Production Alliance)
BtL	Biomass to liquid
BVE	Bundesvereinigung der Deutschen Ernährungsindustrie (Federation of German Food and Drink Industries)
BV Glas	Bundesverband Glasindustrie (Federal Association of the German Glass Industry)
BV Kalk	Bundesverband Kalkindustrie (German Lime Association)
CCS	Carbon Capture and Storage
CCGT	Combined Cycle Gas Turbine
CDM	Clean Development Mechanism (in line with Kyoto Protocol)
CEPI	Confederation of European Paper Industries
CGU	Cogeneration Unit
CH_4	Methane
CHP	Cogeneration of Heat and Power, Combined Heat and Power
CIGS	Copper indium gallium selenide
CLE	Current Legislation (scenario)
CO_2	Carbon Dioxide
CO_{2eq}	CO_2 Equivalent (global warming potential, with $CO_2 = 1$, $CH_4 = 21$, $N_2O = 310$)
COGAS	Combined gas and steam
CONV	conventional
CORINAIR	Coordination of Information on the Environment - Air
CRF	Common Reporting Format

CSP	Concentrating Solar-Thermal Power Plants
CdTe	Cadmium telluride
cf.	compare
CTS	Commerce, Trade, Services
DGE	Deutsche Gesellschaft für Ernährung (German Nutrition Society)
DLM	Digital landscape model
DRI	Directly Reduced Iron
dt	dry tonnes
DVGW	Deutscher Verein des Gas- und Wasserfaches e.V. (German Technical and Scientific Association for Gas and Water)
DWD	Deutscher Wetterdienst (German Meteorological Service)
EAFRD	European Agricultural Fund for Rural Development
EBV	Erdölbevorratungsverband (German National Petroleum Stockpiling Agency)
EC	European Community
ECO	organic
ed.	Editor
EEA	European Environment Agency
EEG	Erneuerbare Energien-Gesetz (Renewable Energy Sources Act)
EEZ	Exclusive Economic Zone
E-factor	Emission Factor
EJ	Exajoule (1018 joules)
El	Electrical
EM	Emissions
EREV	Extended-range electric vehicle
EST	Eisen-, Stahl- und Temperguss (iron, steel and malleable steel casting)
EU	European Union
EWF	Emission weighting factor
FAO	Food and Agriculture Organization (of the United Nations)
FADN	Farm Accountancy Data Network
FAPRI	Food and Agricultural Policy Research Institute
FEC	Final Energy Consumption
F-gas	Fluorinated Greenhouse Gas (HFCs, PFCs and SF_6)
FNR	Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources)
FT	Freight Transport
GEMIS	Globales Emissions-Modell Integrierter Systeme (Global Emission Model for Integrated Systems)

GHG	Greenhouse Gas (as defined in the Kyoto Protocol)
GJ	Gigajoule (10^9 Joule)
GW	Gigawatt (10^9 W)
GWh	Gigawatt Hour (10^9 Wh)
GWP	Global Warming Potential
H-Gas	High calorific gas
ha	Hectare
HBI	Hot Briquetted Iron
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HGV	Heavy Goods Vehicle
hl	Hectolitre
HTC	Hydrothermal Carbonisation
HTE	High-Temperature Electrolysis
HWP	Harvested Wood Products
IAASTD	International Assessment of Agricultural Knowledge, Science and Technology for Development (aka World Agricultural Council)
ICAO	International Civil Aviation Organization
ICT	Information and communications technology
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ITO	Indium tin oxide
JI	Joint Implementation (in line with Kyoto protocol)
JRC	Joint Research Centre
K	Potassium
K2O	Potassium oxide
kg	Kilogramme
kPa	Kilopascal
kt	Kilotonne
kWh	Kilowatt Hour (1 kWh = 1000 Wh)
L-Gas	Low calorific gas
LCV	Light Commercial Vehicle
LNG	Liquified Natural Gas
LR	Institut für Ländliche Räume (Institute of Rural Studies) of the Thünen Institute
LSU	Livestock Unit
LULUCF	Land Use, Land Use Change and Forestry

m	Million
MBT	Mechanical Biological (Waste) Treatment
MBS	Mechanical Biological Stabilisation Plant
MFR	Maximum Feasible Reduction (scenario)
MID	Mobilität in Deutschland (Mobility in Germany)
MIV	Milchindustrie-Verband (Association of the German Dairy Industry)
MJ	Megajoule (10^6 joule)
MPa	Megapascal (unit of pressure)
MPT	Motorised Private Transport
MRI	Max Rubner Institute
Mt	Megatonne (10^6 tonne)
MW	Megawatt (10^6 W)
MWh	Megawatt Hour (1 MWh = 1000 kWh = 10^6 Wh)
M&C	Measurement and control
N	Nitrogen
NEDC	New European Driving Cycle
NFM	Non-Ferrous Metal
NFMC	Non-Ferrous Metal Casting
NH3	Ammonia
NIR	National Inventory Report
Nm^3	Normal Cubic Metre
NMPT	Non-Motorised Private Transport
NMVOC	Non Methane Volatile Organic Compound
N_2O	Nitrogen Dioxide (laughing gas)
NRW	North Rhine-Westphalia
NTC	Net Transfer Capacity
NVS	Nationale Verzehrsstudie (National Nutrition Survey, Germany)
OECD	Organisation for Economic Co-operation and Development
OPTUM	Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen (Optimising the environmental benefit of electric vehicles)
ORC	Organic Rankine Cycle – thermodynamic cycle that uses organic media as an alternative to water – steam cycle, in particular for the use of low-temperature waste heat
p.a.	Per annum
P	Phosphorus
p	persons
PEM electrolysis	Polymer Electrolyte Membrane (or Proton Exchange Membrane) electrolysis

PFC	Perfluorocarbon
PGC	Process gas chromatograph
PHEV	Plug-in hybrid electric vehicle
PJ	Petajoule (10^{15} joules)
Pkm	Passenger-Kilometre
PO	Propylene Oxide
ProBas	Prozessorientierte Basisdaten für Umweltmanagement-Instrumente (process-oriented base data for environment management tools)
PT	Passenger tranport
PtG	Power-to-Gas
PtL	Power-to-Liquid
QSL	Queneau-Schuhmann-Lurgi (lead reduction process)
RAUMIS	Regional differenziertes Agrar- und Umweltinformationssystem für Deutschland (regionalised agricultural and environmental information system in Germany)
RMC	Raw material consumption
RWI	Rheinisch-Westfälisches Institut für Wirtschaftsforschung (Rhine-Westphalia Institute for Economic Research)
SF_6	Sulphur Hexafluoride
s.l.	Sine loco (without place of publication)
SNAP	Selected Nomenclature for Air Pollution
t	Tonne
TDI	Toluene Diisocyanate
Th	Thermic
Tkm	Tonne-kilometre
TREMOD	Transport Emission Model
TRL	Transport Research Laboratory
TWh	Terawatt Hour (10^{12} Wh)
TYNDP	Ten-Year Network Development Plan
UBA	Umweltbundesamt (German Federal Environment Agency)
ULCOS	Ultra Low CO_2 Steelmaking (research consortium)
UNFCCC	United Nations Framework Convention on Climate Change
VDP	Verband Deutscher Papierfabriken (German Pulp and Paper Association)
VdZ	Verein der Zucker Industrie (German Sugar Industry Association)
VEBU	Vegetarierbund Deutschland (Vegetarian Alliance Germany)
VOC	Volatile Organic Compound
Vol.%	Percent by volume

vTI	Thünen-Institute
WEHAM	WaldEntwicklungs- und HolzAufkommensModellierung (forest development and timber resource modelling)
WWF	World Wide Fund For Nature
η	Efficiency Ratio

A. Introduction

Background

Industrial nations bear much of the burden of responsibility for global environmental protection, as they have attained their current level of prosperity through the use of fossil energy sources. They have exploited the Earth's resources and used land intensively. Thus these nations have been the main contributors to the majority of today's environmental problems, such as the rise in global temperatures.

Climate change is already under way. Through the United Nations Framework Convention on Climate Change, the international community has set itself the objective of preventing dangerous disruption of the climate system and its uncontrollable consequences. In order to achieve this, it must prevent the global average temperature from rising by more than 2°C compared to the preindustrial era.

This joint climate protection objective can only be achieved if all nations restrict their emissions of greenhouse gases (the main gases being carbon dioxide — CO_2 —, methane and nitrous oxide) as far as they can, so that by 2050 they achieve greenhouse gas emission reductions in the order of 50% compared 1990 levels. For industrialised nations like Germany, this means they must become practically greenhouse gas-neutral: they will need to reduce their emissions by around 80 to 95% compared with 1990 levels.[I]

The aim of this study

The present study aims to present the technical feasibility of Germany achieving greenhouse gas-neutral status by the accepted target date of 2050.

Within the scope of the various sectors, we intend to set out solution spaces and suggest a range of alternatives, such as variation of parameters and technologies or the development of several scenarios.

Alongside climate protection, there are other guiding principles for a sustainable development in Germany,[II] including:

- Reducing resource utilisation by 50% by 2020 and 90% by 2050.
- Preserving soil with a decrease of new soil sealing to 30 hectares per day by 2020 and the long-term objective of no further soil sealing.

However, the study does not go into the detail of these principles, in the knowledge that more detailed research is required. Examples will be included in several chapters, which will highlight the resources issue.

I In the context of the Kyoto Protocol and the EU's internal burden sharing agreement, Germany had made — and fulfilled — a commitment to reduce greenhouse gas emissions for the period between 2008 and 2012 by 21% compared with 1990 levels. The Federal government also put forward an energy strategy in the autumn of 2010, which was amended in 2011. This provides for an increasing proportion of energy generation from renewables in Germany, in tandem with the phasing out of nuclear energy. Differentiated targets were set for reducing energy consumption in a range of sectors. Concrete targets were also established for the reduction of greenhouse gas emissions compared with 1990 levels: 40% by 2020, 55% by 2030, 70% by 2040 and 80-95% by 2050.

II See also the additional targets in the Federal government's 2002 sustainability strategy 'Unsere Strategie für eine nachhaltige Entwicklung'.

Scenario for a greenhouse gas-neutral Germany by 2050

The scenario for a greenhouse gas-neutral Germany by 2050 illustrates the possibility of Germany becoming GHG-neutral by that date. It does not make any predictions about the probability of such a development; it is not a forecast. Instead, the scenario describes one of several possible ways a greenhouse gas-neutral Germany could turn out. The present study does not cover the routes towards this transformation, any associated economic assessments, or the selection of suitable policy instruments. We show that, by 2050, Germany can in principle cut its greenhouse gas emissions by 95% compared to 1990 levels.

Our premise is that in 2050 Germany will still be a highly-developed industrialised country that has maintained its standard of living, with consumption and behaviour patterns similar to today's.

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

The GHG-neutral 2050 scenario looks at the issue of aiming for greenhouse gas neutrality merely from a national perspective, and does not include interaction with other countries. A national greenhouse gas reduction target of 95% forms the basis for the study and according to the assumptions made this should be achievable in Germany, largely by technical means. Accordingly, calculations are based on GHG emissions arising in Germany. However, Germany is connected to other countries by trade flows and international treaties. These not only affect the release of greenhouse gases, but also the scope for action on climate protection.

The scope of this study does not encompass any emissions arising from imported goods. Conversely, it does cover emissions arising from exported goods. The study does not consider the relocation of production abroad (carbon leakage), which may be a possibility under certain circumstances. If for example a large industrial unit relocates to Portugal and supplies the German market from there, its GHG emissions are no longer recorded in the German inventory, but in the Portuguese. Thus the German inventory will be reduced by the corresponding amount of emissions. However, this will only be a nominal 'reduction' in German emissions, as the products of the industrial unit will still be consumed in Germany, and additional GHG emissions will be caused in Portugal.

This study was based on the assumption that industry sectors which are currently based in Germany will remain there, and continue to operate. Taking current industrial structures as a starting point, we describe technical adaptations to existing industrial processes. The present scenario does not consider the conceivable increase in demand on the international commodity markets in response to reduced fossil fuel consumption in Germany — this is another type of carbon leakage. Some notable individual effects of such relocation will be highlighted here (cf. the chapter).

both itself and each individual Member State to the 2°target. Logically, the next step should be to investigate how a greenhouse gas-neutral Europe could be achieved, and what synergy effects the Member States could harness in so doing. Once again it is important to retain a global perspective, and to note in particular the risk of simply transferring emissions outside the EU.

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 emission reductions achieved 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 emphasises that reductions should primarily be achieved within a country's own borders and reductions abroad should be seen as supplementary measures. The continuation of volume-based 'flexible' instruments also depends on the final shape the new international climate agreement will take. Negotiations will be completed in 2015.

As a Member State of the European Union, Germany is subject to European legislation on environmental policy and the single market. The main steps to be taken towards a greenhouse gas-neutral Germany are closely interlinked with developments in the EU as a whole, and will require European policy which, as a bare minimum, seeks very high greenhouse gas reduction targets throughout the EU, and supports national policies on greenhouse gas neutrality. The EU has committed both itself and each individual Member State to the 2°target. Logically, the next step should be to investigate how a greenhouse gas-neutral Europe could be achieved, and what synergy effects the Member States could harness in so doing. Once again it is important to retain a global perspective, and to note in particular the risk of simply transferring emissions outside the EU.

The calculations made here are based on the assumption that technologies which are used to avoid greenhouse emissions and increase energy efficiency will have progressed from their current pilot status to widespread use in 2050. Accordingly, the scenario assumes significant technical progress and changes will be made. Our analysis is based on the best technology currently available. We do not assume that new inventions will be made, but that existing technology will be developed further.

The present study will not assume any changes in behaviour, such as the development and spread of different lifestyles or changes in consumer patterns (except in the case of food), although the Federal Environment Agency might consider such changes desirable and indeed 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 considering the limits imposed by environmental 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 — for example in the chapters on Transport, Agriculture and Waste Disposal.

We have assumed for the purposes of scenario analysis that Germany in 2050 will be a net exporter, an industrial nation with continued average annual economic growth running at 0.7% of gross domestic product.

The study is also based on the assumption that Germany's population of 82.5 million in 2005 will have dropped by approximately 12.5% by 2050. Thus approximately 72.2 million people would live in Germany in 2050. Our assumption[III] 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.[1]

III The figures are based on variant 1 of the 11th coordinated population projection published by the Federal Statistical Office in 2006.

Greenhouse Gas Emissions in 2050

A narrow interpretation of the expression 'greenhouse gas-neutral' would mean a particular product or process that releases no greenhouse gas emissions. However, in the present study we will broaden the definition to include very low, basically climate-compatible emissions. Accordingly, we set an emissions budget for a GHG-neutral Germany — approximately 60 million tonnes of CO2e, 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 per year to approximately 1 tonne. These figures only include greenhouse gas emissions generated in Germany and recorded in the National Emissions Inventory. Indirect emissions arising in other countries, associated with imported goods, are not included.

It is technically possible to achieve a greenhouse gas-neutral Germany with annual per capita emissions of 1 tonne of CO2e in 2050. This represents a reduction of some 95% compared to 1990. In order to achieve complete GHG-neutrality, the last remaining tonne per capita could be offset against reduction measures outside Germany.

Table A-1 shows how the emissions remaining in 2050 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 a single category.

Table A-1: Distribution of greenhouse gas emissions in the UBA THGND 2050 Scenario

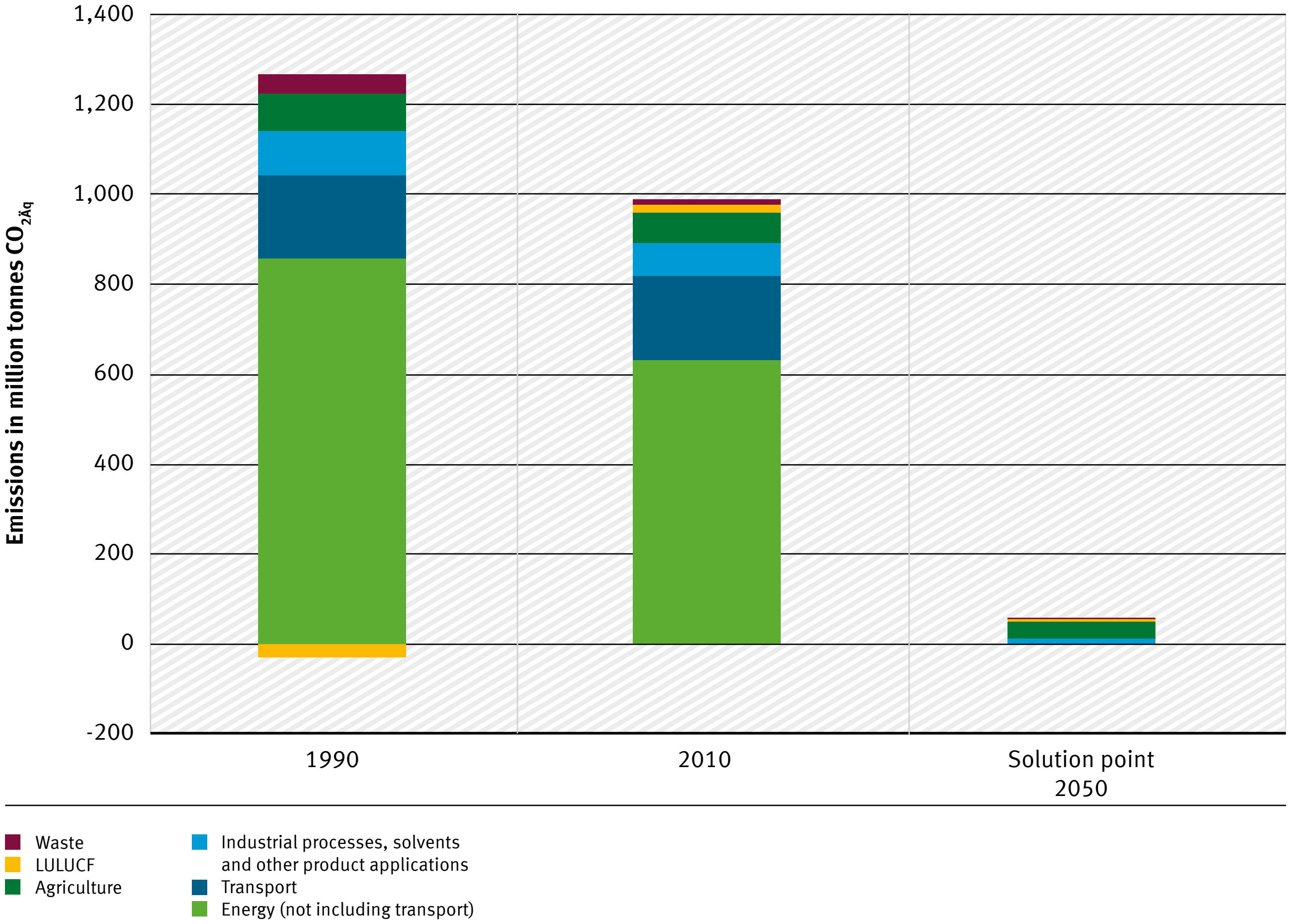
Emission source	CO_{2eq} in million tonnes
Energy[IV]	0
Industrial processes, solvents and other product applications	14
Agriculture	35
LULUCF[V]	8
Waste	3
Total	**60**

shows a reduction of greenhouse gases by 95% compared to the baseline year 1990.

IV Including transport, processing industries etc.

V Land Use, Land Use Change and Forestry

Figure A-1: Greenhouse gas emissions[VI,VII]



VI 1990 and 2010 according to the NIR.

VII Transport, excluding the international part of shipping and aviation.

B. Energy

B.1 Introduction

A secure supply of energy, in the form of electricity, heat and fuels, is a fundamental necessity of modern-day life. It forms the basis of an efficient industrial and service economy and ensures that Germany's current standards of living and welfare are maintained.

Most of Germany's energy is currently provided by fossil fuels, which are linked to considerable greenhouse gas emissions. Energy-related emissions accounted for the majority (83.5%) of greenhouse gas emissions in Germany in 2010.[2] Energy supply therefore needs to be completely restructured if Germany is to achieve its long-term climate targets.

The German government's energy concept contains guidelines for an overall strategy to 2050 outlining how the country's energy supply is to be developed. The guidelines are based on a fundamental decision that the majority of Germany's energy requirements should be met from renewable sources. The following key targets are defined for 2050:[VIII]

- Increase the proportion of electricity generated from renewable sources to at least 80%
- Reduce electricity consumption by 25%
- Reduce primary energy consumption by 50%
- Redevelop the building stock with the aim of achieving climate neutrality
- Reduce final energy consumption in transport by 40%.

It is possible to define a number of different forms of energy in an energy system. Primary energy (e.g. coal and natural gas) is converted into final energy (e.g. electricity and fuels) and then into useful energy (e.g. heat and light). Accounting for primary energy is difficult in a renewable energy system. To simplify matters, this study takes the net electricity generated from renewables as the first accounting level. This is the energy that is then converted into final energy. However, with this method it is not possible to show future efficiency gains or the future useful potential of individual power plants.[IX] In a 100% renewable energy system, renewable electricity can represent final energy if it is used directly, e.g. for lighting. But it can also be converted, for instance to produce hydrogen and then methane. In this case, the methane is the final energy vector.

The following sections will show that, based on the assumptions made for all the sectors considered (see also Chapters C, D and E), it is possible to achieve a virtually greenhouse gas-neutral[X] energy supply entirely on the basis of renewable energy sources. As well as presenting technical options for providing the various different final energy vectors, we show the total final energy consumption based on exploiting most of the potential efficiency gains. We also show that a greenhouse gas-neutral energy supply is based primarily on renewable electricity sources. We demonstrate that Germany is able to achieve its long-term climate protection targets without CCS[XI] or the use of nuclear energy — through energy savings, energy efficiency gains and the systematic use of renewables.

VIII The reference year in each case is 2008, except for transport, where the aim is a reduction compared with 2005.

IX Further technological advances are likely to take place in the next few decades that will make it possible to use renewable energy sources more efficiently, resulting in higher outputs per unit area. However, it is not possible to show the potential of this improved efficiency and the associated efficiency gains for the entire energy system using the method described here.

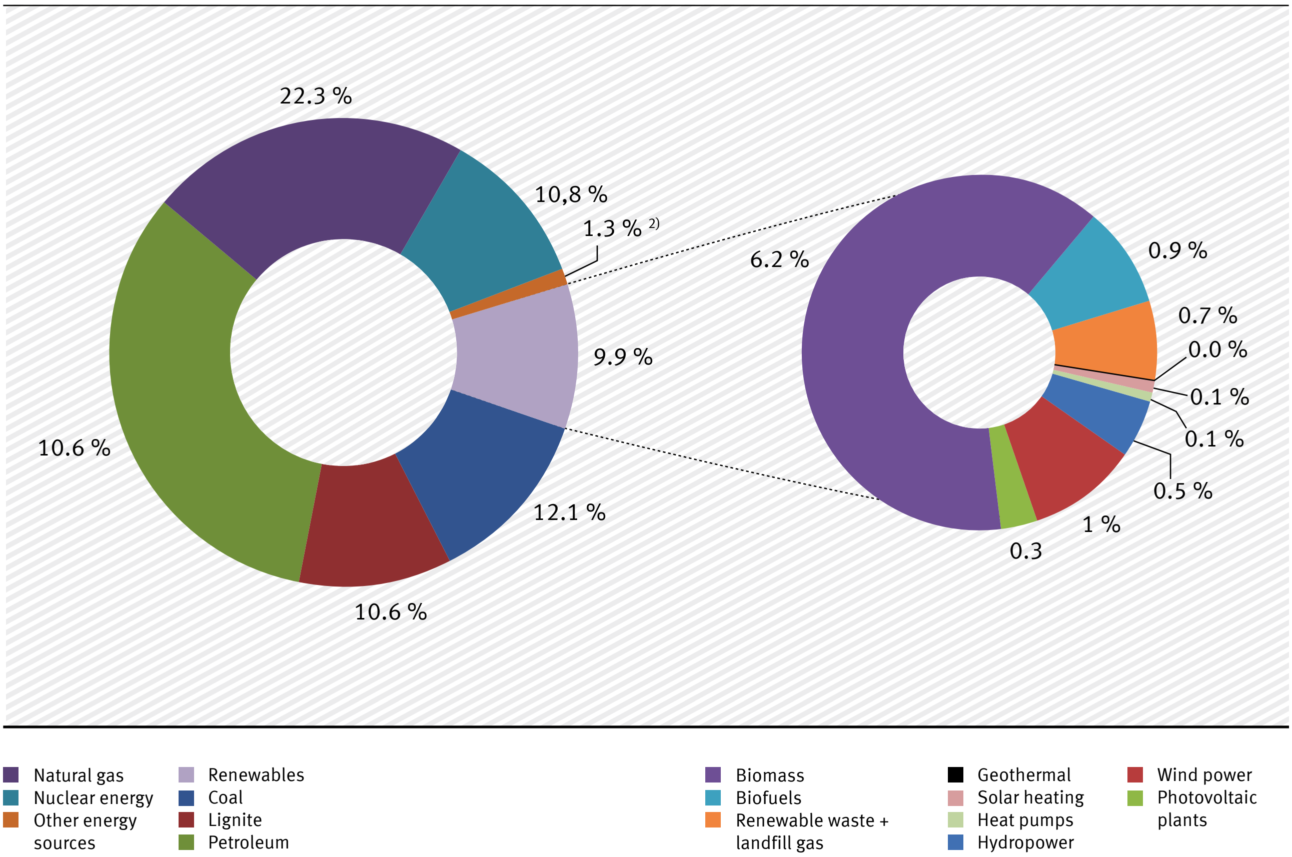
X Technology-related emissions, e.g. methane slip from engines and leakages in the gas grid, also occur when renewable fuels are used.

XI Carbon Capture and Storage — technical separation and geological storage of carbon dioxide.

B.2 Energy supply in Germany 2010

Primary energy consumption in Germany in 2010 was 14,217 PJ (3949.2 TWh). Fossil fuels accounted for the greatest share of primary energy supply in 2010, at 77.9%.[XII] Renewables already provided 9.9%. Primary energy consumption was 4.6% lower than in 1990.

Figure B-1: Primary energy consumption in Germany 2010[3]



2) Other energy sources: Firedamp, non-renewable waste and waste heat, and the electricity exchange balance.

A large proportion (70.2% in 2010) of Germany's primary energy sources are imported,[4] almost exclusively in the form of fossil fuels.[XIII] Germany's net reliance on imports rose constantly between 1990 (around 57%) and 1998 and has stabilised in recent years at around 70%.[5] Today, Germany generates over 4000 PJ (a quarter) of its energy requirements. Imports of energy feedstock rose by 17% to around 11,660 PJ over the same period.

The energy sources produced almost exclusively in Germany are lignite and wind, solar and biomass energy[XIV] and the biogenic fraction of waste. Lignite accounted for around 12% of energy production in 2011 (1990: 19%); renewable energy sources accounted for 11%.

XII According to the current AGEB accounting method.

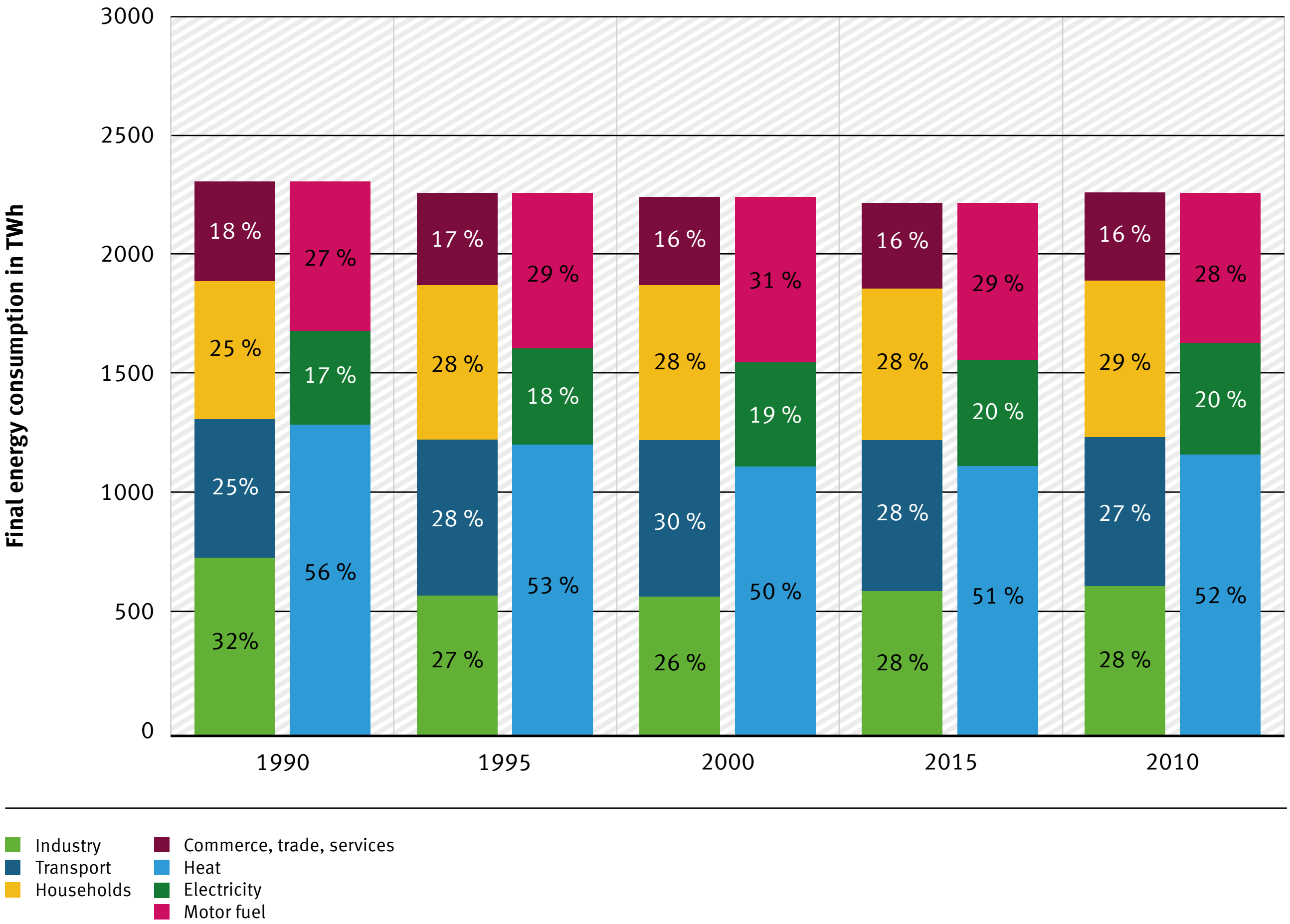
XIII Thanks to constant trade in the European grid, it is also possible for electricity from renewable sources generated in neighbouring countries to reach Germany as a result of short-term load levelling. Germany has been a net exporter of electricity since 2001 (until 2011).

XIV Some fractions of biogenic fuels, including palm oil and bioethanol, are imported.

The main energy imports were petroleum, gas, hard coal and uranium. 100% of the uranium for nuclear energy is imported. 97.8% (2010) of Germany's petroleum requirements come from abroad, as do most of its gas and coal requirements.

Primary energy sources cannot generally be used immediately. They have to be converted to the necessary final energy forms, which entails some conversion losses. The energy is then used in the various different sectors of the economy (industry, private households, commerce, trade and services) and for various applications (heat, electricity and fuels). In addition, the raw materials are used in the chemical industry. The breakdown of final energy consumption is shown in Figure B-2.

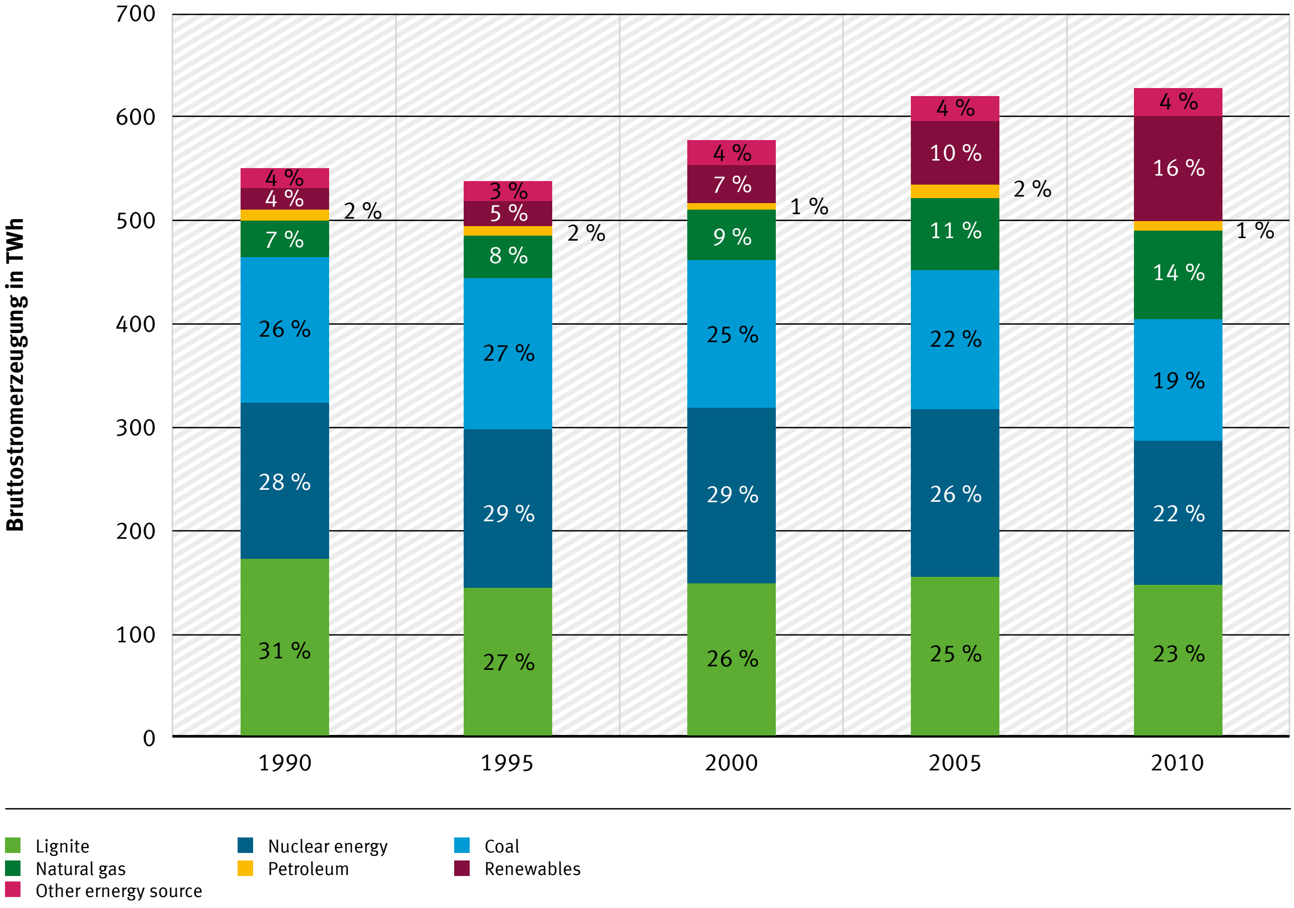
Figure B-2: Final energy consumption by sector/application[6]



B.2.1 Electricity supply

Electricity consumption in the final energy sectors amounted to 527 TWh in 2010. 26.9% was used in private households, 42.1% in industry, 27.9% in the commerce, trade and services sector, and 3.2% in transport. The deregulation of the electricity market in the mid-1990s, the phasing out of nuclear energy and the expansion of renewable energy sources are leading to restructuring and change in the supply of electricity. The majority (79.3%) of electricity is currently supplied by fossil fuel-fired power stations. Renewable energy sources account for a growing proportion of the electricity supply: 16.4% in 2010, with wind energy making the biggest contribution (6.0%).[7]

Figure B-3: Electricity generation by energy source[8]



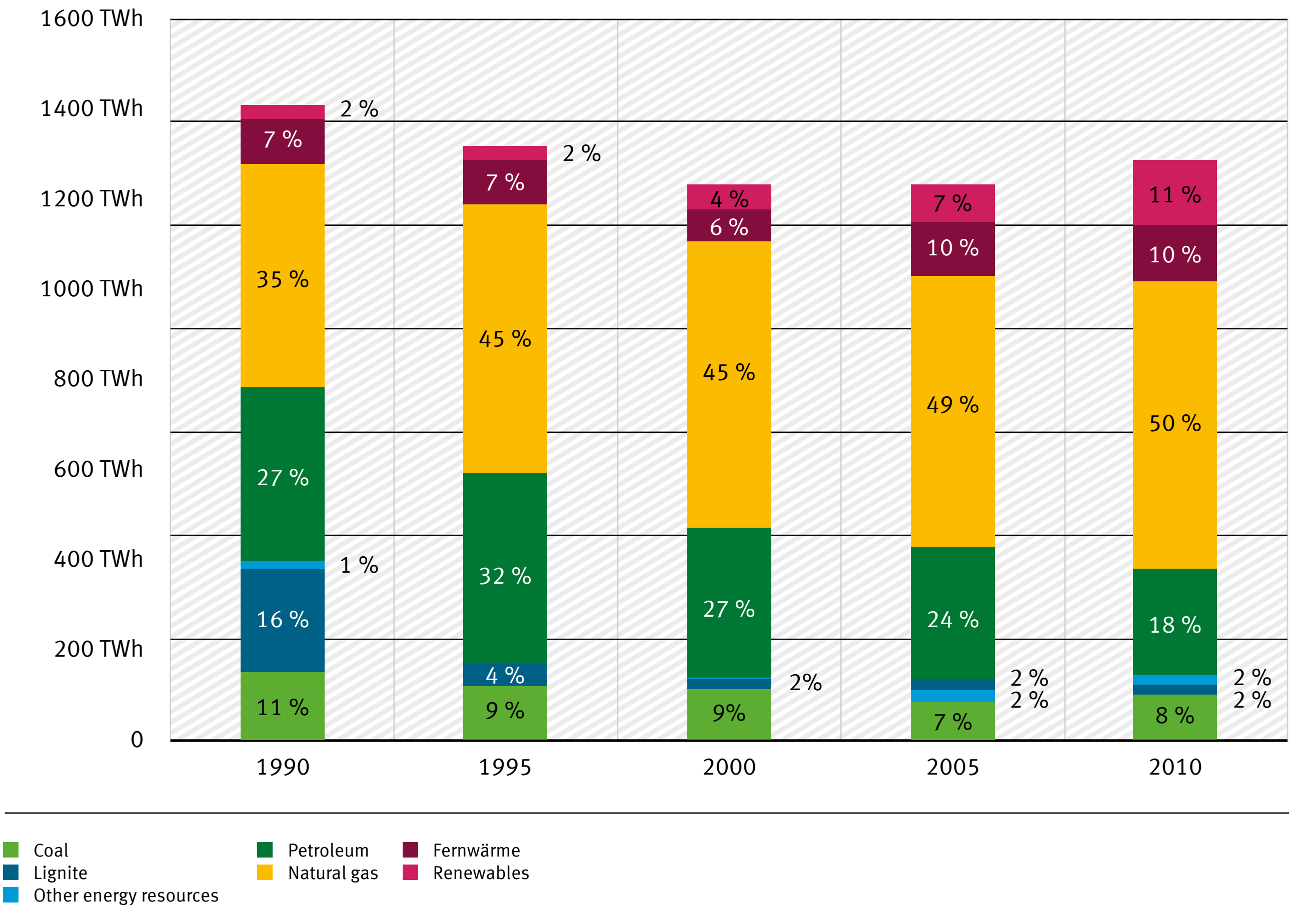
B.2.2 Heat supply

In 2010, 1338 TWh was used to provide heat.[XV] In Germany, heat is supplied in a wide variety of ways: from central heat and power plants or local and district heating plants to local incineration plants, small CHP plants[XVI] and heat pumps. District heating is dominated by fossil fuel-fired CHP plants. Around 11% of heat energy is already provided from renewable sources, the highest proportion coming from biomass, particularly the use of wood in private households.[9]

XV Own calculation based on AGEB evaluation tables 1990–2012.

XVI CHP — combined heat and power.

Figure B-4: Heat supply by energy source[10]



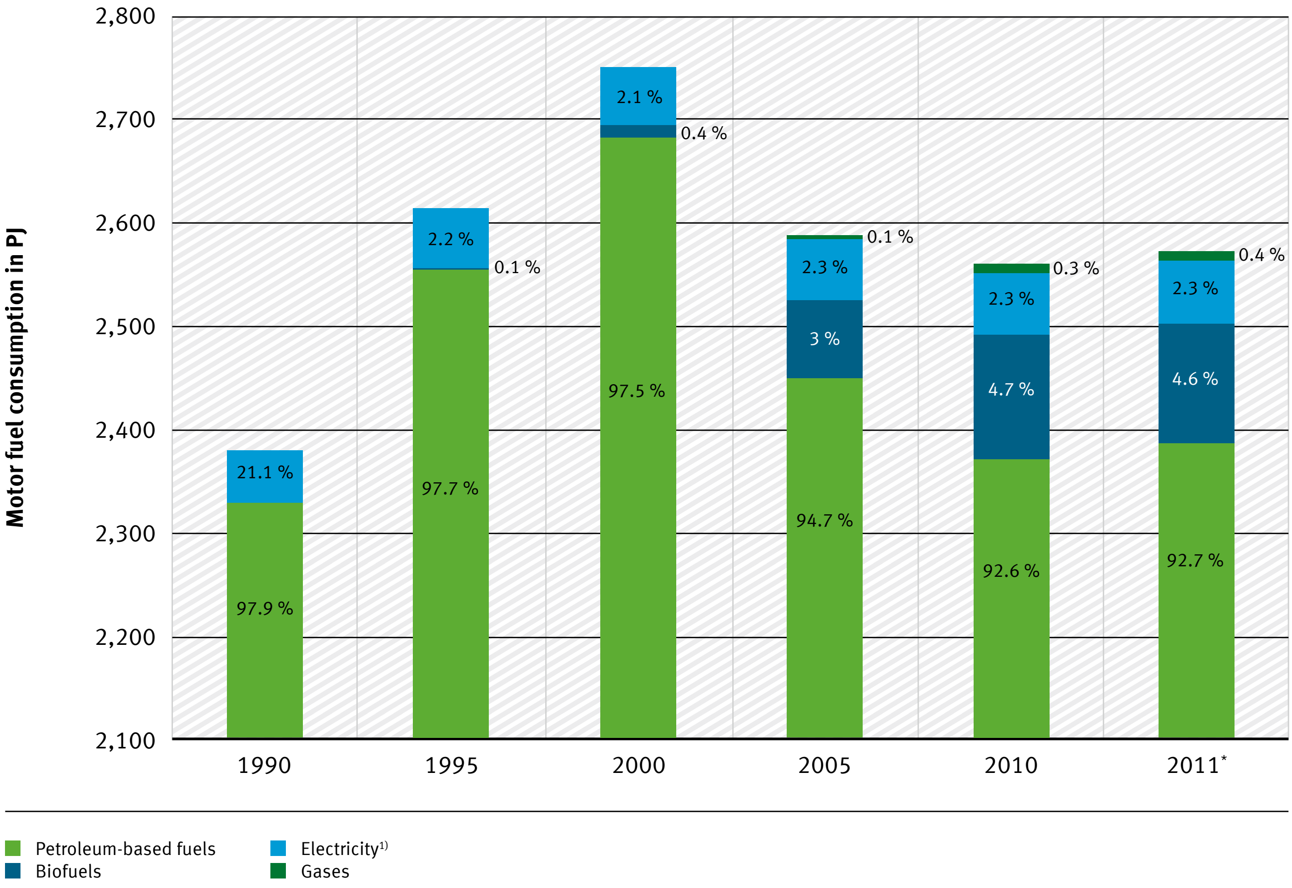
B.2.3 Fuel supply

Fuels accounted for the second highest share of final energy consumption: 721 TWh (2010).[XVII] The majority of the fuel used in Germany is petroleum-based (petrol, diesel, aviation fuel). This proportion has fallen over the past ten years as it has been replaced by biogenic fuels, particularly biodiesel. In 2000, the proportion of fuels derived from petroleum was 97.5%, and by 2010 it had fallen to 92.6%. Biogenic fuels accounted for 5.8% (127.5 PJ) of the engine fuel used in road and rail transport in 2010 (excluding the military).[11] Electricity has so far played only a minor role as an energy source for transport (2.3%).

A detailed description of current and future fuel supply can be found in Chapter C — Transport.

XVII Own calculation based on AGEB Evaluation Tables on the Energy Balance for the Federal Republic of Germany 1990 to 2011.

Figure B-5: Fuel consumption by energy source[12]



1) Including electricity from renewable energy sources
*) provisional

B.2.4 Energy storage

Germany's current energy supply structure already has a large number of energy storage facilities.

In principle, fossil fuels are already an energy storage unit. Unlike renewables that fluctuate, fossil fuels can be stored fairly easily and adapted to consumption requirements to supply final energy. This applies to solid, liquid and gaseous fossil fuels. Germany's gas grid, with its 47 underground gas reservoirs, has a storage capacity of around 220 TWh (thermal)[13] (or 128 TWh (electrical)[XVIII]). In theory this is enough to meet Germany's current natural gas requirements for several weeks. Because of Germany's high reliance on petroleum imports, and as a result of the global oil crisis, compulsory petroleum stockholding was introduced in Germany in the mid-1970s. Under the provisions of Germany's Petroleum Stockholding Act, the level of compulsory stocks is currently a 90-day supply.[XIX] The total stocks held in Germany are often considerably higher because consumers — particularly in the fuel oil sector — store enough to cover more than one heating period, and refineries also have their own reserves to ensure continuous production operations.[14]

XVIII Based on an assumed efficiency level of 58% for reasons of simplicity.

XIX The purpose of the Erdölbevorratungsverband (EBV) is to stockpile at least 90 days' worth of reserves of crude oil and petroleum products (petrol products, diesel fuel, light fuel oil, jet fuel and heavy fuel oil). It does not cover petroleum requirements for the chemical industry, which has its own stockpiling policy for emergencies. Neither does the EBV carry out strategic stockpiling of biofuels, LPG, lubricants, bitumen, etc.

Storage facilities have also been a part of the electricity market for decades, primarily in the form of pumped storage plants. These short-term storage plants can store energy for one or more days and are an effective way of compensating for fluctuations. Pumped storage plants store energy in the form of potential energy. During times of low electricity demand, water is pumped from a lower level (lower reservoir) to a higher one (upper reservoir). During peak load times, water is released from the upper reservoir into the lower one to produce electricity. A particular quality of pumped storage plants is their 'black start' capability, which means they do not need an external electricity supply or voltage to start generating electricity. This is very important in the rare event of a total system collapse. Modern pumped storage plants achieve a storage efficiency level of over 80%. The average storage efficiency of Germany's pumped storage plants is currently around 74%.[15] The installed net nominal output of the pumped storage plants in Germany is currently 6.6 gigawatts.[16] Their total storage capacity is around 40 gigawatt hours (GWh).[17]

There is also a compressed-air storage plant in Huntorf with a net nominal output of 321 MW.[18] In surplus situations the electricity is used to compress air, which can then be stored. When required, this compressed air is burned in a gas turbine with a fuel gas to generate electricity. Compressed-air storage plants cannot be deployed as quickly as pumped storage plants.[19]

Table B-1: Storage capacities in Germany (2008) 19,20 some from own calculations

	Electricity	Gas	Liquid fuels
Final energy consumption in TWh/y	524	895[XX]	696[XXI]
Storage capacity in TWh	0.04[XXIII]	217	min. 250
Coverage in h	approx. 0.7	approx. 2000	approx. 3100

B.2.5 Energy-related greenhouse gas emissions

The supply and consumption of energy accounts for the biggest share of greenhouse gas emissions in Germany: 83.5% in 2010.[22,XXIII] Emissions are reported in the common reporting format (CRF) in accordance with the IPCC Guidelines for National Greenhouse Gas Inventories. The energy-related emissions are listed under the source group 'Energy' (CRF 1) with very detailed subcategories (see Table B-2).

XX Primary energy.

XXI Incl. biofuels.

XXII Only pumped storage plants. Storage capacy of the only German compressed-air storage plant is negligible.

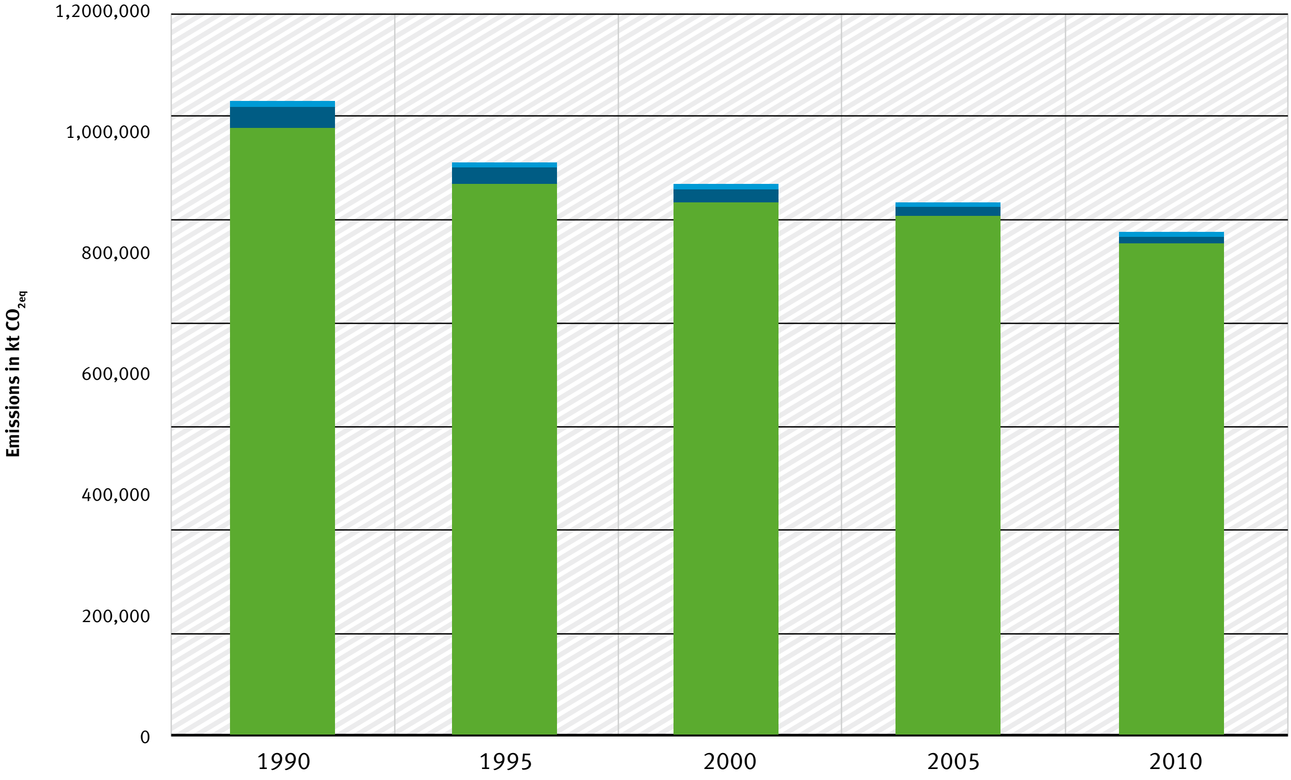
XXIII This figure does not include energy-related emissions from international air and sea transport since they — in line with international agreements — are reported in the national inventory reports only as memo items.

Table B-2: Subcategories of the Energy source group

		Comments
CRF 1A	**Fuel combustion activities**	
CRF 1A1	Energy industries	▸ Emissions from public electricity and heat production, petroleum refining and coking.
CRF 1A2	Manufacturing industries and construction	▸ Energy emissions from industry, including the iron and steel industry, the chemical industry and cement manufacturing.
CRF 1A3	Transport	▸ Emissions from road, rail, ship and other transport, and from civil aviation. ▸ Emissions from international air and sea transport are reported only as memo items and are not included here.
CRF 1A4	Other combustion installations	▸ Emissions from households and commerce, trade and services.
CRF 1A5	Military and other minor sources	▸ Emissions from the military sector.
CRF 1B	**Fugitive emissions from fuels**	
CRF 1B1	Solid fuels	▸ Emissions from extracting, pre-treating, transporting, storing, processing and distributing solid fuels.
CRF 1B2	Oil and natural gas	▸ Emissions from extracting, pre-treating, transporting, storing, processing and distributing oil and gas.

Energy-related greenhouse gas emissions since 1990 are shown in Figure B-6. Emissions in this sector have fallen by 23.4% since 1990. This is primarily the result of reduced emissions from stationary combustion plants: changes to the fuel mix, industrial restructuring in East Germany in the 1990s, improved energy efficiency, more efficient technology and increasing use of renewables. Emissions in the transport sector fell by only just over 6% over the same period, which means the reductions in this sector are smaller than in the area of stationary combustion plants.[23]

Figure B-6: Greenhouse gas emissions in the Energy source group shown over time[24,XXIV]



	1990	1995	2000	2005	2010
N_2O	8,130	7,336	6,735	6,184	6,321
CH_4	33,225	24,531	21,216	14,544	12,258
CO_2	979,404	871,957	829,984	806,307	763,734

B.3 Technical possibilities and potential for GHG-neutral energy supply

B.3.1 Renewable energy potential

Renewable energy potential can be divided into theoretical, technical, ecological and economic potential. The theoretical potential is the usable energy within a region over a specific period of time as dictated by physical laws. The technical potential takes into account technical restrictions, so represents only a proportion of the theoretical potential. The technical-ecological potential also takes into account the environmental impacts associated with developing renewable energy sources. The economic potential takes account of power plant costs.

Because of the available data, in this report we consider the technical potential at global and European levels, and the technical-ecological potential for Germany.

B.3.1.1 European and global renewable energy potential

Europe has a large number of renewable energy resources. Whereas a high proportion (80%) of the technical hydropower potential is already exploited, there is still considerable solar, wind and geothermal energy potential available. Western Europe has an assured technical renewable energy

XXIV Excluding international air and sea transport.

potential of at least 40,000 PJ per year. This is equivalent to around 60% of current primary energy consumption in the EU-27 countries.[25] There is also additional potential that can be developed:

- offshore wind energy 2000 TWh p.a.
- geothermal power 1700 TWh p.a. and
- solar power generated in North Africa as part of the Mediterranean energy ring amounting to tens of thousands of TWh p.a.

Together, these sources produce additional potential of more than 75,000 PJ[XXV] per year.[26]

There are methodological difficulties when it comes to estimating national, European and global bioenergy potential. The main finding from the Federal Environment Agency's analysis of various bioenergy potential studies is that such estimates are strongly influenced by inherently uncertain factors and are likely to be influenced by value judgements.[27] The IPCC's Special Report on Renewable Energy Sources (SRREN) (2011) considers the potential for biomass energy in 2050 to be in the region of 100 to 300 EJ per year, based on an analysis of various biomass and land use studies.[28]

Globally, renewables supplied nearly 13% of primary energy in 2008,[29] with biomass energy accounting for the largest proportion. Various studies have attempted to estimate global renewable energy potential. Direct use of solar radiation, e.g. by photovoltaic plants or CSP power plants,[XXVI] offers the greatest potential globally. There is also great potential for generating electricity from onshore wind energy.[30] According to the IPCC report, around 2.5% of global technical potential is currently being exploited. The globally available technical potential for renewable energy is therefore clearly sufficient to meet global energy requirements in the medium and long term, particularly once energy-efficiency measures are taken into account.

B.3.1.2 National renewable energy potential

In the following we assess the potential for the various different renewable energy resources in Germany.

Photovoltaic

The solar radiation that falls on the Earth is often referred to as global radiation. It consists of direct radiation and diffuse (scattered) radiation.

Solar cells are able to convert sunlight directly into electricity using the photovoltaic effect. Conventional solar cells can make use of both direct and diffuse solar radiation.

The factors that determine Germany's technical-ecological potential for photovoltaic electricity generation are:

- the level of solar radiation in Germany
- the space available for solar panels and
- technology.

XXV Corresponds to 20,833 TWh.

XXVI Concentrating Solar-Thermal Power Plants.

There are significant variations in solar radiation across Germany, particularly between the north and south of the country. According to the German Meteorological Service (DWD), annual global radiation in Germany in 2011 ranged from 987 to 1374 kWh/m².

Figure B-7: Resources required to expand solar power production [XXVII] [XXVIII] [XXIX] [XXX] [XXXI]

The expansion of photovoltaic (PV) power generation has a huge potential in terms of protecting the environment since it does not require the use of fossil or biotic energy vectors and does not produce much in the way of emissions. There is a broad range of technologies available: multi- and monocrystalline silicon solar cells, thin-film applications based on amorphous silicon[XXVII], CdTe[XXVIII], CIGS[XXIX] and organic solar cells.[XXX] However, these technologies use materials that are associated with high specific and absolute environmental impacts during raw material extraction and production. They include tin, silver and wafers for the silicon-based solar cells. There are also uncertainties surrounding the availability of the raw materials. Key resources for thin-film photovoltaic panels, such as indium, tellurium, gallium and germanium, can be obtained only 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 developments. Because the metals required for these technologies are used in very small quantities, there is a risk that they will be irretrievably lost by being dissipated in large material flows, such as glass. Even if take-back and recycling systems like PV-Cycle[XXXI] become more firmly established and large quantities of old solar cells accumulate as waste, the recovery and necessary stockpiling will pose technical, logistical and commercial difficulties. There are some semiconductor substitutes available with the same technological properties, but the same structural risks apply.[31] For these reasons the elements listed here are classed as critical raw materials in relevant studies.[32]

Installing an output capacity of 1 GW with the current technology mix of 80% silicon-based PV and 20% thin-film applications requires around 5 tonnes of indium and 5 tonnes of tellurium. In both cases, this corresponds to around 1% of global primary production. In addition, each GW requires 463 tonnes of tin and 19 tonnes of silver.[33] Then there are material requirements for replacement investments, which need to be planned in advance because of the limited technical lifespan of PV modules (20 to 35 years). Even if we take into account the fact that further advances in thin-film technology, for instance, (increased efficiency and lower material requirements) could lead to a 60-90% reduction in indium and tellurium input, it is not clear whether this would reduce material consumption in absolute terms because such advances would lead to greater market penetration.[34,XXXII]

Notwithstanding these developments, the attractive opto-electronic properties of compounds like indium tin oxide (ITO), a transparent, conductive electrode material, are triggering high demand in other fields of application, such as information and communication technology.

XXVII Cadmium telluride.

XXVIII Copper indium gallium selenide compounds.

XXIX Solar cells based on semi-conducting hydrocarbons.

XXX An organisation that operates a collection and recycling programme for old solar cells in Europe on behalf of solar cell manufacturers and importers: www.pvcycle.org.

XXXI See U.S. Department of Energy (ed.) (2012): SunShot Vision Study. Washington.

When combined with demand from other countries with similar PV expansion scenarios, there is a risk that availability and access to some of the critical technology metals could hinder the expansion of solar power.

If market prices for critical components increase, they could prompt a further shift away from the current technology mix towards crystalline technology, which is considerably less material and energy-intensive. Although large material and energy savings have already been made in the manufacturing processes as a result of the significant expansion of crystalline technology, there is a need for research into ways of making further material savings and to find alternative materials for the various PV technologies.

The Energy Target 2050 study published by the Federal Environment Agency assumes an average annual efficiency level of 17% and 1620 km² of available space. This means that 5.88 m²of land area is required for every kilowatt (kW) of installed capacity. If the entire area were to be covered with solar cells, it would provide an installed capacity of 275 gigawatts (GW). The area figures relate to roofs and building façades and other built-up areas, such as car park roofs and noise protection walls. The figures do not include the use of open spaces such as conversion sites,[XXXII] farmland or grassland.

Assuming 900 full-load hours, this would give an annual electricity output of around 248 TWh. This calculation of the area available for solar power is a conservative estimate. Whether this potential area can be fully exploited will depend on a number of factors, such as public acceptance, government policy, the efficiency of the PV installations and integration of the solar power into the electricity grid. If conversion sites, farmland and grassland are used, it will be possible to achieve an even higher installed solar power capacity in Germany.

Hydropower

Most of Germany's technical-ecological potential for hydropower has been exploited. The main options for tapping additional potential involve modernising and expanding existing plants.

The assumptions for long-term usable hydropower potential in Germany are based on the findings of the DLR study,[35] which predicts an increase in technical potential to 5400 MW (25 TWh p.a.) by 2050 as a result of the modernisation and expansion of existing plants and the construction of small hydropower plants. In addition, it is assumed that the construction of new small hydropower plants on largely unspoilt rivers can be ruled out because of environmental concerns. This reduces the technical-ecological potential for hydropower to a possible installed capacity of 5200 MW or an output of 24 TWh p.a.[XXXIII]

Deep geothermal

The potential contribution of deep geothermal energy to sustainable energy supply was investigated in detail for an assessment report by the Office of Technology Assessment (TAB) at the German Bundestag.[36] It was used to calculate the technical-ecological potential for geothermal power in Germany to 2050 taking into account ecological, regional planning and technical restrictions.[37] According to these forecasts, Germany would be able to realise an installed net geothermal capacity of 6.4 GW by

XXXII Conversion (German: Konversion) is a term used in town planning to refer to the reintegration of derelict military and industrial sites into economic or natural cycles or to a change of use for buildings.

XXXIII For further information see Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau, Chapter 5.4.

2050, which could generate around 50 TWh p.a. of baseload electricity.[XXXIV] This potential can be developed in Germany without damaging the environment. It is also possible to achieve positive environmental effects by using geothermal plants to provide heat.[38,39]

Biomass

There are generally two source categories for biomass energy potential: energy crops and biogenic residual and waste materials, which will be referred to in the following as 'waste biomass'. The Federal Environment Agency is critical of energy crops, partly because of the increasing competition for fertile farmland, the disproportionately large land area required for energy production from energy crops compared with other renewable energy sources, and the socioeconomic issue of the link between energy crops and global food prices. In the following, we therefore consider only the potential of waste biomass because it is less controversial in terms of resources.

In theory, producing energy from waste biomass can also lead to competition with other existing or potential uses, including manufacturing. This should be avoided. Therefore, even in the case of waste biomass, assessments will need to be carried out on a case-by-case basis to check whether its use as an energy source will hinder or prevent a more valuable or otherwise preferable use. Alternative uses can be judged to be more valuable if they lead to greater environmental benefits (greenhouse gas reduction, carbon sequestration, less pressure on certain elements of the environment, providing an alternative to harmful substances, etc.) than the reference option, and if resource utilisation is optimised through cascading use.

A considerable amount of research is still needed to enable us to reliably quantify the optimum potential for power generation from waste biomass in terms of climate protection and resource management. A large number of technologies that make use of biogenic materials in the broadest sense are currently being researched. This is opening up a number of different use and application pathways for many waste materials. They can be used to generate electricity or heat, to produce biomethane or liquid fuel (biomass to liquid, BtL) for the transport sector, or as raw materials in the chemical industry. Since each of the different technology pathways within the energy options has its own specific conversion efficiency rate, the selected technology and field of application present another variable quantity when it comes to calculating potential.

The potential figures presented here for energy from biogenic waste and residues are based on the 'NatureConservationPlus' scenario described in the DLR study.[40] These were calculated from the technical potential figures from the DLR Basic scenario for 2050, from which deductions were made for potential that can be ruled out on clearly explained ecological grounds, and to which additions have been made for expected nature conservation measures. As mentioned above, the number of biomass-processing technologies is expanding rapidly, so that the current division of biomass potential into biogenic waste material that is fermented to produce biogas, and biogenic solid fuels — primarily woody waste, but also clippings from landscape work — will very probably need to be revised in the foreseeable future. However, since these technologies are not yet fully mature and there are still uncertainties surrounding e.g. competing uses and potential environmental risks and benefits, such as nutrient recycling, it is not currently possible to make a valid, comprehensive assessment of the range of processes available. In the following we will therefore continue to use the simplified, conventional classification into solid biofuels and fermentable biomass.

XXXIV For further information see Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau, Chapter 5.5.

This gives a solid fuel potential of 583 PJ. The breakdown is presented in Table B-3. In our view, however, the figures given for forest timber and smallwood are not entirely reliable since there is currently no scientific consensus on forest ecology restrictions (biodiversity, nutrient sustainability, carbon sinks, resilience, etc.), which means that the volumes that can be extracted without damaging the forest ecosystem are still a subject of controversy. If the entire solid fuel potential were used to generate second-generation fuels, it would generate around 81 TWh p.a. of biofuels.[XXXV] It is clear that this represents only a limited contribution in relation to total transport requirements (see Chapter B.4.2).

Table B-3: Technical-ecological potential of individual biomass fractions in 2050[41]

	PJ_{th} p.a.	TWh_{th} p.a.
SOLID FUELS		
Forest timber and smallwood	171	48
Straw	53	15
Mittelwald	11	3
Open ground	22	6
Industrial waste wood	55	15
Wood in household waste	20	6
Mature timber	69	19
Sewage sludge	21	6
Animal materials	14	4
Summer prunings: compensatory areas	8	2
Field biotope network	18	5
Extensive grassland	27	8
Energy crop erosion areas	94	26
Subtotal	**583**	**162**
BIOGAS		
Animal excrement and bedding	88	24
Harvest residues in agriculture	8	2
Waste from trade and industry	6	2
Organic municipal waste	21	6
Sewage gas	20	6
Subtotal	**143**	**40**
Total	**726**	**202**

The calculation of biomass potential for conversion into biogas includes only residue streams, e.g. farmyard manure and the biogenic fractions of household waste (see Table B3). The potential here is

XXXV Based on the simplified assumption of an energy efficiency level of around 50% for the generation of biogenic fuels.

around 143 PJ. Today's achievable annual usage rate of around 57% in combined gas and steam (COGAS) plants and the biogas potential of around 40 TWh_{th} p.a. gives an electricity generation potential of around 23 TWh_{el} p.a. In summary, this means that biogenic resources, including waste and residue streams, represent extremely rare resources. A decision to commit them to particular usage pathways needs to be weighed up carefully. In purely quantitative terms, they cannot make a substantial contribution to restructuring the energy systems in industrialised countries with their high energy consumption rates. At local level and in niche applications, however, they could make small but useful contributions to the energy supply.

Offshore wind energy

In future, a significant proportion of renewable energy is to be provided by offshore wind farms. The wind at sea is stronger and more constant than on land, resulting in much higher energy yields.

The potential for offshore wind energy is based on the available area. Following a reconciliation of various interests, e.g. marine environment, shipping and commercial use, regional plans have been drawn up for the Exclusive Economic Zone (EEZ) in the North Sea and the Baltic Sea. The plans define priority areas for wind power and preclude the approval of wind power stations in Natura 2000 sites.

The Federal Environment Agency's Energy Target 2050 study assumes an installed capacity of 45 GW in the long term, which would approximate to the technical-ecological potential. With an average of 4000 full-load hours per year, this would provide 180 TWh of electricity. Whether it is possible to exploit this technical-ecological potential will depend on government policy, technological progress, power grid connection and cost trends, but also on new research findings in the area of marine conservation.

Figure B-8: Resources required to expand wind power

No fossil fuels are used for the actual conversion of wind energy into electricity. Nevertheless, raw materials — including fossil fuels — are needed to build, erect and maintain wind turbines. The trend towards ever larger, more powerful wind turbines and the high stresses to which offshore wind farms are exposed as a result of low temperatures, salt water and strong winds, increase the material requirements for rotors, nacelles, towers and footings.

Building an additional 1 GW of offshore wind power capacity with today's technology would require:

- approx. 101,000 t of concrete
- 144,000 t of iron and steel
- including at least 1800 t of nickel, chrome, molybdenum and manganese
- 11,000 t of plastics, mostly reinforced with fibreglass or carbon fibre
- 3000 t of copper and
- up to 200 t of rare earth metals.[XXXVI]

XXXVI Calculation based on Faulstich, S., Kühn, P., Pfaffel, S. (2012): Aktualisierung von Ökobilanzdaten für Erneuerbare Energien im Bereich Treibhausgase und Luftschadstoffe. Abschnitt Windenergie. (Update of Life Cycle Assessment Data on Greenhouse Gases and Airborne Pollutants for Renewable Energy; wind power section) Fraunhofer Institute for Wind Energy and Energy System Technology (IWES), Kassel, shortly to be published; and Moss, R.L., Tzimas, E., Kara, H.; Willis, P., Kooroshy, J. (2011): Critical metals in strategic energy technologies — Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. European Union, Joint Research Centre (JRC), Luxembourg.

If we take into account not only the construction and other materials necessary to build this 1 GW of offshore wind energy capacity, but also the raw materials necessary to produce them, including metal ores and fossil fuels, the total material requirements increase to 1.47 million tonnes — equivalent to 0.1% of Germany's total raw material consumption in 2009.[XXXVII] This figure does not include the materials needed for infrastructure, such as grid connections and power transformers, or the materials required for the repair and modernisation of existing turbines. In addition, the rare earth metals used (neodymium and dysprosium) are particularly critical raw materials.[42] As components of electromagnets in highly efficient and low-maintenance gearless wind turbines, they are sought after, but scarce. The main producing country at the moment is China, which has passed export and trade restrictions on rare earth elements in what is already a highly oligopolistic market. Annual global production of dysprosium and neodymium is around 20,000 tonnes, but less than a third of this is available outside China.[43] Electrical coils can be used in place of permanent magnets to create magnetic fields in directly driven synchronous generators. Today's heavy generator designs based on copper coils need further research into material savings and alternative materials.

Similar quantities of materials are needed for onshore wind turbines, but they require less steel and much more concrete for the footings. In addition, the quantities of raw materials can vary dramatically depending on the technology used, e.g. if the towers are made of steel rather than concrete.

In any case, the material intensity of wind farms has serious environmental implications at the production and installation phases. 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 relates to earlier material production chains and installation. Despite this, the wind farm broke even in energy terms in the first seven to nine months of operation.[44] Looking at the energy balance alone does not take into account the environmental impact and health risks involved in mining — the extraction and preparation of raw materials in the countries of origin. Generally, the extraction and preparation of raw materials involves sensitive interventions in the biosphere at regional level, which can lead to acidification of surface water, contamination with heavy metals, subsidence, the destruction of habitats and erosion. In the case of rare earth metals, the scarcity of which has resulted in concerted worldwide exploration efforts, there is also the issue of radioactive contamination. The oxides in the rare earth metals usually occur together with uranium and thorium, which are released during extraction and in the refining process and can contaminate broad stretches of land in the absence of adequate occupational safety and environmental protection measures.

In order to counter-balance the negative effect of mining and refining primary raw materials in the long term, wind turbines at the end of their operational life must be considered man-made reservoirs of raw materials with high reuse and recycling potential. There is also a need for further research into additional material savings and substitute materials for conventional and alternative generator concepts.

Onshore wind energy

The area available (technical-ecological potential) for onshore wind power in Germany was estimated as part of the Federal Environment Agency's Energy Target 2050 study using geographic data sets and taking into account various exclusion criteria (e.g. residential areas). This potential area was used to calculate an approximate minimum potential capacity: 60 GW with a potential output of 180 TWh p.a.

XXXVII Data on raw material consumption (RMC) collected by Germany's Federal Statistical Office 2011.

In 2013 the Federal Environment Agency published a report[XXXVIII] that calculated the onshore wind energy potential more accurately. The potential area and output figures, which had previously been calculated approximately, were calculated more accurately based on agricultural land and other suitable areas (e.g. forests). The potential land area was calculated using the best available geographical data sets,[XXXIX] with a detailed consideration of the exclusion criteria. A model was set up, with state-of-the-art reference turbines assigned to the available potential land areas. The electricity yields were calculated using detailed weather data.

The results show that Germany's onshore wind energy potential is several times higher than previously assumed. This is because of the detailed data sets used and the much more detailed assumptions in terms of exclusion criteria, and reference turbines with lower noise emissions. The use of modern turbines with high hubs and large rotor diameters makes it possible to develop weak-wind locations and leads to high turbine capacity utilisation. Based on the assumptions made and the selected wind turbine technology, the calculated potential area is around 49,400 km² or 13.8% of Germany's total land area. This represents a potential installed capacity of around 1190 GW with an energy yield of 2900 TWh p.a.[45] However, it was not possible to represent issues requiring a case-by-case examination in any meaningful way in this study, which means that the technical-ecological potential (which includes specific species protection) will be considerably smaller. Other influencing factors that were not taken into account in the energy potential study, but which could hinder the realisation of wind energy plans in practice, include: regional planning objectives at local authority level, objections and conditions imposed by land owners or local residents because of a lack of acceptance, the economic conditions in individual cases and specific land use claims that could not be included because of the underlying data.

In view of these factors, in this report we assume that onshore wind energy can contribute around 1000 TWh p.a. in the long term. Whether this will transpire will depend on the aforementioned influencing factors and is a matter for social and political decision-making and planning considerations at the various levels.

B.3.1.3 Summary

The global, technically usable renewable energy potential does not present any limitation on global energy supply, until at least 2050, particularly if energy-efficiency measures are implemented in parallel.

The extent to which the potential for renewable energy in Germany is exploited will depend on a large number of factors: the economic efficiency of German power-generation sites compared with renewable power plants in other countries, social acceptance, dependence on imports and the associated political independence, the availability of and access to resources to build renewable power plants, etc.

B. 3.2 Electricity supply

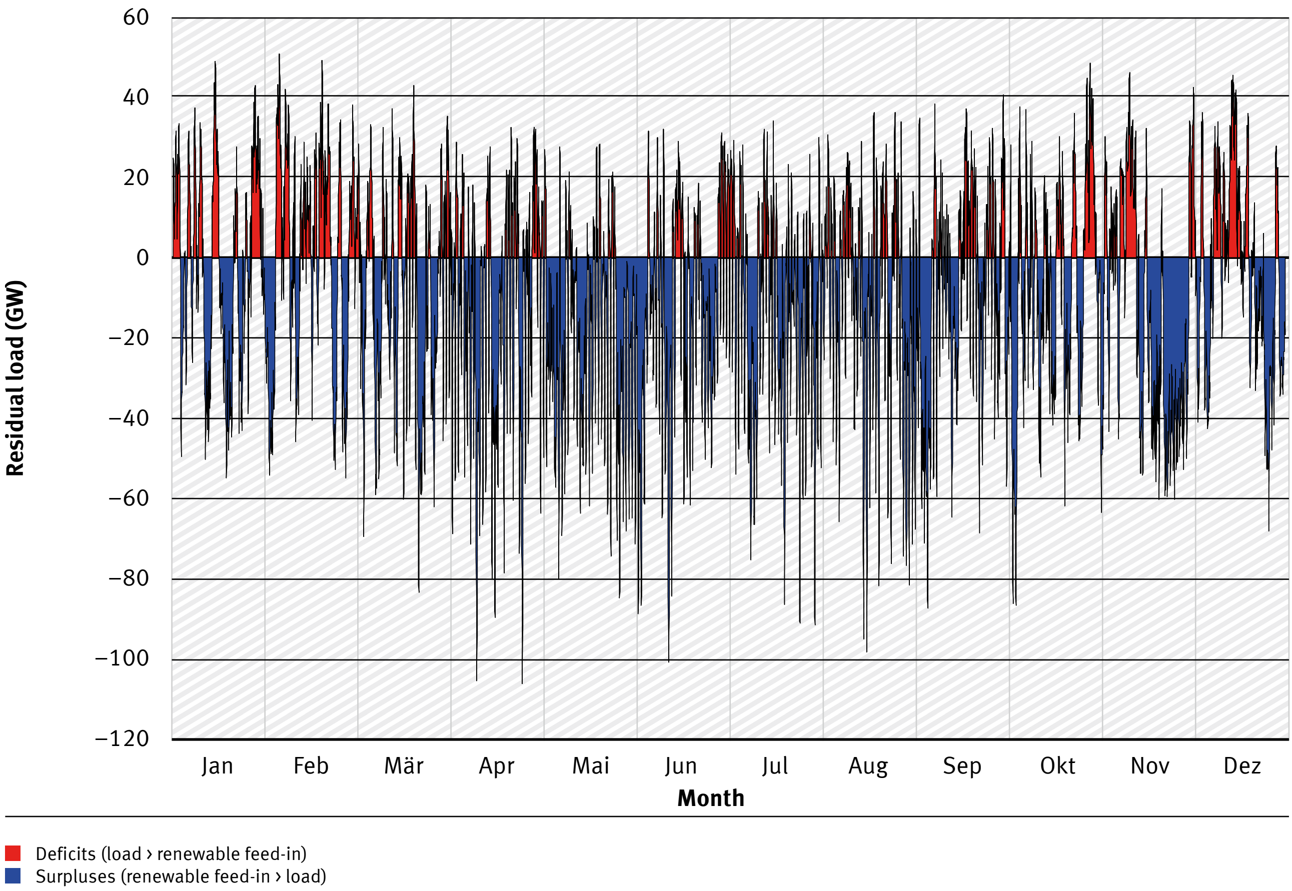
Possibilities for switching to renewable energy sources for Germany's entire electricity supply, in tandem with exploiting potential energy savings, were presented in the Federal Environment Agency's

XXXVIII For more detailed information, see Federal Environment Agency (2013): Potenzial der Windenergie an Land (Onshore wind energy potential), Dessau-Roßlau

XXXIX Based on the digital landscape model (DLM).

Energy Target 2050 study. In accordance with Germany's potential for the various renewable energy sources, electricity supply will be based primarily on wind and photovoltaics, both of which are fluctuating sources of energy. Meteorological data from several years and a number of assumptions[XL] regarding the installed capacity of the different renewable energy sources were used to simulate the amount of electricity that could be generated, which was then used to calculate the residual load. The residual load is the difference between electricity/load demand and the fluctuating amount of energy being fed into the system. It therefore represents the demand that needs to be met by easily regulated backup power plants. The simulations show (see Figure B-9) that there would be surplus situations for several days at a time (negative residual load), but also some fairly long deficit periods (positive residual load).

Figure B-9: Total residual load (taking account of demand-side management and pump storage) for 2050, based on meteorological data from 2009[46]



The extent of the deficit periods can vary as a function of the output of Germany's renewable energy plants, the commercial viability of national potential and electricity demand (load). In addition, the storage requirements for securing electricity supply can be affected by other parameters, including intelligent demand-side management between producers and consumers. In situations where the amount of renewable energy being fed into the system is not sufficient to meet the demand for electricity, peak loads can be reduced through demand-side management — by bringing forward, delaying or shutting down non-critical applications. Major users of electricity in industry and commerce, trade

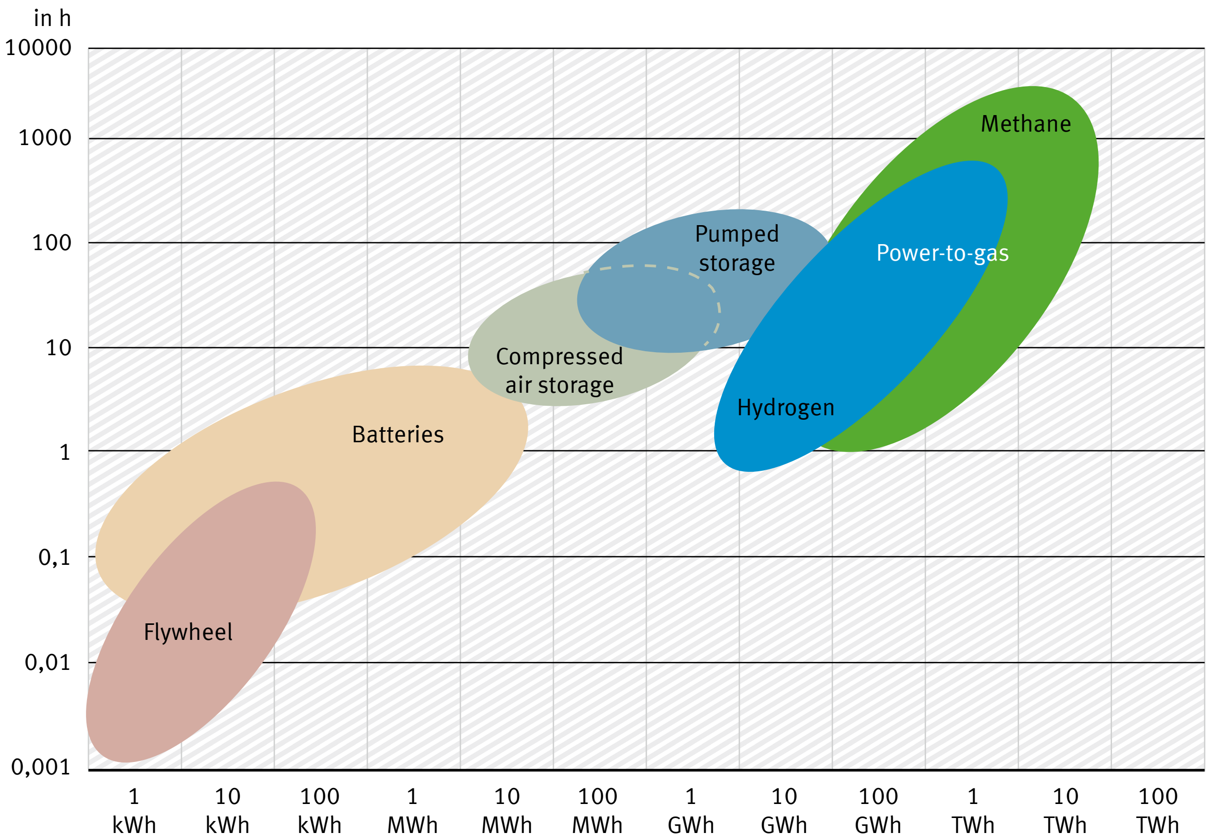
XL PV 120 GW, 104 TWh; wind onshore 60 GW, 170 TWh; wind offshore 45 GW, 177 TWh; hydropower 5.2 GW, 22 TWh; geothermal 6.4 GW, 50 TWh; biogas (waste biomass) 23.3 GW, 11 TWh; total 534 TWh.

and services can make a substantial difference by improving the technology and efficiency of production processes. Peak load reduction can also be achieved by the use of adaptable renewable power generation such as biowaste-fuelled biogas installations, integrated electromobility and adaptations in private households. This approach requires a modern, interconnected information and communication technology infrastructure which enables such loads to be managed intelligently across the entire system.[XLI] In addition, storage requirements can be influenced by expanding the domestic and European network, for instance through better links to Scandinavian pumped storage plants.

Short-term storage will be needed to offset deficits lasting hours or days and to stabilise the electricity system in view of the huge output variations to be expected from the fluctuating energy sources. Long-term storage will be needed to cover renewable feed-in deficits lasting several days or weeks.[XLII]

In principle, the need for storage can be met by a number of different technologies, which vary in terms of their efficiency, available capacity and discharge time. Short-term storage technologies like coils or capacitors are very efficient, with a reconversion rate between 90% and 95%. Electrochemical storage technologies (batteries) can provide power very quickly and also have efficiency levels of up to 90%.[47] Much lower reconversion rates are achieved with compressed-air storage (45–55%) and chemical storage technologies (methane is around 35%). Figure B-10 provides an overview of the different capacities and discharge times.

Figure B-10: Overview of storage technologies — discharge time over storage capacity[48]



XLI More information can be found in Federal Environment Agency (2010): Energy target 2050: 100% renewable electricity supply, Dessau-Roßlau, Chapter 4.2.

XLII Example: A large installed PV capacity very soon produces a high solar feed-in level on a sunny day. When darkness falls this high output disappears again completely from the grid and can no longer make any significant contribution to the electricity supply.

An electricity system based largely on fluctuating renewable energy sources will need short-term storage facilities to secure network stability and cover fluctuations lasting days and weeks. Pumped storage plants will also be used as short-term storage solutions in Germany in the long term. The 2050 technical-ecological potential for pumped storage plants is 8.6 GW.[49] Large batteries can be used primarily to help secure network stability and provide primary backup power. Batteries in electric vehicles have a very low storage potential and can make only a limited contribution to energy storage within demand-side management. The determining factors in the long term will be the availability of resources and the possible lifespan of electrochemical storage devices connected to the grid.

Chemical storage devices are particularly suitable for covering seasonal fluctuations in renewable energies. In times of surplus, when the renewable energy being fed into the grid is higher than demand, the electricity is converted into hydrogen or methane. In times of deficit, when the amount of renewable energy being fed into the grid is insufficient to meet demand, back-up power stations reconvert these energy vectors to electricity. For efficiency reasons, this process should ideally be carried out in gas turbines or combined gas and steam (COGAS) turbines in the vicinity of consumers.

B.3.3 Renewably sourced chemical energy vectors

In a virtually GHG-neutral energy supply system, chemical energy vectors derived from renewables will play an important part, doing far more than just stabilising the electricity supply in their role as storage media. Renewably sourced energy vectors are produced from renewable electricity with the help of power-to-gas technology.

Typical chemical energy vectors/storage media are hydrogen and methane. An overview of their properties is presented in Table B-4. Essentially, hydrogen can be produced more efficiently in energy terms than methane. However, the disadvantage is that hydrogen has only around a third of the energy density by volume.

Table B-4: Comparison of hydrogen and methane

	Renewably derived hydrogen	Methane from renewables
Generation efficiency[XLIV,50]	65–80%	(60–85%) * η hydrogen
Energy density	10 MJ/Nm³ 120 MJ/kg	33 MJ/Nm³ 50 MJ/kg
Inputs required	Water	Water and carbon dioxide
Suitability of natural gas grid	Up to 5 vol%[XLV] hydrogen can currently be blended into the existing gas grid.[51]	Renewably derived methane is a full substitute for fossil gas.
Technological status	▸ Production components available ▸ Energetic use components still at the development and testing phase	▸ Production components still at the development and testing phase, ▸ Energetic use components available

XLIII Cf. Renewables BMU pilot study 2011: ηH_2=72%, ηCH_4=ηH_2*0.79.

XLIV See Chapter B.3.3.3.

If additional catalytic processes are used, other higher hydrocarbons and liquid hydrocarbons (power-to-liquid, see Chapter B.3.3.5) can be produced.

B.3.3.1 Hydrogen

Hydrogen can be produced by electrolysis of water using electricity. The hydrogen can be used directly or as a storage medium for energy and material applications.[XLV] The chemical equation is shown in Formula B-1.

Formula B-1: $2H_2O \leftrightarrow 2H_2 + O_2 \quad \Delta H = +571.8\ kJ/mol$

In principle, three methods can be used to electrolyse water. An overview is shown in Table B-5. Alkaline electrolysis is the state-of-the-art technique and can be operated as an easily regulated power consumer. Polymer electrolyte membrane (PEM) electrolysis is used only in the lower capacity range, and high-temperature electrolysis (HTE) is still at the laboratory stage.

Table B-5: Overview of electrolysis methods[52,53]

	Alkaline electrolysis	PEM electrolysis	HT electrolysis
Experience	In use for 100 years	In use for 20 years	No commercial product, global research
Electrolyte	Base (e.g. 20–30% potassium hydroxide solution) Cathode and anode separated by microporous diaphragm/membrane cell	Solid polymer membrane (proton-conducting membrane) with distilled water	ZrO2 ceramic as the electrolyte and water vapour as the H2 source
H2 production	1–760 Nm^3/h	0.06–30 Nm^3/h 53	5.7 Nm^3/h (lab)
Connected wattage per module	5 kW to 3.4 MW	Up to 150 kW	18 kW (lab)
Specific energy consumption per system/stack	4.5–7.0 kWh/Nm^3 4.1–5.0 kWh/Nm^3	4.5–7.5 kWh/Nm^3 3.9–5.1 kWh/Nm^3	-
Part-load range	20–40%	0–10%	-
Lifespan	Up to 90,000 h	Up to 20,000 h	-
Advantages	Low cost (currently), pressure up to 30 bar (2013), (up to 100 bar depending on manufacturer)	No corrosive materials or reaction products, high current densities, high pressure possible (> 30 bar)	Waste heat, e.g. from the methanation reaction, can produce reaction enthalpies, see B.3.3.2

XLV Further information can also be found in Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau, Chapter 4.1.2.1.

	Alkaline electrolysis	PEM electrolysis	HT electrolysis
Disadvantages	Low current density (see PEM), high maintenance costs	Expensive, only small-scale products currently available	Material degradation
Development status	Technological status	Technological status	Laboratory
	Need for improvement (see Chapter B.3.3.7)		

Hydrogen electrolysis is already used on an industrial scale in the chemical industry, e.g. to produce ammonia-based nitrogen fertilisers. This process currently uses fossil energy sources, but it could use renewably sourced hydrogen instead.[XLVI]

Around 0.8 to 1 l of water is required to produce 1 m^3 of hydrogen. At least 226–283 l of water are needed to produce 1 MWh of hydrogen.[XLVII] This water has to be of drinking water quality or better, and its conductivity should not exceed 1 µS.[55]

After electrolysis, hydrogen can be compressed and pumped through pipelines. Hydrogen pipelines are already in use in a number of regions, e.g. in North Rhine-Westphalia (approx. 240 km) and in the Halle–Leipzig–Bitterfeld region to supply the chemical industry. Unlike the methane[XLVIII] storage system, hydrogen would require the development of a large distribution grid. It is not simply a matter of converting the existing natural gas network to a hydrogen network; the pipeline and gas measurement and control equipment would also need to be adapted. It would, however, be possible to inject small quantities of hydrogen into the natural gas network (see Chapter B.3.3.3). As the hydrogen economy grows, through the addition of more hydrogen to the natural gas network (>20 vol%) or through the development of extensive hydrogen networks, the networks would need to meet higher safety standards.

The hydrogen stored in the network could then be converted back into electricity as required, used as fuel, for heat generation or supplied to the chemical industry as a starting material. While it is relatively easy to produce pure hydrogen, its energetic use, e.g. in fuel cells, still needs a great deal of further research and development.

B.3.3.2 Methane

The hydrogen can be converted to methane by reacting it with CO_2 in the presence of a modified nickel catalyst at temperatures of 250–500°C and pressures of up to 2.5 MPa.[XLIX,56] The chemical equation is shown in Formula B-2. The high-temperature reaction heat can be used for further applications, e.g. high-temperature electrolysis.

Formula B-2: $$4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O \qquad \Delta H = -164.9 \; kJ/mol$$

XLVI Provided the by-products from fossil-based hydrogen production are not required, or can also be produced from renewable resources.

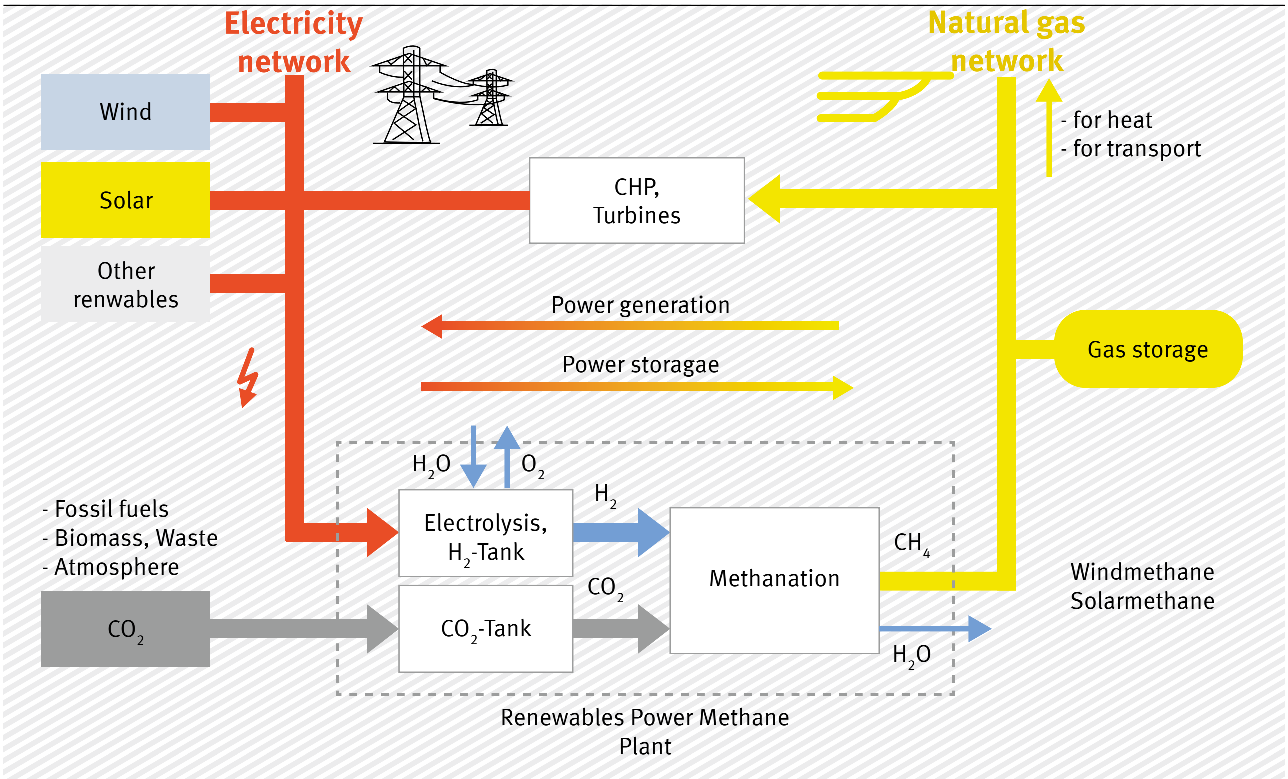
XLVII Values achieved in practice may be higher than these theoretical values.

XLVIII Methane generated from renewable energy sources using power-to-gas technology.

XLIX The process is described in greater detail in Umweltbundesamt (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau, Chapter 4.1.2.1.

The renewably derived methane produced in this way is almost exactly the same quality as fossil gas.[L] The existing natural gas grid infrastructure could be used without restriction. There is no need to adapt the system or to increase safety provisions.

Figure B-11: Diagram showing the methanation process and its integration into the energy system[57]



CO_2 needs to be available for methanation at the site of the electrolysis plant. In a sustainable energy system, this CO_2 should come from a renewable source, e.g. from biogas plants, thermochemical gasification plants, sewage treatment plants or breweries.

In general, it is possible to link biogas plants and methanation plants. The biogas is removed from the fermenter and the CO_2 fraction is reacted with hydrogen in the presence of a catalyst to produce methane, as described above. This increases the CH_4 content of the gas to the same level as natural gas (>95%). The feed-in gas can be stored and used in the natural gas network in the same way as renewably sourced methane.

The methane stored in the network could then be converted back into electricity as required, used as fuel, for heat generation or supplied to the chemical industry (as the basis for organic chemistry). Renewably sourced methane is a full substitute for fossil-based natural gas, which means that it can be used with all application technologies (gas turbines, burners, boilers, vehicle technology) without restriction. There is a need for further research and development here, particularly in the area of production technology.

L Fossil gas contains other hydrocarbon compounds besides methane.

The electrical efficiency of this system for the entire chain (surplus electricity — hydrogen production — methanation — storage — reconversion of methane in COGAS plants) is around 35%. The catalytic reaction of hydrogen and carbon dioxide is exothermic, producing heat of between 250°C and 500°C.[58] This heat can be used to generate electricity in ORC plants,[LI] fed into a district heating system or used for other technical processes, e.g. high-temperature electrolysis.

B.3.3.3 Adding hydrogen to methane

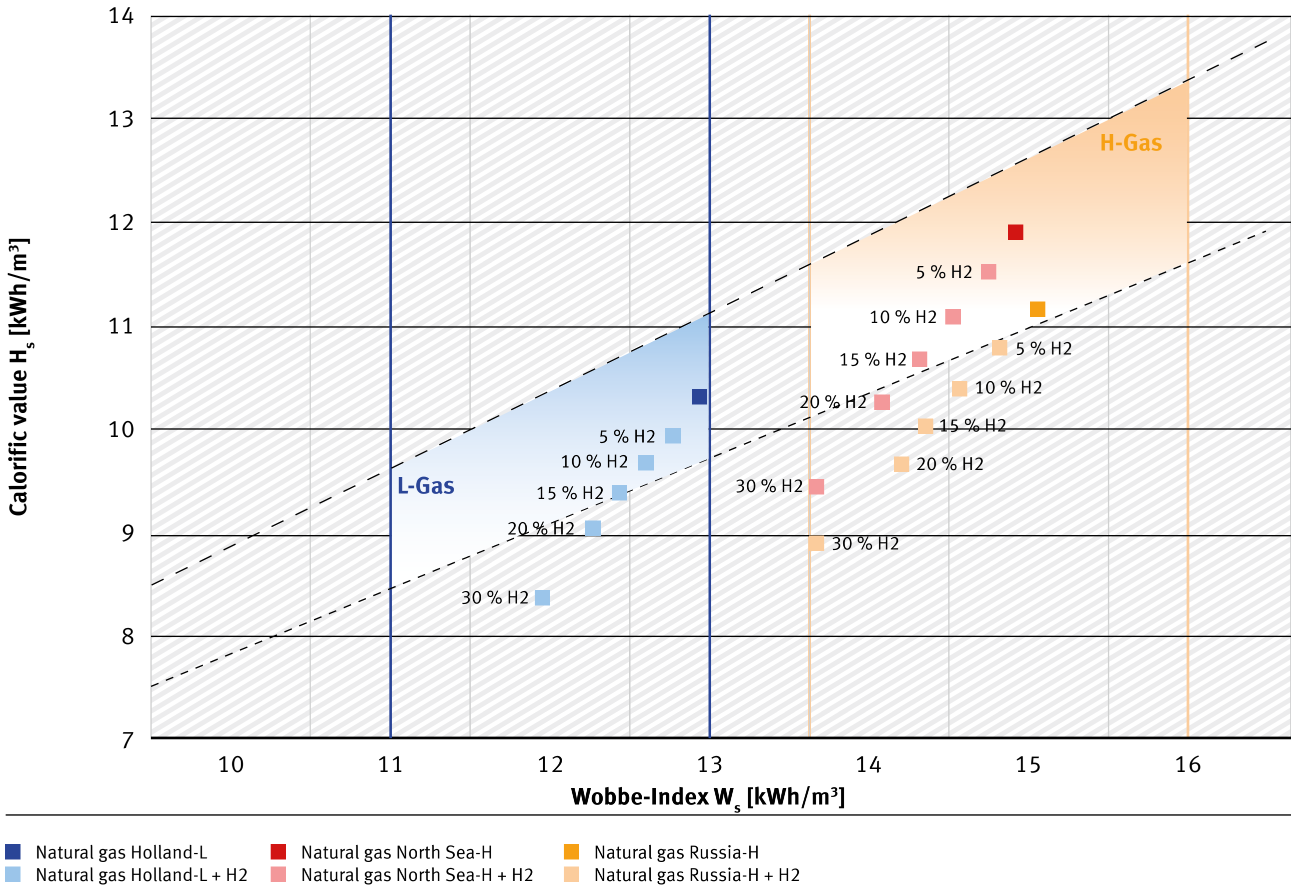
The composition of natural gas varies depending on where it is produced. The key components are methane and higher hydrocarbons, such as ethane and propane. Added hydrogen has so far played only a minor role. However, hydrogen has a significant impact on the material properties of the gas and on safety during gas transport, storage and use.

The effect on the quality of the combustion gas of adding hydrogen can be shown with the help of the Wobbe Index.[LII] Figure B-12 shows this index as a function of the production location and the amount of hydrogen added. It can be seen that it is possible to add around 15% hydrogen to gas from the North Sea. By contrast, less than 5% can be added to gas produced in Russia. Standard European and international rules need to be drawn up for maximum hydrogen concentrations in the natural gas grid.

LI Organic Rankine Cycle.

LII The Wobbe Index describes the interchangeability of fuel gases. It represents an adjusted calorific value and the combustion behaviour of different gases.

Figure B-12: Wobbe Index as a function of hydrogen content and gas production location[LIII,59]



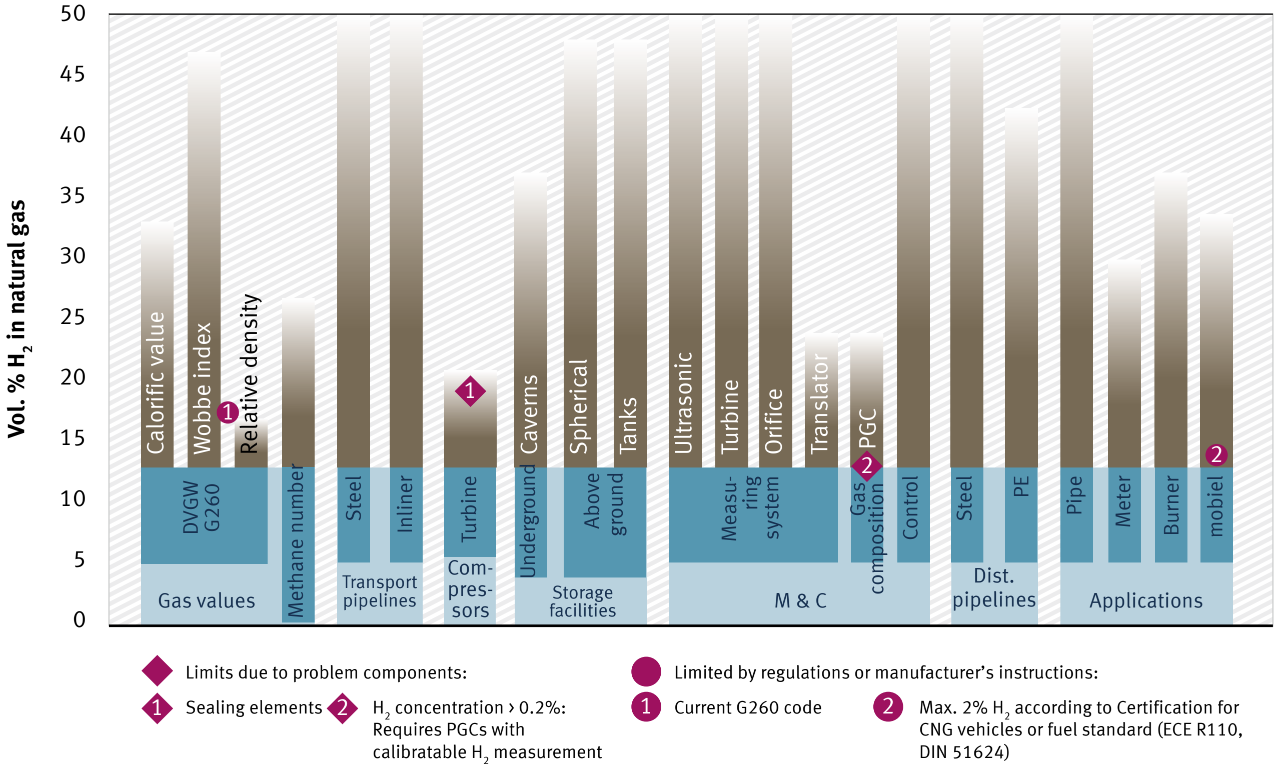
The amount of hydrogen that can be fed into the German natural gas grid is currently limited by regulations and standards and by the use of special technical components. An overview of the maximum hydrogen limits, above which damage or malfunctions could occur, is shown in Figure B13. The hydrogen content in Germany's natural gas system is currently limited to a maximum of 5%.[LIV,60] The lower limit, particularly when natural gas is used in CNG vehicles, is 2 vol% hydrogen.[LV] The use of hydrogen/natural gas mixtures in gas turbines is currently limited to around 4 vol%.[61] Some system components and some application technologies can tolerate higher hydrogen concentrations without any problems.[62] For instance, gas-powered devices in private households can be expected to cope with up to around 20 vol% hydrogen without any adverse effects.[63]

LIII H-Gas: high-caloric gas, L-Gas: low-caloric gas.

LIV DVGW Code of Practice G 260: Gas Composition.

LV DIN 51624 and ECE R110.

Figure B-13: Current technical limits of hydrogen blending[64]



Until the end of the 1980s, Germany's town gas (Stadtgas) contained up to 60% hydrogen,[LVI] and was used on a wide scale. High hydrogen concentrations (over 50%) can speed up crack growth in gas pipelines.[65] The permeation[LVII] of hydrogen through pipelines etc. does not present any higher safety risk than natural gas.[66] These losses can be regarded as minor compared with the leakage losses in the gas system. Because of the density of hydrogen, higher hydrogen concentrations result in higher leakage flow rates. At the same time, the mass flow rate and energy content are lower.[67] The energy losses incurred through leaks in the current gas grid are estimated to be below 1%.[LVIII] In addition, gas with 20 vol% hydrogen is expected to have the same diffusion properties and explosion probability, and to produce the same scale of damage in the event of an explosion.[68] A 10% to 15% hydrogen concentration in the natural gas system appears realistic in the medium term.[69]

Around 220 TWh_{th} can be stored in today's gas network in the form of methane. If all of it is converted back into electricity,[LIX] it can provide around 128 TWh_{el}. Blending in renewably sourced gases would change the potential amounts of renewable electricity that could be stored. The theoretical range for the existing system is shown in Table B-6. If we consider the entire gas network and actual gas throughput, it is possible to store large volumes of renewably sourced electricity in the form of hydrogen. Estimates by the GWI, a gas research institute based in Essen, found 5.01 billion m^3 of hydrogen

LVI 1959: 2nd revised edition of G 260, H2 (43–50 vol% for group A and 50–60 vol% for group B). Up until 1996 in West Berlin.

LVII Permeation refers to a substance passing through a solid (in this case the pipeline) because of concentration or pressure differences.

LVIII Own assessment based on NIR.

LIX Assumed reconversion efficiency rate: 58%

could be blended into the system each year.[70] This equates to 20.6 TWh of renewable electricity for electrolysis.[LX]

Table B-6: Storage capacities in the current gas network for renewably sourced chemical energy vectors

	Renewable electricity	Storage volume	Electricity provided assuming full reconversion
Renewable CH_4 system	387 TWh_{el}	220 TWh_{th}	128TWh_{el}
currently max. 5 vol% eH2	approx. 5.5 TWh_{el}	approx. 4 TWh_{th}	approx. 2.3 TWh_{el}

B.3.3.4 National storage capacities for renewably sourced gases

Fundamentally, the existing natural gas infrastructure with its underground storage reservoirs can be used to store renewably sourced hydrogen and methane and can be expanded in line with demand. The storage capacity for natural gas is currently around 20 billion Nm^3,[LXI,71] with around 50% in pore storage facilities[LXII] and 50% in salt caverns.[LXIII] Preparations are under way to significantly expand the number of salt caverns. Unfavourable price developments for energy storage have put a brake on the expansion plans for the moment. If all the planned projects are realised, the installed storage capacity will increase in the medium term to around 32 billion Nm^3.[LXIV,72]

Whereas there are no restrictions on the type of storage facility that can be used for methane, the requirements for hydrogen storage are more stringent. Salt caverns are the most suitable storage solution for hydrogen. It is uncertain whether pore storage facilities are impermeable enough for storing hydrogen, and whether micro-organisms in the storage structure would have an effect. This could potentially lead to the pores becoming blocked even with higher hydrogen blends. Salt caverns offer extra advantages, including faster withdrawal and replenishment rates and a lower cushion requirement.[LXV,73]

We can assume a technical-ecological expansion potential for new cavern storage facilities of 400 salt caverns, with a maximum usable working volume of 21.6 billion Nm^3.[74] Together with existing and planned natural gas storage facilities, the long-term total working gas volume could amount to a maximum of 53.6 billion Nm^3. As shown in Table B-7, around 80% of this would be in caverns that are suitable for natural gas, methane or hydrogen storage, and around 20% would be in pore storage facilities, which are less suitable for hydrogen.

LX In a departure from the GWI calculation, we assume an electrolysis efficiency rate of 72%.

LXI Usually also shown as V_n.

LXII Exhausted carbon dioxide reservoirs or, to a lesser extent, aquifers.

LXIII Caverns are created by leaching suitable salt structures.

LXIV Around 11 billion m^3 (V_n) in pore storage facilities and around 21 billion Nm^3 in salt caverns.

LXV The ratio between working gas and cushion gas — the gas that remains in the storage facility during a normal withdrawal and replenishment cycle — is more favourable for salt caverns than for pore storage facilities.

Table B-7: Long-term total working gas volume capacities of cavern and pore storage facilities

Max. usable working gas	Caverns, billion Nm^3	Pore storage, billion Nm^3	Total, billion Nm^3
Renewable hydrogen	43.0	0	43.0
Natural gas/renewable methane	43.0	10.7	53.7

However, it is uncertain whether the full potential capacity can be exploited, in view of the long planning and construction time frame[LXVI] and the problems of salt water disposal.[LXVII] An in-depth analysis of the potential is currently being conducted as part of a study.[75] A pressure range for caverns of between 60 and 180 bar was assumed when calculating the expansion potential given above. However, if the usual seasonal mode of operation is abandoned in favour of greater flexibility, the working gas volumes given here would need to be recalculated.[LXVIII]

Sites suitable for salt cavern leaching in Germany are found primarily in the north and east of the country (the North German Basin), and are therefore close to wind farms (although the suitability of coastal sites for storage facilities needs particularly thorough assessment because of widespread subsidence).[LXIX] Gas storage could find itself in competition with compressed air storage, which also makes use of caverns. There are already pore storage facilities in the North German Basin, but also in the foothills of the Alps in Bavaria and in the Upper Rhine Rift.

B.3.3.5 Liquid hydrocarbons

The production of power-derived liquid fuels (power-to-liquid) involves several steps: first, a hydrogen/carbon monoxide[LXX] mixture is produced, which is then converted into long-chain hydrocarbons using the Fischer Tropsch process. The resultant mixture of various long-chain hydrocarbons undergoes further processing and fractionation. Various synthesis processes, e.g. methanol synthesis, can also be carried out. Producing renewable power-to-liquid fuels involves considerable technical and energy inputs, which means that system efficiency levels will be low.

Liquid energy vectors have much higher energy densities than gaseous energy vectors. This makes them particularly indispensable in air transport (see Chapter C). These renewable fuels would offer environmental advantages in production compared with biogenic fuels.

Renewably sourced fuels could be used primarily in transport, but also for reconversion to electricity, to provide heat and as inputs in the chemical industry. The existing infrastructure and application technologies can be used without restriction.

LXVI The process usually takes more than five years per cavern and can be much longer if a greenfield site investigation is necessary because there are no existing results that can be used, and if an environmental impact assessment is required. The number of service providers is also limited.

LXVII See Umweltbundesamt (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau, Chapter 4.1.2.4.

LXVIII The lower pressure limit would need to be raised in the event of flexible operation to avoid damaging the storage facilities. It could then be necessary to take into account the annual turnover rate when calculating the capacity of the storage facilities.

LXIX Volume decreases (convergence) during leaching and operation of caverns are usually transmitted to the surface without causing shearing.

LXX By reducing carbon dioxide.

Storage of liquid hydrocarbons ties in with the current strategic reserve and storage of fossil petroleum products and is also state of the art. Because of the options for above-ground storage, storage capacities are not subject to technical restrictions.

B.3.3.6 Sources of CO_2

An energy system based on renewably sourced hydrocarbons needs a carbon source for the synthesis processes. This source should be as GHG-neutral as possible. In theory, generating 1 m^3 of renewable methane requires 1 m^3 of carbon dioxide. 1 MWh of renewable methane requires around 46 kg of carbon dioxide.

This CO_2 could, for instance, be obtained from biomass applications. The biogas produced when biomass is fermented contains around 40% CO_2 and 60% methane, depending on the substrate. When biogas is fed into the gas network — which occurs today as a way of separating biogas utilisation from biogas production — it is necessary to convert the biogas into biomethane, which involves capturing the CO_2. Assuming that only waste and residual materials will be converted into energy in biogas plants in the long term (see Chapter B.3.1), and that the entire CO_2 fraction can be captured, it would be possible to provide 2.67 billion m^3 of carbon dioxide.[LXXI] Where waste and residual materials are used in thermochemical gasification plants to produce second-generation biofuels, CO_2 streams will be used during the Fischer Tropsch process to produce the liquid fuels.

In addition, large volumes of carbon dioxide are produced in certain manufacturing industries — primarily the quicklime and cement industry. Here too, it is possible to obtain carbon dioxide from the exhaust gases with the help of energy. Although this carbon dioxide cannot be classed as GHG-neutral, the process-related emissions cannot be avoided altogether. According to the assumptions made in the industry chapter (see Chapter D) nearly 14 million tonnes of CO_2 would be available from industrial processes in 2050.

According to the above assumptions, we can expect an annual availability of 19.25 million tonnes of CO_2 in 2050 (see Table B-8), which could be used to generate around 419 TWh p.a. of renewable methane.

Table B-8: Overview of the additional annual CO_2 quantities produced in 2050 and available for recovery

CO_2 source	CO_2 in tonnes
Biogas	5,280,000
Industry	13,783,420
Total	19,253,062

Carbon dioxide can also be obtained from the atmosphere. However, because of the low concentration of carbon dioxide in the air, air separation is very costly in terms of energy and process technology. Air-capture technology, which is currently undergoing laboratory testing, could be used in the future as an alternative to classic air-separation processes.[76] In the air-capture process, air flows naturally through a filter, which absorbs the CO_2. It is then bound with the help of a solvent, and cleaned in a

LXXI The calculation is based on a technical-ecological biogas potential of 40 TWh (in line with Chapter B.3.1.2) with a carbon dioxide content of 40%.

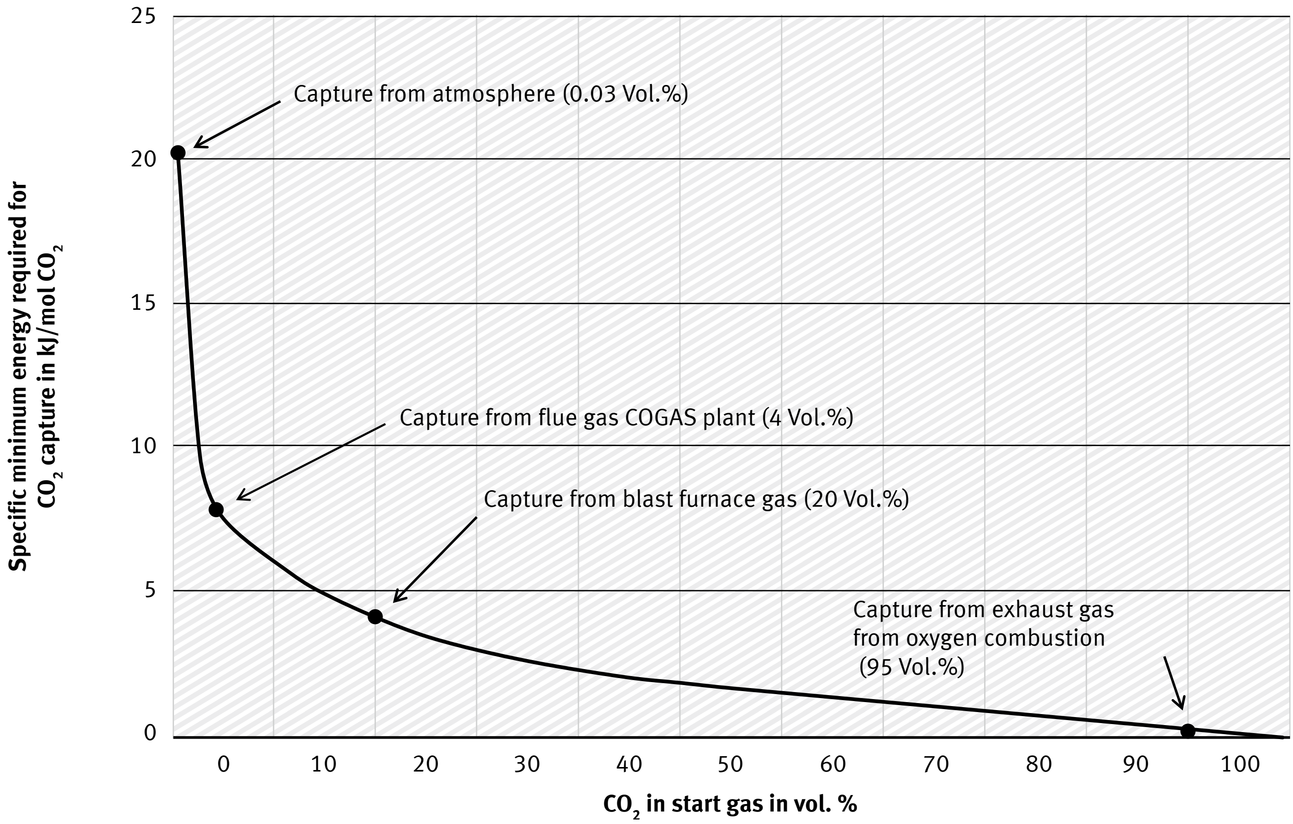
purification step. But energy is also required to extract the CO_2 and reprocess the solvent. In principle, large amounts of energy are required to obtain CO_2 from the air because of its low concentration. The costs should therefore be rated higher for these kinds of plant than for plants that recover CO_2 from concentrated exhaust gas streams.[77]

In an energy system based on renewable energies and renewably sourced hydrocarbons it would therefore make sense to create material cycles so as to ensure an efficient supply of the necessary volumes of carbon carriers. The biggest demand for renewably sourced hydrocarbons is in the transport sector, where they are used in individual vehicles and aircraft. It is almost impossible to close the carbon cycle here by recovering CO_2 from these scattered sources. The only way to create a complete carbon cycle here is by recovering the carbon dioxide from the atmosphere. For this reason, efforts should be made to recover CO_2 primarily in places where renewably sourced hydrocarbons are produced in stationary processes, i.e. in industrial and electricity and heat supply facilities. In line with the assumptions made in Chapter B.4.5, around 269 TWh p.a. of renewable methane will be used for energy purposes in stationary processes in Germany in 2050. If closed CO_2 cycles were realised for all stationary applications, i.e. if the released CO_2 were recaptured, around 467 TWh p.a. of renewable electricity (net electricity generation) would be needed to produce a constant supply of methane for fuel.[LXXII] However, it should be noted that the carbon dioxide must be available at the site of the methanation plant. This is therefore a simplified view of theoretical limits and is less likely to be achieved in practice, particularly in the case of stationary devices in private households, because of the technology required and the associated financial outlay. In addition, a completely closed CO_2 cycle in Germany makes sense only if the fuel supply (methane) is not based on imports.

Figure B-14 shows the minimum energy required to separate the exhaust gas components. This represents an idealised, loss-free view. The energy requirements for actual gas capture can be two to ten times the theoretical values shown.[78]

LXXII Assuming full recovery and ignoring the energy required for capture and transport.

Figure B-14: Minimum energy required for CO_2 capture as a function of CO_2 concentration[79]

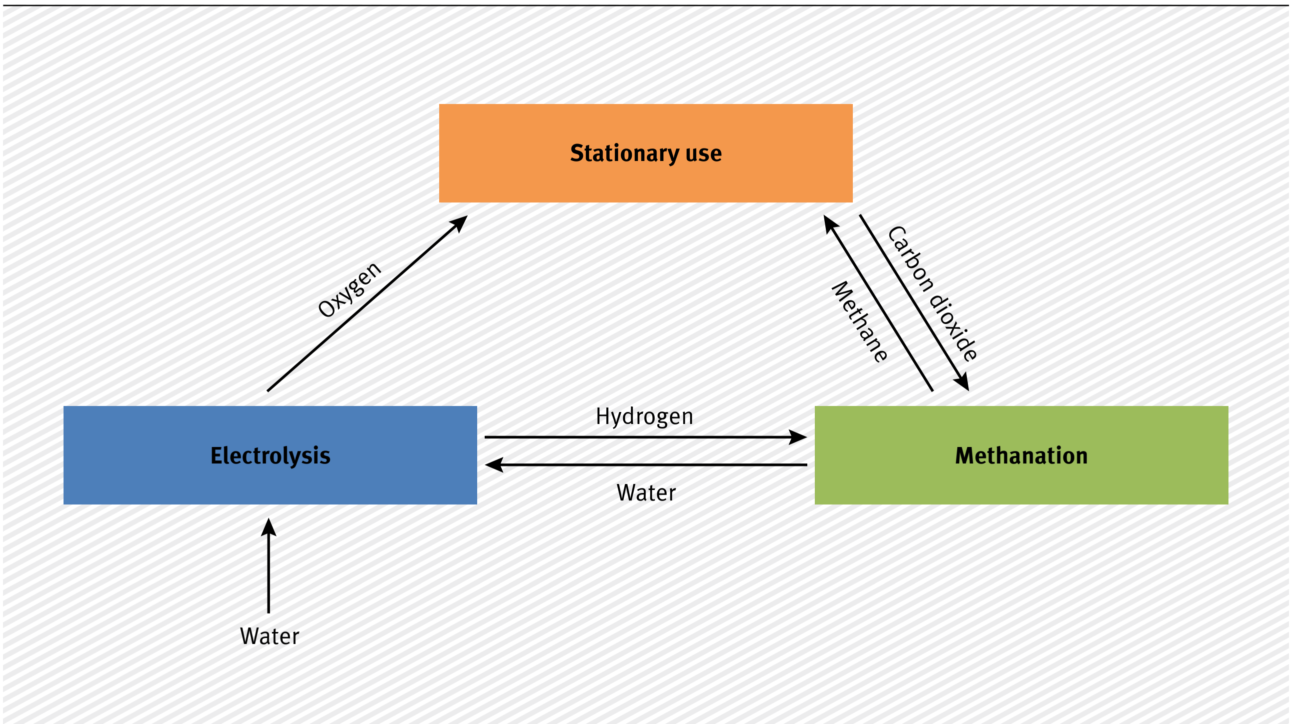


To optimise recovery and increase the concentration of CO_2 in the exhaust gases, it is possible to burn pure oxygen using oxy-fuel technology. The resulting exhaust flow consists primarily of water vapour and carbon dioxide, particularly when synthetic fuels are used,[LXXIII] which means less conditioning is required. Conventional air separation combined with energy inputs could be used to provide the oxygen for the stationary energetic use of renewable methane or renewable liquid hydrocarbons. The amount of energy required depends on the technology used. Air separation using the low-temperature method needs 0.05 kWh/kg air or 0.21–0.29 kWh/kg O2 with a purity level of 99.5 vol% O2.[80] Adsorption methods produce a product stream with a maximum oxygen content of 95%, with a specific energy consumption of 0.31–0.4 kWh/m^3 oxygen.[81] If all stationary processes are switched to pure oxygen combustion by 2050, at least 9.7 TWh p.a.[LXXIV] would be needed for air separation. The oxygen from hydrogen electrolysis could also be used (see Formula B-1). The energy system as a whole could be made more efficient by linking the individual elements and closing material cycles. This is illustrated in Figure B-15.

LXXIII Based on methane and hydrocarbons derived from renewable electricity.

LXXIV With a specific energy consumption of 0.21 kWh/kg O_2.

Figure B-15: Possibilities for realising material cycles in a renewable energy system, own graphics



In summary, we can state that it is not possible to achieve completely closed CO_2 cycles because the transport sector needs primarily carbon-based energy carriers and the carbon dioxide is not emitted at a fixed location. In addition to biomass and process-related emissions in industry, the atmosphere is a potential GHG-neutral source of carbon. Because of the high amount of energy needed to obtain CO_2 from the air, and the associated costs, closed CO_2 cycles should be created for the stationary combustion of renewable methane. The main problems to be overcome for this kind of carbon cycle management are the extreme complexity, and the difficulty of linking generating facilities (most of which may be abroad) to the plants that use renewable hydrocarbons.

B.3.3.7 Development status of power-to-gas technology

Power-to-gas technology is in its infancy. Much more research is needed before it can be used on an industrial scale.[82] A few aspects requiring research will be outlined here for the two key components: electrolysis and methanation.

For electrolysis, the key research areas are:

- Improving energy efficiency
- Adapting the system to fluctuating electricity-generation operations
- Optimising part-load performance by increasing the lifespan of the components
- Cutting costs by finding substitutes for expensive catalyst materials.[83]

High-temperature electrolysis (HTE), particularly solid oxide electrolysis, is still at the laboratory stage. The main requirement here is to reduce the material degradation caused by temperature fluctuations.

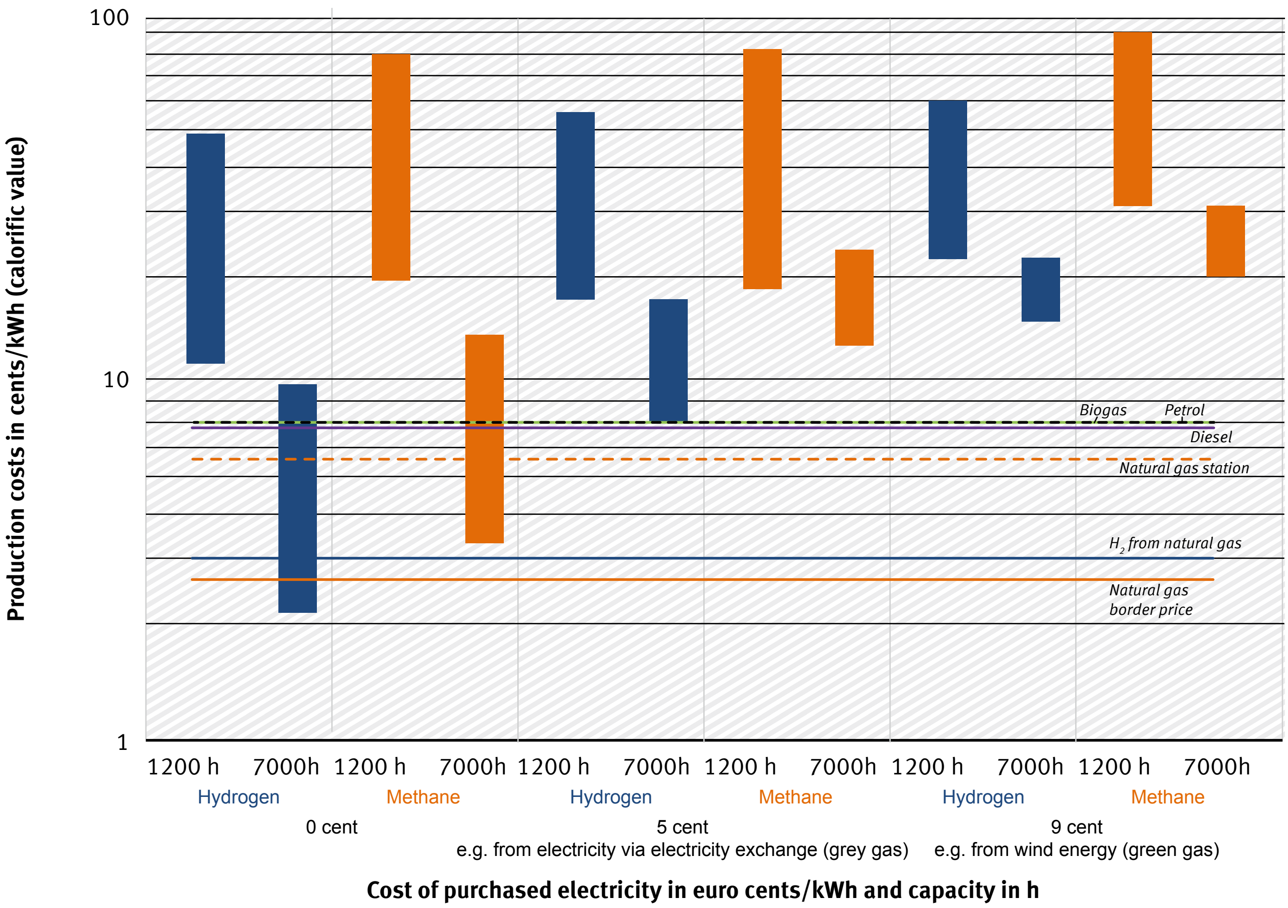
For methanation, the key research areas are:

- Gathering practical experience from initial pilot projects and developing the process technology further
- Studying different utilisation scenarios for the plant and testing the stability of the catalysts
- Investigating the suitability of renewable CO_2 sources (biogas, breweries, biomass gasification, etc.) and CO_2 from industrial processes.

In general, there is a particular need to investigate and optimise ways of combining electrolysis and methanation, particularly since the electrolysis process needs to be driven by electricity, while methanation cannot yet be effectively driven by hydrogen. In addition, the interoperability of power units, including auxiliary equipment (converters, safety systems, process technology), needs to be optimised. In an energy supply system based primarily on renewable gases, there is a need for more detailed scientific analysis of the expansion potential for underground storage facilities. This includes investigating the suitability of pore storage facilities for renewable hydrogen.

Because of the current status of development of power-to-gas technology and the wide range of possible applications, it is difficult to predict how the technology required to deliver an energy vector/ energy vector mix (hydrogen or methane) will develop. It is also difficult to predict the costs. Storage facilities for the electricity market, particularly pumped storage facilities and long-term storage facilities, are capital-intensive and comparatively expensive. Furthermore, it is not possible at the moment to generate sufficient revenues from storage facilities on the spot market. An advantage of power-to-gas technology is that the existing gas network can be used to store hydrogen and particularly methane. Long-term cost developments will depend on a large number of factors (global development of GHG-neutral energy supply, demand for such plants, catalyst materials, water treatment, availability of carbon dioxide, etc.). Power-to-gas technology will be able to gain a foothold on the fuel market in the long term because of the need to meet climate protection targets. This will bring financial benefits and the first commercial applications can be expected in the transport sector. An overview of the production costs of renewable gases under a range of different conditions is shown in Figure B-16.

Figure B-16: Cost comparison between power-to-gas technology and other fuels[84]



B.3.3.8 Summary

A future GHG-neutral energy system will require large quantities of renewably derived hydrocarbons (motor and heating fuels). In this scenario, power-to-gas will be very important in the long term for the entire energy market, i.e. not just for power generation, but also for the fuel market in particular.

Power-to-gas technology will be needed for the electricity system only once renewables start to account for around 70% to 80% of Germany's gross electricity consumption, or when the majority of the power generated in Germany comes from fluctuating renewable energy sources. Before then, however, situations could occur in some regions that would prevent the distribution grids from coping with such high levels of electricity. In these regions, power-to-gas technologies could start to make sense in just a few years' time, offering an easily regulated load that can provide potential capacity on the backup power market and help take pressure off the grid.

Power-to-gas technology could be needed sooner in the transport sector as an alternative to biofuels from energy crops because of the need to meet climate protection targets in this sector. The first commercial applications can also be expected in the transport sector.

Much more efficient GHG-neutral alternatives are available for space heating applications, such as heat pumps driven by renewable electricity. Heating fuels produced using power-to-gas technology should therefore be used primarily in combination with hybrid CHP plants.[LXXV] Fuels produced using power-to-gas technology are very important for supplying GHG-neutral process heat.

In addition, if this technology becomes sufficiently well established, it could be used to provide GHG-neutral raw materials for industry in the long term. Power-to-gas can therefore play an important part in reducing greenhouse gases in this sector.

A key aspect affecting the long-term integration of power-to-gas technology is the availability of process materials (water and carbon dioxide). The water has to be very pure, which usually requires the addition of upstream treatment processes. However, sourcing high-quality water can be a problem worldwide, particularly in good power generation locations (desert regions with high solar power potential). In these cases, the power will have to be transported to large water sources first (seas or oceans). Salty sea water has to be treated, which involves using more energy. If a long-term switch to this kind of system is to take place globally, it could have impacts on natural water levels since large quantities of water are removed from the power plant location and released in another part of the world when the energy vector is used. Moreover, an ethical conflict could arise if clean water is used to provide power rather than being used for drinking water and food production.

In the long term, a GHG-neutral energy system cannot obtain the carbon dioxide needed for power-to-gas technology from fossil CO_2 sources such as power stations. Carbon dioxide would have to be obtained from biogenic sources, such as biogas plants, and from process-related CO_2 emissions,[LXXVI] e.g. from the cement industry. The potential locations outside Germany do not usually have the equivalent volumes of carbon dioxide available to convert the renewably derived hydrogen. In these cases, large amounts of energy would have to be used to obtain carbon dioxide from the surrounding atmosphere using air-separation plants. At the current stage of development, it is not possible to predict the availability of water and carbon dioxide or the potential conflicts or restrictions that may arise in relation to resource conservation and the catalyst materials and quantities required.

Increasing use of hydrogen would result in fewer losses and would require fewer renewable production plants. Moreover, less GHG-neutral carbon would be needed for methanation.[LXXVII]

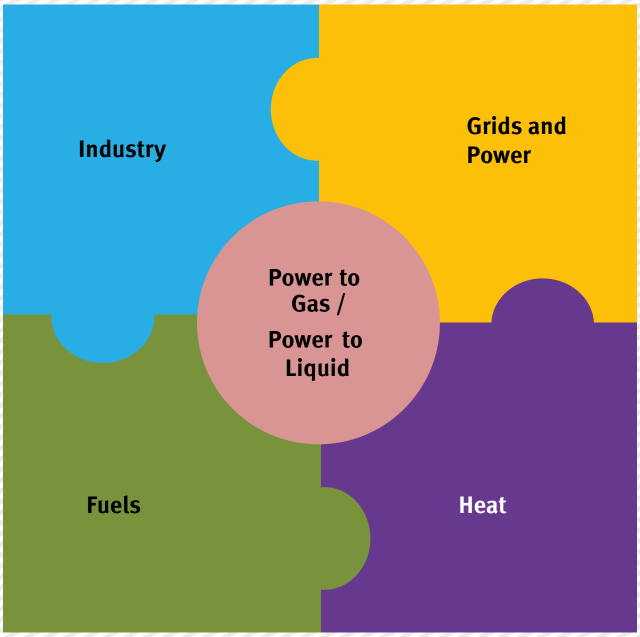
Because of the current status of this technology and the economic aspects, support for research and development will be needed in the short and medium term, and pilot plants will need to be funded to ensure that the technology will be ready in time.

LXXV Combined heat and power plant with a district heating system in combination with direct electric heating, which uses electricity to provide heat in absolute surplus situations.

LXXVI These are not GHG-neutral.

LXXVII In the form of carbon dioxide.

Figure B-17: Overview of the potential scope of application of power-to-gas/power-to-liquid technology[85]



B.3.4 Heat supply

The majority of final energy is currently used to provide heat. Systematic energy-savings could bring about a significant reduction in this high consumption rate. Updating the existing building stock and tightening the provisions of Germany's Energy Saving Ordinance (Energieeinsparverordnung) can make a significant contribution towards lowering final energy consumption. There is also a big potential for energy savings in industry, through systematic in-house (cascading) and external use of industrial waste heat.

In principle, it is possible to completely restructure heat production as a GHG-neutral system based on renewables. GHG-neutral space heating can be achieved by switching to direct use of renewable energy sources, including solar thermal and geothermal energy. In addition, renewable electricity can be used in efficient heat pumps, and renewable fuels, such as methane, can be used in condensing boilers or CHP plants. The choice of technology and source of final energy will depend on the commercially viable energy savings that can be made, the heat consumption, the availability of the energy vector and the costs of the different technologies.

In the long term, assuming that significant energy savings are made, a renewable energy system is likely to involve stronger links between the power and heat markets. At the moment, this occurs primarily in CHP plants, which offer efficient electricity generation and heat provision. The potential applications and cost-effectiveness of CHP plants are likely to change considerably in the future as a result of a steep decline in space heat consumption. CHP plants can perform a stabilising function in an energy supply system based on fluctuating renewables in combination with heating grids and heat storage facilities and can act as backup power stations for the reconversion of renewably sourced fuels into electricity. In addition, in times of particularly high renewable power generation, which exceeds the demand for electricity at the time and the available conversion capacity of the hydrogen electrolysis plants, CHP plants can convert electricity directly into heat. This heat could be used on an industrial scale via the heating network and in conjunction with decentralised heat storage facilities and heat pumps. The technology for converting electricity directly into heat on an industrial scale is cost-efficient and state-of-the-art. Furthermore, storing the heat makes it possible to save on renewable fuels (methane or hydrogen) later on when heat is in demand. This power-to-heat technology can be a useful component of renewable energy supply in the context of demand-side management in the medium and long term.

GHG-neutral process heat can be supplied by converting process technology, making greater use of renewable electricity and using renewable fuels. The potential renewable fuels are primarily renewably sourced hydrogen and methane. When methane is used as an energy vector, all the elements of the existing natural gas system can be used, so it is possible to switch to methane without problems. Moreover, a switch to pure oxygen combustion or the oxy-fuel method could be possible for stationary applications.

B.3.5 Energy imports

On account of the regional spread and existing potential for renewables, and the economic aspects associated with developing them, a proportion of Germany's GHG-neutral energy supply will continue to be based on energy imports, even in the long term. These imports could take the form of renewable electricity, renewable hydrogen, methane or renewable liquid fuels. The various different import pathways and their possibilities are outlined below.

B.3.5.1 Electricity

When assessing potential energy imports in the form of electricity, the main consideration is the transmission capacity of the electricity network bringing the power to Germany. In the following we provide an overview for this import option based on a study of the literature, and estimate the potential long-term import capacity.

Interconnector cables,[LXXVIII] link the German transmission network to neighbouring countries, thereby integrating it into the European transmission network. The European transmission network is densely structured, which makes it very difficult to provide figures for physical transmission capacities between countries. This would require complex load flow calculations, so, in order to be able to provide information, simplified potential import/export transactions between the individual countries are published. According to these figures, the German interconnector cables had a usable export capacity of around 15.5 GW in 2010 and an import capacity of around 18.5 GW.[LXXIX,86] These net transfer capacity (NTC) values represent the maximum marketable capacity, rather than the maximum physical flow. The actual available capacities may be different since they are subject to seasonal fluctuations (e.g. between summer and winter) and the interactive effects of interconnector cables.

LXXVIII An interconnector cable is a cross-border connection between one electrical control area and another. It is a cable linking electrical substations in different control areas.

LXXIX Net transfer capacity (NTC) values for 2010.

The interconnector cables and the entire European transmission network will need to be expanded, partly to balance out fluctuations in renewable energy over a wide area, but also to create a single European market for electricity. Because of its location, Germany will become increasingly important as a central electricity transit country as cross-border trade in electricity grows.

Based on several studies,[LXXX] it is possible to calculate an increase in the transmission capacity of the interconnector cables (for electricity imports) to between around 40.4 and 41.5 GW by 2030[87,88] and to between around 57.9 and 64.1 GW[89,90] by 2050 (around 10 GW every ten years on average). According to these forecasts, the greatest expansion will involve interconnector cables between Germany and its neighbours to the south and south-west (Austria, Switzerland and France) and Scandinavia. Since it is difficult to take account of network technology and social aspects in the network expansion scenarios, a pilot study by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU pilot study)[91] assumes that only half of the cost-optimal network expansion level for 2030 can be implemented because of the situation on the energy market, the political context and social barriers, such as a lack of acceptance. Based on this, a further network expansion was calculated for 2050, entirely on the assumption that specific investment in underground cables will be five times higher. The BMU pilot study assumes an additional transmission capacity amounting to 79.4 GW by 2050 for transporting electricity from solar thermal power stations in north-west Africa to Europe (38.9 GW via Spain and 40.5 GW via Italy). It is the need to transport these electricity imports to the individual countries that accounts for most of the additional network expansion measures listed in the BMU pilot study. The predicted expansion goes far beyond existing plans. Timely, Europe-wide coordination, planning and implementation of the expansion measures are therefore vital, as well as promotion to gain the necessary acceptance.

Expanding the European network will considerably reduce bottlenecks in electricity transmission, which means the European electricity generation capacity can be used to cover national electricity demand. The energy scenarios for the German government's energy concept 2011[92] show that the cost advantages that can be achieved from this (particularly through the use of wind energy in northern Europe and solar energy in the Mediterranean) will lead to increasing net electricity imports for Germany. The maximum net electricity import level calculated in the study is 143.3 TWh. The net electricity import figure for 2050 calculated by Dena, the German Energy Agency, is of a similar magnitude: 134 TWh.[93] However, these values are not the maximum possible imports. They represent the imports necessary (as calculated in the simulations) to meet domestic demand for electricity. Taking the current average capacity utilisation of the interconnector cables (ratio of imported energy volumes to the NTC value) of 2358 h and the aforementioned NTC values for 2050, gives a figure for possible electricity imports of around 137 to 151 TWh for 2050.[LXXXI] In theory, a maximum of 507 to 561 TWh p.a. would be possible with full capacity utilisation (8760 h) — less exports, which at present amount to around 56 TWh[94] (the Dena analyses[95] produced a virtually constant export rate up until 2050). This is not realistic in practice, however, since the NTC values represent maximum values and cannot be achieved simultaneously, since this could, in the worst case, overload the dense network. Moreover, some of the transmission capacity may be intended for onward transport to other countries, which

LXXX Power Grid Development Plan 2012, BMU pilot study 2011 and energy scenarios for a national German energy concept.

LXXXI Analyses in the Dena study on integrating renewables into the German/European electricity market showed that the average capacity of the German cross-border transmission cables, taking account of existing capacities and expected expansion projects in the Ten-Year Network Development Plan (TYNDP) particularly in terms of imports, will be nowhere near fully utilised (only 25% in 2020). The main bottlenecks at the moment affect German exports.

means the amounts cannot be apportioned in full to trade between Germany and the neighbouring country in question.

Key factors affecting the possibilities and potential of this import option will be timely discussion and planning of a European electricity network for 2050. The agreement needed to achieve this faces major challenges. National interests, financing issues and low levels of public acceptance (because of interventions in the landscape and natural environment and because of potential health risks, particularly in transit countries) play a particularly important role.

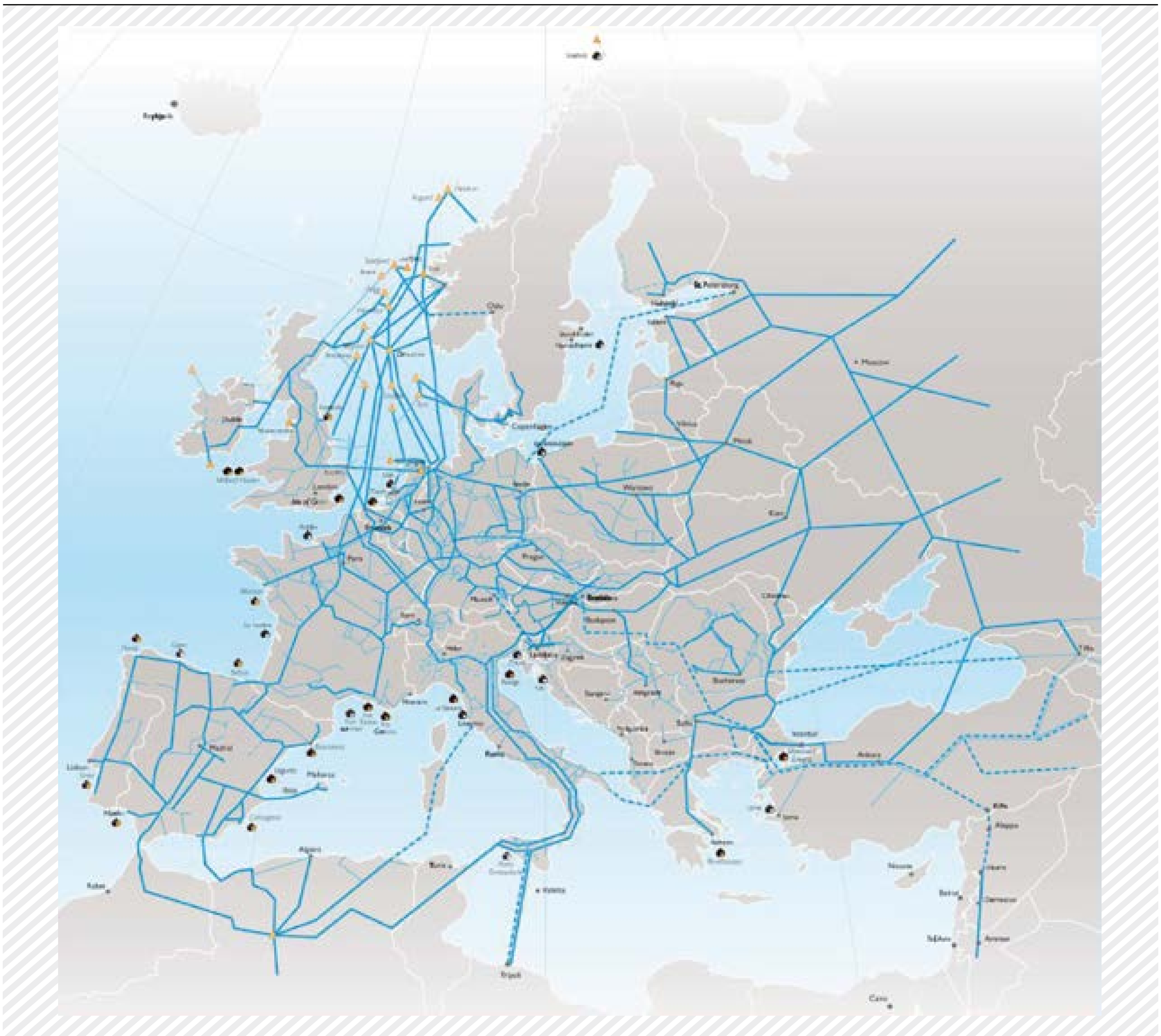
B.3.5.2 Renewably sourced gases

In the following we give a brief overview of the possibilities for importing renewably sourced gases.

Germany's gas grid is connected to neighbouring countries and integrated in the European network via gas pipelines. Integration of the natural gas storage facilities is largely via the gas pipeline network, upstream of the transport and distribution grids. Germany has a much denser gas supply grid than other European countries (20% of all European natural gas pipelines are installed in Germany). Uptake and distribution of renewably sourced gases within this network is therefore much less of a problem than in other European countries. Scandinavia, for instance, has no nationwide supply network and few natural gas export pipelines. In addition, North Africa does not have a well-developed gas network infrastructure to export renewable gases. The local infrastructure will have to be expanded in order to export the gases produced at decentralised renewable energy production locations in other countries to Germany or other European countries. As with the electricity network, the planning and financing of such major international projects is extremely complex and time-consuming. Interventions in the landscape and natural surroundings tend to be less severe for the construction and operation of natural gas transport pipelines than for electric power lines, which means there is greater public acceptance for them.

Renewably sourced hydrogen can be transported by pipeline by blending it into the natural gas network. The disadvantage of this, however, is that the hydrogen can then no longer be used as a raw material. No limit values have been set for hydrogen in the gas quality standards specified for cross-border transport within Europe (EASEE-Gas).

Figure B-18: European gas network map[96]



Other pipelines
- existing
- under concstruction, projected or planned
- natural gas field

Liquified natural gas (LNG) receiving terminal
- in operation
- under construction pr projected

As an alternative to pipeline transportation, methane can be transported in the form of liquefied natural gas (LNG). Once the renewable methane has been produced, it is transported by pipeline to the LNG terminal, where it is liquefied and dispatched. The liquefaction process is energy-intensive and usually involves cooling the gas to below its boiling point. Shipping the LNG results in a loss of 0.15 %/d[97] as a result of the gas evaporating again. Regasification takes place at the import terminal by decompressing and warming the methane. Figure B18 shows LNG terminal locations. There are as yet no LNG terminals in Germany. In addition, potential countries for renewable power plants have no LNG export capacity (e.g. Turkey) or only limited capacity (North Africa), so that major infrastructure investments would be necessary in the long term if this transport option were to be implemented on a greater scale.

B.3.5.3 Summary

Not all power production locations are suitable for every type of energy transport. Local conditions, such as connection to the electricity or gas network and spare transport capacity, the availability of LNG export terminals, etc. play a crucial role. In addition, import routes involving pipeline and cable transport are dependent on pipeline and transmission capacity. Energy losses vary depending on the route and means of transport.

Essentially, importing electricity directly via the transmission network is the most energy-efficient way of meeting electricity demand. The efficiency rate for converting hydrogen and methane back into electricity is around 35%. If we also take into account the transport losses between the place of production and Germany, the efficiency level is much lower. Various studies assume a potential electricity import level of around 150 TWh p.a. in the long term. In technological terms, a bigger expansion of the electricity networks is conceivable, but low levels of public acceptance because of interventions in the landscape and natural environment need to be taken into account.

There are three main import options for the provision of renewable gases: transporting electricity to Germany and using it for conversion processes there, transporting gases by pipeline, or transporting gases by ship (LNG). All these routes require different energy inputs. Moreover, further energy inputs are required depending on the distance between the place of production and place of use. Since the LNG/ship route allows transport to be adjusted in line with demand, there are no restrictions on transport capacities, at least in terms of the technology.

Importing renewable methane results in variable energy losses because of the wide range of import routes and the number of different production locations. In energy terms, this import option is most efficient when there is infrastructure in place. In the case of distant production locations and unfavourable infrastructure conditions (e.g. in Egypt), transport in the form of LNG can be more efficient.

Where imported hydrogen is used for energy or as a raw material, transporting it from nearby production locations in the form of electricity and converting it in Germany is more energy-efficient.

When considering the extent to which energy will be imported and in what form, particular attention should be paid to the cost of producing electricity at the various different locations and the cost of developing these locations. In all cases it will be necessary to expand and adapt the relevant infrastructure.

B.4 Final energy consumption 2050

Our results show that a complete switch to a renewable energy supply is possible in the long term. This would reduce energy-related greenhouse gas emissions to almost zero. There is a limitation where technology-related GHG emissions are concerned. For instance, methane slip in combustion engines cannot be avoided even when renewable fuels are used. Because of their low levels, such emissions are disregarded in this study.

To be able to achieve a GHG-neutral energy supply, it will be necessary to make systematic use of potential efficiency gains and energy savings.

In the following sections we present the final energy consumption figures for 2050, based on the Federal Environment Agency's Energy Target 2050 study and on Chapters C and D.

B.4.1 Final energy consumption in private households

Final energy consumption by private households in Germany in 2050 was estimated in the Federal Environment Agency's Energy Target 2050 study to be 105.4 TWh. According to the assumptions on which this calculation is based, there will no longer be any demand for fuels by then — just for renewable electricity. In terms of space heating for residential buildings, the study assumed an ambitious increase in insulation standards and, as a result, a very low demand for heat, provided exclusively by heat pumps supported by solar thermal collectors. Since current renovation practices are wildly different from these assumptions in terms of the standard and rate of refurbishment, we present two further possible development scenarios for final energy demand in 2050.

By way of comparison, the first variant (V1) presents the assumptions from the Energy Target 2050 study. This assumed an energy-efficiency renovation rate of 2.7% p.a. and an average useful energy requirement after renovation of 30 kWh/m²p.a.[LXXXII]

A second variant (V2) assumes that the proportion of buildings undergoing energy-efficiency renovation work from 2020 onwards will be only 1% per year instead of 2.7%, in line with the current renovation rate. The assumptions for energy requirements following renovation are the same as those used in V1, which means that V2 is also more ambitious than current renovation practice. Renovation measures that comply with Germany's Energy Saving Ordinance (Energieeinsparverordnung) 2009 currently result in a useful energy requirement of around 60 to 110 kWh/m² p.a.

The third variant (V3) assumes a high renovation rate of 2.7%, but assumes a higher proportion (around 11%) of the buildings will be suitable for only limited energy-efficiency measures e.g. because they are classed as protected monuments. This is a higher figure than in the original variant (V1). The specific useful heat requirement in these cases is only reduced from 144 kWh/m²p.a. to around 90 kWh/m²p.a., and in the other cases to 30 kWh/m²p.a. This assumption is based on the dissertation by Vallentin (2001),[98] which calculates the optimum climate protection standards achievable with today's technologies.[LXXXIII] According to these, the achievable useful energy requirement taking into account economic aspects is between 70 and 120 kWh/m²p.a.

The assumptions for new buildings are the same in all variants. Table B-9 provides an overview of the assumptions and the proportion of total living space that each type of building is expected to occupy.

The final energy requirement will depend on the structure of the final energy vectors and the heating technologies used. In V1 the fully renovated building stock is heated with electric heat pumps combined with solar thermal collectors. The use of electric heat pumps in unrenovated buildings is not efficient. We therefore assume that unrenovated buildings in V2 and partially renovated buildings in V3 are heated with gas-fired condensing boilers that use renewably sourced methane. District heating plants could also be used to convert the methane back into electricity, but gas-fired condensing boilers, a somewhat less favourable technology, were deliberately chosen for a more conservative estimate. Since high flow temperatures would still be required in unrenovated and partially renovated buildings, solar thermal support for space heating would not be used in these cases. Figure B-19 shows the energy requirement for space heating in residential buildings for the three variants described.

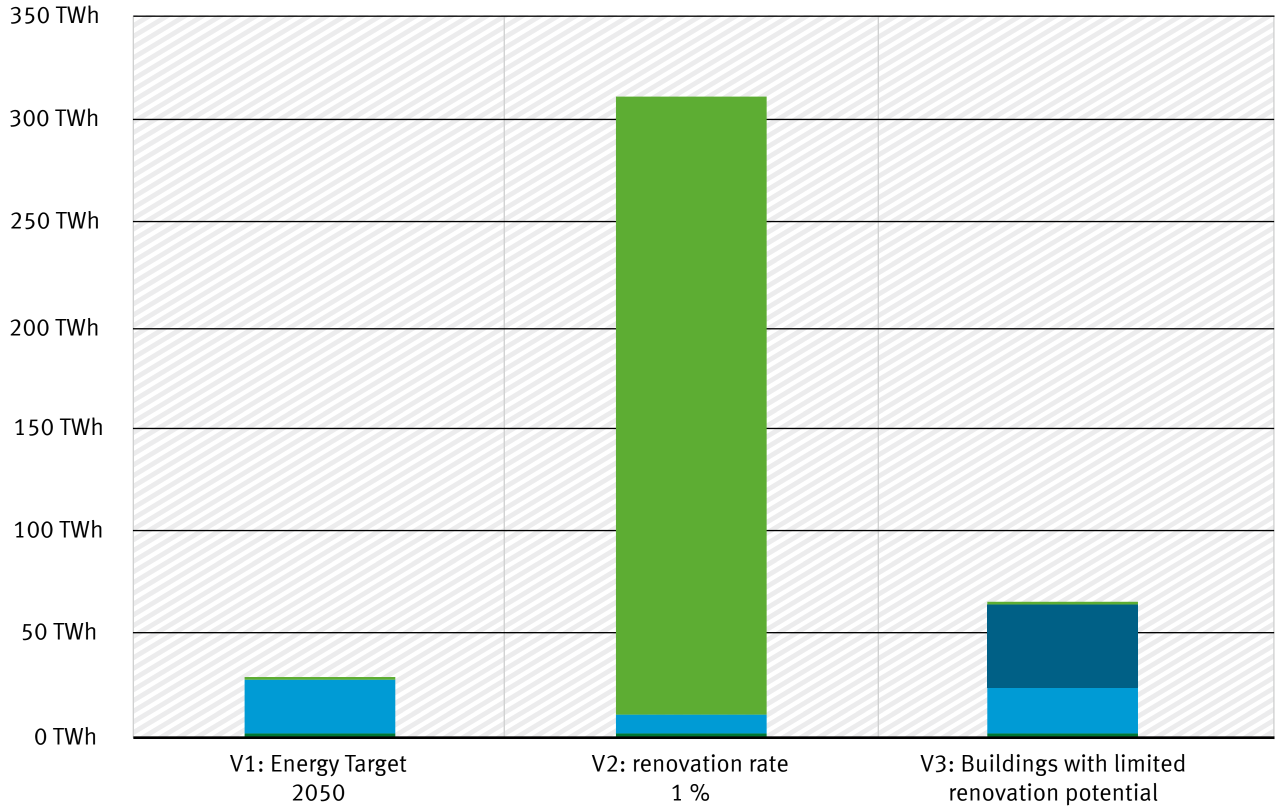
LXXXII This average value already includes buildings that are harder to renovate. The higher energy requirement for these is offset by buildings that can be renovated to a higher standard.

LXXXIII The research also confirms the assumption for buildings capable of high renovation standards (target standard 35 kWh/m²p.a., and says useful energy requirements as low as 20 kWh/m²p.a. are technically feasible).

Table B-9: Overview of assumptions for three different scenarios for space heating requirements in 2050

	V1 **Target 2050**	**V2** **1% renovation rate**	**V3** **Buildings with limited renovation potential**
Energy-efficiency renovation rate	2.7% p.a.	1% p.a.	2.7% p.a.
	Specific useful heat requirement [kWh/m2 p.a.]:		
New buildings	10	10	10
Renovated buildings	30	30	30
Buildings with limited renovation potential	-	-	90
Unrenovated buildings	-	144	-
	Share of living space in 2050 (living space 2050: 3.53 billion m^3):		
New buildings	18%	18%	18%
Modernised buildings	82%	30%	71%
Buildings with limited modernisation potential	-	-	11%
Unmodernised buildings	-	52%	-

Figure B-19: Final energy consumption for space heating in 2050 for three different scenarios



	V1: Energy Target 2050	V2: renovation rate 1 %	V3: Buildings with limited renovation potential
Unrated buildings (gas boiler)	0.0	299.9	0.0
Buildings with limited renovation potential (gas boiler)	0.0	0.0	39.7
Renovated buildings (electric heat pumps + solar)	25.4	9.3	22.0
New buildings (electric heat pumps + solar)	1.9	1.9	1.9
Total	27.3	311.1	63.5

It can be seen that a low renovation rate (V2) would result in a more than tenfold increase in the final energy requirement for space heating in residential buildings, as a result of the extra 300 TWh of renewable methane required each year for unrenovated buildings. The higher figure for partially renovated buildings in V3 doubles the final energy consumption compared with V1, but the methane increase is moderate at just under 40 TWh p.a. The fact that around 11% of the buildings in V3 consume more than 60% of the final energy demand for space heating suggests that paying for heating in these partially renovated residential buildings could be a problem in the future. The energy requirement for new buildings plays only a minor role in all variants (1.9 TWh p.a electricity for heat pumps).

In addition to the final energy requirement for space heating there is the final energy required to heat water. Hot water requirements are not linked to the renovation status of a building. Consequently, only the heating technologies differ from the *Energy Target 2050* study: unrenovated (V2) and partially renovated buildings (V3) use gas-fired condensing boilers for water heating instead of electric heat pumps, supported by solar thermal plants. The final energy requirement for space heating and hot water in residential buildings is summarised in Table B-10.

Table B-10: Annual final energy requirement for space heating and hot water in residential buildings for three different scenarios

	V1 Target 2050	V2 1% renovation rate	V3 Buildings with limited renovation potential
Electricity	40.7 TWh	17.6 TWh	35.8 TWh
Methane	0.0 TWh	322.5 TWh	44.5 TWh
Total	**40.7 TWh**	**340.1 TWh**	**80.3 TWh**
For information: Solar heat	29.7 TWh	26.5 TWh	29.0 TWh

The following calculations are based on the third variant (V3). This assumes a wider range of solutions for residential buildings, takes account of a more varied heating structure and still complies with the ambitious conditions of the Energy Target 2050 study.

In addition, private households will need final energy to operate solar and circulation pumps, for lighting and other applications (cooking, washing, etc.). Final energy consumption is summarised in Table B-11.

Table B-11: Final energy consumption by application and energy vector in households in the Federal Environment Agency's GHG-neutral Germany 2050 scenario

	Electricity in TWh	Renewable methane in TWh
Space heating	23.9	39.7
Hot water	11.9	4.8
Solar and circulation pumps	3.6	0
Lighting	1.8	0
Other applications	63.5	0
Total	**104.7**	**44.5**
	149.2	

B.4.2 Final energy consumption in transport

A combination of traffic-avoidance measures, shifts in modes of transport and technical measures designed to increase energy efficiency can lower energy demand in the transport sector in the long term. As explained in Chapter C, we assume direct electricity consumption of 91 TWh, in part for electric vehicles, and liquid fuel consumption of around 533 TWh. This includes Germany's share of international aviation and shipping, which is not included under the current energy accounting rules.

It was not possible to investigate the use of fuel gases in this study. An advantage of these fuels is the low energy losses associated with their production (see Chapter B.5.1).

B.4.3 Final energy consumption in commerce, trade and services

All the assumptions about final energy consumption in this sector have been taken from the Federal Environment Agency's Energy Target 2050 study. Most of them were based on the assumptions in the reference scenario of the WWF's *Modell Deutschland* study.[99] For the year 2050 they include energy efficiency gains in the various fields of application, greater use of waste heat and the use of heat pumps to provide space heating.

Table B-12 shows the final energy requirement in the commerce, trade and services sector in 2050.

Table B-12: Final energy consumption by application and energy vector in the commerce, trade and services sector in the Federal Environment Agency's GHG-neutral Germany 2050 scenario[100]

	Electricity in TWh	Renewable methane in TWh	Renewable fuels in TWh
Space heating	1.9	0	0
Air-conditioning and ventilation	28.1	0	0
ICT[LXXXV]	7.8	0	0
Lighting	18.3	0	0
Mechanical energy	15.8	0	18.6[LXXXVI]
Process heat	18.4	62.4	0
Total energy	**90.3**	**62.4**	**18.6**
		171.3	

B.4.4 Final energy consumption in industry

As explained in Chapter D, we assume industrial processes will consume 159 TWh of electricity in 2050. This figure is on the same scale as the electricity consumption figure calculated for the reference scenario in the WWF's *Modell Deutschland* study.[101] Consumption of renewable fuels and renewable methane is around 199 TWh p.a., which is much lower than in the reference scenario of the WWF study.

In addition to the electricity required for industrial processes, some will be needed for space heating, lighting and ICT. All the assumptions for these are taken from the Federal Environment Agency's *Energy Target 2050* study. Table B-13 shows final energy consumption for industry in 2050. In addition, around 15 TWh of production-related biogenic residual materials will continue to be used in the paper industry (see Chapter D.9). In addition, 282 TWh of renewable methane will be needed in 2050 as a material input in the chemical industry.[LXXXVI]

LXXXIV Information and Communications Technology

LXXXV Fuels for largely mobile applications in combustion engines, particularly for agriculture and forestry, construction vehicles and the military.

LXXXVI Raw material usage in industry is currently not included in final energy accounting.

Table B-13: Final energy consumption in industry in the Federal Environment Agency's GHG-Neutral Germany 2050 scenario (own calculations)[102 LXXXVII]

	Electricity in TWh	Renewable methane in TWh
Space heating	5.8	0
Lighting + ICT	14.7	0
Mechanical energy + process heat	159.2	198.8
Total energy	**179.7**	**198.8**
	378.58	
Material use		**282**

B.5.4 Summary

Table B-14 shows final energy consumption in 2050 for the entire energy sector. Despite shifts towards electricity-based applications in industrial process chains, for space heating and transport, electricity consumption is on the same scale as at present. This is only possible with systematic implementation of energy-efficiency measures. With assumed increases in traffic volumes, final energy consumption in transport can be significantly reduced through the use of efficient engine technologies. Fuel consumption can be lowered considerably by reducing space heating requirements and through in-house heat recovery in industrial applications.

Table B-14: Total energy consumption in the Federal Environment Agency's GHG-Neutral Germany 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	90.3	62.4	18.6
Industry[LXXXIX,XC]	179.7	198.8	0
Transport	91.1	0	533.3
Total energy	**465.8**	**305.7**	**551.9**
		1323.4	
Industry material use		282	
Total energy and material		**1605.4**	

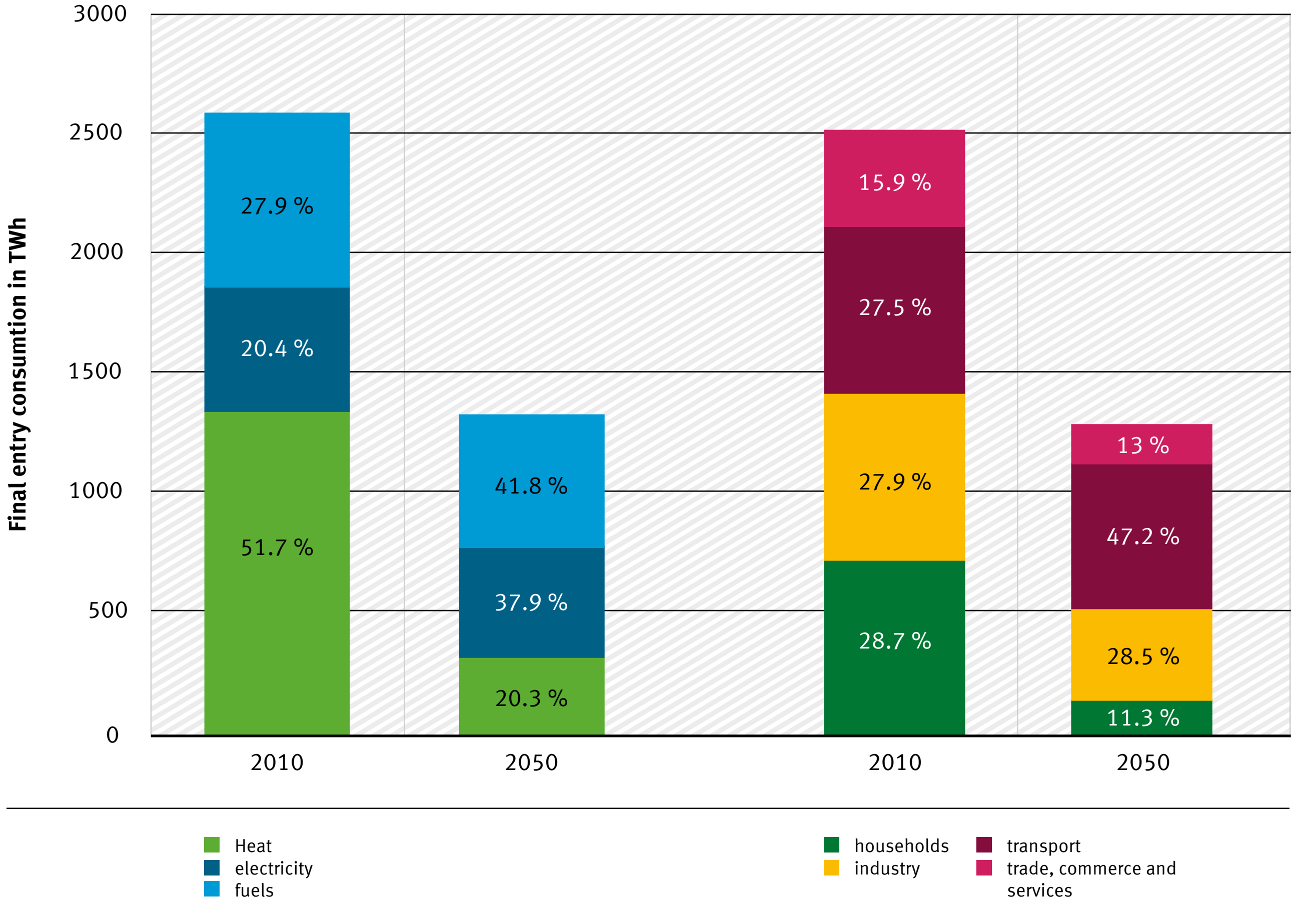
LXXXVII Not including around 15.1 TWh in the paper industry, which is covered by in-house product streams.

LXXXVIII Not including material use amounting to 282 TWh.

LXXXIX Not including around 15.1 TWh from internal product streams in the paper industry.

Figure B-20 shows a comparison of final energy consumption for the years 2010 and 2050.[XC] Overall, final energy consumption can be halved between 2010 and 2050.[XCI]
In particular, considerable reductions can be achieved in the area of heat consumption in private households. Final energy consumption in industry and in commerce, trade and services can also be reduced by at least half, according to our assumptions. Energy accounting calculations for shipping transport in 2010 include only domestic bunker volumes. The German share of international shipping is excluded. Similar rules apply to aviation calculations. Leaving aside the German share of international shipping and aviation transport would considerably reduce final energy consumption in 2050. When this value is included for 2050, there is only a slight reduction in final energy consumption in the transport sector in 2050 compared with 2010 (see Figure B-20).

Figure B-20: Comparison of final energy in 2010 and 2050 (left: by application, right: by sector)[XCII]



XC Use of methane as a material in industry is not included here because it is not included in the 2010 reference values.

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

XCII Not including final energy in the form of renewable methane for use as an input in the chemical industry.

B.5 GHG-neutral energy supply 2050

B.5.1 Total energy demand

As explained in Chapter B.4.5, some energy will be lost during conversion even in a renewable energy system. The following chapter provides an overview of the total energy demand in 2050, i.e. the net electricity generation required.

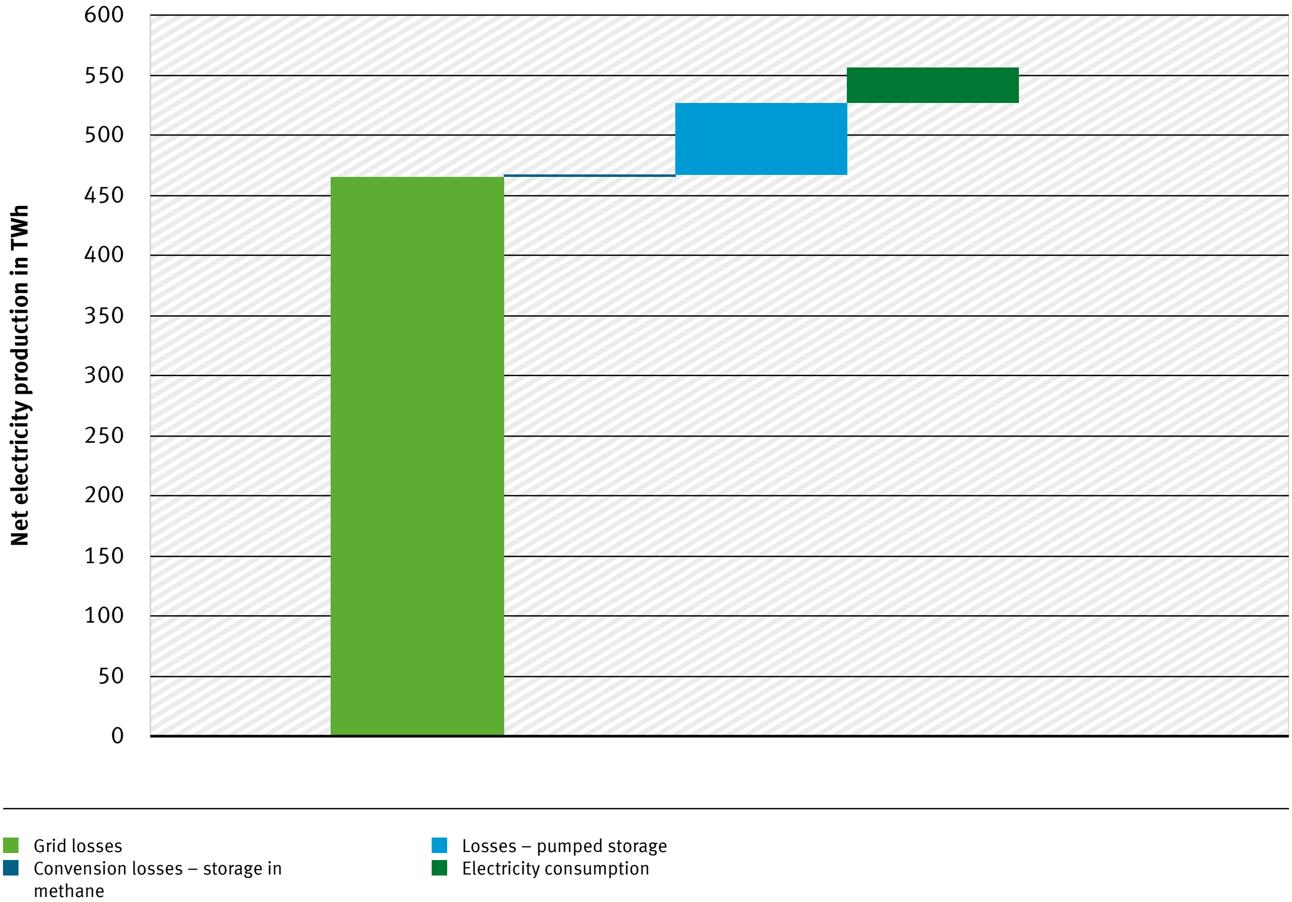
B.5.1.1 Energy required for electricity

A system based on intermittent renewable energy sources has to store energy to average out seasonal fluctuations in the electricity supply. In times of surplus, electricity is converted via electrolysis — and methanation where relevant — into a chemical energy vector: hydrogen or methane (see Chapters B.3.2 and B.3.3). In times when the electricity generated from renewables is not sufficient to meet demand, the hydrogen or methane can be converted back into electricity by back-up power stations. The Federal Environment Agency's Energy Target 2050 study simulated an electricity supply system based entirely on renewable energy sources. The storage requirement was calculated based on an assumed direct electricity consumption of 471.5 TWh p.a.[103] (in this study the assumed figure is around 466 TWh p.a.). The storage requirement varies depending on the assumptions made regarding domestic and European grid expansion, the renewables mix, demand-side management, etc. No simulations were carried out for the present study. In order to be able to make predictions about storage demand, electricity transport losses and net electricity generation, we have made some estimates based on the Federal Environment Agency's *Energy Target 2050* study.[XCIII] This appears justified in view of the fact that the electricity consumption figures are very similar. The resulting energy demand or net electricity generation figures are presented in Figure B-21. A total of 557 TWh p.a. will be needed to meet the demand for electricity.[XCIV]

XCIII See section 7.3.4 of Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

XCIV In the Federal Environment Agency's *Energy Target 2050* study, the net electricity generation required is 564 TWh for an electricity consumption level of 471.5 TWh.

Figure B-21: Net electricity generation to cover direct electricity use in the Federal Environment Agency's GHG-neutral Germany 2050 scenario.



B.5.12 Energy required for heating fuel and material uses

In 2050, renewable methane will be used as a fuel and as an input material in the chemical industry. Some energy is lost during the conversion processes involved in methane production. When calculating the losses we have assumed a general efficiency rate (in line with Chapter B.3.3) of 72% for electrolysis and 80% for methanation.[104]

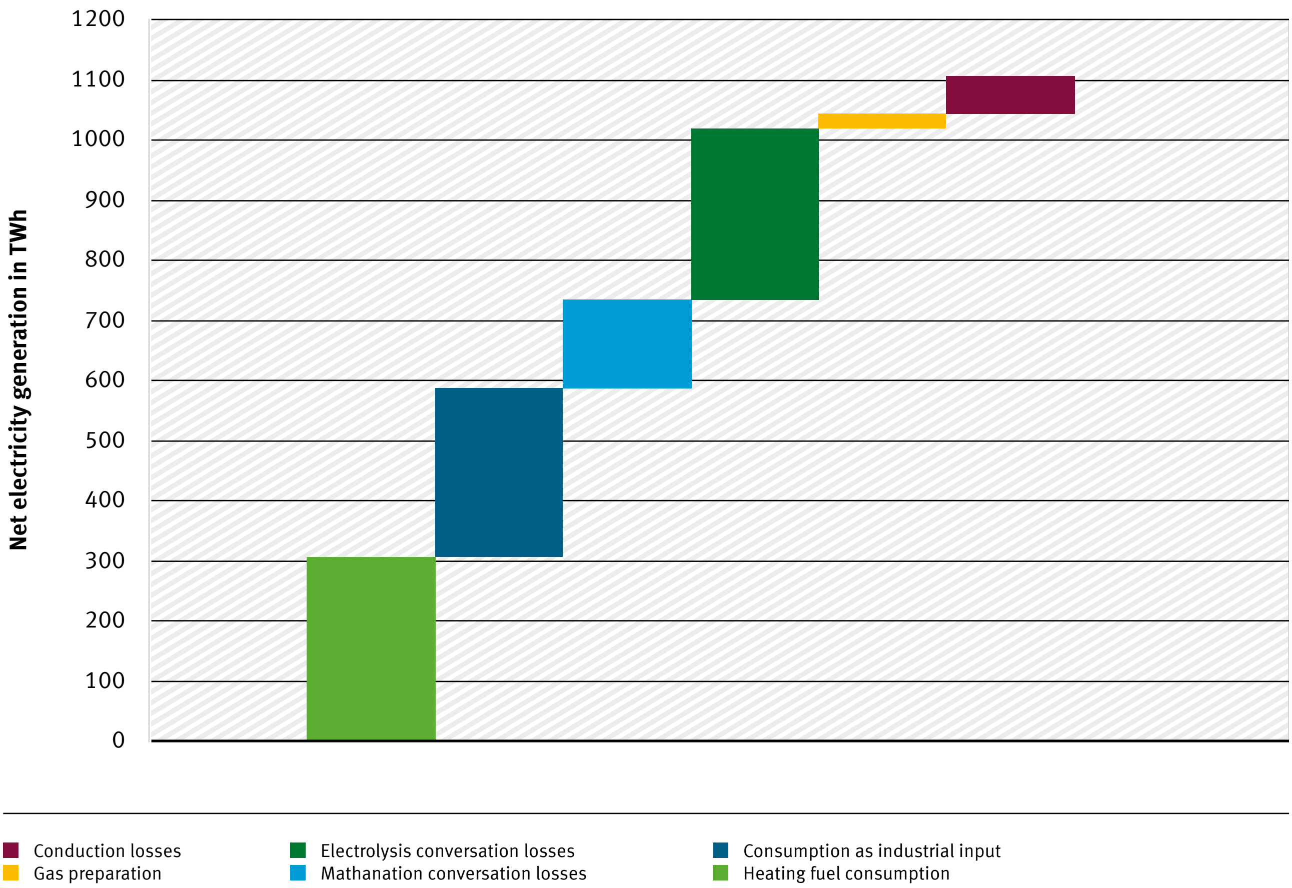
Different energy inputs are needed to produce these materials depending on the CO_2 source used. Within Germany, all the CO_2 produced in biomass fermentation plants, industrial processes and stationary fuel applications[XCV] can be captured and made available for domestic methanation processes. The total amount of CO_2 available from these sources is around 24.6 million tonnes. Around 27 million tonnes of CO_2 will be needed each year to meet the energy and material demand for renewable methane. Depending on the availability and viability of domestic locations, the atmosphere can also be a source of carbon. Another possibility is for methane to be produced from atmospheric CO_2 at low-cost locations in other countries.

Nevertheless, we need a rough estimate of the net electricity that needs to be generated to produce around 588 TWh p.a. of methane. To calculate this, the assumed energy demand for gas processing, i.e. to obtain CO_2 from exhaust gases and from the atmosphere, and the energy required to obtain oxy-

XCV By realising virtually closed cycles for energy applications of fuels (methane).

gen for the oxy-fuel process are based on the figures in Chapter B.3.3.6. It is evident that the oxy-fuel process and methanation based on domestic CO_2 streams are more energy-efficient than obtaining the entire CO_2 requirement from the atmosphere. Gas processing to obtain CO_2 therefore represents only a minor amount in Figure B-22.

Figure B-22: Net electricity generation required for the supply of heating fuel in the Federal Environment Agency's GHG-neutral Germany 2050 scenario



In total, we estimate that over 1000 TWh p.a. net electricity will need to be generated to meet the final energy demand for heating fuel. In addition, some energy is lost when methane is imported. The extent of these losses varies depending on the production location, transport route and mode of transport (methane via pipeline and the gas grid or as LNG). These losses are not investigated in detail here, although we are aware that they are not negligible and can amount to several hundred TWh per year.[XCVI]

B.5.1.3 Energy required for motor fuel

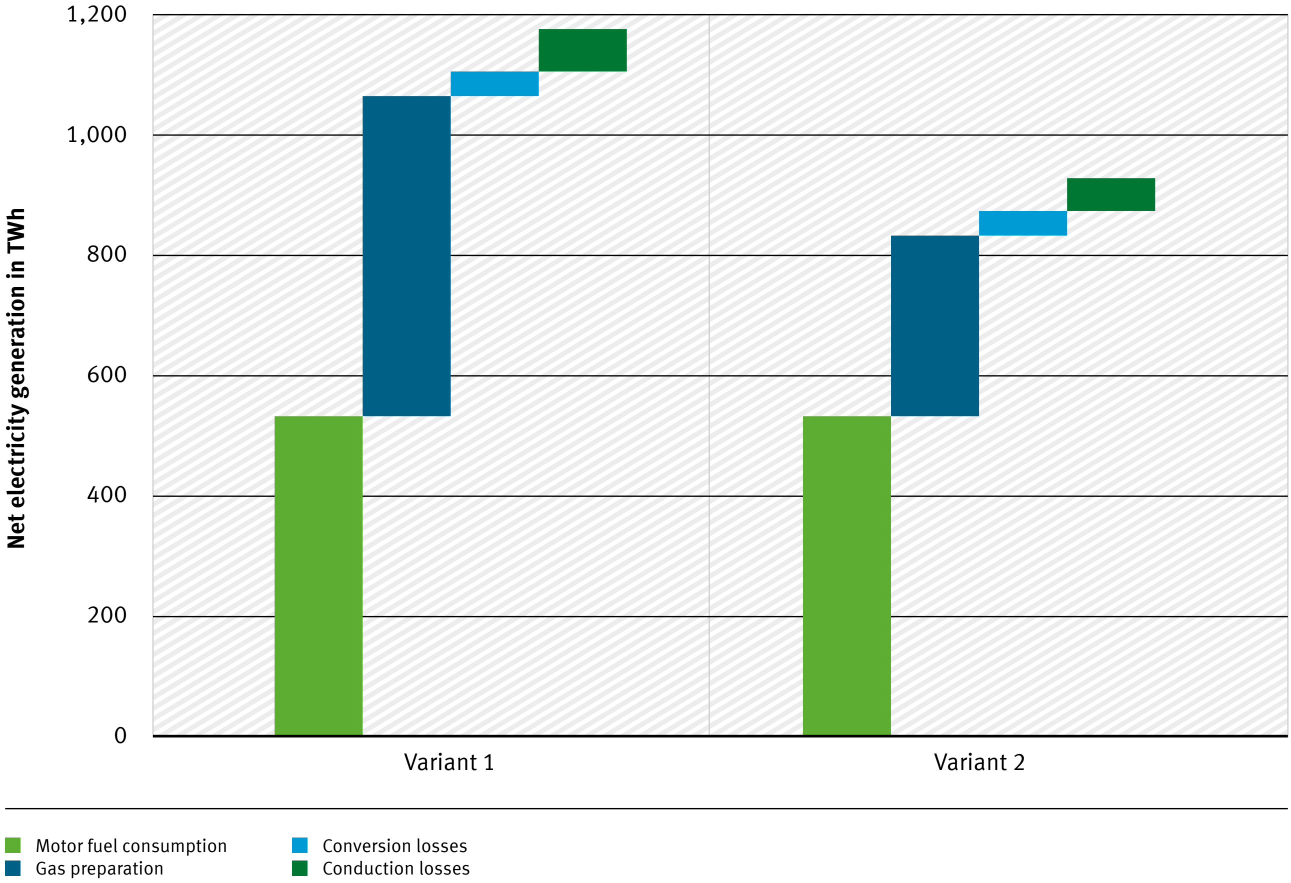
The motor fuel supply is based primarily on renewably sourced liquid fuels produced in power-to-liquid facilities. Since this technology is still in the early stages of development, it is difficult to estimate how efficient it will be and to estimate the amount of renewable electricity that will be required. In

XCVI Particularly if the entire fuel requirement is imported and if it is transported in the form of LNG.

order to give an indication of scale, in the following we have assumed a conservative overall efficiency rate of 50% (variant 1) and a forward-looking rate of 64%[XCVII] (variant 2).

Carbon dioxide is also needed for the production of liquid fuels. Most of it must be extracted from the atmosphere. The possible energy requirement range is shown in Figure B-23. Electricity for direct use in the transport sector (electric vehicles, etc.) is already included in the calculations for the energy required for electricity (see Chapter B.5.1.1). The energy losses associated with fuel transport have been ignored.[XCVIII]

Figure B-23: Net electricity generation[XCIX] for the supply of motor fuel in the Federal Environment Agency's GHG-neutral Germany 2050 scenario



B.5.1.4 Summary

The total energy demand for the energy supply, transport and industry sectors is difficult to determine because of the large number of possible combinations. Nevertheless, we have attempted to calculate a rough estimate of the energy required based on the assumptions given. The estimated net electricity generation required is between 2600 and 2850 TWh p.a. Allowing for further losses, it can be assumed that, based on the assumptions made and the associated energy-efficiency measures and techni-

XCVII Based on the Federal Environment Agency's study (2013): Treibhausgasneutraler Verkehr 2050: Ein Szenario zur zunehmenden Elektrifizierung und dem Einsatz stromerzeugter Kraftstoffe im Verkehr (GHG-neutral transport 2050: A scenario for increasing electrificatiob and the use of power-derived fuels in transport).

XCVIII See Chapter B.5.1.2.

XCIX Variant 1 assumes an efficiency rate of 50%; variant 2 assumes an efficiency rate of 64%.

cal process improvements, around 3000 TWh (net) renewable electricity will be required each year for a 100% renewable energy supply. These figures include the energy required to produce renewable methane for material applications.

B.5.2 General overview for developing a GHG-neutral energy supply

The results show that switching the entire energy supply to renewables is technically feasible. The system would be based largely on direct use of renewable electricity, renewably sourced hydrogen produced by electrolysis of water and renewably sourced hydrocarbon compounds (methane and fuels). The proportion of each of these three energy vectors in the final mix is limited by technology. To aid comprehension, a qualitative representation of a feasible solution space for this mix is provided in Figure B-24.

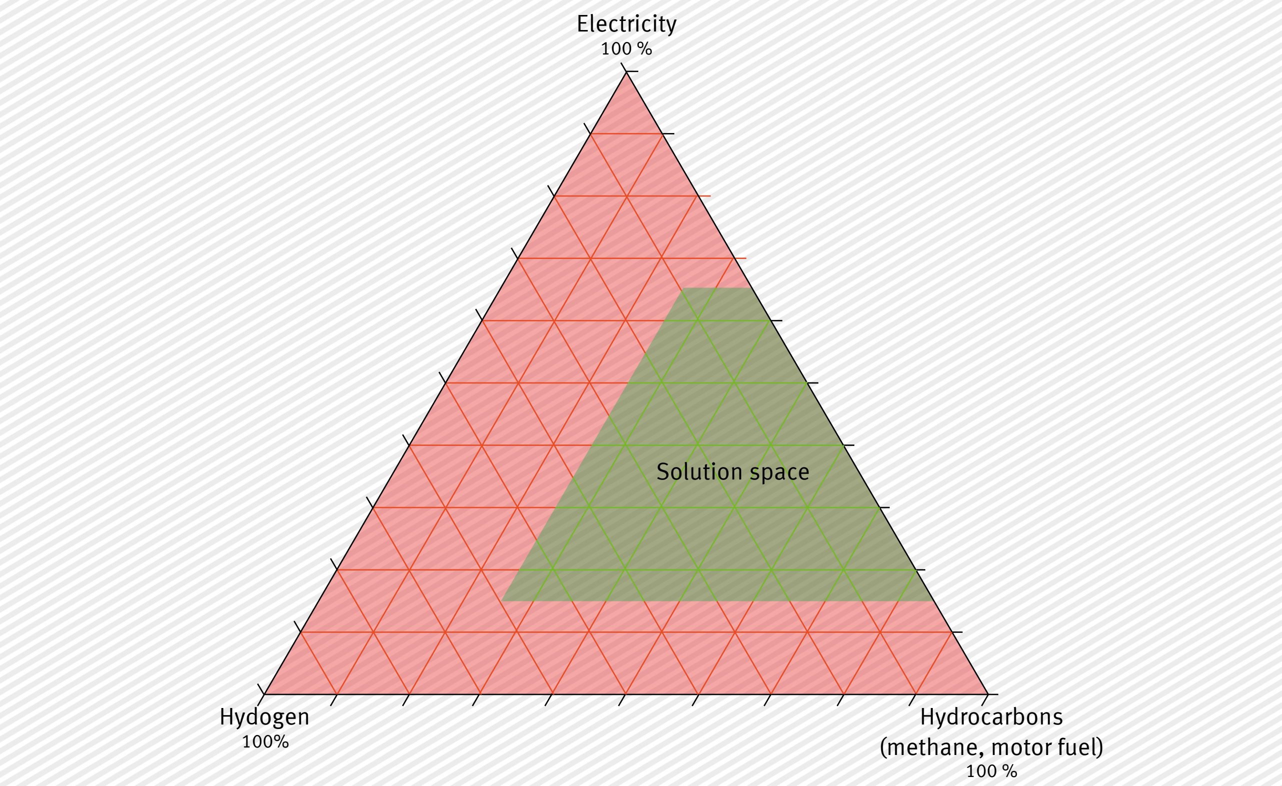
It is not possible to base the entire energy supply on renewable electricity as the final energy vector because its use is limited in some areas, particularly in the transport sector, and electricity cannot be used directly in aviation and shipping. It is not possible to do without electricity as a final energy vector altogether because it is required for certain applications, e.g. communications technology and lighting. It is realistic to assume that there would be a very high proportion of electricity in the final energy vector mix in a renewable energy system. This also became apparent in the previous sections, e.g. with the shift towards efficient electricity-based space heating (using heat pumps) and towards a heavily electricity-based energy supply for process heat.

The maximum share of hydrogen in the final energy carrier mix is also limited by technology because it cannot be used in some areas of the transport sector, particularly on long-haul flights. There is no minimum limit. As the previous sections show, a GHG-neutral energy supply without hydrogen as a final energy vector would be feasible. However, because of the higher energy efficiency levels associated with hydrogen production, and the fact that no carbon source is needed, a higher share of hydrogen would be advantageous. Because of the need for more research and development, this path has not been investigated in greater detail in this study.

Since the potential for fuels from biomass is small (see Chapter B.3.1), there is no alternative to renewably sourced hydrocarbon compounds for heating and motor fuels in a GHG-neutral energy system if biomass is not to be used for energy purposes.

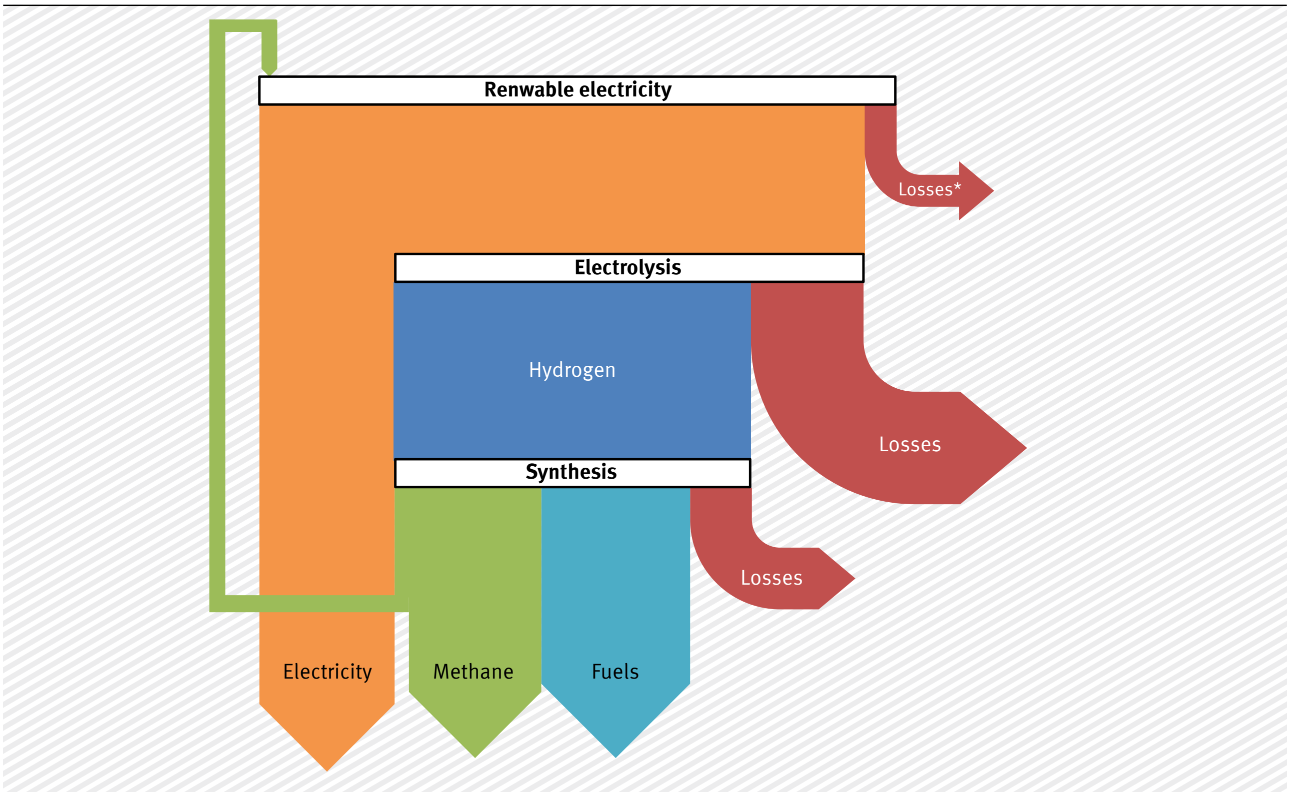
The possible solution space for the mix of final energy vectors will depend on changes in the ratios as a result of technological developments, and changes to the current technical limitations on using the individual final energy vectors. The final energy vector mix will settle within the bounds of these technical restrictions, based on the energy losses, efficiency levels, availability of resources, usability in various fields of application and further technological developments.

Figure B-24: Qualitative representation of the final energy vector mix in a triangle diagram, own graphics.



The possible energy flow is shown in qualitative terms in Figure B-25. The size of the arrows is proportional to the calculated energy flows. The figure does not show further transport losses incurred when importing renewable gas and fuels or the potential for hydrogen applications.

Figure B-25: Qualitative energy flow representation,[C,CI] own graphics



* incl. grid losses, losses from consumption of methane into electricity and losses from use of biomass for electricity provision

The results show that the provision of heating and motor fuels leads to greater conversion losses in a renewable energy system than in today's fossil energy system (see Figure B-26). In 2010, statistics showed losses[CII] of around 27% in the existing energy system. Based on the assumptions above, a renewable energy system would produce losses[CIII] of approximately 44%.[CIV]

C Including demand for renewable inputs for the chemical industry.

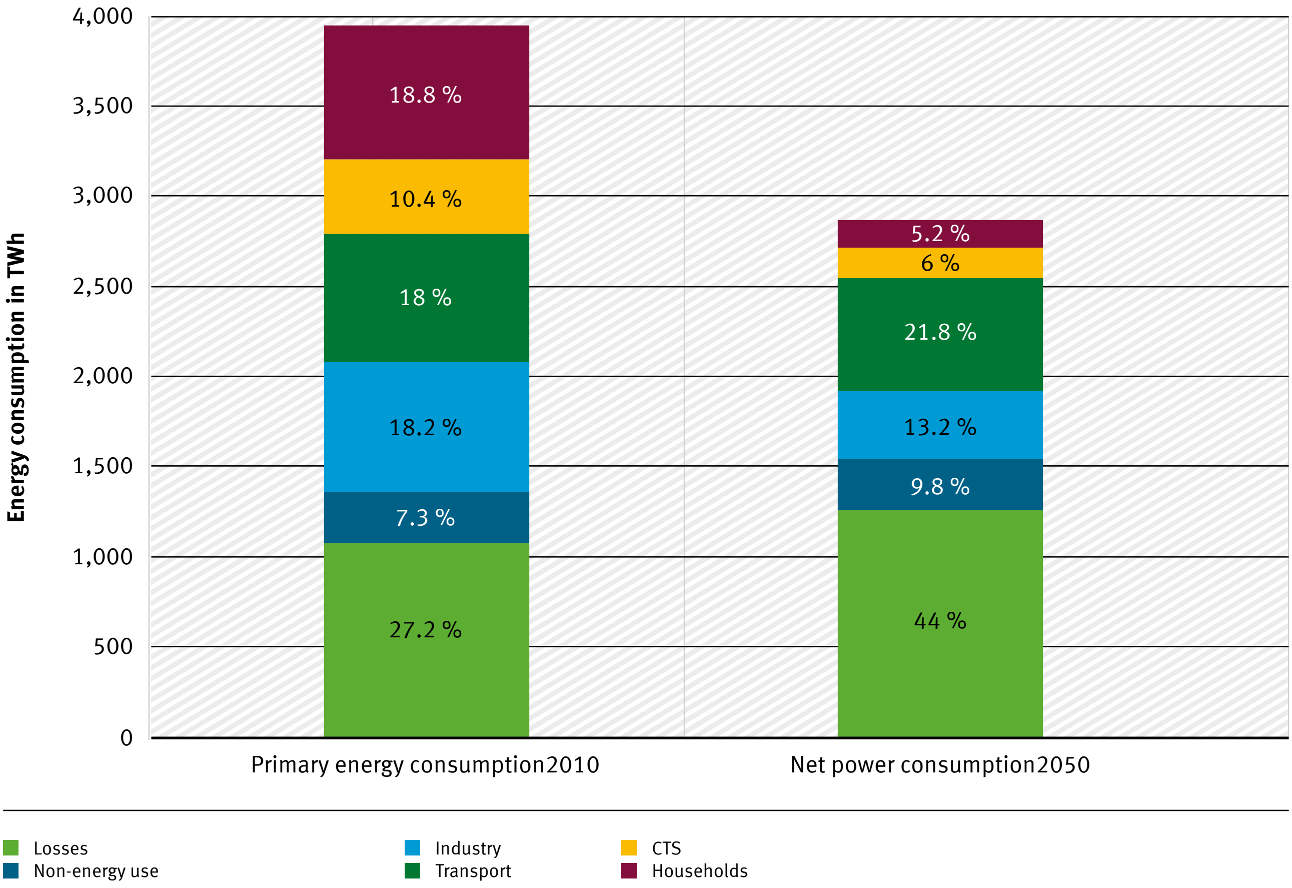
CI Representations of energy flows are proportional to the energy flows required, as calculated for the Federal Environment Agency's GHG-neutral Germany 2050 scenario.

CII Relating to primary energy.

CIII Relating to net electricity generation.

CIV An efficiency rate of 50% was assumed for the supply of motor fuel in variant 1.

Figure B-26: Energy consumption by sector in 2010 and 2050



The previous sections show that a GHG-neutral, sustainable energy supply will be based primarily on renewable electricity. In view of the likely increase in competition for biomass and land use, biomass should be used only in the form of waste biomass, which means it can make only a very small contribution to the energy system. In our scenario, demand for electricity is met primarily by wind and PV power stations, in line with domestic and global potential. Hydro power and geothermal plants make a smaller contribution. Renewable electricity for direct use (around 466 TWh p.a. final energy according to the assumptions) can be generated in Germany, which has the necessary technical-ecological potential. A large proportion of the electricity needed to produce renewable methane and renewable fuels will probably come from production locations in other countries, which are likely to be more economical. Any transport of energy, whether in the form of electricity, methane or fuel, is associated with energy losses, which must also be factored into the required output. It can be assumed that in a large international energy network, the production locations for the various final energy vectors will be determined by the energy transport losses and electricity generation costs. This means that electricity will be transported to Germany from nearby production locations, e.g. wind energy or hydro power from Scandinavia. The electricity can be used directly, to stabilise the electricity supply, or indirectly in electrolysis and methanation plants. More distant energy-production locations, e.g. PV and CSP plants in Africa, could transport electricity to coastal electrolysis plants, mainly for conversion into methane and fuels. The energy could then be transported to Germany in the form of the required final energy vector, primarily by ship, and to a lesser extent via pipeline and the gas grid.

The proportion of imported energy in a GHG-neutral energy system will depend to a great extent on how far domestic potential is developed. From Chapter B.3.1.2 it is clear that a 100% renewable electricity supply (a total of around 3000 TWh net electricity generation, including the electricity required to produce power-derived fuels) cannot be achieved using domestic technical-ecological potential alone.[CV] Depending on the economic efficiency of domestic power production plants, public acceptance, the political desire for full energy independence and other factors, a proportion of Germany's energy supply will continue to be based on imports even in the long term. On the assumption that Germany will strive to achieve an independent electricity supply (i.e. the electricity required as final energy will be generated in Germany), this would mean that imports would account for 62% of final energy consumption. Because of the complex calculations required to determine the primary energy of renewables, it is not possible/practical to draw a comparison with Germany's current level of dependence on imports.[CVI] In the event of electric power independence, the import share for net electricity generation would be around 80%, based on the assumptions made here.

B.6 Summary

In order to meet climate protection goals, in the long term Germany will need not only to switch to GHG-neutral electricity supply, but to a completely GHG-neutral energy supply, including heating and motor fuel. This kind of restructuring of the energy supply system is technically possible. The previous chapters have shown that a GHG-neutral energy supply will be based primarily on electricity generated from wind and solar energy. Biomass cannot make a significant contribution to energy supply for the reasons explained.

Final energy demand for electricity cannot be reduced significantly in the long term. This is the case even if we assume considerable efficiency gains. The main reason for this is the shift towards electricity-based technologies like heat pumps for heating and towards electricity-based industrial processes. A significant long-term reduction in the final energy demand for electricity is therefore not achievable, even if huge efforts are made to improve efficiency.

A key part of GHG-neutral energy supply is the conversion of renewable electricity into chemical energy sources. This power-to-gas technology uses water electrolysis to produce renewable hydrogen, which can in turn be used in a catalytic reaction to produce renewable methane. Renewable liquid fuels can also be provided (power-to-liquid technology). The importance of power-to-gas technology is not limited to its role in electricity supply. In the long term it will be a key component of a virtually GHG-neutral energy supply system. In addition, in the long term this technology can be used to provide GHG-neutral raw materials for industry, thereby helping lower GHG emissions in this sector as well. A basic condition for this technology is the availability of water and a GHG-neutral source of carbon (usually in the form of CO_2). Besides industrial-scale implementation of the technology, its further development will depend largely on the availability of the inputs, or on how much energy will be needed to supply them. It is this that will determine the potential contribution of power-to-gas technology in the energy system. Hydrogen technology should also play a part in a system based on renewables because the hydrogen production process is more energy efficient and has the advantage of not needing a carbon source.

The long-term demand for final energy is estimated to be 466 TWh p.a. for electricity, 306 TWh p.a. for heating fuel, 282 TWh p.a. for renewable inputs for the chemical industry and 552 TW p.a. for motor fuels. The production of renewable heating and motor fuels is associated with considerable losses

CV The technical-ecological potential takes ecological aspects into account as well, and represents only a part of the technical potential available.

CVI 70.2% in 2010.

compared with the existing fossil fuel system. Because of these losses, e.g. transport losses, the net electricity generation required will be 3000 TWh p.a. as a rough estimate. It is possible to meet the demand for electricity from domestic potential. In addition, it is likely that in an international energy network, renewable electricity will be generated at low-cost locations in other countries and then converted into hydrogen, and possibly also into motor fuels and methane, on site or nearby. It is therefore likely that most of Germany's heating and motor fuel requirements will continue to be met by imports. It is realistic to assume that the import ratio will remain at today's levels.

C. Transport

C.1 Introduction

According to the NIR[105], in 2010 the transport sector's combustion-related energy demand was 2226 PJ or 618 TWh.[CVIII] This corresponds to around one fifth (20.1%) of Germany's total final energy demand. In 2010 greenhouse gas emissions from transport amounted to 154 million tonnes of CO_2 equivalent (CO_{2eq}), making this sector responsible for 19.8% of all energy-related greenhouse gas emissions. CO_2 accounts for over 99% of all greenhouse gas emissions in the transport sector, which produces almost negligible amounts of other greenhouse gases such as CH_4 (methane) and N_2O (nitrous oxide).[106]

To achieve the goal of a greenhouse gas-neutral society, transport emissions must be reduced to zero. To meet this challenge, the entire sector's final energy demand will have to be drastically reduced, since only limited quantities of renewable fuels are available and these are subject to economic restrictions. In view of the predicted rise in traffic volume – especially freight traffic – this calls for urgent action.

For the purpose of analysing transport, we make a distinction between 'transport volume' and 'transport performance' Transport volume describes the quantity of persons or goods transported, measured in persons (p) or tonnes (t). Transport performance, on the other hand, also takes into account the distance covered, measured in terms of passenger-kilometres (pkm) or tonne-kilometres (tkm).

This chapter presents measures which illustrate how final energy demand and greenhouse gas emissions can be reduced in the transport sector assuming that transport volume and performance, modal split, final energy demand and greenhouse gas emissions continue to develop at their current level. The Öko-Institut (Institute for Applied Ecology) was commissioned by the UBA[107] to undertake a research project to develop a scenario for carbon-neutral transport in 2050. The findings of this study constitute the basis for this chapter.

C.2 Trends and status quo in Germany

The reason why the transport sector has had little impact on climate protection so far is largely due to the fact that transport performance has increased.[CIX] Between 1990 and 2010 freight transport performance – measured in tonne-kilometres (tkm) – increased by more than two thirds and passenger transport performance – measured in passenger-kilometres (pkm) – by around a quarter (see Table C-3 and Table C-4).

Between 1991 and 2010, the German public road network increased by 2%, whilst German motorways increased by as much as 17%. In contrast, the German rail network shrank by 6%.[108] This pronounced unilateral expansion of infrastructure prompted the modal split to shift in favour of road transport. At the same time, in the case of passenger transport for example, most of the time saved as a result of decreasing journey times was used to make longer journeys. Consequently, 15 to 20% of the growth in traffic can be attributed to the expansion of the transport infrastructure. This trend is referred to as 'induced traffic'.[109]

CVIII Excluding maritime transport; in contrast the AGEB (Energy Balances Working Group) cites a consumption figure of 711 TWh for 2010. This is because the AGEB data also includes biofuels, the transport sector's electricity demand and kerosene consumption during international flights.

CIX This is also referred to as traffic volume in transport statistics

The increase in passenger transport performance in Germany is directly linked to residential development. From the 1960s onwards, homes and businesses first became established in suburbs and out-of-town areas, followed by an increasing number of large retail and service outlets (in other areas). The following developments were the driving force behind this trend:

- falling costs of car travel (especially purchasing and fuel costs, combined with greater buying power)
- massive expansion of the road network
- low cost of land in out-of-town areas
- favourable tax incentives (e.g. lower business tax rate in communities surrounding towns and cities, commuter tax relief, grant scheme for first-home buyers)

This has given rise to a sprawling and in some cases monofunctional residential structure. As a result, journeys have become longer and more difficult to coordinate. The majority are undertaken by car because travellers are unable to reach this type of residential structure as conveniently using public transport or non-motorised means of transport.

As markets have become increasingly globalised, especially since the 1980s, the movement of goods has increased more than three times as fast as gross world product, which has been reflected in a dramatic rise in freight traffic.[110] This has also had an impact on the development of transport. Freight traffic is essential for supplying consumers with durable and non-durable consumer goods and businesses with raw materials and semi-finished products. It is key to ensuring a wide supply of goods and a geographical organisation of production systems. The closer the trade links between regions and the greater the distance between these regions, the more freight traffic is generated.

C.2.1 Transport volume

C.2.1.1 Passenger transport

The volume of passenger transport rose steadily from 1970 until the early 1990s. Table C-1 shows that the volume more than doubled between 1970 and 2000. Since 1994 the rate of growth has been slowing down and passenger numbers have now stabilised at a high level with continuing slight growth.

Table C-1: Development of passenger transport volume in Germany 1970-2010[CX,111]

	1970	1990	2000	2010
Passenger transport volume (in billion persons)	30.4	45.7	65.4	68.3

C.2.1.2 Freight traffic

Between 1970 and 2000, the volume of freight traffic — measured by weight of transported goods — rose by barely a tenth in Germany (see Table C-2). From the early 1990s up to the present day, this volume has fluctuated between 3.5 and 4.1 billion tonnes, and is largely dependent on the prevailing

CX Incl. domestic air traffic.

economic situation. In 2010, 54% of road freight was transported over distances of less than 50 km, i.e. locally.[112]

However, the increase in freight mobility[CXI] is often underestimated because transport statistics tend to be based on the weight of goods. But the trend in recent years has been for specialised industrial products to become lighter. Furthermore, industrial production is shifting in favour of goods with a higher value-to-weight ratio. This means that today, more goods of higher value are transported for the same tonnage. Packaging materials are also becoming lighter and at the same time more voluminous.

Table C-2: Development of freight transport volume in Germany 1970-2010[CXII,113]

	1970	1990	2000	2010
Freight traffic volume (in billion tonnes)	3.5	3.4	3.8	3.7

C.2.2 Transport performance

Passenger transport

Passenger transport performance also rose between 1970 and 2010 in line with the rise in passenger transport volume (see Table C-3). However, this trend has been slowing down increasingly and since the mid-nineties a slight saturation in passenger transport performance has been observed.

Table C-3: Development of passenger transport performance in Germany 1970–2010[CXIII,114]

	1970	1990	2000	2010
Passenger transport performance (in billion pkm)	530	859	10[12]	1077

Freight traffic

The continuous growth in freight transport performance in the last two decades cannot be explained by a rise in the volume of freight transport, since this has stagnated (see Table C-2). Freight transport performance rose by more than two thirds between 1990 and 2010 (see Table C-4).

This is due to an increase in transport distances in addition to the trend for lighter goods described above. For example, the average distance covered by goods vehicles rose by 38% from 88 km to 121 km per journey between 1995 and 2010. During the same period, the average length of freight journeys by rail rose by 41% from 214 km to 302 km.[115]

CXI The term 'goods mobility' describes the transport of goods and their semi-finished products irrespective of their weight or volume. As individual products become smaller and lighter – as has been the case with IT products in recent years – the weight of the same volume of products falls considerably. As a result, the transport volume in tonnes falls, even if the same number of products is transported over the same distances.

CXII Excluding shipping and pipelines, incl. domestic air traffic.

CXIII Incl. domestic air traffic.

Table C-4: Development of freight transport performance in Germany 1970-2010[CXIV,116]

	1970	1990	2000	2010
Freight traffic performance (in billion tkm)	266	353	496	604

C.2.3 Modal Split[CXV]

C.2.3.1 Passenger transport

Rapid rise in car ownership in the 1950s and 60s meant that by 1970 the car was already responsible for a relatively high share of the total transport performance. Table A5 shows that this share continued to grow until 1990, where it has since remained at around 84%. Rail travel and public transport has had around a 15% share of the modal split since the 1990s, and air travel around a 1% share — although the current trend is for a small but steady rise in this mode.

Table C-5: Development of the modal split of passenger transport in Germany 1970-2010 (shares of total transport performance)[117]

Year	Road	Rail + public transport	Air (domestic flights)
1970	77.7%	21.6%	0.7%
1990	83.9%	15.3%	0.8%
2000	84.0%	15.1%	0.9%
2010	84.0%	15.0%	1.0%

C.2.3.2 Freight traffic

In 1970 the majority of freight in East and West Germany (46.2%) was still transported by rail. Next came goods vehicles with a share of around one third, followed by inland waterway vessels accounting for one fifth of the transport performance. Over the following decades up to the present day there has been a fundamental change in the modal split, with goods vehicles becoming more dominant. Slight increases in rail transport between 2000 and 2010 did nothing to diminish this, since the share of inland waterway vessels during this period fell by around three percentage points (see Table C-6).

Table C-6: Development of the modal split of freight traffic in Germany 1970-2010 (shares of total transport performance)[118]

Year	Road	Rail	Inland waterway vessel
1970	34.6%	46.2%	19.2%
1990	52.4%	31.4%	16.2%
2000	69.9%	16.7%	13.4%
2010	71.9%	17.8%	10.3%

CXIV Incl. domestic air traffic.

CXV ‘Modal split’ in this context describes the share of individual modes of transport in the overall transport performance.

C.2.4 Final energy consumption and greenhouse gas emissions[CXVI]

Final energy consumption in the transport sector rose by 16% between 1990 and 2000, but then fell by around 7% up until 2010. The share of electricity demand in the final energy demand is indicated separately, since this is allocated to the energy sector (see Chapter B.4) (see Table C-7).

Similarly, direct greenhouse gas emissions from transport increased significantly at first, but fell in the last decade up till 2010. Greenhouse gas emissions arising from power generation are not included here (see Table C-8).

Table C-7: Development of final energy consumption in Germany[CXVII,119]

Year	Passenger transport	Freight transport	Total transport
1990	1797 PJ	572 PJ	2369 PJ
of which power	26 PJ	14 PJ	40 PJ
2000	1864 PJ	875 PJ	2739 PJ
of which power	34 PJ	12 PJ	46 PJ
2010	1713 PJ	831 PJ	2544 PJ
of which power	32 PJ	12 PJ	45 PJ

Table C-8: Development of direct greenhouse gas emissions (CO_2) in the transport sector in Germany[CXVIII,120]

Year	Passenger transport	Freight transport	Total transport
1990	128.4 million tonnes	41.3 million tonnes	169.7 million tonnes
2000	132.8 million tonnes	63.7 million tonnes	196.5 million tonnes
2010	122.2 million tonnes	60.3 million tonnes	182.5 million tonnes

C.3 Measures to reduce greenhouse gas emissions

A substantial reduction in the energy demand is a prerequisite – if not *the* prerequisite – for powering the transport sector on the basis of renewable energies by 2050. However, technical measures to increase the efficiency of vehicles alone will not be enough to dispense with fossil fuels and the use of biomass in the transport sector (see Chapter B.3.1). It will also be necessary to reduce the demand for transport (traffic avoidance) or to make greater use of energy-efficient modes of transport for passengers and goods (modal shift) by actively shaping transport policy. Significant reductions in the final energy demand can only be achieved through a combination of measures aimed at encouraging traffic avoidance, modal shift and efficiency improvements.

CXVI Since the NIR does not distinguish between passenger and freight transport, this section uses data sourced from TREMOD (unlike the introduction to the Transport chapter).

CXVII Incl. biofuels, according to the point-of-sale principle (based on energy sales and energy balance figures).

CXVIII Direct emissions (excluding power; emissions from power generation are allocated to the 'energy' sector), excluding upstream chain, incl. biofuels, according to the point-of-sale principle (based on energy sales and energy balance figures).

C.3.1 Traffic avoidance

Non-motorised vehicles do not produce CO_2 emissions. Traffic avoidance is thus the most fundamental way of reducing greenhouse gas emissions.

However, traffic is not — as is often falsely assumed — synonymous with mobility: the same level of mobility can be achieved with more or less traffic. The determining factor is the range of activities offered within an individual's radius of action — and not the distance covered or even the mode of transport. In concrete terms this means that someone who commutes 100 km to work by car is not necessarily more mobile than someone who cycles 5 km to work.

The term 'traffic avoidance' does not primarily imply avoiding or even abandoning journeys altogether, but rather reversing the trend in favour of shorter journeys. Thus avoiding traffic and facilitating mobility are not necessarily mutually exclusive. A high level of mobility and a reliable supply of goods can be achieved with very different transport performance – measured in passenger-kilometres and tonne-kilometres.

To avoid traffic, measures must be implemented which tackle the underlying causes of traffic. Residential, industrial and infrastructure development over decades has created ever increasing distances between a journey's starting point and its destination. Transport performance can be reduced by adapting regional planning policies to lower induced transport needs. This is a prerequisite for sustainable economic development which enables individual mobility and a geographical organisation of production systems even with lower transport performance.

The number of journeys and average journey lengths can be reduced by increasing the vertical range of manufacture, low-traffic logistics systems (including warehousing) and an increasingly decentralised commercial distribution system. The creation of settlement structures and residential environments which require short journeys and therefore less traffic, combined with the promotion of regional economies, will also reduce the demand for traffic.

C.3.2 Modal shift

Greenhouse gas emissions per transported person or tonne vary across different modes of transport (see Table C-9).

Table C-9: Comparison of specific greenhouse gas emissions in passenger and freight traffic (2010)[CXIX,121]

	Air	Car	Coach	Rail (long-distance)	Rail (regional)	Public transport
Greenhouse gases	228 g/pkm	124 g/pkm	30 g/pkm	45 g/pkm	78 g/pkm	76 g/pkm
	Air	**HGV**	**Rail**	**Inland waterway vessel**		
Greenhouse gases	1383 g/tkm	98 g/tkm	24 g/tkm	30 g/tkm		

Greenhouse gas emissions can also be reduced by shifting from high-emission modes of transport (truck, car, plane) to low-emission modes of transport (train, ship, public transport) or zero-emission transport such as cycling or walking. Suitable measures must be in place to enable a modal shift to take place (see Chapters C.4.1 and C.4.2).

C.3.3 Reducing emissions

The third pillar of a sustainable and climate-friendly transport sector is to reduce the specific[CXX] emissions from each mode of transport. The main way to achieve this is by increasing the efficiency of vehicles and drive systems. CO_2 emissions can also be substantially reduced by encouraging more fuel-efficient driving.

Implementation of these measures — backed up by non-technical (e.g. regulatory or economic) tools — is already producing a CO_2 emissions reduction in the short term.

One fundamental means of reducing greenhouse gas emissions is to use energy sources that are less CO_2-intensive — or even CO_2-neutral. These include renewable energy as well as synthetic fuels produced from renewable energy, as described in Chapter C.4.4.

C.4 Scenario for greenhouse gas-neutral transport in Germany in 2050

The *Szenario für einen treibhausneutralen Verkehr* (Scenario for greenhouse gas-neutral transport, or GHG-neutral transport scenario) outlined below was developed by the Öko-Institut (Institute for Applied Ecology) for inclusion in a Federal Environment Agency report.[CXXI] [122]The GHG-neutral transport scenario is based on a trend scenario which assumes that existing trends will continue without structural changes ('business as usual').[CXXII] Assumptions about traffic demand are based on the 2007[123]

CXIX Emissions from the preparation of energy sources and their conversion to electricity, petrol, diesel and kerosene are considered; CO_2, CH_4 and N_2O are indicated as CO_2 equivalents; all effects on climate from air traffic are taken into account (EWF (emission weighting factor) = 2.0) and figures are based on average capacity utilisation.

CXX This refers to emissions per vehicle, person or tonne.

CXXI Some sections of Chapter C.4 are an abridged version of the above-mentioned study.

CXXII This trend or 'business as usual' scenario will hereafter be referred to as the trend or baseline.

traffic forecast produced by the German Federal Ministry of Transport, Building and Urban Development (BMVBS), which has been adapted to allow for updated information and findings.

The GHG-neutral transport scenario illustrates one possible route to achieving a greenhouse gas-neutral transport sector by 2050. First we propose measures to promote this aim and quantify them where possible. Then we describe the essential characteristics of the scenario in terms of demand, technology and fuel, with most of our assumptions based on the underlying measures.

We have adopted a somewhat conservative approach to quantifying the effects of the measures on transport demand and modal split to avoid overestimating their impact. However, this is not intended to imply that the cited measures for transforming the transport sector are not relevant.

The future technical development of drive systems and alternative fuels — and likewise that of transport demand — is fraught with uncertainty. The greenhouse gas-neutral transport sector in 2050 proposed in this scenario is based on electric drives and power-generated liquid fuels. The use of power-generated methane in the transport sector — currently a frequent topic of discussion — is not considered in this scenario, because the process chain for the production of methane is similar to that of synthetic liquid fuels. However, since the infrastructure for synthetic liquid fuels is already in place in the transport sector, this route was chosen in preference to power-generated methane. Another reason for choosing this route is that at present we cannot predict what share of the different modes of transport gases and synthetic liquid fuels will ultimately have. It has to be emphasised that this scenario is just one of several possible scenarios. Further research is needed in this area. With regard to the development of drive systems, we assume that battery-electric motors are technically feasible for cars, light commercial vehicles and goods vehicles with a gross weight of up to 12 tonnes. To ensure that the remaining vehicles which continue to use conventional combustion engines meet the aim of a greenhouse gas-neutral transport sector, in this scenario they will run on synthetic liquid fuels produced using renewable energy and ideally, greenhouse gas-neutral CO_2 (see Chapter B.3.3.6). In contrast to road traffic, a shift to alternative drive systems is not envisaged for shipping and air traffic; instead these modes of transport will use synthetic fuels based on renewable energy.

Figure C-1: Resource consumption through the increased use of electromobility

Electromobility is thought to reduce emissions in the transport sector of the future. In this context, batteries in electric vehicles can have a dual function as flexible consumers of electricity from renewable sources, as well as potential intermediate storage facilities for renewable electricity. It is expected that a large proportion of future electric vehicles will rely on traction batteries based on lithium-ion technology. These contain the following quantities of lithium and cobalt, depending on cathode types:[124]

Lithium-iron-phosphate cathodes (LFP): 101 g lithium per kWh, no cobalt

Lithium-nickel-manganese-cobalt cathodes (NMC): 157 g lithium per kWh and 490 g cobalt per kWh.

According to scenario calculations conducted by Umbrella in 2011, in 2050 global lithium consumption is expected to be between 150,000 and just under 450,000 tonnes p.a. and global cobalt consumption between 0.4 and 1 million tonnes p.a. for traction batteries and other applications. This is based on the assumption that in 2050 demand for lithium in Europe will be approximately 20,000 to 50,000 tonnes p.a. and demand for cobalt approximately 66,000 to 140,000 tonnes p.a. For cobalt, this would mean an eight to twentyfold increase in global demand compared to current levels. According to Umbrella in 2011, geological reserves of lithium will meet demand for several decades to come, whereas for cobalt, consumption could exceed reserves (7.3 million tonnes) known to date between 2040 and 2050. It is therefore crucial to roll out pilot schemes for recycling methods on an industrial scale within the next decade. Due to the longevity of electric vehicles and their batteries, the secondary lithium and cobalt that could be thus recovered will only help to meet demand in the long term. In 2050 it is expected that secondary production will account for around one sixth of lithium demand and around one third of cobalt demand.[125]

Further research is needed regarding the resource consumption of other storage batteries that can be used to control load management in power grids (see Chapter B.3.2).

The high proportion of synthetic liquid fuels calls for some highly ambitious technical advances. We cannot say with certainty whether the amount of synthetic liquid fuels required for this scenario, together with the necessary installations, will actually be available in time (see Chapters B.3.3.7 and B.3.3.8). We can, however, estimate the amount of renewable energy that would be required based on the assumptions we have made.

C.4.1 Measures to promote a greenhouse gas-neutral transport sector

A whole gamut of measures must be implemented inside as well as outside the transport sector in order to make it GHG-neutral. Incentives for technological innovation must be complemented by underpinning measures designed to encourage traffic avoidance and modal shift.

This chapter describes measures to promote greenhouse gas-neutral transport, but makes no claim to be exhaustive. In selecting the measures, we have taken the utmost care to ensure that they meet minimum requirements in terms of their further ecological, economic and social effects. The GHG-neutral transport scenario focuses primarily on developing a technical solution for achieving a greenhouse gas-neutral transport sector, since the underlying research project provided only rough estimates for evaluating measures aimed at avoiding traffic and shifting to alternative modes of transport. In this scenario we considered the following regulatory, economic and supporting measures and implemented them according to the effect indicated. In order to see their full impact by 2050, the timeframe for their introduction is generally between 2015 and 2030.

C.4.1.1 Regulatory measures

Tightening emission limits

CO_2 emission limits for cars and light commercial vehicles will be tightened to a greater degree compared with the trend. In addition, we assume that CO_2 emission controls will be imposed on heavy goods vehicles (HGVs). An equivalent process has already begun at EU level and corresponding regulation for HGVs is anticipated. In the case of cars and light commercial vehicles, CO_2 emission targets cannot be achieved purely by applying technical measures to conventional vehicles. A significantly higher proportion of vehicles with alternative drive systems (e.g. hybrid engines) will be needed.

The introduction of CO_2 emission limits for HGVs will lead to the development of ambitious levels of efficiency in conventional vehicles compared with the trend.

Motorway speed limit

A speed limit of 120 km/h will be introduced on German motorways.

This measure will reduce the average fuel consumption of cars on motorway sections that have no current speed limit. According to the *Bundesanstalt für Straßenwesen* (Federal Highways Research Institute)[126], these sections account for 65.5% of the German motorway system. Based on TRL[127] and assuming a starting (pre-limit) speed of 140 km/h, this will reduce fuel consumption on motorway sections which have no current speed limit by 13% on average, depending on the vehicle size class. This reduction in fuel consumption will apply to all conventional cars.

Low-emission zones in city centres from 2025

Low-emission zones will be implemented in cities in a series of stages. These environment zones will be augmented by an additional ‘U50’ category which only vehicles with CO_2 emissions below 50 g CO_2/km may enter. The European Commission’s White Paper[128] proposes ‘emission-free city centres’. However, the ‘U50 zone’ is better suited to promoting plug-in hybrid vehicles as well. Extended-range electric vehicles (EREVs) which revert to a combustion engine when the battery range is reached are an effective means of controlling pollution and emissions and this measure should make a substantial contribution to reducing pollution levels. Some current plug-in hybrid electric vehicles (PHEV) can already be driven solely in electric mode for urban journeys.

We assume that this measure — in conjunction with the reform of company car tax (see below) —will have an impact on the composition of new car registrations. All vehicles making deliveries in urban areas will also be affected by this measure. Consequently, it is anticipated that there will be a higher proportion of light commercial vehicles and light goods vehicles with electric drive systems.

C.4.1.2 Economic measures

Increasing fuel tax

Fuel tax will soon switch to a system based on stipulating CO_2 intensity and fuel energy content. When stipulating CO_2 intensity, emissions from upstream chains will be taken into account to provide tax incentives for the lower greenhouse gas intensity of synthetic fuels from renewable energy and electric vehicles. Fuel taxes will be configured in such a way that the average cost of private motorised vehicle kilometres rises by 10% compared with the baseline. The level of taxation required to achieve this thus depends on the price trend. As far as freight traffic is concerned, the impact of fuel tax will be quantified alongside other measures (see Chapter A.4.3.2). In order to quantify the impact of price changes on demand for private motorised transport, we have assumed that there will be a price elasticity of -0.25.[129]

As a result, the demand for private motorised passenger transport will fall by 2.4% compared with the baseline.

Abolishing commuter tax relief

Entfernungspauschale — commuter tax relief — will shortly be abolished. This measure has been quantified by calculating the lengths of commuting distances on the basis of the MID survey[CXXIII][130] and using the methodology developed by the UBA[131]. We assume that abolishing commuter tax relief will make homes closer to the workplace a more attractive proposition.

The results suggest a 16% reduction in average commuting distances by 2050.

Changing the company car tax system

The flat-rate taxation on company cars is soon to be reformed through a scheme consisting of two components:

- Linking the deductibility of company cars for corporation tax purposes to CO_2 emissions through the introduction of a climate factor.
- Replacing the existing flat-rate tax on company cars with a 'combined private usage rate' which will depend on driving performance (kilometres travelled) and emissions.

The structuring of this new policy is based on a study on company car tax.[132]

Together with 'low-emission zones' in city centres, this measure will have an impact on the composition of new car registrations. This will promote the use of more efficient cars and in particular, electric and plug-in hybrid vehicles.

Changing the aviation tax system

A kerosene tax will be introduced on domestic flights within Germany[133] and VAT will be levied on international flights departing from Germany. However, tax reforms for international flights would require the Convention on International Civil Aviation (the Chicago Convention) to be revised.

CXXIII 'Mobility in Germany' survey (MID).

This measure will have an impact on passenger transport demand and encourage developments in efficiency. We assume that user costs will rise by 19% compared with developments without additional pricing measures, which will lead to a fall in demand. This is illustrated by an iso-elastic price-demand function and a price elasticity of -0.375.[134] Accordingly, air passenger demand for international flights will fall by 6.3% compared with the baseline.

The ICAO (International Civil Aviation Organisation) fuel efficiency improvement target of 2% per year for both passenger and freight traffic will also be achieved through the resulting pressure on prices.

Expanding and further developing the truck toll system

The truck toll system will soon be amended to include pollution and noise costs and extended to all goods vehicles with a gross vehicle weight of 3.5 tonnes or above and to the entire road network.

In conjunction with other measures affecting freight traffic, this will trigger a modal shift from road to rail.

C.4.1.3 Supporting measures

Infrastructure measures to encourage cycling and walking

A bundle of measures will be implemented to encourage cycling and walking. These include:

- expansion of the cycling network
- introduction of bicycle stations
- extensive installation of high quality bicycle racks
- extension of pedestrian zones and traffic-calming areas.

The potential for shifting from motorised to non-motorised private transport is determined by analysing journey lengths based on the MID survey (Mobility in Germany). Some journeys up to a distance of 7 km will shift from car to bicycle / foot. The shift potential ranges from 30% (very short journeys) to 5% depending on the distance category. By 2050 this potential will be fully exploited. In total, 2% of motorised private transport demand will shift to cycling and/or walking.

Expanding and increasing the capacity of the rail network

Operational measures and smaller infrastructure measures will be implemented in the short term. In the medium term, new routes will be created to eliminate bottlenecks. This will be achieved by increasing the volume of investment and structuring the *Bedarfsplan Schiene* (railway demand plan) specifically to eliminate bottlenecks.

In conjunction with other measures affecting freight traffic, this will help bring about a modal shift to rail.

Promoting regional economic circuits

We propose a package of measures to promote regional economic circuits and halt the trend of rising transportation distances. These include the introduction of a binding traffic impact assessment for activities aimed at promoting economic development and the introduction of minimum standards for the labelling of regional products.

These measures are designed to shorten the average transport distances for freight traffic.

C.4.2 Impact of the measures on transport demand

C.4.2.1 Passenger transport

Abolishing commuter tax relief and amending the fuel tax policy will encourage traffic avoidance. Further measures (speed limit, company car tax) will tend to encourage traffic avoidance as well, although this cannot be explicitly considered in this scenario as it has yet to be quantified. Measures to promote cycling and walking will encourage a modal shift.

The additional aviation taxes will cut demand for flights, leading to a 6.3% fall in passenger transport demand compared with the trend.

C.4.2.2 Freight transport

Promoting regional economic circuits, expanding the truck toll system and increasing fuel tax will have an impact on freight traffic. We assume that these measures will have two principle effects: reduce transport distances in the medium term and change the modal split. The share of rail freight in the modal split (based on transport performance) will rise to the detriment of road freight.

The effect of introducing kerosene tax on the demand for air freight was not calculated separately since air freight accounts for only a tiny proportion of freight traffic demand (see Fig. C-4).

Measures aimed at achieving climate goals for shipping have not been quantified. Corresponding measures should, where possible, be put in place at international or at least EU level. Furthermore, shipping measures should not be evaluated independently of other modes of transport. Regionally limited climate protection measures could for example lead to a situation where unaffected ports are more heavily frequented, leading to a corresponding shift to hinterland routes, which in the worst-case scenario could increase transport distances.

A greenhouse gas-neutral Germany designed to substantially reduce dependency on coal and oil imports would reduce the volume of maritime traffic allocated to Germany. In 2010 coal, crude oil and natural gas accounted for 14.2% of the total cargo handled in German ports.[135]

C.4.3 Advances in technology and efficiency

The measures described will principally result in a higher proportion of alternative drive systems for cars and small to medium-sized goods vehicles. In addition, more ambitious levels of efficiency for road freight will be developed as a result of emission limits for goods vehicles and light commercial vehicles.

C.4.3.1 Cars

Composition of new vehicle registrations

The following measures, introduced incrementally, will have an impact on the composition of new car registrations compared with the base scenario:

- changing the company car tax system
- calculating fuel tax on the basis of a vehicle's CO_2 emissions
- tightening CO_2 emission limits
- low-emission zones in city centres.

These measures will trigger a premature diffusion of electric and plug-in hybrid vehicle technologies. We also assume that conventional cars will need a greater degree of hybridisation to meet the low emission limit. It follows that conventional cars will then offer virtually no cost advantages compared with plug-in hybrid electric vehicles and thus the share of conventional cars will decline substantially in favour of plug-in hybrids. Higher fuel prices resulting from changes to fuel and energy taxation will make electric vehicles an even more attractive proposition for car drivers. Furthermore, the higher road tax imposed on diesel cars as a result of this measure will cut the number of new diesel vehicles being registered.[CXXIV]

Assumptions about the potential user base for alternative drive systems are derived from OPTUM[CXXV,136] to determine the role that battery-electric vehicles and plug-in hybrids will play in the composition of new vehicle registrations. Assuming that a range of 250 km will be achieved thanks to advances in battery technology, in 2050 all-electric vehicles will account for a maximum potential of 23% (small) and 12% (medium-sized) of new vehicle registrations. Plug-in hybrids have no range restrictions compared with battery-electric vehicles. Furthermore, it is likely that there will be only slight differences in cost compared with heavily hybridised conventional vehicles. Thus we assume that the maximum potential for plug-in hybrid electric vehicles is unlimited.

We have taken into account the supply side by illustrating the technical diffusion of alternative drive systems with the aid of a Gompertz curve (S-shaped) produced as part of the OPTUM project. This shows what share of the maximum potential the electric market will achieve. In 2050 this figure is set at 93%. This suggests that not all newly registered vehicles will be battery-electric or plug-in hybrids in 2050 — 7% of them will be conventional vehicles.

Advances in improve efficiency

We assume that tightened CO_2 emissions limits will not be met by aspirational efficiency improvements to conventional vehicles, but rather by increasing the number of vehicles with alternative drive systems — backed up by incentives on the demand-side.

Developments aimed at improving the efficiency of conventional vehicles are thus based on current trends without any additional measures being implemented. There is one difference however; through the introduction of a speed limit on German motorways, the fuel consumption of conventional vehicles will drop by 3%. The corresponding reduction in 'actual impact' compared with the baseline will be reflected in the NEDC[CXXVI] figures.

CXXIV This will also apply to synthetic diesel.

CXXV Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen. (Optimising the environmental benefits of electric vehicles)

CXXVI New European Driving Cycle.

C.4.3.2 Goods vehicles and light commercial vehicles

Composition of new vehicle registrations

The GHG-neutral transport scenario envisages the use of vehicles with alternative drive systems alongside conventional vehicles. This assumption is based on the fact that new CO_2 emissions limits will be introduced and existing ones tightened, combined with the introduction of low-emission zones in inner cities.

To model the composition of new registrations, we used the same system that was used for cars; having established a maximum potential, we modelled the composition of new vehicle registrations for road freight on the basis of a technical diffusion curve.

The drive and storage technology required to power large HGVs by alternative drive systems would be sufficiently bulky and heavy to severely restrict their load-carrying capacity. Consequently, the GHG-neutral transport scenario assumes that in 2050 HGVs with a gross vehicle weight of over 12 t will be entirely conventional vehicles running on synthetic liquid fuels.

In the case of lighter goods vehicles we assume a maximum potential of 100% for plug-in hybrids by 2050, since widespread hybridisation will have taken place to meet CO_2 emissions limits and consequently there will be no significant cost difference between plug-in hybrids and conventional hybrid goods vehicles. Furthermore, the introduction of low-emission zones in town centres will create the need for urban delivery vehicles with electric capabilities.

Light commercial vehicles with regular usage profiles (e.g. courier services) have the potential to be fully electric. We assume that they will have a maximum potential of 20%.[127] In contrast, plug-in hybrid vehicles theoretically have no usage restrictions (range etc.).

Advances in efficiency

The introduction of CO_2 limits for heavy goods vehicles will bring about aspirational developments aimed at improving efficiency. For conventional vehicles these will be based on the maximum technically feasible efficiency scenario[138] and will achieve average efficiency improvements of 50% by 2050.

For goods vehicles with a gross vehicle weight of up to 12 t, data from SULTAN[CXXVII 139] will be used to calculate the energy consumption of vehicles with alternative drive systems by adopting the relative efficiency benefits and developments of alternative drive systems compared with conventional ones illustrated in this tool.

C.4.3.3 Aviation

We assume that the ICAO target of a 2% annual fuel efficiency improvement will be achieved through the pressure on prices imposed by the kerosene tax. This corresponds to a reduction of over 60% by 2050. However, we do not assume that alternative drive systems will be used in the aviation industry.

CXXVII Development of an Illustrative Scenarios Tool for Assessing Potential Impacts of Measures on EU Transport GHG.

C.4.3.4 Maritime shipping

The use of LNG[CXXVIII] as an alternative fuel for shipping is currently being debated, prompted by regulations concerning sulphur oxide and nitrogen oxide emissions. Provided that fuel is generated entirely using renewable power, direct conversion to a synthetic liquid fuel is more efficient than methanation and subsequent liquefaction, so synthetic fuels rather than LNG will also be used in maritime shipping. With advances in efficiency, the average IMO route achieves a 39% increase in efficiency between 2007 and 2050.[140]

C.4.3.5 Other modes of transport

No specific measures designed to improve efficiency or encourage technical developments are envisaged for other modes of transport. Here too, conventional fuels will increasingly be replaced by synthetic liquid fuels.

C.4.4 Energy sources and fuels

C.4.4.1 Fuels

Contrary to the trend, in the GHG-neutral transport scenario up to 2050 the transport sector is dominated by synthetic liquid fuels (also called power-to-liquid fuels, PtL). According to our assumption, these will come onto the market in the medium term. By 2050, in line with the goal of a greenhouse gas-neutral transport sector, 100% of the liquid fuel required will be provided by PtL technology. Due to growing competition for uses of biomass, biofuel will no longer be used in 2050 (see Chapter B.3.1.2, Biomass section).

Synthetic liquid fuels are manufactured on the basis of hydrogen electrolysis. The additional process step required to convert hydrogen to liquid fuels rather than using the hydrogen directly entails conversion losses. However, compared with the use of fuel cells, the advantage of this approach is that it can use existing vehicle technology and is also suitable for use in freight traffic. Furthermore, proven technologies and infrastructure are available for storage and distribution.

C.4.4.2 Hydrogen

Hydrogen is widely used today in industry, where the main method for producing hydrogen is central gas reforming at the point of use.[141] In theory it is possible to produce hydrogen using a wide variety of processes based on different primary energy sources. However, the use of hydrogen to fuel vehicles only makes environmental sense if the hydrogen is produced from a renewable power source which does not increase the use of fossil fuels elsewhere.

In the GHG-neutral transport scenario, hydrogen is produced by means of electrolysis. The dominant technology today is alkaline electrolysis, with a small quantity being produced by polymer electrolyte membrane (PEM) electrolysis. It is assumed that high-temperature electrolysis (HTEL) will be the established technology in 2050. However, at present this is still in the early stages of development (see Chapter B.3.3.1).

CXXVIII Liquefied natural gas.

A particularly high level of efficiency can be achieved with high-temperature electrolysis, provided that the waste process heat (e.g. generated by Fischer-Tropsch synthesis during the production of liquid fuels) can be used to overcome the enthalpy of evaporation (i.e. to supply its heat source). Under this proviso, HTEL can conceivably achieve an efficiency rate of 90%. However, this is a very simplistic assumption.

C.4.4.3 Synthetic liquid fuels (PtL)

Synthetic liquid fuels are produced via a process chain involving CO_2 electrolysis (product: hydrogen), the water-gas-shift reaction (product: synthetic gas), Fischer-Tropsch synthesis (product: hydrocarbon chains) and the final refining stage. We have assumed that there will be an adequate supply of CO_2. The energy required to supply carbon dioxide, extracted from the atmosphere if necessary, is addressed in the energy supply section of Chapter B.5.1.3.

In the GHG-neutral transport scenario we assume that PtL fuels will be produced from 2020, mostly on the basis of PEM electrolysis initially, but increasingly via high-temperature electrolysis (Table 5). The latter will make use of the waste heat from the exothermic Fischer-Tropsch process.

C.4.5 Results

C.4.5.1 Transport demand

In the GHG-neutral transport scenario the transport performance for both passenger and freight traffic will grow at a slower rate than the trend. However, conservative assumptions regarding the quantification of measures suggest that traffic avoidance will have only relatively modest effects.

Passenger transport

As Figure C-2 illustrates, the effects of traffic avoidance and modal shift kick in from 2015, as a result of which transport performance in 2050, at 1566 billion pkm, is 3.1% lower than the anticipated trend without further measures. Passenger transport performance also includes non-motorised private transport. This mode plays a far greater role in the GHG-neutral transport scenario, accounting for 84 billion pkm by 2050 — 42% higher than the trend of 59 billion pkm. The promotion of cycling and walking is key to this outcome. However, air traffic and motorised private transport's share of the modal split falls only slightly compared with the trend (from 67.3% to 65.9% and 20% to 19.4% respectively).

Greater differences between the GHG-neutral transport scenario and the trend (baseline) can be seen in the drive systems used, especially for cars. The transport performance (kilometres travelled) by drive types shown in Figure C-3 demonstrates a clear shift in favour of electric drives and hybrids.

Figure C-2: Passenger transport performance

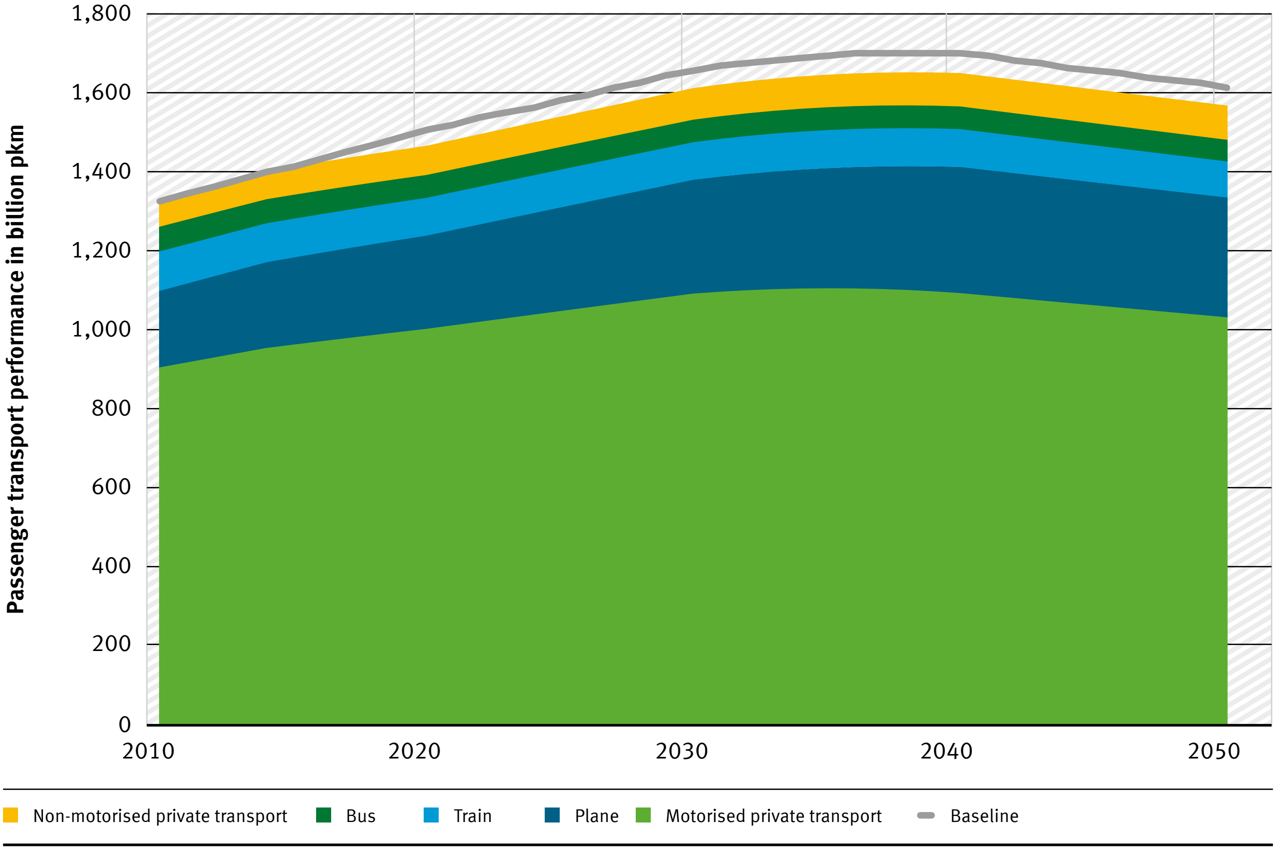
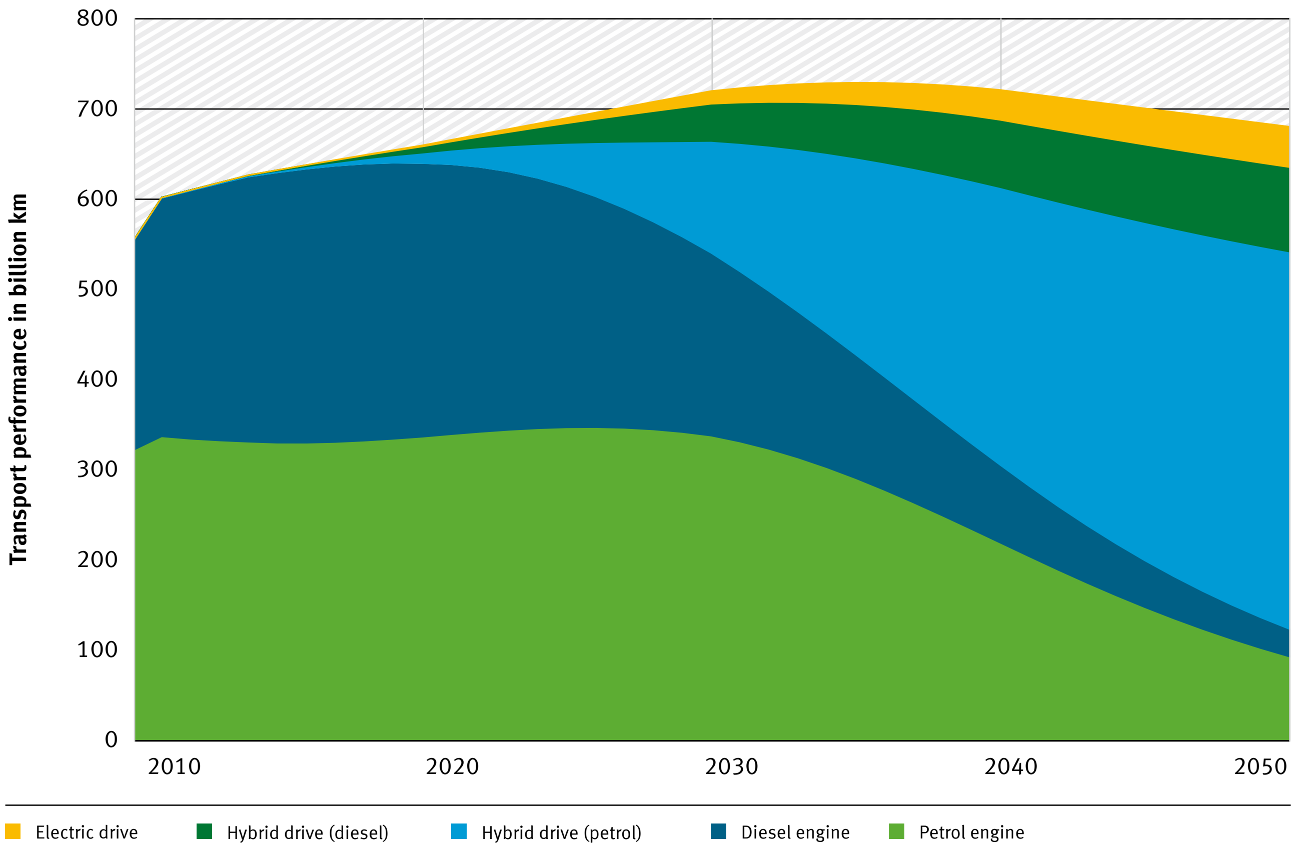


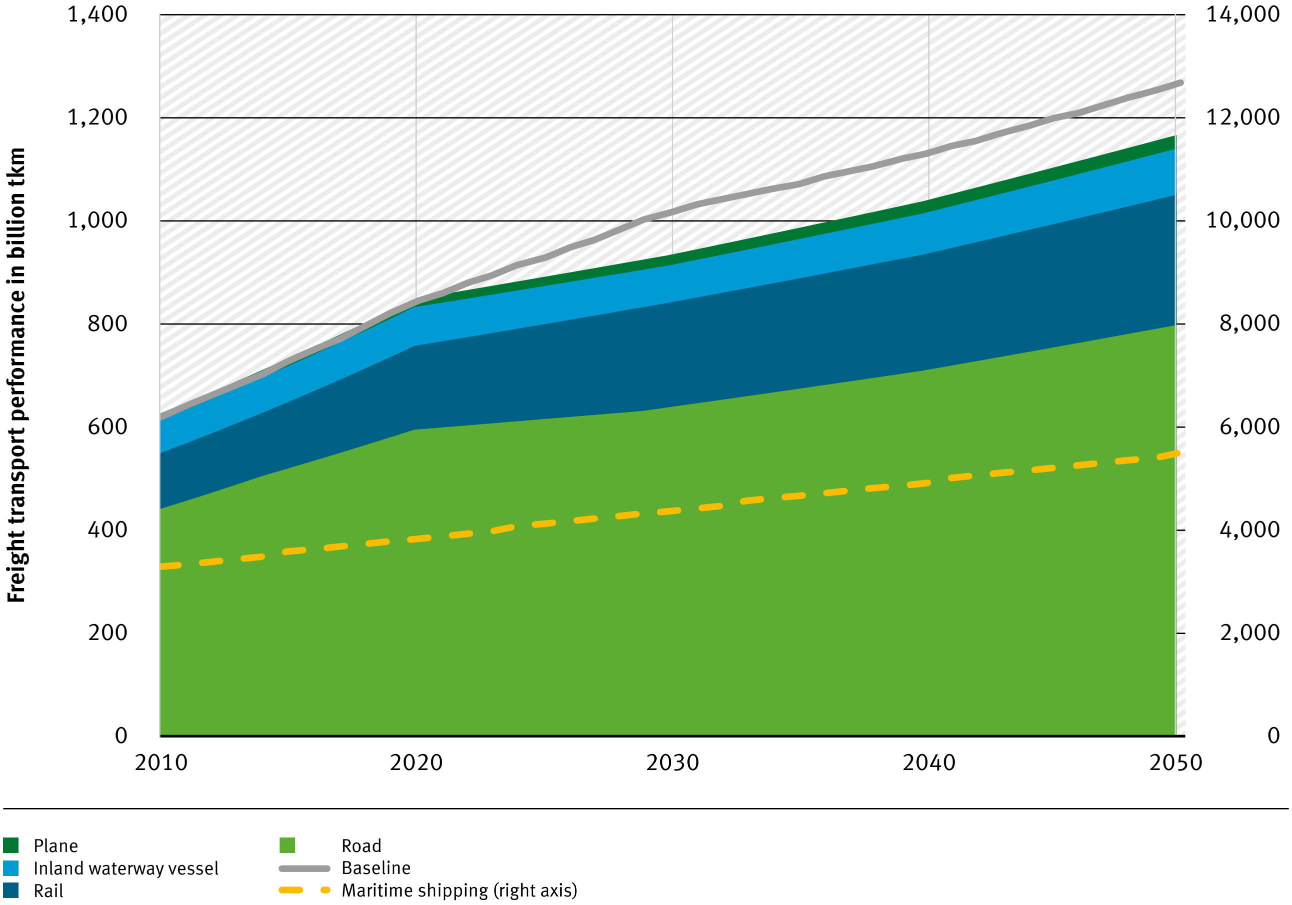
Figure C-3: Car performance by drive type



In 2050 electric and plug-in hybrid vehicles will account for 82% of the kilometres travelled by cars. Since plug-in hybrid vehicles are not used solely in all-electric mode, we have assumed an electric mode share of 67%. Combined with all-electric vehicles, this puts the overall electric share at 57% (387 billion km) of the kilometres travelled by car.

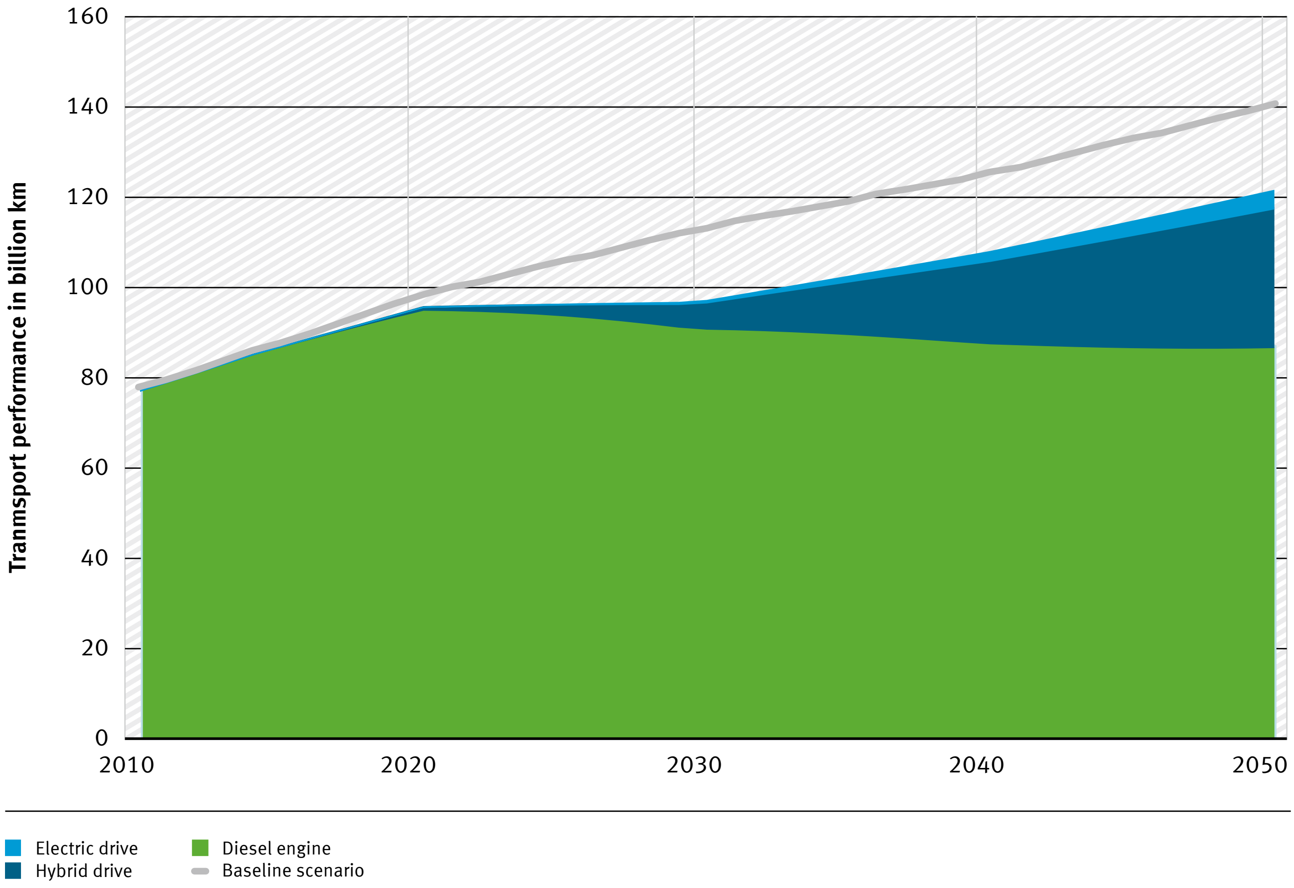
Freight traffic

Figure C-4: Freight transport performance



In the GHG-neutral transport scenario the transport performance for freight traffic in 2050 is 1143 billion tkm, which is 8.3% lower than the trend (baseline, see Figure C-4). This is largely due to a substantial 134 billion tkm fall in road freight compared with the trend, which also entails a corresponding decline in transport performance of goods vehicles (see Figure C-5). In contrast, rail freight increases by 39 billion tkm to 235 billion tkm. In the Environmental Report 2012 published by the German Advisory Council on the Environment[142] a rail freight transport performance of 300 to 500 billion tkm is considered possible if a variety of measures are consistently implemented. The GHG-neutral transport scenario makes no proviso for traffic avoidance measures in the case of maritime transport, which explains why the transport performance here corresponds to the trend.

Figure C-5: Goods vehicle transport performance by drive type



C.4.5.2 Final energy demand

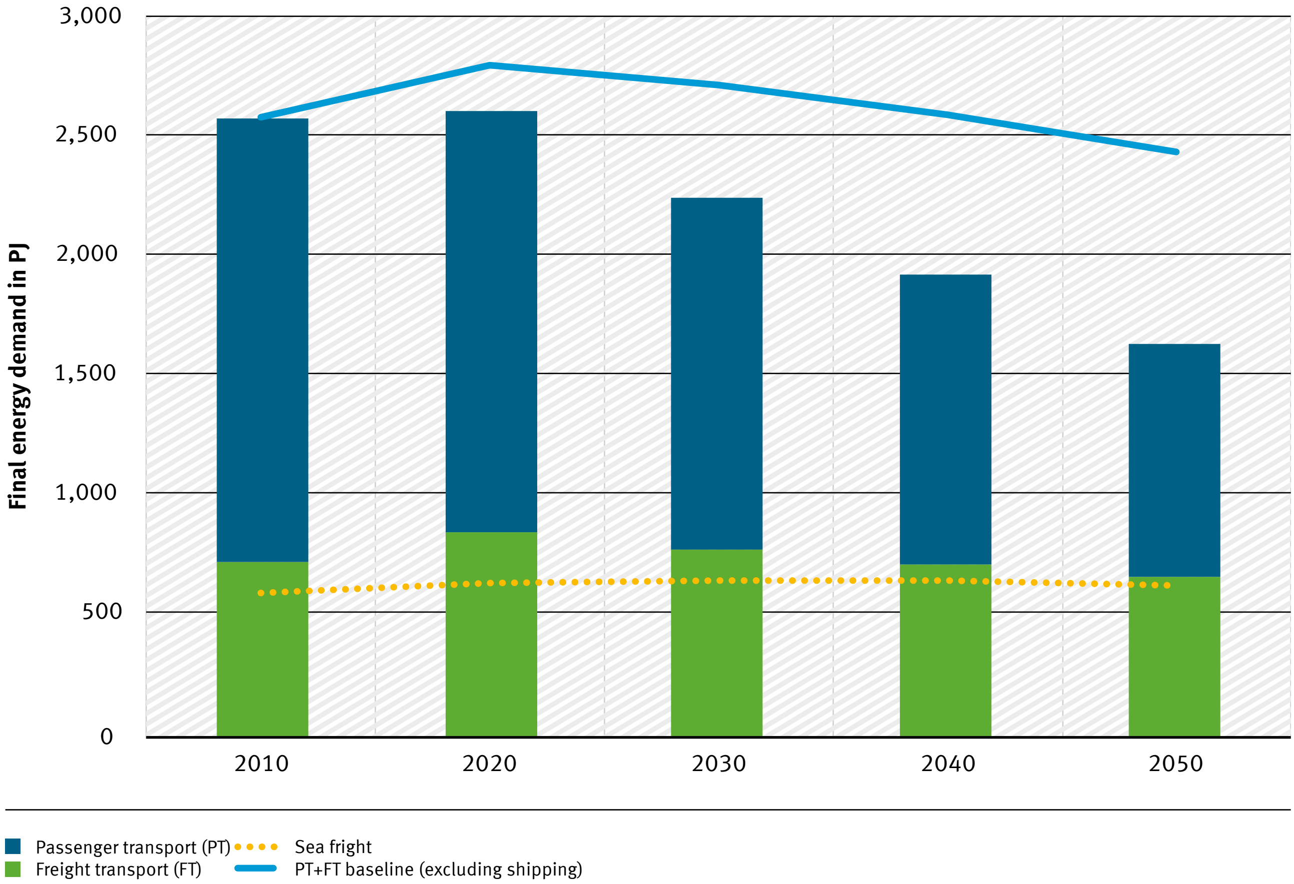
The GHG-neutral transport scenario envisages a final energy demand for the transport sector of 1623 PJ or 451 TWh (2248 PJ or 624 TWh including shipping), which is 33% (or 26%) below the final energy demand for the trend (see Figure C-6). Apart from the slightly reduced transport performance and modal shift towards lower-energy modes of transport, this is largely due to the higher proportion of electric vehicles on the roads. Compared with 2010, the GHG-neutral transport scenario cuts the final energy demand by 36.3%.

Freight traffic plays a significant part in this: In contrast to the trend, which sees a 46% rise in the final energy demand for freight traffic between 2010 and 2050, lower transport performance, modal shifts and more efficient goods vehicles in the GHG-neutral transport scenario can reduce it to 664 PJ (184 TWh) by 2050, after an initial rise. This corresponds to an 8% reduction compared with 2010 and a 37% reduction compared with the final energy demand in 2050 based on a continuation of the existing trend.

In the GHG-neutral transport scenario we also assume that there will be a significant 29% drop in passenger transport compared with the trend due to modal shifts and more fuel-efficient vehicles. As a result, in 2050 the final energy demand for passenger transport will be 958 PJ, which equates to 59% of the overall final energy demand for the transport sector (excluding shipping).

No measures were included for shipping, which explains why the final energy demand for shipping is identical in both the baseline trend and the GHG-neutral transport scenario.

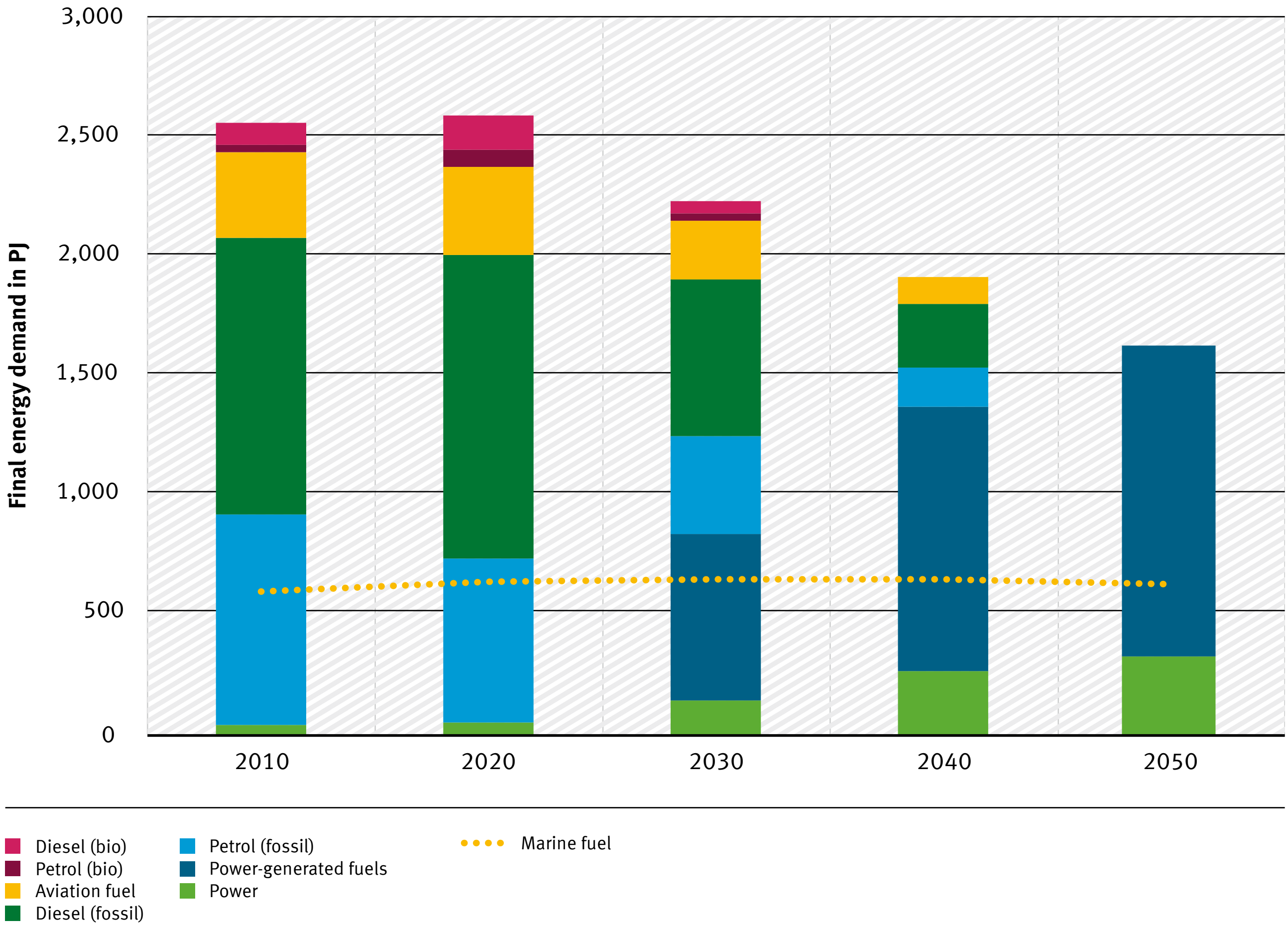
Figure C-6: Final energy demand by mode of transport



The GHG-neutral transport scenario assumes that 20% of transport in 2050 will be powered through the direct use of electricity and 80% will run on power-generated fuels (excluding shipping, see Figure C-7). The reason for this high proportion of power-generated fuels is that 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 so a substantial proportion of vehicles will continue to use conventional combustion engines.

It is important to be aware that the above-mentioned figure of 1623 PJ (or 2248 PJ including shipping) is the final energy demand, i.e. the energy content of the fuels and traction power used. However, generating fuel from power entails high conversion losses, and these must be factored into the calculations. The overall demand for power (net power generation) in the transport sector is dealt with in Chapter B.5.1.3.

Figure C-7: Final energy demand by energy source



C.5 Summary

The 'Scenario for greenhouse gas-neutral transport in Germany in 2050' presented in this study demonstrates that it is possible for the entire transport sector to switch to (renewable) electricity by 2050. However, this would imply a correspondingly high, additional demand for power and power-generated synthetic fuels.

The transport sector can reduce its final energy demand only through a combination of measures aimed at encouraging traffic avoidance, modal shift and technical measures to improve efficiency. This, combined with the exclusive use of renewable energy sources, provides the basis for greenhouse gas neutral transport in Germany in 2050. Our scenario assumes that the transport sector's final energy demand in 2050 will be 2248 PJ or 624 TWh (including shipping). This is approximately three quarters of the final energy demand that would be expected if the existing trend were to continue without implementation of the stated measures.

However, the final energy demand takes into account only the energy content of the fuels and power used. High conversion losses are also incurred when synthetic fuels are generated from power. These must be factored in when calculating the overall demand for electricity (net power generation) in the transport sector, which is dealt with in Chapter B.5.1.3.

In this scenario, the share of power-generated fuels is over 80%; only 20% of the power is used directly. The main reason for this is that, given our current knowledge, we cannot assume a potential for the direct use of electricity to power the increasing long-distance road haulage, air traffic and shipping. However, unlike the direct use of electricity in electric vehicles, the production of power-generated fuels entails conversion losses. In terms of the energy efficiency per kilometre driven, the direct use of power in electric vehicles is therefore preferable. On the other hand, power-generated fuels have certain advantages: they can be stored and used in those areas of the transport sector where the direct use of electricity is not an option.

In the interests of producing a comprehensive assessment, it is also important to consider the costs of the various drive systems and fuel technologies, but this aspect cannot be addressed here.

The aim of this chapter is to develop a consistent scenario for greenhouse gas-neutral transport in Germany in 2050. We have developed a scenario with the focus on power-based fuels in which the final energy demand falls, but the quantity of electricity required to achieve this increases substantially. A greenhouse gas-neutral transport sector is only achievable if an adequate supply of power from renewable sources is available.

D. Industry

D.1 Introduction

In 2008, final energy consumption (FEC) in the industrial sector was 702 TWh p.a.[CXXIX] or 28% of the total FEC in Germany.[143] Quite a significant part, approximately two thirds, came from the direct use of fossil fuels. If Germany is to become a greenhouse gas-neutral society, the entire industrial and manufacturing sector faces[CXXX] the challenge of reducing this share of its FEC to near zero. The purpose of this chapter is therefore to develop a scenario for the German industrial sector in 2050, in which industrial, fuel-induced greenhouse gas emissions drop to greenhouse gas-neutral levels, i.e. near zero. At the same time, the scenario looks at halving energy consumption in the industrial sector.

In the context of the greenhouse gas-neutral scenario, we were also looking for solutions that would reduce process-related greenhouse gas emissions, i.e. greenhouse gas emissions that are not energy-related, but associated with the use of raw materials in production and various applications. This would apply to cement manufacturing and various processes in the chemical industry.

In this chapter, examples from FEC-relevant industries will be used to demonstrate how developments, changes and innovations would enable them to reach their target by 2050. These options have been worked out for a set of conditions defined below, representing a scenario for a greenhouse gas-neutral and energy-efficient industrial sector in the Germany of 2050.

1. Germany's power supply relies 100% on renewably produced or totally greenhouse gas-neutral sources; non-renewable or nuclear power generation is not part of the scenario.
2. Only renewably produced fuels (solid, liquid or gaseous) are used, which, in turn, are produced with renewable power. The use of biomass or fossil fuels is not part of the scenario.
3. Energy efficiency potentials are harnessed as far as scientifically and technically possible. This should reduce FEC to nearly half the current level.
4. In the future, power from renewable resources will be cheaper to produce than renewable fuels because these will be produced using renewable power.
5. There are no supply shortages in renewable energy.
6. In 2050, fossil raw materials are no longer used as a carbon source for chemical synthesis and have been largely replaced by carbon sources based on renewable methane.
7. The structure of the industrial sector in 2050 is comparable to its current structure (with the possible exception of the chemical industry, see point 6). New industries that may emerge are, by definition, not part of this report.
8. Germany will continue to be a major industrial nation in 2050. The economy is expected to grow at an average rate of 0.7% p.a. by 2050. This assumption has been checked against expected developments in individual industries and elaborated in more detail where appropriate.

D.1.1 Selection of industries to be highlighted in the report

The industries included in this report were chosen on the basis of their final energy consumption (FEC) according to sectors, as described in the UBA publication *Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008)*, (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008).[144] The aim was to achieve a FEC-weighted selection

CXXIX AGEB (Arbeitsgemeinschaft Energiebilanzen - Energy Balances Work Group) states a consumption of 718 TWh p.a. for 2008.

CXXX The term industrial sector will be used from now on as an umbrella term for the industrial sector and manufacturing, including the use of F-gases and of solvents.

of industries in order to include FEC-relevant industries in the report. The industries to be looked at should cover at least two thirds of the overall industrial FEC. Looking at all areas of the economy and including all industries would have been impossible within the framework of this study, not only from a cost-benefit perspective, but also due to the availability of data and the complex and heterogeneous structure of industries and sectors. For those industries not included in the report, we assume that the solutions and potential developments shown for the industries included could, in principle, be transferred and specifically adapted to fit the 2050 scenario.

The subdivision of industries into sectors of economic activity in the above publication follows the Energy Balances for Germany.[145] The various industries and processes are assigned to these sectors of economic activity. With the objective of this report in mind, industries were selected as described below. No special attention was given to process-related greenhouse gas emissions because the energy balance does not provide data for the sectors listed.

In a first step, the industrial sectors were ranked (ranks 1 to 14, where 1 = very large proportion and 14 = very small proportion) according to their FEC for fuels, which amounted to 469.75 TWh/p.a. in 2008.[146] The FEC for fuels was used as a parameter for fuel-related greenhouse gas emissions. The FEC from renewable fuels and district heating was not subtracted from the fuels FEC because the volume was insignificant. In a second step, the industrial sectors were ranked according to the overall FEC. On the basis of these two rankings, an overall ranking was established for the fourteen industrial sectors (see Table D-1). For the reasons given above, we were unable to include all fourteen sectors in this report and decided instead to select eight of the ten highest-ranking sectors, which, in combination, cover 75-80% of the overall FEC and the FEC for fuels. Within these eight sectors, relevant industries were chosen for each sector in order to look at them in more detail in the report (see Table D-1). In addition, the textile industry and the production and use of fluorinated greenhouse gases as well as emissions from the use of nitrous oxide and solvents and other product uses were included in the study, in line with the categories in the National Inventory Report (NIR)[CXXXI], and added to this chapter. The ceramics industry is not part of the report because of insufficient data, its low final energy consumption (e.g. production of bricks and structural ceramics with only 0.3% of the overall FEC[147]), and because it is a highly heterogeneous industry. By the same token, industries such as the manufacture of transport equipment and machinery, rubber and plastic goods, mining and quarrying and other manufacturing industries do not figure in this report.

Table D-1: Selection of industries to be highlighted in the report based on final energy consumption (FEC) in the 14 industrial sectors of the economy for 2008 as listed in the UBA Climate Change 07/2012[148] publication

Industrial Sector	Rel. proportion of FEC for fuels in %	Rank (FEC for fuels)	Rel. proportion of overall FEC in %	Rank (overall FEC)	Combined rank	Selection of industries in report
Metal production (steel industry)	27.6	1	21.5	1	1	**Steel industry**
Basic chemicals	13.5	2	15.2	2	**2**	**Chemical industry**

CXXXI National Inventory Report (NIR).

Industrial Sector	Rel. proportion of FEC for fuels in %	Rank (FEC for fuels)	Rel. proportion of overall FEC in %	Rank (overall FEC)	Combined rank	Selection of industries in report
Paper industry	9.4	4	9.2	3	**4**	**Paper and pulp industry**
Mined or quarried non-metallic minerals	10.4	3	8.1	5	**4**	**Cement industry, lime industry**
Other manufacturing sectors	6.8	6	8.2	4	5	not included due to heterogeneity of industries involved
Food and tobacco	8.1	5	7.9	6	**6**	**Food industry**
NFM, foundries	3.5	10	5.4	7	**9**	**Non-ferrous metal (NFM) industry, Foundry industry (iron, steel, malleable iron and NFM casting)**
Glass & ceramics	4.3	7	3.6	11	**9**	**Glass industry**
Metal processing	3.7	9	4.5	9	9	not included due to heterogeneity of industries involved
Remaining chemical industry	3.9	8	3.7	10	**9**	**Chemical industry**
Vehicle manufacturing	3.4	11	4.9	8	10	not included due to heterogeneity of industries involved
Machinery manufacturing	2.6	12	3.4	12	12	not included due to heterogeneity of industries involved
Rubber and plastic goods	2.0	13	3.3	13	13	not included
Mining and quarrying	0.9	14	0.9	14	14	not included

D.1.2 Justification of deviations from the NIR source group classification

The selection of industries analysed in this report deviates from the NIR classification system in many ways. The purpose of the NIR is to give a comprehensive account of all greenhouse gas emissions in Germany. Industry and manufacturing are only one of many greenhouse gas source categories represented in the NIR. In some instances, greenhouse gas emissions from some industries are reported in different places or subcategories in the NIR. Thus, greenhouse gas emissions from the steel industry are divided into 5 NIR source categories.[CXXXII] Conversely, greenhouse gas data from a variety of industries are often aggregated because the underlying data do not permit any other form of representation. This leads to incongruences between the internationally agreed NIR framework of source categories for GHG emissions and the categories that reflect existing and historical structures within the industrial sector in Germany. In other words, the NIR categories are not always compatible with the industry selection of this study. This will be further elaborated below.

In the NIR, the various source categories for greenhouse gases listed in the IPCC Guidelines for National Greenhouse Gas Inventories are divided into seven CRF (Common Reporting Format) sectors. The source categories for industry and manufacturing are part of CRF sectors 1 (energy) and 2 (industrial processes). CRF sector 1 covers energy and fuel-related greenhouse gas emissions, while CRF sector 2 covers process-related GHG emissions.[CXXXIII]

Source subcategories that are particularly relevant in terms of greenhouse gas emissions were brought together in overarching source categories and assigned specific CRF codes. The source subcategories themselves, however, usually consist of further subcategories, which, in turn, are frequently assigned to various individual industries. Thus, in CRF sector 1 (energy), fuel-related greenhouse gas emissions from production areas pig iron (furnaces), sinter, rolled steel, steel and malleable cast iron, open-hearth steel and electric furnace steel are reported under "Combustion of fuels (CRF 1.A)" as well as the source category "Manufacturing (CRF 1.A.2)", subcategory "Manufacturing industries and construction – iron and steel (CRF1.A.2a)". It becomes clear that the source subcategory mentioned contains further sub-subcategories, some of which pertain to the steel industry, others to foundries. Technically, however, the foundry industry is not part of the iron and steel industry, but of the metal-processing sector.

Due to the inventory structure, the following sub-subcategories fall under source category "Manufacturing (CRF 1.A.2)" "Manufacturing industries and construction – Other energy production (1.A.2.f)":

- "1.A.2.f Cement" (structural element "Production of cement clinkers (process combustion)"),
- "1.A.2f "Ceramics" (structural element "Production of ceramics products (process combustion)"),
- "1.A.2.f Glass (structural element "Production of glass (process combustion)"),
- "1.A.2.f Lime (structural element "Production of lime (process combustion)") and
- "1.A.2.f Other".

This is just to demonstrate that under CRF Code 1.A.2.f in the NIR, fuel-related greenhouse gas emissions are reported from a wide range of different industries. These industries, in turn, may be subdivided into several sub-industries and sub-sectors.[149] For example, "1.A.2.f Glass" covers process combustion-related greenhouse gas emissions from the sub-industries flat glass, concave glass, glass fibres, finishing and processing of flat glass, as well as production and finishing of other glass and technical glass products. In addition, "1.A.2.f Other" acts as an umbrella category, containing emissions such as those from power and heat generation in industrial power stations and industrial boilers as well as all energy-related emissions for the entire chemical industry. The source subcategory "1.A.2.f Other" thus contains all reports of emissions that cannot be disaggregated in terms of energy use in line with the structure of source category "1.A.2 Manufacturing". According to the NIR, source subcategory "1.A.2.f Other" accounts for around 75% of the overall CO_2 emissions in source category "1.A.2 Manufacturing". In theory, a large proportion of energy uses in "1.A.2.f Other" should be assigned to the relevant industry. This cannot be done at the moment, due to lack of data. As a result, the

CXXXII See also Chapter D.2.

CXXXIII On CRF sector 1 see also chapter 0.

NIR contains no more than an aggregated overview, which does not permit industry-specific analyses and evaluations of current and future greenhouse gas emissions. It is therefore not very helpful for this study.

For most industries looked at in this report, greenhouse gas emissions are reported in two or even more source categories in the NIR. Table D-2 shows the relevant source categories and/or CRF codes in the NIR for the industries included in this report. In most cases, the way an industry is dissected into several source categories does not reflect actual industrial procedures and processes and does not offer any support for the development of greenhouse gas-neutral strategies within the industries. This is why this chapter of the study generally does not follow the NIR categories when discussing individual industries. Also, the division into energy- and process-related greenhouse gas emissions established in emissions reporting does not apply to all industries because either no process-related emissions arise or there is no clear division between energy-related and process-related greenhouse gas emissions, as in the use of coke as a reducing agent in the steel industry. The chapters on individual industries will therefore have a specific description of the division into energy- and process-related emissions.

Table D-2: Assignment of industries included in the report to NIR source categories. (NIR: National Inventory Report; CRF: Common Reporting Format)

		Categorisation according to NIR (CRF Code)		
Industrial Sector	Subsector	Energy (CRF Sector 1)	Industrial processes (CRF Sector 2)	Comment
Metal industry				
Steel industry	Primary iron and steel production on the basis of iron ore (sintering installations and conversion in oxygen steel works), secondary steel production on the basis of scrap iron and steel (electric arc furnaces), steel processing in hot rolling mills.	1.A.1.a, 1.A.2.a, 1.A.2.f Others, 1.A.1.c, 1.B.1.b	2.C.1, 2.A.3	1.A.1.a: includes greenhouse gas emissions from process gases used for power and heat generation in the steel industry. 1.A.2.a: a subset of greenhouse gas emissions from the steel industry, which, by convention, are considered to be “energy-related” (as opposed to emissions in 2.C1) 1.A.2.f Others: includes greenhouse gas emissions from process gases used for power and heat generation in the steel industry. 1.A.1.c: includes greenhouse gas emissions from coke furnace undergrate firing. 1.B.1.b: includes other greenhouse gas emissions from coking plants. 2.C1: a subset of greenhouse gas emissions from the steel industry, which, by convention, are considered to be “process-related” (as opposed to emissions in 1.A.2.a) 2.A.3: includes process-related greenhouse gas emissions from using limestone and dolomite for flue gas desulphurization in power station (addition of lime), while greenhouse gas emissions are reported under 1.A.1.a. 2.A.3 also includes process-related greenhouse gas emissions from using limestone and dolomite in iron and steel production (addition of limestone for pig iron and sintering). These, however, are reported under 2.C.1

		Categorisation according to NIR (CRF Code)		
Non-ferrous metal industry	Aluminium (primary and secondary), copper, lead and zinc as well as gold, silver, titanium and magnesium	1.A.2.b	2.C.2, 2.C.3, 2.C.4, 2.C.5 Others	1.A.2.b contains an aggregated report of all NF metal industries, including NF metal foundries Energy-related greenhouse gas emissions from subsets of industries cannot be disaggregated. Process-related greenhouse gas emissions are reported only for ferrous alloys (2.C.2), primary aluminium industry (2.C.3), SF_6 emissions from AL and Mn production (2.C.4) and for the lead, copper and zinc industries (2.C.5).
Foundry industry	Iron, steel, malleable iron and NFM casting	1.A.2.a, 1.A.2.b	2.C.1, 2.C.4	1.A.2 covers energy-related and 2.C.1 process-related greenhouse gas emissions in the sectors iron, steel and malleable iron as part of the iron and steel industry (1.A.2.a) and metal production: Iron and steel production (2.C.1). For the NF metal foundry sector, energy-related greenhouse gas emissions are reported in non-disaggregated form, i.e. as a sum, under 1.A.2.b. (Manufacturing - non-ferrous metals). Process-related greenhouse gas emissions are only reported in terms of SF_6 use under SF_6 in Al and Mn production (2.C4).
Chemical industry				
Chemical industry		1.A.2.c, 1.A.2.f Other.	2.B.1 to 2.B.5	Process combustion and own power generation in the chemical industry are not listed separately in the NIR, but summarised under 1.A.2.f Other in non-disaggregated form. The greenhouse gas emissions of the entire source category 1.A.2.c Manufacturing - Chemical industry are thus accounted for elsewhere. Division according to industries is impossible.
Ammonia production		1.A.2.c, 1.A.2.f Other.	2.B.1	For energy-related greenhouse gas emissions see comment on entire chemical industry. Overall process-related greenhouse gas emissions for ammonia production are reported under 2.B.1 because the different types of installations for the production of ammonia cannot be divided into individual aggregates, as the procedure is highly integrated and cannot be split into different steps that can be compared separately.

	Categorisation according to NIR (CRF Code)		
Nitric acid production	1.A.2.c, 1.A.2.f Other.	2.B.2	For energy-related greenhouse gas emissions see comment on entire chemical industry. Process-related greenhouse gas emissions arise during the production of nitric acid when nitrous oxide (N_2O is produced in a side reaction. These are reported under 2.B.2.
Adipic acid production	1.A.2.c, 1.A.2.f Other.	2.B.3	For energy-related -related greenhouse gas emissions see comment on entire chemical industry. Process-related greenhouse gas emissions arise during the production of adipic acid in the form of nitrous oxide (N_2O) and are reported under 2.B.3.
Other production processes	1.A.2.c, 1.A.2.f Other.	2.B.5	For energy-related -related greenhouse gas emissions see comment on entire chemical industry. 2.B.5 is an umbrella source category, which includes fertiliser and laughing gas production, organic chemical products, the production of carbon black, titanium dioxide and sulphuric acid as well as coke burn-off for catalyst regeneration in refineries. Process-related greenhouse gas emissions are summarised and cannot be disaggregated in the report. Division according to industries is impossible.
Minerals Industry			
Cement industry	1.A.2.f Other.	2.A.1	Energy-related greenhouse gas emissions are only summarised and reported as an aggregate under 1.A.2.f Other. Process-related greenhouse gas emissions are reported under 2.A.1 Mineral products: cement.

		Categorisation according to NIR (CRF Code)		
Glass industry	Container glass, flat glass, household and table glassware, special glass and also mineral fibres (glass and rock wool)	1.A.2.f Other.	2.A.7.a, 2.A.3, 2.A.4	Energy-related greenhouse gas emissions are only summarised and reported as an aggregate under 1.A.2.f Other. The IPCC Good Practice Guidance does not contain any suggestions or guidance on the determination of process-related CO_2 greenhouse gas emissions for the glass industry. Based on general advice in the IPCC Good Practice Guidance, a specific methodology was developed. Process-related greenhouse gas emissions are reported under 2.A.7.a. Glass. Process-related greenhouse gas emissions from the use of limestone and dolomite are reported in their own source category 2.A.3, which, however, does not include greenhouse gas emissions from glass production (limestone proportion in the mix) because these are reported under 2.A.7. Process-related greenhouse gas emissions from the use of soda ashes in the glass industry should be reported under 2.A.4, but are actually also reported under 2.A.7.
Lime industry		1.A.2.f Other.	2.A.2	Energy-related greenhouse gas emissions are only summarised and reported as an aggregate under 1.A.2.f Other. Process-related greenhouse gas emissions are reported under 2.A.2. Mineral Products: Lime.

	Categorisation according to NIR (CRF Code)		
Paper and pulp industry	1.A.2.d, 1.A.2.f Other.	2.D.1	1.A.2.d Manufacturing – pulp, paper and print products report their energy-related greenhouse gas emissions in the paper and pulp industry. The NIR classification system assigns print products to this source category although they are not part of the paper and pulp industry. Energy consumption for the production of pulp, paper and print products can only be shown in terms of substitute fuels. Greenhouse gas emissions from the use of regular fuels in process combustion and greenhouse gas emissions for own power producers are not shown separately, but summarised under 1.A.2.f Other and cannot be disaggregated. Process-related emissions are reported under 2.D.1 Other production: Pulp and paper production. However, climate-relevant greenhouse gas emissions as defined in the IPCC Good Practice Guidance do not arise in pulp and paper production.
Food, nutrition and tobacco, meat processing, milk processing, production of starch, pastry products, sugar and beer	1.A.2.e, 1.A.2.f Other.	2.D.2	Energy-related greenhouse gas emissions from the food industry are reported in the umbrella source category 1.A.2.f. Other and cannot be disaggregated. Division according to industries is impossible. Energy-related greenhouse gas emissions are reported separately only for the sugar industry under 1.A.2.e. In food and drinks production the process-related greenhouse gas emissions that matter are not greenhouse gases as such, but non-methane organic compounds (NMVOCs). Carbon dioxide emissions from foodstuffs undergoing processing are not reported in 2.D.2 because they originate from biological carbon and do not contribute to net CO_2 emissions.
Textile industry	probably in 1.A.2.f Other		The textile industry does not feature among NIR categories. Presumably, energy-related greenhouse gas emissions are also reported under 1.A.2.f Other and cannot be disaggregated. Process-related greenhouse gas emissions do not arise.

	Categorisation according to NIR (CRF Code)		
Production and use of fluorinated greenhouse gases			
Production and use of fluorinated greenhouse gases		2.C.3, 2.C.4, 2.C.5, 2.E.1, 2.E.2, 2.F.1, 2.F.2, 2.F.3, 2.F.4, 2.F.5, 2.F.7, 2.F.8, 2.F.9	F-gas emissions from the aluminium and magnesium industries are reported in source categories 2.C.3, 2.C.4 and 2.C.5. Process-related greenhouse gas emissions from fluorinated greenhouse gases are reported under 2.E. The use of fluorinated greenhouse gases in itself does not constitute an industry sector. It is reported instead under 2.F (2.F.1 to 2.F.89), where the use of fluorinated greenhouse gases from various industries and sectors are listed as individual source categories.
Aluminium and magnesium industry		2.C.2, 2.C.3, 2.C.4, 2.C.5	In source category 2.C.3, fluorinated greenhouse gases (CFCs) arise as by-products in the production of primary aluminium. In source category 2.C.4, SF_6 is used for cleaning and protection in Al and Mg foundries. In source category 2.C.5, hydrofluorocarbon-134a is used as protective gas in Mg foundries.
Production of fluorinated greenhouse gases		2.E.1, 2.E.2	Source category 2.E is divided into emissions from by-products (2.E.1 By-product Emissions) and production-related emissions (2.E.2 Fugitive Emissions).
Refrigeration units, air conditioning and heat pumps		2.F.1	HFC and CFC emissions from the use of refrigerants are reported in source category 2.F.1.
Production of insulation material		2.F.2	HFC emissions from the production and use of foams are reported in source category 2.F.2.
Fire extinguishing agents		2.F.3	HFC emissions from the use of fire extinguishing agents are reported in source category 2.F.3.
Aerosols and solvents		2.F.4, 2.F.5	HFC emissions from the use of blowing agents in aerosols are reported in source category 2.F.4. HFC emissions from the use of solvents are reported in source category 2.F.5.
Semi-conductor production		2.F.7	HFC, CFC and SF_6 emissions from use as etching or cleaning gas in semi-conductor production are reported in source category 2.F.7.

	Categorisation according to NIR (CRF Code)		
Electrical production equipment		2.F.8	SF_6 emissions arising from insulants are reported in source category 2.F.8.
Other SF_6 applications		2.F.9, partially under 2.G	SF_6 emissions from use in insulated glazing, car tyres, sports shoes, trace gas, AWACS servicing, welding, optical glass fibres and photovoltaics are reported in source category 2.F.9. In addition, CFC emissions from sports shoes and photovoltaics.
Emissions from solvents and other product uses			
Emissions from solvents and other product uses		3.A, 3.B, 3.C, 3.D (NM-VOCs)	Source category “Emissions from solvents and other product uses” (CRF 3) is an umbrella category for emissions from the use of chemical products in industry, trade and private households. It is divided into three subcategories “Use of paint and varnish” (CRF 3.A), “Degreasing and dry cleaning” (CRF 3.B), “Production and use of chemical products” (CRF 3.C) and “Other solvent applications” (CRF 3.D).
Use of paint and varnish		3.A (NM-VOCs)	NMVOC emissions from the use of paint and varnish are reported in source category 3.A.
Degreasing and dry cleaning		3.B (NM-VOCs)	NMVOC emissions from the use of solvents in degreasing and dry cleaning are reported in source category 3.B.
Production and use of chemical products		3.C (NM-VOCs)	NMVOC emissions from the use of solvents in the production and use of chemical products are reported in source category 3.C.
Other solvent applications		3.D (NM-VOCs)	NMVOC emissions from the use of solvents in other applications are reported in source category 3.D.

D.1.3 Status quo: Greenhouse gas emissions and energy data

2010 was chosen as the reference year when developing a future perspective for the industrial sector. However, data on energy use and greenhouse gas emissions were not available for all industries in that year. Thus, data from 2008 were used for Non-ferrous metal (NFM) industry , the foundry industry and the food industry,[150] while data from 2009 were used for the chemical industry[151] in this study (see Table D-3). By contrast, all data on process-related greenhouse gas emissions in the chemical industry refer to 2010 and were taken from the NIR. According to AGEB (AG Energiebilanzen - working group energy balances), the overall industrial FEC for 2010 was 720 TWh p.a. and 718.6 TWh p.a. for 2008. We can conclude that for the above-mentioned industries, the FEC of 2010 will be similar to that of 2008. It is, however, unclear if and to what extent the economic downturn of 2009 affected the FEC of the chemical industry. We therefore assume that the available data from the chemical industry in 2009 are comparable to those of 2010. For those industries that are not looked at in detail in this report, the overall FEC for 2010 was calculated as the difference between the overall industrial FEC, as shown in AGEB, and the sum of overall FEC of the industries included.

The initial situation for the industrial sector with greenhouse gas emissions and energy data for the reference year 2010 are shown in Table A3. For 2010, an overall FEC of 600 TWh p.a. or 83% of the entire industrial sector was recorded for the industries included. Only 120 TWh p.a. of the 720 TWh p.a. of the overall industrial FEC for 2010 are attributed to other industries which are not part of the study, such as machine and vehicle manufacturing. At the same time, approximately 470 TWh p.a. of fuel-related FEC was recorded. No conclusions can be drawn regarding energy-related and fuel-related greenhouse gas emissions in power generation, due to missing data and variations in industry-specific CO_2 emission factors. Not including the steel industry, where all greenhouse gas emissions were classified as energy-related, process-related greenhouse gas emissions amounted to 58 million tonnes of CO_{2eq} in 2010.

Table D-3: Initial situation: Greenhouse gas emissions and energy data in the industrial and manufacturing sectors[CXXXIV]

		Final energy consumption (FEC) in TWh p.a.		**Energy-related greenhouse gas emissions (GHG-EM) in tonnes of CO_{2eq} p.a.**		**Process-related greenhouse gas emissions (proc. GHG-EM)**	**Reference year**
Industry sector	Industry subsector	Overall FEC	Fuel-related FEC (excluding electricity)	Overall GHG-EM (fuel and electricity)	Direct GHG-EM (fuel only)	in tonnes of CO_{2eq} p.a.	
Metal industry							
	Steel industry	181.10	168.90	56,247,753			2010

CXXXIV The source references for the data shown can be found in the relevant individual chapters.

CXXXV The use of flourinated greenhouse gases and NMVOCs as solvents and/or other product uses does not represent an industrial sector in its own right.

		Final energy consumption (FEC) in TWh p.a.		Energy-related greenhouse gas emissions (GHG-EM) in tonnes of CO_{2eq} p.a.		Process-related greenhouse gas emissions (proc. GHG-EM)	Reference year
	Non-ferrous metal industry	25.50	9.80	11,091,000	2,117,000	2,909,000	2008
	Foundry industry	12.85	7.00		1,919,000		2008
Chemical industry		182.00	137.00	37,400,000			2009
	Ammonia production					7,400,000	2010
	Adipic and nitric acid production					3,750,000	2010
	Other production processes					8,900,000	2010
Minerals Industry							
	Cement industry	27.80	24.44	10,305,000	8,472,000	12,488,000	2010
	Glass industry	25.47	14.10	9,193,853	2,966,000	761,563	2010
	Lime industry	8.25	7.61	2,691,506	2,343,950	5,000,000	2010
Paper and pulp industry		72.42	60.70	18,717,883	10,936,053		2010
Food industry		55.80	37.94		7,797,229		2008
Textile industry		8.39	3.47	3,434,548			2010
Production and use of fluorinated greenhouse gases[CXXXV]							
	Aluminium and magnesium industry					262,000	2010

		Final energy consumption (FEC) in TWh p.a.		Energy-related greenhouse gas emissions (GHG-EM) in tonnes of CO_{2eq} p.a.		Process-related greenhouse gas emissions (proc. GHG-EM)	Reference year
	Production of fluorinated greenhouse gases					256,000	2010
	Refrigeration units, air conditioning and heat pumps					10,139,000	2010
	Production of insulation material					670,000	2010
	Fire extinguishing agents					24,000	2010
	Aerosols and solvents					458,000	2010
	Semi-conductor production					148,000	2010
	Electrical production equipment					543,000	2010
	Other SF_6 applications					2,655,000	2010

		Final energy consumption (FEC) in TWh p.a.		Energy-related greenhouse gas emissions (GHG-EM) in tonnes of CO_{2eq} p.a.		Process-related greenhouse gas emissions (proc. GHG-EM)	Reference year
Emissions from solvents and other product uses							
	Use of paint and varnish					572,860	2010
	Degreasing and dry cleaning					82,474	2010
	Production and use of chemical products					123,141	2010
	Other solvent applications					804,690	2010
Total		599.58	470.96			57,946,728	
Other industries (not included in the report) [CXXXVI]		120.42					
Industrial sector overall [CXXXVII]		720,00 [CXXXVIII]				58,245,728 [CXXXIX]	

CXXXVI Calculations of the overall FEC for the other industries that are not part of the report are based on the industrial FEC for 2010 according to AGEB (AG Energiebilanzen), which amounts to 720 TWh p.a. The FEC for 2010 is thus similar to that of 2008 (718.6 TWh p.a.) which also provided some data for the report.

CXXXVII For some industries, data were not available for the reference year 2010, but only for 2008 or 2009. It was therefore assumed that the FEC for 2010 in these industries would be similar to 2008 and 2009.

CXXXVIII For 2010 according to AGEB.

CXXXIX Including 299,000 tonnes of CO2eq from the use of nitrous oxide.

D.2 Steel industry

D.2.1 Status quo

D.2.1.1 Structure and economic significance of the steel industry

Although the industrial sector underwent structural changes the in the 20th century, the production of iron and steel is still one of the most important industries in Germany. Its wide range of products, comprising approximately 2000 steel grades, also provides a major material resource for other industry sectors.

There are two main production routes for steel in Germany:

1. Primary iron and steel production is based on the agglomeration of iron ore in sinter plants, which is then reduced to pig iron in blast furnaces, using coke, and finally converted into lower-carbon steel in oxygen converters. The latter two processes gave this production method its name – it is either referred to as the blast furnace or oxygen steel production route.
2. Secondary steel production is based on scrap iron and steel which is melted in electric arc furnaces and processed into crude steel. This steel is referred to as secondary steel or electric arc furnace (EAF) steel.

Of the crude steel produced in German oxygen steel converters and electric arc furnaces, 85% undergoes further processing in hot rolling mills. Rolled steel products include sheet steel, girders, rails and steel wire. Production volumes from the individual processing steps in the steel industry are shown in Table D-4.

Table D-4: Production volumes for installation types and process steps in the German steel industry 1995–2010[152]

Processing step	Product	Unit	1995	2000	2005	2010
Sinter plants	slag	tonnes	28,243,000	27,959,000	28,517,000	26,788,359
Coke ovens	coke	tonnes	11,102,000	9,115,000	8,397,000	8,171,000
Blast furnaces	pig iron	tonnes	30,012,000	30,845,000	28,854,000	28,559,947
Oxygen steel converters	oxygen steel	tonnes	31,908,000	33,052,000	30,857,000	30,615,171
Electric arc furnaces	electric arc furnace steel.	tonnes	10,143,000	13,324,000	13,667,000	13,215,185
Hot rolling mills	rolled steel	tonnes	34,316,000	38,974,000	37,771,254	36,826,655

The most noticeable changes in Table D-4 occurred in coke and electric arc furnace steel production. Domestic coke production dropped by approximately a quarter in the period in question because some of the coke required was imported and up to 30% of blast furnaces switched to other reducing agents. By comparison, electric arc furnace steel production went up by approximately 30% and now accounts for 30% of the overall crude steel production. Overall steel production, however, only increased until 1997 and has remained at more or less the same level since - about 45 million tonnes per annum.

Iron and steel are not only very versatile materials, but, from an environmental perspective, their advantage lies in their virtually unlimited recyclability. New products can be made without any loss of quality. Secondary steelmaking from scrap requires substantially less energy and produces fewer emissions. It is, however, not possible to increase secondary steel production at will because the quantity of available scrap material is limited, as more and more steel is locked into durable goods (e.g. machinery, vehicles or buildings) and because products containing steel are exported and no longer available for recycling at national level. Although practically 100% of all available scrap is recycled, our economy cannot do without resource-intensive primary steelmaking.

Scrap recycling amounts to 45% of the total steel production in Germany. The size of the share depends on the available volume of scrap as well as on the available mix of installations for primary and secondary steel production. While the production of EAF steel is based on 100% scrap as raw material, no more than 25% scrap is added in primary steel production in an oxygen steel converter.

D.2.1.2 Energy use and greenhouse gas emissions from the steel industry

According to the specifications for greenhouse gas emissions reporting, greenhouse gas emissions directly associated with steel production are attributed to many different source categories (see Table D-5). These include emissions from the production of coke from black coal because Germany's five coke ovens produce coke for blast furnaces only. Four of these coke ovens are also part of the energy supply networks of integrated steel mills (in official statistics, however, coke ovens have traditionally been listed under energy generation).

Table D-5: Source categories in the National Emissions Inventory[153] where greenhouse gas emissions directly associated with steelmaking are reported

CRF Code	Source category	Comment
1.A.1.a	Public power and heat supply	Includes greenhouse gas emissions from the use of process gases from the steel industry for power and heat generation (public supply)
1.A.2.a	Manufacturing industries and construction - iron and steel	A subset of greenhouse gas emissions from the steel industry, which, by convention, are considered to be "energy-related" (as opposed to emissions in 2.C1)
1.A.2.f	Manufacturing industries and construction - other energy generation	Includes greenhouse gas emissions from the use of process gases from the steel industry for industrial power and heat generation.
1.A.1.c	Manufacture of solid fuels and other energy industries	Includes greenhouse gas emissions from coke oven undergrate firing.
1.B.1.b	Fugitive emissions from solid fuel transformation	Includes other greenhouse gas emissions from coke oven plants.

CRF Code	Source category	Comment
2.C.1	Metal production: Iron and steel production	A subset of greenhouse gas emissions from the steel industry, which, by convention, are considered to be "process-related" (as opposed to emissions in 1.A.2.a)

These categories have their limitations when it comes to developing a long-term concept for the structure of a GHG-neutral steel industry, as they do not reveal the actual energy consumption and greenhouse gas emissions of individual processes or production routes. The division into energy- and process-related emissions in particular – standard in emissions reporting – proves counter-productive when looking at the long-term perspective of the steel industry. A large proportion of those energy vectors that cause greenhouse gas emissions have their place in the technical process (namely for reducing the iron oxide contained in the ore), while the arising process gases (blast furnace gas from furnaces and converter gas from oxygen converters) can be re-used as energy sources in various industrial processes.

Germany's steel industry has a high demand for energy and as such, is one of the energy-intensive industry sectors. Its final energy consumption in 2010 amounted to a total of 608 PJ of solid, liquid and gaseous fuels, plus 21.7 TWh of electric power, of which 9.5 TWh (44 %) were generated from process gases arising during steelmaking. Its net power consumption is therefore no more than 12.2 TWh per annum. Assuming an efficiency ratio of 42%, this would be equivalent to a primary energy consumption of approximately 105 PJ per annum.[CXL]

Apart from changes after German reunification in 1990/91 and the dramatic economic downturn in 2009, no distinct trend could be observed in the use of fuels/reducing agents and in electricity consumption in absolute terms. Bearing in mind that during the period in question, the production of crude steel rose by a mean value of 0.3 million tonnes per annum, figures suggest that the specific consumption of primary energy carriers fell by approximately 1% or 0.18 GJ per tonne of crude steel. The decreasing consumption can largely be explained by the increasing share of electric arc furnace steel in overall steel production, which only requires approximately one third of the primary energy required for primary oxygen steelmaking (oxygen steel converter route), even allowing for the conversion efficiency of power generation.

Table D-6: Specific consumption of primary energy carriers and power and specific (direct) CO_2 emissions from the German steel industry in 2010[CXL]

	Production	Primary energy	CO_2 emissions	Power consumption	
	tonnes p.a.	GJ per tonne of steel	kg per tonne of steel	MWh per tonne	GWh p.a.
Sinter plants	26,788,359	1.86	246		
Coke ovens	8,171,000	1.20a)	183a)		
Blast furnaces and oxygen steel converters	30,615,171	14.23	1,225b)		

CXL UBA calculations, based on energy data supplied by the German Steel Federation for emissions reporting (see bibl. ref. no.152).

	Production	Primary energy	CO_2 emissions	Power consumption	
Subtotal for primary steel production	30,615,171	17.29	1,654a)b)	-0.146b) c)	-4,469b) c)
Electric arc furnaces	13,215,185	0.61	47	0.565	7,464
Hot rolling mills	36,826,655	2.20	184	0.151	5,550
Total power consumption					8,544*)

a) Since Germany imports approximately one third of its coke, the specific energy use and specific emissions from German coke oven plants were extrapolated to match the amount of coke used for crude steel production.

b) Factoring in power generation from process gases (blast furnace and converter gas)

c) Primary steel production was credited 544 kg of CO_2 per MWh for generating electricity from blast furnace and converter gas, based on the CO_2 emission factor for the German electricity mix in 2010[154]

Absolute power consumption did not increase in spite of the increase in EAF steel production. One explanation could be that during that period, electric arc furnaces were increasing the proportion of their energy supply coming from fossil fuels. It can also be assumed that the steel industry actually improved its energy efficiency in terms of power consumption. However, these efficiency gains were largely cancelled out by an increase in EAF steel production and thus did not have an impact on the overall power consumption of the sector.

Table A6 compares the specific consumption of primary energy carriers and power as well as (direct) CO_2 emissions arising from the use of primary energy sources for the various individual plant types and process routes within the German steel industry in 2010.

CO_2 emissions from 1995 to 2010 are shown in Table D 7. As some of the CO_2 emissions from the blast furnace - oxygen converter route are only released when process gas is used in other installations, Table D 7 also contains emissions attributed to power and heat generation. At the same time, primary steel production was credited 544 kg of CO_2 per MWh for power generated from process gases (CO_2 emission factor for the German electricity mix in 2010[154]).

Table D-7: CO_2 emissions for different installation types and process steps in the German steel industry 1995–2010[CXL]

	Unit	1995	2000	2005	2010
Sinter plant	tonnes of CO_2	7,225,575	7,324,508	6,782,014	7,518,318
Coke oven	tonnes of CO_2	6,225,109	4,331,024	3,769,336	3,834,811
Blast Furnace and oxygen steel converter	tonnes of CO_2	17,323,525	19,242,548	20,042,565	16,996,269
Power generation	tonnes of CO_2	16,069,289	16,102,645	16,882,732	18,561,074
Heat generation	tonnes of CO_2	7,890,699	7,192,879	5,181,556	7,093,782

CXLI As data for own power generation was available for 2010 only[152], estimates for the other years were made on the basis of total pig iron production.

	Unit	1995	2000	2005	2010
CO_2 credit for generated power[CXLI]	tonnes of CO_2	-5,401,637	-5,551,562	-5,193,217	-5,140,292
Subtotal for primary steel production	tonnes of CO_2	49,332,561	48,642,041	47,464,987	48,863,960
Electric arc furnace steel production	tonnes of CO_2	392,004	554,332	574,068	616,055
Hot rolling mill	tonnes of CO_2	6,095,924	6,467,452	6,980,338	6,767,738
Steel industry overall	**tonnes of CO_2**	**55,820,488**	**55,663,825**	**55,019,393**	**56,247,753**

D.2.2 Strategies for reducing GHG emissions in the German steel industry

D.2.2.1 Improving resource efficiency

Resource efficiency in the steel industry sector may be improved at different levels:

- a higher yield of steel from the material input, i.e. less material is lost and more steel produced per tonne of ore or scrap
- an increased recycling rate, in particular a higher share of EAF-based secondary steelmaking in the overall crude steel production
- a more efficient use of steel, e.g. by lightweight construction using high-strength steel, which will achieve the same or an even better level of stability with less steel.

The German steel industry has been continuously increasing the yield of steel from input materials over the past decades. Nowadays, approximately 90% of the iron content in the input material (blast furnace burden material as well as scrap) is converted into marketable products (rolled steel products, including semi-manufactured products) [155]. In view of inevitable losses of iron due to high processing temperatures, the scope for further yield improvements is probably very limited. Even if it were possible to increase the yield by a further 5%, it would probably not help to reduce GHG emissions significantly because it would require a disproportionate amount of energy to increase the yield.

Increasing the recycling rate would not only improve resource efficiency in steel production, but with less energy required for iron reduction, specific energy demand as well as greenhouse gas emissions would be considerably reduced. Whether the secondary steelmaking sector can expand, however, very much depends on the availability of suitable ferrous metal scrap. Although one would generally expect that in an industrial society, scrap recovery will gradually reach levels similar to new steel production (saturation phenomenon), we have not yet reached that stage by any means. The availability of scrap for national steel production is largely limited by the following factors:

- an export surplus for steel, steel-containing products (e.g. machinery, new and used cars) and scrap metal
- an increasing amount of steel that is locked into durable consumer goods, buildings and other infrastructure (e.g. pipelines, pylons or wind turbines) (anthropogenic storage)
- dissipative loss of steel through weathering or residual waste disposal.

In 2008, the German steel industry used 20.7 million tonnes of scrap to produce approximately 45% of its crude steel.[156] However, given that part of the scrap is needed to cool the weld pool in the oxygen steel converter, the actual share of EAF-based secondary steel production amounted to only around 30%. Since there is a worldwide demand for scrap metal and this trend is set to increase, expanding the import of scrap does not seem the way forward to meet demands in the future. With less scrap metal available domestically than required to cover the current demand for steel, some steel must be produced from primary raw material (iron ore), which requires a lot of energy.

More efficient use of resources means that the same functionality can now be achieved using less steel. Such innovations include the use of high-strength steel and innovative steel processing (e.g. the use of tailored blanks — semi-manufactured products with diameters and material properties adapted to customers' specifications). The resulting light-weight constructions help reduce greenhouse gas emissions, not only because less material is required to produce them, but also because their use in vehicle construction will cut down on energy (fuel) in the subsequent usage period. However, we do not know yet whether such resource-efficient use of steel will reduce demand for steel, simply because many of the innovative materials and processing methods have limited scopes of application. Neither can we predict the impact these new developments will have on the foreign trade balance for steel products in the future — negative or positive.

D.2.2.2 Enhancing energy efficiency

Shortening process chains/production from a single heat source

A generally valid approach to improving energy efficiency is shortening process chains. In terms of industrial steel production, this means above all avoiding heat losses in repeated cooling and heating processes.

In crude steel production, shortening process chains could mean dispensing with the energy-intensive steps of iron ore sintering and coal coking, for instance. However, since pig iron production in blast furnaces requires agglomerated iron ore and lumpy coke, dispensing with sinter and coke oven plants would only be feasible if pig iron production underwent a fundamental change (see Chapter A.2.2.3).

Another option for shortening processing chains would be the use of near-net shape casting methods. In contrast to the conventional continuous casting of slabs and billets, near-net shape casting means casting the crude steel as closely as possible to the final measurements of the product (sheet thickness) so that only a few rolling cycles are needed to finish off the product. This cuts out a large amount of reshaping and re-heating processes. Until recently, near-net shape casting methods were only applicable to a small range of steel grades and product shapes. As part of the environmental innovation programme funded by the Federal Ministry for the Environment (BMU), Salzgitter AG is currently building a strip caster that enables near-net shape casting for a significantly wider range of products, resulting in an overall saving of primary energy and power of 2.1 GJ per tonne.[157]

The transition from crude steel production to further processing in rolling mills offers further energy-saving opportunities. In traditional continuous casting, slabs and billets need to cool down thoroughly before being passed on to the rolling mill, where they are reheated to the required processing temperature (800–1150°C). If, instead, the still hot slabs and billets could be processed in the rolling mill as soon as they have consolidated, the reheating process could be largely dispensed with, saving 0.4 to 0.6 GJ per tonne. So far, however, hot-charging, as it is known, has met with various practical obstacles concerning the metallurgic process, installation layout or logistics. As part of its environmental innovation scheme, the BMU is currently co-funding an electric arc furnace plant in which the whole processing sequence will be optimised to permit direct processing of 80% of the billets at temperatures up to 950°C.[158]

More efficient exploitation of process gases, e.g. by redirecting blast furnace gas into the furnace

The process gases arising from blast furnaces and oxygen steel converters are high in carbon monoxide and have so far been used to generate process heat (e.g. in hot blast stoves) and for power generation. Due to their low calorific value, however, the efficiency ratio for power generation is comparatively low (36%). A new process has therefore been developed as part of the EU-funded steel industry research consortium ULCOS. It involves switching blast furnaces from hot blast (air) to pure oxygen operation and separating carbon monoxide from process gas (blast furnace gas), which is then reused in the furnace as reducing agent[159]. This cuts the coke consumption of blast furnaces by 25% and reduces CO_2 emissions associated with primary steel-processing by 16%.

In order to further reduce direct CO_2 emissions, the ULCOS consortium is also championing carbon capture and storage (CCS). The Federal Environment Agency, however, does not consider this to be an option for achieving carbon neutrality in Germany.

Systematic use of waste heat (for up-and downstream processes or power generation)

The most efficient way of dealing with waste heat would be to avoid generating it in the first place, i.e. by supplying process energy with very little heat loss (e.g. inductive heating of components) and recovering heat from products and auxiliary materials for downstream use (see also Section *Production from a single heat source)*. Where heat is transferred, transported, stored or transformed, as the case may be, heat loss occurs. Thus, harnessing waste heat for other processes or power generation should only be considered if the heat cannot be reused within the same installation.

Although the steel industry has made efforts to improve its energy efficiency, there is a huge unexploited potential of waste heat released to the environment. For instance, waste heat from the flue gas of an electric arc furnace, still holding about 30% of the energy supplied to the furnace, is mostly released to the environment and not used.[160] A major reason why this large potential has so far been unexploited lies in the high temperatures required for metallurgic processing. The temperature of the waste heat is too low for further use within the plant. Also, there is considerable fluctuation in the availability of waste heat because major furnaces, such as electric arc furnaces and oxygen converters, run batches rather than continuous processes. So the waste heat may not be available when required. This rather restricts the number of possible users in the immediate neighbourhood of steel mills.

Downstream use of waste heat from steel production would therefore involve transfer, transport, storage or transformation of the heat - costly measures that often wipe out any efficiency gains. One example is the conversion of waste heat into electricity, using ORC (Organic Rankine Cycle) technology. In theory, it could be applied everywhere, but because of its low return on investment, it has hardly ever been used in the context of the steel industry. However, as energy prices are expected to increase in the future, a more systematic exploitation of waste heat potential will become an option. Improvements in furnace technology, pre-heating processes for scrap metal or methods of exploiting waste gas heat could reduce the energy demand of electric arc furnaces by 20%.

D.2.2.3 Technological changes

GHG-neutral production of electric arc furnace steel.

In terms of greenhouse gas-neutrality, secondary steel production in electric arc furnaces (EAF) seems to be the most promising because the main energy carrier is electricity, which could come from renewable sources. Currently, however, even in electric arc furnace steel production, almost a quarter (23%) of the energy required comes from additional combustion of fossil fuels (mainly natural gas). In addition, an average of 4.4 kg of coal dust per tonne of electric arc furnace steel. , 12 are added to produce foam slag, which improves energy input into melting baths, reduces heat loss through furnace walls — thus extending the service life of furnace walls. If extra CO_2 emissions (47 kg of CO_2 per tonne of steel) could be avoided by phasing out additional fossil fuel combustion and introducing the carbon-free production of foam slag, the specific power consumption of electric arc furnace steel, production would increase by 0.17 MWh per tonne.

This would still not achieve completely GHG emission-free EAF steel production because the graphite electrodes in electric arc furnaces are subject to wear and tear, currently causing CO_2 emissions of 7.4 kg CO_2 per tonne of EAF steel.[161] So far, there is no known carbon-free substitute. One reason for this is that carbon from graphite electrodes can sometimes rebalance carbon losses from the melt. It is, however, thought that advances in furnace technology and furnace operation will reduce electrode consumption to 1kg per tonne of steel[162](equivalent to 3.6 kg of CO_2 per tonne of steel).

Substituting coke-based pig iron production in furnaces by renewable methane-based direct reduction processes or electrolytic methods

Since pig iron production in blast furnaces requires the use of coke, the long-term role of primary steel production in blast furnaces and oxygen steel converters, in terms of compatibility with climate objectives, must be revisited. At the same time, demand for iron production from primary material (iron ore) will rise, as available quantities of scrap iron are not sufficient to meet future demand for new steel. Looking at currently available technology, two production methods are best suited for (largely) greenhouse gas-neutral iron production from primary resources:

- gas-based direct reduction processes
- electrolytic methods

In modern gas-based direct reduction, lump ore or pellets of iron ore are reduced with the help of natural gas – i.e. the carbon monoxide and hydrogen derived from it – at temperatures below its melting point. This results in the generation of directly reduced iron (DRI, also known as 'sponge iron'), which has an iron content of 92—95%. It also contains 1-2% carbon and 3-6% foreign components of the ore known as gangue.[163]Sponge iron is normally processed together with scrap in an electric arc furnace. Sponge iron that cannot be smelted immediately can be hot-pressed into hot briquetted iron (HBI) in order to avoid re-oxidation.

Numerous variants of direct reduction processes are used all over the world on an industrial scale (including many installations that use coal as reducing agent, which limits their value in terms of greenhouse gas mitigation). In gas-based methods, switching to renewable methane should not pose any difficulty and it may even be possible to partially switch to renewable hydrogen, which would be preferable from an energy perspective. Depending on the process, direct reduction requires an energy input of 10.5 to 12.5 GJ per tonne DRI[163]. When calculating the mass of crude steel produced, the proportion of gangue must be subtracted (factor 1.05), and the specific power consumption for EAF production must be taken into account (0.59 MWh per tonne or 2.11 GJ per tonne; see Chapters A.2.2.3

and A.2.3.3). The Federal Environment Agency does not have any data on the actual power consumption of direct reduction plants.

Electrolytic iron reduction methods are still at an early stage of development. In contrast to the established electrolytic process used in aluminium production, the electrolysis of iron ore requires novel process engineering solutions, due to the substantially higher melting point. While ULCOS (see above) favours an electrolytic process in an aqueous medium,[164] the USA are engaged in developing molten-oxide electrolysis for processing iron ore.[165]

In molten-oxide electrolysis, iron ore is dissolved in an oxide melt at 1600°C. In this type of electrolysis, the cathode consists of liquid iron that collects at the bottom of the container, while gaseous oxygen bubbles up at the anode suspended in the melt cell.

So far, electrolytic methods have only been used to produce iron on a laboratory scale. It is currently thought that the energy required for the process is on a similar scale as for direct reduction or the blast furnace process route (13.8 GJ per tonne[CXLII]). Since the only energy source used in the process is electricity, this type of iron production could be entirely GHG-neutral if electricity from renewable sources were used. At this point in time, however, we cannot predict what further processes the iron resulting from electrolysis must still undergo to become steel. Because of the very high purity of electrolytically produced iron and the possibility of it being already in a liquid state, the energy required for the production of steel may be less than for the processing of DRI/HBI into steel in electric arc furnaces.

Converting rolling mill furnaces to electric (e.g. induction) heating methods

Almost all furnaces – including heat treatment furnaces in rolling mills are operated with fossil fuels, mainly natural gas, but sometimes also enriched blast furnace and converter gas. While it would be possible to reduce greenhouse gas emissions by switching to renewable methane, in most cases, switching to induction (electric) heating would probably be even more efficient. Up to now, however, such methods have only been used sporadically in steel processing. If all furnaces switched to electric heating, electricity consumption in rolling mills would increase accordingly.

D.2.3 The German steel industry in 2050

D.2.3.1 Assumptions regarding the development of production volumes by 2050

Assuming an annual growth of 0.7%, turnover in the steel industry would grow by approximately 30% by 2050. In view of the persisting trend towards higher-grade steels, we assume that growth will be qualitative and the volume of steel produced will remain constant at around 45 million tonnes per annum (annual production has been hovering around this mark since 1997 without showing a clear trend). By providing higher-grade steels, the steel industry makes a significant contribution to resource-efficient growth in other sectors such as machine and vehicle construction and GHG-neutral energy generation.

CXLII Own calculations based on data in http://steeltrp.com/Briefing07slides/09-TRP9956_MIT-07IBS.pdf, last accessed on 13/08/2012.

D.2.3.2 Possible structure of the German steel industry in 2050

As explained in Chapter A.2.2.3, an almost GHG-neutral steel production can only be achieved by dispensing with the blast furnace and oxygen converter routes in primary steel production. As it is as yet unclear whether and which technology might then allow primary steel production based on electrolytic iron reduction, our scenario can only include the option of EAF steel production based on both scrap and DRI. The only energy source considered for the direct reduction process is renewable methane, while electric arc furnaces and rolling mill furnaces are powered exclusively by renewable electricity.

Assuming that the scrap volume can be increased to 30 million tonnes (equivalent to 66.7% of new steel production) by better-coordinated collection and separation as well as by avoiding unwanted losses of scrap, 20 million tonnes of sponge iron would be required for the production of 45 million tonnes of steel in EAF furnaces, based on an assumed 90% yield of iron from input materials..

In the case of hot rolling products, it is assumed that their share in crude steel production will remain more or less the same (85%).

D.2.3.3 Energy demand and greenhouse gas emissions in the German steel industry in 2050

According to the above assumptions, in the long-term, today's all-important energy demand for the various steps of the blast furnace – oxygen converter route will no longer exist, whereas demand for renewable methane or hydrogen from new installations for DRI will be considerable (240 PJ per annum).

Electricity demand for EAF steel production will increase by a factor of 3.5 compared to 2010. This is because on the one hand, it is assumed that the share of EAF steel in overall steel production will increase from 30 to 100%, while on the other, it is thought that giving up primary energy vectors will increase specific electricity consumption by 4% to just under 0.6 MWh per tonne.

As for rolled steel production, it is assumed that near-net shape casting methods will be used as extensively as possible; the option of hot-charging (read about both technologies in Chapter A.2.2.2) will be used systematically and melting and heat treatment furnaces will be switched to electric (induction) heating. This will reduce specific heat demand by two thirds and current demand for electricity by one third. As energy demand is entirely met by electricity, specific electricity consumption for hot rolling will double to 0.3 MWh per tonne.

Based on these assumptions for the steel industry in 2050, the resulting energy demand will be 240 PJ of renewable methane or hydrogen and approximately 38 TWh of renewable power (see Table A8). Demand for renewable methane or hydrogen will be approximately 60% lower than the consumption of primary energy sources in 2010, whereas electricity consumption will rise by approximately 29.5 TWh.

According to the assumptions above, the only source of CO_2 emissions will be the burn-up of graphite electrodes in electric arc furnaces (162,000 tonnes per annum). Total CO_2 emissions from steel production will thus be reduced by 99.7%. However, CO_2 emissions such as those that may arise from steel processing through surface-near oxidation of carbon contained in steel were not taken into account.

Table D-8: Energy demand and greenhouse gas emissions from the German steel industry in the UBA THGND 2050 Scenario

		Production	Consumption of CH_4		Electricity consumption		CO_2 emissions	
		tonnes p.a.	GJ per tonne of steel	PJ per annum	MWh per tonne	GWh per annum	kg per tonne of steel	tonnes of CO_2 per annum
Scrap volume		30,000,000						
Direct reduction		20,000,000	12	240				
Iron output	90%							
From scrap		27,000,000						
From sponge iron		18,000,000						
Production of electric arc furnace steel.		45,000,000			0.59	26,404	3.6	162,000
Hot rolling mill		38,250,000			0.30	11,626		
Total				**240**		**38,030**		**162,000**
Changes compared with 2010				-61% [CXLIII]		+29,486		-99.7%

If electrolytic methods of iron production become widely applicable in the long term, these could partially or entirely replace primary production through direct reduction. The advantage would lie in the direct use of renewable power in the electrolytic processes and no conversion into methane with associated energy loss would be needed. This would presumably also reduce power consumption for steel production in electric arc furnaces because turning electrolytically produced iron into steel would not require much energy.

D.2.4 Summary on the steel industry

Germany's steel industry has a high demand for energy and as such, is one of the energy-intensive industry sectors. Although there have been various approaches to improving the energy and resource efficiency of existing process routes, the steel industry can become (largely) GHG-neutral only if it undergoes fundamental changes in its production routes.

The only viable/realistic option currently available seems to be electric arc furnace steel production, based on scrap and DRI and the exclusive use of renewable methane or hydrogen as energy vectors in direct reduction, while only renewable power is used to operate electric arc furnaces and rolling mill furnaces.

CXLIII Reference current consumption of primary energy sources.

It is assumed that in the long term, revenue in the steel industry will rise by approximately 30% by 2050, as higher-grade steels will be produced, but the volume of steel produced will remain constant at 45 million tonnes per year. Although we predict an increase of available scrap to 30 million tonnes (making up two thirds of new steel production), the production of 45 million tonnes of steel still requires an additional 20 million tonnes of DRI.

Based on these assumptions, the resulting energy demand of the steel industry will be 240 PJ of renewable methane or hydrogen and approximately 38 TWh of renewable power.

According to the assumptions made above, the only source of CO_2 emissions in 2050 will be the burn-up of graphite electrodes in electric arc furnaces (162,000 tonnes per annum). CO_2 emissions from steel production will thus be reduced by 99.7%.

D.3 Non-Ferrous Metal Industry

D.3.1 The non-ferrous metal industry in Germany - its structure and economic significance

As an extractive industry, the German NFM industry is the first link in the industrial value-added chain – processing not only widely used metals such as aluminium, copper, lead and zinc, but also rare metals like gold, silver, titanium or magnesium. Its product range comprises liquid metal, ingots and semi-manufactured products such as pipes, foils and cables. All these are indispensable prime materials for vehicle and machine construction, electrical engineering and the construction sector. Moreover, there is a growing demand for NFMs, associated with the extension of the power grid, increased electromobility and a wider use of renewable energy. The construction of an offshore wind farm, for instance, requires up to 30 tonnes of copper.[166]

The NFM industry will be a key player in the quest for a greenhouse gas-neutral supply of energy in Germany by 2050.

Germany's NFM industry employs a workforce of about 106,624 in 665 plants. In 2008, the production sector produced approximately 2.8 million tonnes of NFMs and alloys from primary and secondary raw materials. The semi-manufactured product sector produced approximately 4.4 million tonnes.[167]

D.3.2 Energy consumption and greenhouse gas emissions in the German NFM industry in 2008

The NFM industry is one of the most energy-intensive industries in Germany. The final energy consumption of the entire NFM industry in Germany (not including NFM foundries, see Chapter D.4) was approximately 25.5 TWh p.a. in 2008, of which around 9.8 TWh p.a. or 38% came from fossil fuels, such as coal (0.2 TWh p.a.), oil (2.0 TWh p.a.) and above all natural gas (7.5 TWh p.a.) (see Table D-9).[168]

Table D-9: Production and final energy consumption of the German NFM industry in 2008[169]

	Reference year 2008[170]						
	Production in tonnes	rel. producti-on in 2008	Overall energy consumption in TWh	Electri-city in TWh	Coal in TWh	Oil n TWh	Natural gas in TWh
Primary production	1,234,000	0.17	13.0	-	-	-	-
Secondary production	1,566,000	0.22	3.3	-	-	-	-
Semi-ma-nufactured products	4,400,000	0.61	9.2	-	-	-	-
Total	7,200,000	1.00	25.5	15.8	0.2	2	7.5

According to the energy consumption data shown in Table D-9 for 2008, the overall fuel-related CO_2 emissions amounted to 2.117 million tonnes per annum.[CXLIV] The largest share by far (62%) of the energy used, however, was supplied in the form of electricity, generating 8.974 million tonnes of CO_2 emissions.[CXLV] Alongside fuel and electricity-related CO_2 emissions, there are also process-related greenhouse gas emissions in the NFM industry. These arise from reduction processes during metal refining (e.g. poling in the copper sector) or consumption of carbon anodes in the electrolysis cells of the primary aluminium sector. As there were no specific data available, the share of process-related greenhouse gas emissions is estimated on the basis of overall CO_2 emissions from the NFM industry (see Table D-10), electricity and fuel-related CO_2 emissions. These amount to 2.909 million tonnes per annum. By contrast, data on anode burn-off in the primary aluminium industry are reliable. In the reference year 2008, process-related CO_2 emissions in the primary aluminium industry caused by anode burn-off amounted to approximately 800,000 tonnes.[171] In addition, perfluorocarbons (PFCs) are emitted as a result of what is known as anode effects.

Table D-10 gives an overview of the overall trend in CO_2 emissions (including power generation) in the NFM industry from 1990 to 2008.

CXLIV Fuel-related CO_2 emissions, calculated according to final energy consumption figures obtained by the Federal Environment Agency: Climate Change 07/2012 and emission factors based on NIR, Table 281, comprising: Coal (coke) 377,997 t CO_2/TWh, lignite 388,797 t CO_2/TWh, petroleum 266,398 t CO_2/TWh, gas (natural gas) 201,598 t CO_2/TWh (Federal Environment Agency (2011): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 - National Inventory Report for the German Greenhouse Gas Inventory 1990-2009, Climate Change 11/2011, Dessau-Roßlau.

CXLV Calculated from the specific CO_2 emission factor of 568 g/kWh of electricity for 2008

Table D-10: Development of direct and indirect CO_2 emissions in the NFM industry[172]

Year	1990	1995	2000	2005	2008
CO emissions in million tonnes	14.6	12.9	14.3	14.3	14.0
specific CO_2 emissions in kg of CO_2 per tonne	2378	2005	1816	1834	1709

D.3.3 Energy consumption in smelting and refining

The highest demand for energy in the NFM industry comes from smelting and refining. Depending on the metal and the type of primary material such as ore, contaminated scrap or clean scrap, various aggregates with different energy consumption are used.

Energy consumption is highest by far in the primary aluminium industry — 13,500 kWh per tonne of aluminium produced. All energy used is electric power.

Energy consumption for secondary aluminium production ranges from 520 to 2055 kWh per tonne of aluminium produced.[173] By comparison, the theoretical minimum amount of energy required for melting aluminium scrap is 329 kWh per tonne.

In the German primary copper production industry, 2400 kWh per tonne of copper are required.[174] In secondary copper production, melting aggregates may require between 194.4[175] and 954.2 kWh per tonne.[176] However, when looking at an entire installation and its peripheral facilities, there are configurations in secondary copper production (e.g. the use of electrolysis or energy-intensive off-gas cleaning), where up to 2400 kWh per tonne are required.[177]

In the German primary lead industry, the QSL reactor consumes around 1390 kWh per tonne of lead produced, whereas in lead recycling, melting aggregates may require between 500 and 900 kWh per tonne, depending on the furnace.[178]

Germany's primary zinc industry requires just around 140 kWh per tonne of zinc for fuel.[179] The largest share of energy used in the primary zinc industry (approximately 4000 kWh per tonne), by contrast, is electricity for electrolytic baths. The final product of the German secondary zinc industry is rotary oxide, which is then re-used in the primary zinc industry. This is why energy consumption in this process is related to the raw materials (zinc containing waste). It amounts to approximately 650 kWh per tonne.[180]

D.3.4 Outlining possible solutions for GHG mitigation in source categories and sub-source categories

Specific energy consumption in the NFM industry decreased by 26.2% between 1990 and 2008.[181] Specific fuel-related CO_2 emissions in the primary copper industry, for example, went down by 69% between 1990 and 2010, following steps to increase efficiency. However, it turned out that over time, the potential for efficiency gains decreased, while specific investment cost, per tonne of CO_2 saved, rose continuously.[182]

In order to achieve future greenhouse gas mitigation beyond efficiency gains in the NFM industry, the following strategies should be applied:

- Increasing scrap recycling
- Enhancing energy efficiency
  - reducing energy consumption in smelting and in upstream and downstream processes
  - re-using residual and waste heat
  - comprehensive introduction of energy management systems
- Reducing and avoiding process-related greenhouse gas emissions
  - using renewable reducing agents
  - using inert anodes in the primary aluminium industry

D.3.4.1 Increasing scrap recycling

Recycling NFMs such as aluminium, copper or lead requires far less energy than primary production from ore. Recycling of aluminium, for instance, requires only 5% of the energy required for primary production. This is equivalent to specific CO_2 savings of 9.87 tonnes per tonne of aluminium produced. In copper recycling, 3.52 tonnes of CO_2 per tonne of copper are saved, which is 36% compared to primary production from copper ore.[183] In addition, the secondary production of NFMs is clearly more resource-friendly and environmentally friendly than primary production, as it is possible to recycle the material virtually ad infinitum without any quality losses.

The potential for NFM recycling is by no means exhausted yet. In 2011, the end-of-life recycling rate (EOL RR) for copper was 43-53%, for aluminium 42-70% and 35-60% for zinc.[184] The use of novel collection and recycling technology could increase the EOL RR to over 95% in the long-term - a figure that is already being achieved in lead recycling.

In 2008, the share of recycled products in overall production in Germany was 54% for aluminium, 56% for copper, 73% for lead and 27% for zinc.[185]

D.3.4.2 Enhancing energy efficiency

In the NFM industry, 20-30% of the energy consumed is used for heat treatment of the metals to be processed. Most pyrometallurgical melting processes require high temperatures above 1000°C. These high temperatures offer much scope for introducing greenhouse gas mitigation strategies.

Strategies for GHG mitigation:

- Substituting fossil fuels with renewables such as hydrogen and methane
- Substituting fuel-fired furnaces with electric furnaces
- Process optimisation through regular servicing and modernisation of combustion installations
- Increasing energy efficiency by using technology that enhances the fuel efficiency of furnaces and burners etc.
- Systematic recovery of waste heat
  a. waste heat from furnace cooling systems and flue gases
  b. recovery from solidifying/cooling ingots

c. recovery from cooling slag

- Comprehensive introduction of energy management systems.

D.3.43 Reducing and avoiding process-related greenhouse gas emissions

As far as future process-related emissions from metal refinery are concerned, fossil reducing agents (coke, natural gas) can be replaced by renewable reducing agents such as renewable methane or hydrogen. It is, however, currently impossible to predict the quantity of renewable methane or hydrogen required because the data are not available.

The primary aluminium industry is a special case where aluminium oxide (Al_2O_3) is reduced to aluminium and oxygen by electrolysis (Hall-Héroult process). In an immediate reaction, the oxygen formed at the carbon-rich anode produces CO_2. This type of process-related CO_2 emission is unavoidable. However, if inert anodes were used instead, these emissions could be avoided altogether. Inert anodes consist not of carbon, but of metallic or ceramic materials and will generate pure oxygen rather than CO_2 at the anode. With no free carbon available, the formation of PFCs can be avoided and energy efficiency increased. Thus, process-related greenhouse gas emissions can be avoided altogether. Research and development on inert anodes has seen much progress over recent years and the technology has matured and is now ready for use on a large scale. A study commissioned by the International Energy Agency predicts that inert anodes will be ready for large-scale use by 2015 and commercially used by 2030.[44] For instance, RUSAL, the largest aluminium producer worldwide, is currently preparing for the large-scale use of electrolytic cells with inert anodes in Krasnoyarsk, Russia. These cells are set to become part of ongoing production by 2015.[45]

D.3.5 Outlining a GHG mitigation scenario for the German NFM industry in 2050

It is assumed that the German NFM industry will grow by 0.7% p.a. until 2050. This means that around 3.8 million tonnes of NFM will be produced in 2050. Over the same period, the share of semi-manufactured products will increase to 5.9 million tonnes.

We can also assume that the share of recycled material in overall production will increase significantly. End-of-life recycling rates will continue to rise, while at the same time urban mining will provide new opportunities for recovering recycling materials. We assume that the share of recycled copper, aluminium, lead and zinc in overall metal production will account for 90% by 2050. The mean energy requirements for the secondary production of NFMs in 2050 will be only 20% of primary production requirements.

It is also estimated that between 2008 and 2050, energy efficiency gains of approximately 30% will be achieved through new technology and process optimisation.

On the basis of these assumptions, the specific energy consumption of 3542 kWh per tonne in 2008 will decrease to 1705 kWh per tonne in 2050. These are relative energy savings of 52%. Absolute energy consumption in the NFM industry will decrease from 25.5 TWh in 2008 to 16.5 TWh in 2050. These are absolute energy savings of 35%.

Predictions based on the assumptions above on production and final energy consumption in the German NFM industry sector in 2050 are summarised in Table D-11.

Table D-11: Production and final energy consumption of the German NFM industry in the UBA THGND 2050 Scenario.

	Reference year 2050				
	Production in tonnes	**rel. production in 2050**	**Overall energy consumption in TWh**	**Electricity in TWh**	**renewable methane in TWh**
Primary production	375,315	0.04	2.8	-	-
Secondary production	3,377,834	0.35	5.0	-	-
Semi-manufactured products	5,897,805	0.61	8.7	-	-
Total	**9,650,954**	**1.00**	**16.5**	**10.2**	**6.3**

Fossil energy vectors such as coal, natural gas and oil are replaced by renewable methane, avoiding energy-related emissions altogether. Process-related greenhouse gas emissions are avoided altogether by using renewable reducing agents and employing inert anodes in primary aluminium production. At 62%, the share of electricity in the overall energy consumption remains constant in 2050, compared to 2008. The electricity used, however, comes entirely from renewable sources. While electricity-intensive primary production will decrease significantly, the low cost of renewable electricity will cause many gas-fired smelters to be replaced by electricity-powered induction furnaces.

D.3.6 Non-ferrous metal industry summary

The German NFM industry is key to achieving GHG neutrality in Germany. The industry's products are essential for developing renewable energy and electromobility.

It is therefore expected that the production of NFMs will increase by a quarter by 2050.

Due to its higher share of recycled resources and further energy efficiency gains, specific energy consumption per tonne of metal will decrease by 52% by 2050. These are absolute energy savings of 35% compared to 2008.

The NFM industry can become greenhouse gas-neutral in the long term. In 2050, 62% of the energy required will come from renewable electricity. The remaining 38% is energy from fuel and can be supplied by renewable methane. Process-related greenhouse gas emissions are avoided altogether by using renewable reducing agents and inert anodes in primary aluminium production.

D.4 The foundry industry

D.4.1 The foundry industry in Germany — its structure and economic importance

Foundries are places where iron and non-ferrous metals and alloys are melted, cast into moulds and, once the metal or alloy has solidified, formed into final or near-net shape products. The foundry sector plays a crucial role in the metal industry cycle because it is here that steel, cast metal and aluminium scrap are all transformed into new, high-grade products for use in virtually all sectors of industry. More than three quarters of cast metal products are currently produced for automobile and machine manufacture. Approximately 40% of iron-containing cast products are exported.[188] This background makes it likely that in the long-term, the foundry industry will retain its position in Germany as a key export sector. Cast metal products will be in demand in many areas, including wind energy, electromobility and the automotive industry.

The German foundry sector comprises mainly medium-sized companies and employed a workforce of approximately 87,000 in over 600 companies in 2008.[189] Of the approximately 5.8 million tonnes of marketable casting products, around 95% were manufactured in companies with less than 500 employees, and 30-40% in companies with under 50 employees.[190] In 2008, the iron, steel and malleable iron casting sector produced approximately 4.8 million tonnes of castings in 266 foundries,[CXLVI] including 6% steel castings and 93% iron castings, i.e. grey and spheroidal graphite (SG) cast iron. In non-ferrous metal casting (NFM casting), 346 foundries produced 1.0 million tonnes of castings, of which 80% were aluminium and 12% copper.[191] The production value achieved in 2008 was approximately 8.3 billion euros for iron, steel and malleable iron and 5.3 billion euros for NFM casting.[192] This leaves Germany, together with Japan, in fourth position among the world's largest cast metal producers after the People's Republic of China, India and the USA and makes it the largest producer in Europe.

D.4.2 Energy consumption and greenhouse gas emissions in the German foundry industry in 2008

With its high demand for energy, Germany's foundry industry is an energy-intensive industry sector. Final energy consumption for the entire foundry industry in 2008 amounted to approximately 12.85 TWh/p.a.. Of this, around 7 TWh p.a. or 55% came from fossil fuels such as coke (2.55 TWh p.a.), which is used only in iron, steel and malleable iron foundries, natural gas (3.39 TWh p.a.) and petroleum (0.96 TWh p.a.) (see Table D-12). The remaining energy demand is met by electric power.[193] Overall fuel-related CO_2 emissions in 2008 amounted to 1.919 kT p.a., with specific fuel-related CO_2 emissions per tonne of castings accounting for 333 kg (see Table D-13). There are no process-related greenhouse gas emissions to speak of in the foundry industry.

CXLVI In the following, cast metal will be used synonymously with saleable cast products.

Table D-12: Final energy consumption in the German foundry industry for 2008 according to the NIR (UBA Climate Change 07/2012) and productivity figures for 2008 and 2010 according to the European Foundry Association (CAEF)[CXLVII]

	Production in million tonnes of castings per annum[CXLVIII]		Overall final energy consumption in TWh p.a.	Electricity in TWh p.a.	Fuel, district heat in TWh p.a.[CXLIX]	Including				
	2008	2010				Coal (coke)	Lignite	Petroleum	Gas (natural gas)	District gas
Iron casting (grey iron, spheroidal graphite (SG) iron and malleable iron casting)	4.565	3.672	8.516	3.792	4.724	2.550	0.037	0.721	1.389	0.026
Steel casting	0.220	0.192	1.032	0.496	0.536	0	0	0.031	0.505	0.001
Light alloy casting			2.953	1.310	1.643	0	0	0.194	1.430	0.018
Non-ferrous metal casting			0.351	0.264	0.087	0	0	0.018	0.067	0.001
Iron and steel casting	4.785	3.864	9.548	4.288	5.260	2.550	0.037	0.752	1.894	0.027
Light and non-ferrous metal casting	0.982	0.930	3.304	1.574	1.730	0.000	0.000	0.213	1.498	0.020
Total foundries	**5.767**	**4.794**	**12.852**	**5.862**	**6.990**	**2.550**	**0.037**	**0.965**	**3.392**	**0.047**

CXLVII after database of [193].

CXLVIII The European Foundry Industry 2010, The European Foundry Association (CAEF) (2011).

CXLIX No renewable or other energy vectors are used.

Table D-13: Fuel-related CO_2 emissions in the German foundry industry for 2008, calculated on the basis of final energy consumption data according to UBA Climate Change 07/2012[CL]

Reference year 2008	Fuel-related CO_2 emissions in tonnes p.a.	Including				Specific fuel-related CO_2 emissions in tonnes of CO_2 per tonne of cast metal
		Coal (coke)	Lignite	Petroleum	Gas (natural gas)	
Iron casting (grey iron, SG iron and malleable iron casting)	1,450,438	963,897	14,318	192,153	280,070	0.318
Steel casting	109,996	0	0	8,267	101,729	0.500
Light alloy casting	340,136	0	19	51,741	288,375	
Non-ferrous metal casting	18,432	0	0	4,882	13,550	
Iron and steel casting	1,560,434	963,897	14,318	200,419	381,799	0.326
Light and non-ferrous metal casting	358,568	0	19	56,624	301,925	0.365
Total foundries	**1,919,002**	**963,897**	**14,338**	**257,043**	**683,724**	**0.333**

D.4.2.1 Energy consumption for melting metal charges

In foundries, the highest share of energy is required for melting the metal charge, on average 45-65% of the total energy consumption. Actual energy consumption during melting depends both on the metal and the type of furnace. A further 15-25% is required for engines and fans, 5-7% for heating and lighting and another 4% to pre-heat ladles.[194]

In iron, steel and malleable iron foundries, the metal charge is mostly melted in electric furnaces (e.g. medium-frequency induction furnaces), but also in coke-fired cupola furnaces, which are hot-air furnaces used for continuous serial production on a large scale. There are also cold-blast cupola furnaces, usually for non-continuous production in small and medium foundries. NFM foundries mainly use electric furnaces and furnaces fired by natural gas (e.g. tower furnaces). Medium to large foundries may also have liquid metal delivered from melting plants.

CL Fuel-related CO_2 emissions, calculated according to final energy consumption figures obtained by the Federal Environment Agency: Climate Change 07/2012 and emission factors based on NIR, Table 281, comprising: Coal (coke) 377,997 t CO_2/TWh, lignite 388,797 t CO_2/TWh, petroleum 266,398 t CO_2/TWh, gas (natural gas) 201,598 t CO_2/TWh (Federal Environment Agency (2011): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 - National Inventory Report for the German Greenhouse Gas Inventory 1990-2009, Climate Change 11/2011, Dessau-Roßlau.

At 1000 kWh per tonne of liquid iron on average, the specific energy consumption of coke-fired cupola furnaces is significantly higher than modern induction furnaces, which require around 600 kWh per tonne of iron melt.[195] Coke-free, (natural) gas-fired cupola furnaces with an energy consumption of 530 kWh per tonne of iron melt and a tapping temperature of 1420°C could be an alternative.[196] For aluminium, specific energy consumption in electric melting furnaces is currently between 440 and 550 kWh_{el} per tonne of aluminium melt, at an efficiency of 60-70 %.[197] For copper, it is between 250 and 380 kWh_{el} per tonne of copper melt, at an efficiency of 54-60% (crucible furnaces) and 73-82 % (channel furnaces).[198] The specific melting enthalpy for aluminium, including superheat, is 329 kWh per tonne, which is the amount of energy physically required to effect the change from solid to liquid (i.e. melting aluminium) and to overheat the melt up to a casting specific temperature .[199] For non-alloy cast iron, the specific melting enthalpy is 390 kWh per tonne at a temperature of 1500°C.[200] These values define the minimum energy physically required for melting NFM and iron casting materials. Our aim for the future must be to reduce energy consumption for melting to levels close to the specific melting enthalpy, including superheat, of the various metals to be cast.

D.4.3 Outlining possible solutions for GHG mitigation

Key strategies for a future greenhouse gas mitigation policy in the foundry industry include:

- Enhancing casting yield
- Enhancing energy efficiency
  - reducing energy consumption in melting and
  - upstream and downstream processes (e.g. in manufacturing cores and moulds and finishing after casting)
  - systematic re-use of residual and waste heat.

D.4.3.1 Enhancing casting yield

Presently, the casting yield — which is the quantity of cast metal manufactured in relation to the melted metal charge — is 40-95% for iron casting,[201] whereas for the entire foundry industry, the current average casting yield is 65 %.[202] It largely depends on the type of manufacturing involved (e.g. serial cast or hand moulding), the metal charge and the size, quality and complexity of the castings. The aim must therefore be to maximise casting yield as far as technically possible and work towards a 100% output. As an example, the use of feeders insulated with ceramic foam inlays and the redesigning of cast parts increased the casting yield from 52 to 85% in one foundry alone.[203]

D.4.3.2 Enhancing energy efficiency

In hot blast cupola furnaces, 55% of the energy used in the melting process goes into melt and slag, while 40% ends up in the flu gas of the combustion chamber.[204] The remaining 12% are required for the generation of the hot blast, while 3% are lost. Thus from an average of 1000 kWh per tonne of iron melt produced,[205] approximately 550 kWh end up in melt and slag.

For crucible induction furnaces, , approximately 43% or 280 kWh of the 640 kWh consumed per tonne of iron melt can be recovered.[CLI] Currently, 20-30% of the energy used in induction furnaces

CLI Forschungsvorhaben REGIE (2006) (research project REGIE) as quoted in Institut für Gießereitechnik gGmbH (IfG) (2009): Energieeffizienter Gießereibetrieb (Energy-efficient operation of foundries) (Version 1.0), Bundesverband der Deutschen Gießerei-Industrie (published by the German foundries association, BDG).

is lost as waste heat andreleased to the environment via cooling processes.[206] Trials in a large German foundry in 2006 have shown that it is generally possible to recover heat from cooling cast metal pieces and casting moulds.[CLII] In another project, it was demonstrated that up to 90% of waste heat from the flue gas of a hot blast cupola furnace could be recovered using a heat exchanger and thermal oil (including hot blast generation).[207] Assuming that 40% of the energy used goes into flue gas,[208] this would mean that around 35% of the energy contained in flue gas is recoverable. Modern aluminium furnaces heated by natural gas are fitted with a flue gas recovery system, where the recovery of residual heat from flue gas can reduce the average heat consumption by 20-30% compared to furnaces with an open flue gas system.[209]

D.4.4 Scenario for the German foundry industry in 2050

It is assumed that production in iron, steel and malleable iron casting will grow annually by 0.7% and NFM casting by 1.6% until 2050. The higher growth rate in NFM casting can be explained by the expected higher demand for lightweight construction materials (e.g. in the automobile industry) which will lead to increased production of aluminium casting, and also magnesium casting in the future. The share of magnesium casting is expected to rise from a current level of 3%[210] to up to 13% by 2050. Overall, however, we assume in this scenario that the cast material distribution will be comparable to that of 2008. Table A14 shows the cast metal production expected for 2050. For iron and steel castings, production is expected to rise by 6.41 million tonnes of castings per annum (+34% compared to 2008), while for NFM castings, an increase of 1.91 million tonnes of castings per annum (+95% compared to 2008) is anticipated. It is also assumed that by 2050, the average casting yield will reach 90%. This would mean that only 1.112 tonnes of metal need to be melted and processed to produce a tonne of castings, compared to 1.538 tonnes required today, which is a 30% efficiency increase for metal charge. The overall specific energy consumption per tonne of castings would thus fall by approximately 25%. Of these energy savings, 15% are the result of lower quantities of metal melt required, while an estimated further 10% come from obsolete upstream and downstream processing, as well as improvements in the production and preparation of mould material.

We expect that by 2050, the majority of fuel-fired furnaces will have been replaced by electric furnaces, as renewable power generation will generally have become energetically as well as economically more viable than renewable fuel production. We also assume that in 2050, furnaces fired by solid or liquid fuels such as coke or oil will no longer be in operation within the German foundry sector. For the purpose of this study, it is therefore assumed that in 2050, 85% of the iron, steel and malleable iron as well as NFM castings will be melted in electric furnaces. Only foundries in the serial casting sector will still operate large gas-heated furnaces such as coke-free cupola furnaces for iron casting. These will be fuelled by renewable methane. Carbonisers in the form of renewable carbon are added to cast iron in order to maintain the required carbon levels, making up around 3% of the annual cast iron production — approximately 184,000 tonnes for an anticipated 6.12 million tonnes of cast iron in 2050. The energy content of the carbon is irrelevant here, as the use of carbon for the carbonisation of cast iron is not part of energy generation, but a component of an iron-carbon alloy cast product.

On the basis of the data extracted above, we assume that technological measures will ensure that in the long-term, energy consumption for melting will be 1.15 times the specific melting enthalpy, including superheat, for the various cast materials. We assume that in electric furnaces, for example, the overall energy efficiency ratio will be 85-90%. This could be achieved by using superconductor

CLII Forschungsvorhaben REGIE (2006) (research project REGIE) as quoted in Institut für Gießereitechnik gGmbH (IfG) (2009): Energieeffizienter Gießereibetrieb (Energy-efficient operation of foundries) (Version 1.0), Bundesverband der Deutschen Gießerei-Industrie (published by the German foundries association, BDG).

technology comparable to billet heating for press plants[211] and further technological innovations that reduce losses in coils, inverters and other components of current state-of-the art medium frequency induction furnaces. Thus, we assume that in iron, steel and malleable iron casting, the mean specific energy consumption for melting will be 450 kWh per tonne of liquid metal in electric furnaces and 510 kWh per tonne in gas-fired furnaces in 2050. In the aluminium casting sector, a mean electricity consumption of 380 kWh per tonne of liquid metal is assumed for melting in electric furnaces and gas-fired furnaces with flue gas recovery. We assume that electric melting of copper material would require 230 kWh per tonne of liquid metal, while magnesium material and others would require 370 kWh per tonne.

If we assume that in 2050, the share of energy required for melting accounts for 55% of the total energy consumption per tonne of casting, on the basis of the aforementioned assumptions together with specific energy consumption values for the melting process, the following figures for future total specific energy consumption would apply:

- 837 kWh per tonne mean consumption for iron, steel and malleable iron casting
  - foundries with electric furnaces: 820 kWh per tonne of cast metal (85% share of total production)
  - foundries with gas-fired furnaces: 930 kWh per tonne of cast metal (15% share)
- 656 kWh per tonne mean consumption for non-ferrous metal casting
  - aluminium foundries with electric or gas-fired furnaces: 690 kWh per tonne of cast metal (70-80% share of total production)
  - copper foundries: 420 kWh per tonne of cast metal (12% share)
  - magnesium casting and others: 670 kWh per tonne of cast metal (8-18% share)

This means that significant savings in energy consumption can be made in the production stages before and after melting, due to new technology and process-related solutions. However, since melting is the major contributor to overall energy consumption, solutions for up and downstream production processes are not looked at in detail in this study.

The overall final energy consumption in the German foundry industry for 2050 is calculated from the overall specific consumption values given above and the production figures. It amounts to approximately 6.5 TWh p.a. (see Table A14). Of this, approximately 5.5 TWh p.a. comes from renewable electricity and around 1 TWh p.a. from renewable methane. For the entire sector, final energy consumption is reduced by 50% compared to 2008. Taking into account higher production levels for 2050, the mean energy efficiency rate per tonne of cast metal is increased by a factor of 2.85. No industry-specific greenhouse gas emissions will arise because by 2050, the German foundry industry will have switched to renewable energy vectors throughout.

It is also assumed that by 2050, 30% of the energy used in the melting process will be recoverable as residual heat from cooling cast products and slag as well as through the use of insulating material for permanent moulds. After pouring the melt, the energy can be recovered by appropriate technology and used internally or externally as process heat or for heating purposes, or the waste heat can be converted into renewable electricity and then re-used. The above figures for the final energy consumption for 2050 suggest that approximately 1.1 TWh p.a. will be available for residual heat recovery from cooling cast products and moulds. The actual amount of energy recovered, however, depends on the technology available in the future and can therefore not yet be quantified. What is clear, however, is that there is potential for further reductions in the final energy consumption of the industry.

D.4.5 German foundry industry summary

We assume that in 2050, the foundry industry in Germany will remain a key export sector. Demand for cast products will come from areas such as wind energy generation with all its growth potential, electromobility and the automotive industry of the future. Increased demand is also expected in lightweight construction (e.g. the automobile industry) and will be reflected in increasing production figures for aluminium and magnesium casting. Compared to 2008, production in iron, steel and malleable iron casting will increase by about a third to 6.41 million tonnes of cast metal and almost double in the NFM casting sector to 1.91 million tonnes by 2050. In spite of rising production figures, final energy consumption within the sector will decrease by approximately 50% compared to 2008 — and the production of cast metal in Germany in 2050 will be greenhouse gas-neutral. This can be achieved by increasing the casting yield to an average of 90%, substituting fuel-fired furnaces with electric furnaces and by improving the energy efficiency of the entire casting production system. In the serial casting sector, however, large gas-fired furnaces such as coke-free cupola furnaces will continue to be used in the long-term, but they could be fuelled by renewable methane. Energy consumption during melting will be significantly reduced in comparison to today's levels, as efficiency rates of furnaces improve and further technical innovations, such as superconductor technology, come into play. In addition, systematic recovery and recycling techniques will harness residual and waste heat along the entire production chain. These will include, for instance, the use of waste heat from melting and cooling cycles as process heat in upstream and downstream process steps such as core and mould production and drying. Overall, the foundry industry's mean energy efficiency rate per tonne of cast metal is expected to increase by a factor of 2.85 in 2050, compared to 2008.

Table D-14: Expected final energy consumption of the German foundry industry for 2050 and productivity figures for 2008 and 2050

	Production in million tonnes of cast metal per annum		Rel. changes in production levels for 2050/2008 in %	Total final energy consumption for 2050 in TWh p.a. including waste heat use[CLIII]	Total final energy consumption for 2050 in TWh p.a. [CLIV]	Including		Rel. changes in residual heat recovery for 2050/2008 in %	Rel. changes in final energy consumption for 2050/2008 in %
	2008[212]	2050[CLV]				renewable electricity in TWh p.a. [CLVI]	renewable methane in TWh p.a. [CLVII]		
Iron and steel casting	4.785	6.414	34%	4.4	5.2	4.4	0.8	-54%	-45%
Light and non-ferrous metal casting (NFM foundries)	0.982	1.912	95%	1.0	1.3	1.1	0.2	-68%	-62%
Total foundries	**5.767**	**8.326**	**44%**	**5.4**	**6.5**	**5.5**	**1**	**-58%**	**-49%**

CLIII Expected final energy consumption per tonne of cast metal in 2050: 837 kWh per tonne of cast iron and steel and 656 kWh per tonne of cast non-ferrous metal.

CLIV Expected final energy consumption per tonne of cast metal in 2050: 837 kWh per tonne of cast iron and steel and 656 kWh per tonne of cast non-ferrous metal.

CLV Production trend, assuming an annual growth rate of 0.7% for iron, steel and malleable iron casting, and 1.6% for NFM casting, compared to the annual production baseline of 2008.

CLVI Assuming that renewable electricity accounts for 85% of the industry's overall final energy consumption in 2050 and renewable methane 15%.

CLVII Assuming that renewable electricity accounts for 85% of the industry's overall final energy consumption in 2050 and renewable methane 15%.

D.5 Chemical industry

D.5.1 The chemical industry – status quo

The chemistry sector is one of the most important industries not only in Europe, but at a global level. Its overall energy consumption of 182 TWh in 2009 makes the chemical industry one of the most energy-intensive industries in Germany.

D.5.1.1 Structure and economic significance of the chemical industry in Germany

In 2011[213], the German chemical industry generated 184.2 billion euros of revenue. This puts it in fourth position among the manufacturing industries in Germany. Its global market share was 5.5% – another fourth position. The approximately 1700 chemical companies, of which 90% are small and medium-sized enterprises, employ a workforce of 427,000 people.

Table D-15: The most important chemistry sectors in Germany

Bulk inorganic chemicals	8.4 percent of the 2008 production value[214]
Petrochemicals and derivatives	17.9 percent
Polymers	19.6 percent
Fine and speciality chemicals	24.6 percent
Pharmaceuticals	20.6 percent
Detergents and personal hygiene products	7.6 percent

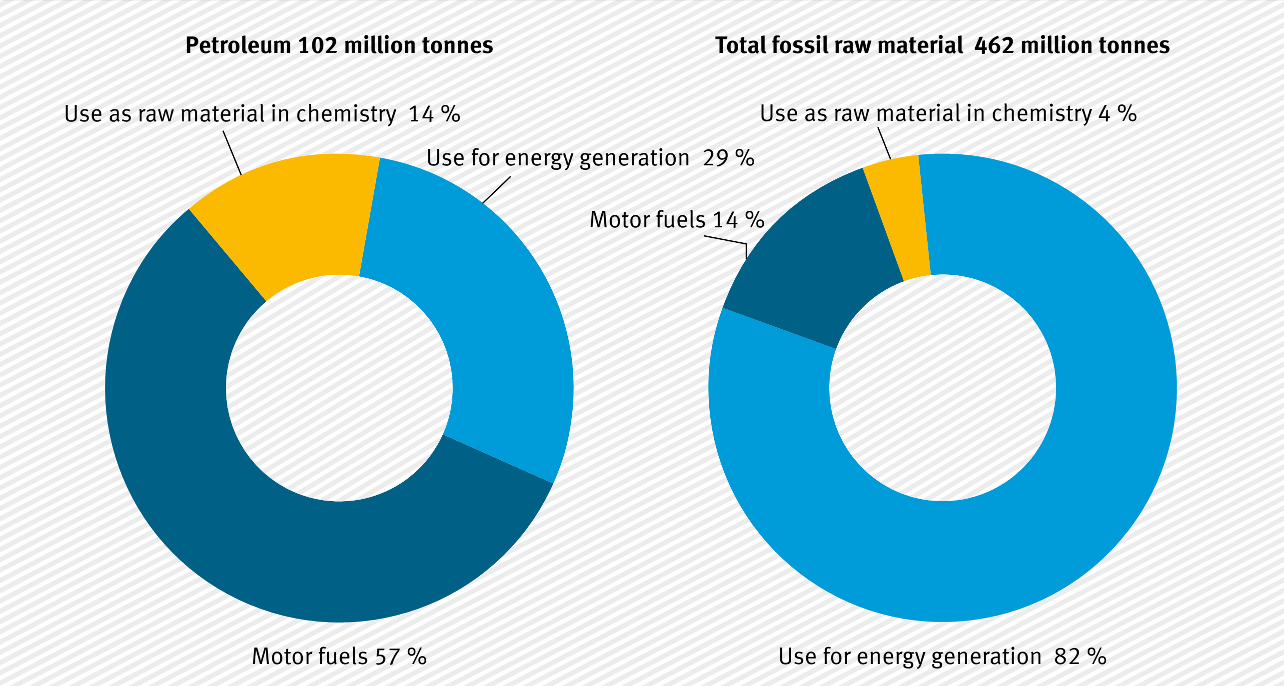
A study by the International Council of Chemistry Associations ICCA in 2009 came to the conclusion that 2.6 times the greenhouse gas emissions from all chemical manufacturing processes can be saved by using chemical products. For instance, insulating buildings with polystyrol panels will reduce the consumption of heating oil per square metre by up to two thirds. Further examples include the use of polyurethane in roof insulation and insulation foam in refrigerators and freezers. In addition, an increasing amount of plastic and high-performance glue is used in the construction of vehicles, resulting in lighter vehicles and lower fuel consumption.[215]

D.5.1.2 Material use of fossil and renewable resources in the chemical industry

In 2009, the use of fossil resources (petroleum, natural gas and coal) in the chemical industry accounted for 18.4 million tonnes (Figure D-1), while in 2008, fossil resource consumption amounted to 18.5 million tonnes, which is just marginally higher.

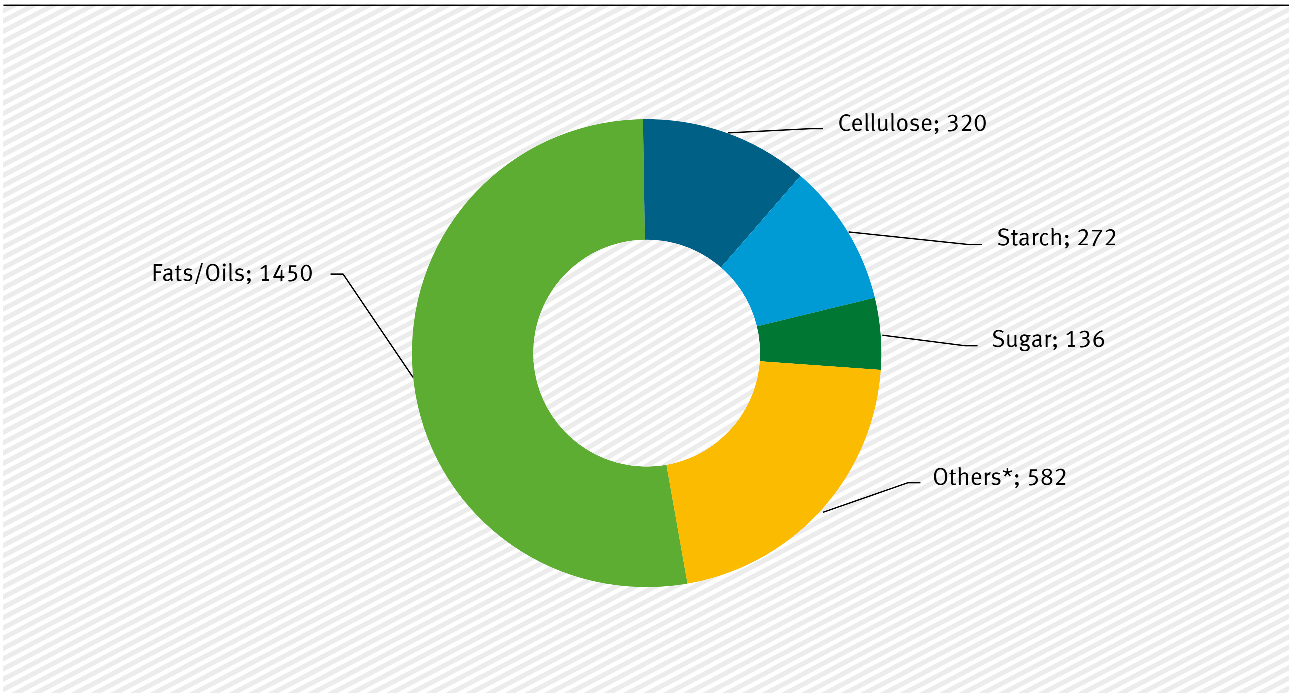
Figure D-2 shows the use of renewable resources (NaWaRos) in the chemical industry, illustrating how they are used throughout the chemical industry. Most products manufactured from these resources are thermally recycled at the end of their lives – including plastics, scrap tyres for use as fuel surrogate or reducing agent (see, for example in Chapter D.6 on cement).

Figure D-1: Share of the chemical industry in the use of fossil resources (Germany 2009)[216]



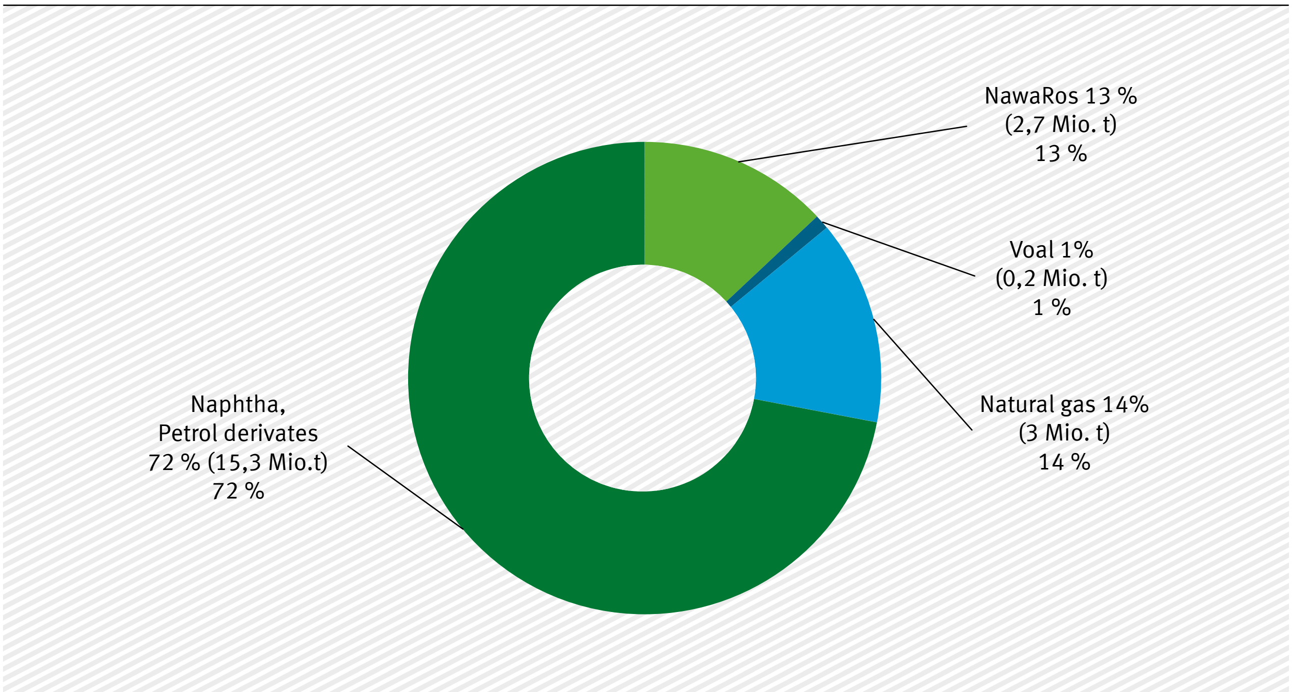
Of Germany's annual petroleum consumption, the chemical industry uses 14 percent as raw material. Just over half the total petroleum is used for motor fuel production while the rest is used for energy generation (mostly heating fuel). Overall, in 2009 the chemical industry used 18.4 million tonnes of fossil raw materials (petroleum derivatives, natural gas and coal). After initial processing, these form the basic components for sheer endless synthetic possibilities.

Figure D-2: Use of renewable resources in the German chemical industry in 2008 (in 1000 tonnes)[217]



* Natural caoutchouc. plat wax, resin, tanning agents, glycerine. medicinal plants

Figure D-3: Composition of raw materials used in the German chemical industry in 2008[218]



D.5.1.3 Energy use and greenhouse gas emissions from the chemical industry

Energy consumption

The chemical industry has been remarkably successful in reducing its energy consumption: according to the VCI, the use of energy in the chemical industry between 1990 and 2009 was reduced by 33%.[219] This is equivalent to an average annual reduction of almost 1.7% – an efficiency rate similar to the annual energy savings target set in the draft EU Energy Efficiency Directive for the period 2014 to 2020.

Table D-16: Energy consumption of the chemical industry in TWh[220]

	1990	1995	2000	2005	2009
Natural gas/methane	*	*	*	*	71
Petroleum products	*	*	*	*	60
Electricity	*	*	49.8	52.8	45
Coal	*	*	10.9	4.3	6
Total	**272**	*	202	178	**182**

* No differentiated data available.

The data (Table D-16) of the Federal Statistical Office/VCI on the energy vectors natural gas and petroleum products between 1990 and 2005 are not comparable to those of 2009 due to the use of different sector definitions in the Federal Statistics. Energy consumption causes CO_2 emissions, which are shown in Table D-17 .

Table D-17: CO_2 emissions from the chemical and pharmaceutical industry[221]

	1990	1995	2000	2005	2009
in million tonnes	65.4	48.4	44.1	41.8	37.4

During this period, the industry was able to reduce greenhouse gas emissions by 47% (energy-related carbon dioxide and dinitrogen monoxide – laughing gas emissions) in spite of a production increase of 42%.[222]

Process-related greenhouse gas emissions

The following synthetic processes are major sources of process-related greenhouse gas emissions, resulting in the production of

- Nitric acid
- Adipic acid
- Ammonia
- Other substances (e.g. carbon black, methanol, olefins and soda ash, including coke burn-off for catalyst regeneration in refineries.[CLVIII])

Table D-18: Process-related greenhouse gas emissions from the chemical industry in million tonnes of CO_{2eq}[223]

	1990	1995	2000	2005	2010
Adipic and nitric acid production (N_2O emissions)	22.2	24.5	5.2	8.2	3.8
Ammonia production (CO_2 emissions)	5.7	7.0	7.5	7.8	7.4
Production of other substances (CO_2 emissions)	6.3	7.4	8.6	8.6	8.9
Total emissions in tonnes of CO_{2eq}	34.2	38.9	21.3	24.6	20

Ammonia

Ammonia is the starting material for many nitrogen-containing chemical products, in particular nitric acid, nitrogen-containing mineral fertilisers and urea resins. Ammonia is produced by a reaction of hydrogen with nitrogen in the Haber-Bosch process. To generate the starting mixture, nitrogen is extracted from the air, while hydrogen is obtained from steam reforming and also by partial oxidation based on fossil fuels or their precursors, such as residues from fractionation distillation. CO^2 is released in the process of obtaining H2.

CLVIII Soda ash production is not attributed to the chemical industry in the NIR.

The volume of CO_2 emissions is determined by fossil primary materials. In Germany, natural gas-based steam reforming is used as well as partial oxidation with heavy oil. The latter is associated with higher CO_2 emissions. Although ammonia production in Germany has remained at the same level over the past 20 years, it has risen two-and-a half-fold during the same period worldwide.

Carbon dioxide that arises from ammonia production can be extracted and re-used for the synthesis of other products such as urea, fertiliser and methanol as well as in the drinks industry. This share of CO_2 emissions is therefore included in the emissions. A large share of the arising CO_2 is emitted without being re-used.

Adipic and nitric acid

Adipic acid is synthesised on a technical scale by oxidation of a mix of cyclohexanol and cyclohexanone (ratio 93/7) with nitric acid. This reaction generates considerable amounts of nitrous oxide (N_2O) – approximately 300 kg per tonne of adipic acid produced. All nitrous oxide was emitted into the atmosphere until the end of 1993. The first thermolytic reactor for conversion of nitrous oxide into nitrogen and oxygen went into service in late 1994. A catalytic decomposition installation followed at the end of 1997. Until then, nitrous oxide emissions amounted on average to > 20 million tonnes CO2eq per annum. Emissions fell significantly in subsequent years to an average of 4.3 million tonnes CO2eq per annum, although the production of adipic acid has more than doubled since 1990.

In order to achieve further nitrous oxide mitigation, Joint Implementation projects were carried out within the framework of the Kyoto Protocol. In 2008/9, two German companies added second (redundant) nitrous oxide decomposition installations to their existing installations. This resulted in another considerable reduction. In 2010, nitrous oxide emissions amounted to < 0.8 million tonnes $CO_{2eq.}$

Nitric acid is produced on a technical scale by the catalytic oxidation of ammonia and purified air. In a side reaction, nitrous oxide (N_2O) is produced. Nitric acid is the starting substance not only for adipic acid, but also for many other nitrogen-containing chemical products, e.g. fertilisers and explosives. Production volumes correlated with N_2O emissions until 2006. Since then, N_2O emissions have decoupled from production volume, which can be attributed to an increased use of secondary catalyst technology for mitigation. The aggregated emission factor for the seven German installations was 3.89 kg N_2O per tonne of nitric acid in 2010.

Other production processes – emissions from soda use

Soda ash is predominantly used in the glass industry, the production of detergent and cleaning agents and in the chemical industry. In line with NIR categories, emissions from glass production are not included here. The use of soda ash outside the glass industry has not changed since 2000 (approx. 0.3 million tonnes).

In terms of calcium carbonate use, soda ash production is carbon-neutral because carbon dioxide from limestone is bound in the soda ash product and is only released with the use of soda ash elsewhere.

D.5.2 Strategies for GHG mitigation in the chemical industry

Assuming that fossil fuels can be replaced with renewables, energy-related greenhouse gas emissions can be avoided altogether and only process-related emissions would have to be accounted for in the chemical industry. In the following, the main emission sources are described:

Adipic acid

A 100% reduction of nitrous oxide can only be achieved if a substitute for the oxidant nitric acid is used. Alternative oxidants such as hydrogen peroxide or oxygen have not yet found their way into industrial-scale production and/or suitable procedures are yet to be developed. It is not clear whether by 2050 such procedures will be available. Alternative syntheses, such as the reaction of acetylene with acetic acid to produce adipic acid, have only been tested on a laboratory scale to date. However, a fermentation-based process for the production of adipic acid has been developed in the US and is being used on a pilotplant scale.

Nitric acid

It is already technically possible to achieve a 99% reduction of nitrous oxide emissions from nitric acid production. Assuming that existing installations will use the full range of currently available mitigation technology, which may include more efficient catalyst technology – nitrous oxide emissions from adipic and nitric acid production could be reduced to 0.5 million tonnes CO_{2eq}.

The oxidation reactions occurring during the production of nitric acid are exothermic. The waste heat can be used to pre-heat the residual gases and to generate steam and electricity for the process.

Soda ash

The carbon contained in soda ash is usually released in the shape of CO_2 sooner or later, irrespective of the type of use. The mitigation of non-energy-related CO_2 emissions from soda ash use therefore directly depends on a decreased demand for soda ash.

Ammonia

If ammonia synthesis could be switched to renewable hydrogen altogether, no more fossil material would be needed. This would mean complete CO_2 mitigation.

Other processes

Other examples of technical processes in the chemical industry that lead to considerable energy savings, either at present or in the medium-term, include:

Gas-phase phosgenation to TDI[CLIX] results in 60% energy saving and also uses 80% less solvent. TDI is an important precursor product for the synthesis of polyurethanes, which, in turn, are used for the production of insulating foams and boards, glue, mattresses, varnish etc.

Direct oxidation of propylene oxide (PO) can also save considerable amounts of energy. PO is an essential precursor product for polyurethane, polyester and other products.

CLIX Toluol diisocyanate.

Further energy savings can be made by synthesising epichlorohydrin from glycerol. This also protects resources, as it replaces propene. Epichlorohydrin is an important precursor product for epoxy resins with a wide range of applications.

Microreactor technology can be used to convert discontinuous large-volume stirring processes into continuous processes. This would not only save energy, but also increase product yields.

Ionic fluids (IFs) are salts that are liquid below 100°C and do not have measurable vapour pressure. They can replace conventional solvents. Thus, emissions would not arise and the use of IFs would also save energy as there would be no solvent emissions to be treated and volatile products would be easily separable.

Options for reducing electricity use

In the medium-term, electricity consumption will be reduced in chlorine production. The conversion of all German amalgam plants to membrane electrolysis would save 840 GWh of electricity by 2020. If all German chlorine-producing plants switched to oxygen depolarised cathodes, approximately 5.8 TWh could be saved. However, the drawback of this method would be that hydrogen would no longer be generated as a by-product. The production volume for chlorine is expected to decline in any case. One reason is the development of chlorine-free production processes, such as the synthesis of propylene oxide.

A further example of reduced energy use is the catalytic rather than electrolytic cleavage of HCl, as it does not require electricity.

D.5.3 The chemical industry in 2050

Assuming that overall economic development would permit an annual growth of 0.7%, production in the chemical industry would grow by approximately 30% by 2050.

During the period between 1990 and 2009, however, chemical production went up by 42%. This is an increase of 2.2% per annum and, on this basis, production could increase by 80% by 2050. Such data give rise to the expectation that growth in the chemical industry may well exceed the average economic growth rate in Germany.

D.5.3.1 Resource consumption and greenhouse gas emissions in 2050

Fossil resources such as naphtha/petroleum derivatives and natural gas can be replaced by renewable methane. Methane can be used for the synthesis of all higher-grade hydrocarbons. These include, among others, olefins, aromatics and paraffins, which, in turn, give rise to polymers (e.g. PE, PP, PET[CLX], polyamides), dyes, pharmaceuticals, pesticides etc. In the future, higher hydrocarbons might be produced in a direct reaction of carbon dioxide with hydrogen. However, the technology is not available yet.

Coal is used in the chemical industry mainly as a reducing agent or absorbent (activated coal). Some of the coal is anticipated to be replaced by substances such as zeolites.

CLX Polyethylene, polypropylene and polyethylene terephthalate.

Table D-19: Mix of primary resources in the chemical industry in the UBA THGND 2050 Scenario, own calculations

[million tonnes]	2050
NaWaRos (regrowing raw materials)	3.6
Renewable raw materials	18.3 methane 0.1 charcoal ≡ 282 TWh[CLXI,CLXII]
Raw materials total	22

Assuming that, in 2050, fossil resources will no longer provide carbon for chemical synthesis which is based on renewable methane, there will no longer be greenhouse gas emissions and the processes will be carbon-neutral. (Table D-20).

Table D-20: Process-related greenhouse gas emissions from the chemical industry in million tonnes of CO_{2eq} in the THGND 2050 Scenario, own calculations

	2050
Adipic and nitric acid production (N_2O emissions)	0.5
Ammonia production (CO_2 emissions)	0
Production of other substances (CO_2 emissions)	0
Total emissions in CO_{2eq}	0.5

Although production is expected to increase, raw material input will not increase to 80% by 2050.

One reason will be the more efficient use of resources. Replacing fossil-based polymers with biopolymers (currently < 1%) will further reduce the use of fossil raw materials.

Renewable resources can generally be expected to gain importance as input materials in the chemical industry. This will reduce the consumption of fossil resources (e.g. naphtha). It is also true that in the past decade, the use of regrowing resources as raw material in the chemical industry made rather slow progress.

Another way of reducing demand for petroleum derivatives is the electrolytic production of renewable hydrogen. The LPG (liquefied petroleum gas) fraction from petroleum distillation is mainly used as raw material for synthesis gas and for hydrogen generation.

It is possible that in the future, large-volume output of basic chemicals will become less important in Germany as growing markets will mainly be in Asia. Overall, it can therefore be assumed that in spite of increased production, the quantities of resources will remain similar to 2008.

CLXI The caloric value of methane is 55.5 MJ/kg. For 18.3 Mio. tonnes of methane, this would amount to 282 TWh.

CLXII During the synthesis of hydrocarbons to olefins and aromatics, hydrogen is cleaved off. It is available as starting material (NH3 synthesis) or for thermal use. H2 generating around 19.7 TWh is required for the synthesis of 3 million tonnes of NH3. This H2 required can be almost entirely obtained from ethene, propene and aromatics synthesis.

D.5.3.2 Final energy consumption for 2050 in TWh

Assuming a mitigation rate of 1.5% per annum, final energy consumption will fall by 55.5% between 2013 and 2050. This is equivalent to an energy efficiency factor of 1.80. Based on the overall energy demand of the chemical industry for 2009 (Table D-16) and 2013, the overall energy demand for 2050 amounts to 81 TWh.

Table D-21: Final energy consumption in the chemical industry in the UBA THGND 2050 Scenario, own calculations

	TWh
Electricity	20
Methane or hydrogen	61
Total energy demand	**81**

If, by 2050, the energy demand of the chemical industry is entirely met by renewable methane, there will be no energy-related CO_2 emissions. Renewable hydrogen would be a possible alternative energy source. A range is given, based on the assumption that of the 1.5% mitigation achieved by all energy vectors, 61 TWh could be attributed to methane and 20 TWh to electricity.

It is expected that by 2050, coal will no longer be used as an energy vector in the chemical industry.

D.5.4 Chemical industry summary

Based on these assumptions for the chemical industry, the resulting energy demand will be 81 TWh, of which 20 will come from renewable power and 61 from renewable methane or hydrogen. Energy-related greenhouse gas emissions will be avoided altogether.

It is conceivable that in the long-term, process-related CO_2 emissions will fall to 0.5 million tonnes CO2eq. This would be equivalent to an emission reduction of 98.5% compared to 1990.

The use of renewable methane as a production resource would require a further 18.3 million tonnes. This energy requirement of about 282 TWh significantly exceeds the final energy consumption for energy generation.

Table D-22: Final energy consumption and use of resources in the chemical industry in the UBA THGND 2050 Scenario

Total energy demand	81 TWh
Raw materials	282 TWh

D.6 Cement industry

D.6.1 The cement industry in Germany – status quo

D.6.1.1 Structure and economic significance of the cement industry in Germany

The production of Portland cement in Germany has a history that goes back to the middle of the 19th century.[224] Portland cement is mainly used in concrete production, where it is blended with water, sand and gravel. Concrete is widely used in housing construction and infrastructure projects.

Cement is a building material that hardens in a reaction with added water. There are various types of cement that are produced from Portland cement clinker (sintered constituent of cement), gypsum and, if applicable, other major and minor components (e.g. limestone, blast furnace slag, fly ash, trass). Portland cement clinker (in the following referred to as cement clinker or clinker) is a component of all types of cement in varying proportions (from 10 to almost 100%).[225]

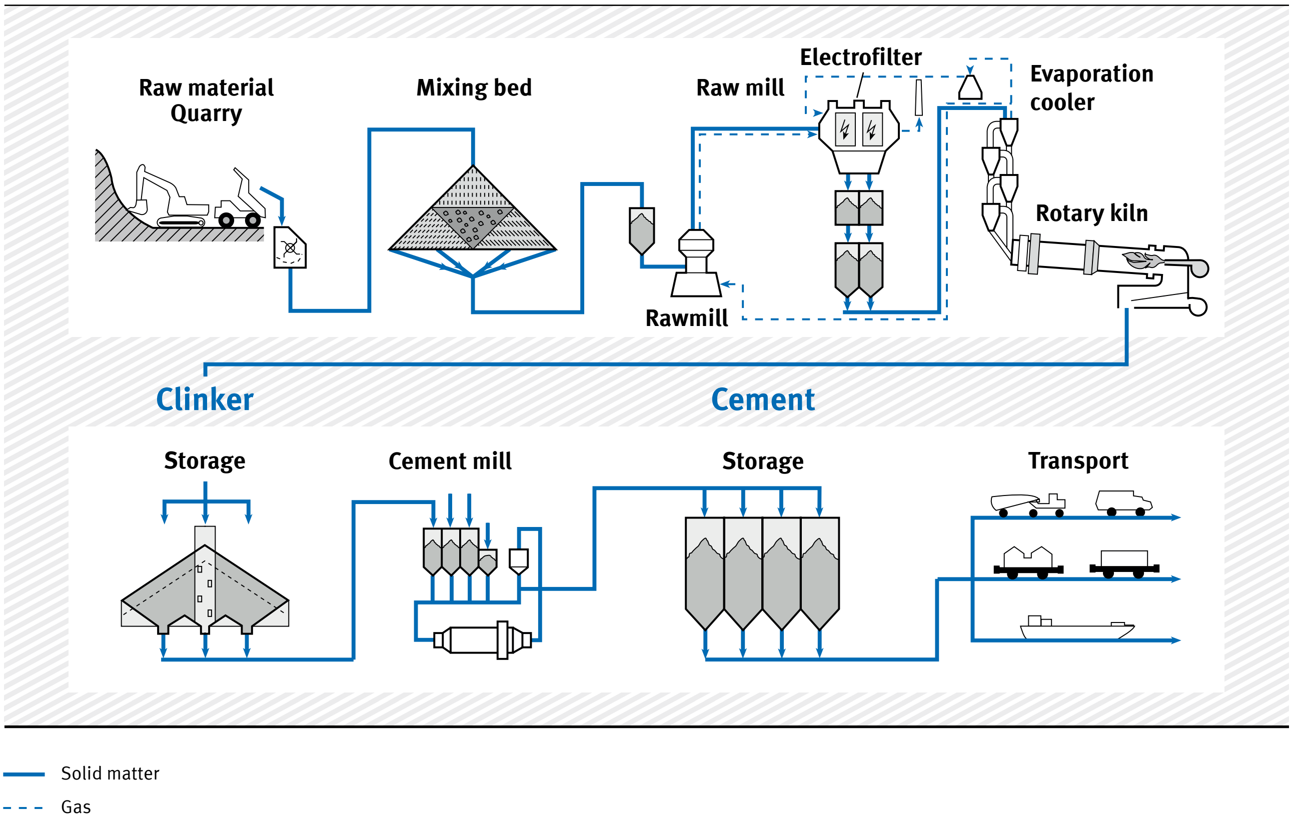
Cement clinker is prepared by blending raw materials containing calcium oxide (CaO), silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and ferrous oxide, which have been milled in special mills and homogenised. The most important primary materials are limestone, chalk and clay. Ferrous oxide is a mineral that is either contained in clay or added in the form of iron ore.[226]

Of the maximum authorised capacity for cement clinker produced in Germany in 2010, 88.4% was produced using the dry process in rotary kilns with cyclone preheaters, while 10.7% was produced with the semi-dry process. This involves heating pellets of raw material in a grate preheater (Lepol preheater) before they are sintered to clinker in rotary kilns. The remaining 0.9% of the maximum authorised capacity for clinker was produced in shaft kilns.[82]

The homogenised blend of raw materials is heated for sintering in a rotary kiln up to 1450°C. Clinker phases form during this process. The resulting clinker is then ground up with other components (e.g. limestone, blast furnace slag or fly ash) to form cement, depending on the type of cement required.[228]

The cement production process is shown as a diagram in Figure D-4.

Figure D-4: Diagram of the cement production process[229]



In 2010, 47 rotary kilns in 34 cement plants belonging to 22 companies produced cement clinker in Germany. The clinker was then processed into cement in 54 plants (of which 20 are just grinding units with no clinker production).[230] Cement production in 2010 amounted to approximately 31 milli-on tonnes (see Table D-23).

Table D-23: Cement clinker and cement production in Germany[CLXIII]

Product	Unit	1990	1995	2000	2005	2010
Cement clinker	kiloton-nes p.a.	26.0	27.7	28.0	25.1	23.6
Cement[231]	kiloton-nes p.a.	34.2	34.2	35.0	31.8	30.6
Clinker fac-tor[232]	$t_{Clinker}$/ t_{Cement}	0.76	0.81	0.8	0.79	0.77

In 2011, Germany was ranked 16th among the world's cement producers. Within the EU, Germany ranked second behind Italy in 2011; whereas on a global scale, China and India are uncontested leaders.[223]

CLXIII The clinker factor was calculated using the specifications on cement and cement clinker production in Chapter 4.2.1.1 of the National Inventory Report for the German Greenhouse Gas Inventory 1990–2010. The factor was then applied to the cement production figures in this table, which were taken from the RWI monitoring report. The approx-imate figures for cement clinker production were calculated as the product of cement production and clinker factor for the relevant year.

Like most other sectors in the minerals and aggregates industry, cement production is subject to economic fluctuation, reflecting not only the entire economic situation, but in particular that of the construction industry. While increased building activity (in housing as well as infrastructure) led to an increased demand for cement during the first years after German reunification, there has been a distinct downward trend since 2000.[234]

D.6.1.2 Energy consumption and greenhouse gas emissions from the cement industry

Energy consumption

The cement industry is one of the most energy and resource-intensive industry sectors in Germany and worldwide. In 2010, the final energy consumption of the German cement industry amounted to a total of 24.2 TWh (approx. 88 PJ) of solid, liquid and gaseous fuels as well as 3.37 TWh (12.13 PJ) of electric power.[235]

Energy from fuel is mainly required for sintering cement clinker. Thermal energy input levels depend on factors such as the composition and moisture content of the raw meal (which is the kiln-ready blend of raw materials), production method and kiln configuration.

The theoretical energy demand or reaction enthalpy for the combustion process amounts to between 1650 and 1800 MJ per tClinker. Depending on the moisture content of the raw material, energy demand may increase by 200 to 1000 MJ per tonne, increasing the minimum energy demand for sintering cement clinker (including drying) to 1850–2800 MJ per $t_{Clinker}$.[236]

The actual energy demand, however, is higher because the moisture content of fuels used in the kiln involves additional drying and there is heat loss in the kiln system. Other factors include chemical and mineralogical properties of the input material and the capacity of the installation.[237] In the early 1990s, average fuel energy consumption was approximately 1000 kWh/$t_{Clinker}$ (3600 MJ/$t_{Clinker}$). Specific fuel-related energy demand for the production of a tonne of cement clinker was 1038 kWh/$t_{Clinker}$ (3735 MJ/$t_{Clinker}$) in 2010 (see Table D-24). This is higher than for 1990. Whereas during the first years after reunification, the modernisation of installations and decommissioning of old installations resulted in a slight reduction of specific fuel-related energy consumption, this trend has been reversed over the past decade.[238] The increase coincides with an increased use of (waste-derived) secondary fuels with properties (calorific value, moisture content) that may have a negative impact on specific fuel-related energy use in the cement industry (see source[239]). The share of secondary fuels (e.g. fractions of commercial waste, waste tyres, solvents) in total thermal energy consumption (fuel-related energy) was almost 61% in 2010, equivalent to an energy volume of 14.9 TWh (53.7 PJ)[240]. In 2000, this share amounted to approximately 26% (see Table A24).

Specific thermal energy consumption in relation to the production of a tonne of cement, however, has been falling more or less continuously since 1990. This can be essentially explained by two factors:[241]

- Generally improved efficiency in production
- Lower specific cement clinker input per tonne of cement (increased use of milling additives such as blast furnace slag, which reduces the share of sintered clinker and hence the amount of energy required for sintering). In 2010, approximately 1 tonne of cement was produced using 0.77 tonnes of clinker. In other words, the clinker factor (ratio of clinker to cement produced) was 0.77 (see Table D-23).

In 2010, the production of 1 tonne of cement required on average approximately 799 kWh (2876 MJ) of fuel-related energy.

In 2010, the electric energy required for the production of 1 tonne of cement was 109.8 kWh.[242] Electric energy is used predominantly for preparing raw materials (35%), operating kiln and cooler (22%) and grinding cement (38%).[243]

Table D-24: Energy use in the German cement industry[244]

			1990	1995	2000	2005	2010
Fuels	Fuel-related energy input[245]	PJ	109.5	102.8	99.3	88.7	88.0
		TWh	30.42	28.56	27.58	24.64	24.44
	Fossil fuels	PJ	101.4	91.8	73.8	45.4	34.3
	Secondary fuels	PJ	8.1	11.0	25.5	43.3	53.7
	Share of secondary fuels	%	7	11	26	49	61
	Fuel-related energy input (specific)	kJ/kg_{Cement}	2,999	3,000	2,835	2,785	2,876
		kJ/kg_{Cement}	0.833	0.833	0.788	0.774	0.799
		$kJ/kg_{Clinker}$ [CLXIV]	3,946	3,704	3,544	3,525	3,735
		$kJ/kg_{Clinker}$ [CLXV]	1.096	1.029	0.984	0.979	1.038
Electricity	Off-site electricity generation	TWh p.a.	3.67	3.64	3.55	3.24	3.37
	Electric energy input (specific)	kWh/t_{Cement}	107.4	$10^{6}.5$	101.5	101.9	109.8
Total energy input		TWh	34.1	32.2	31.1	27.9	27.8

Greenhouse gas emissions

The cement industry causes considerable greenhouse gas emissions, of which CO_2 emissions make up the largest share. Other climate-relevant gases, such as CH_4 are emitted in very small amounts only.[246,247] Therefore, CO_2 emissions will be at the heart of our discussion.

CO_2 emissions are process as well as energy-related. Process-related CO_2 emissions arise during the calcination of limestone, as shown in Formula D-1.

Formula D-1: $CaCO_3 \rightarrow CaO + CO_2$

Energy-related CO_2 emissions arise both directly from fuel combustion (thermal emissions) and indirectly from generating the electrical energy required for the cement production process (e.g. for preparing raw material and grinding cement). An overview of sources of CO_2 are given in Table D-26.

CLXIV Own calculations

CLXV Own calculations

Table D-25: Sources of CO_2 in the cement production process, own compilation

Process stage	CO_2 sources
Preparation	Indirect CO_2 emissions from power generation for the preparation of raw materials
Sintering and cooling	Direct CO_2 emissions from primary and secondary fuels
	Direct CO_2 emissions from power generation from calcination of limestone
	Indirect CO_2 emissions from power generation for the operation of kilns and coolers
Grinding cement	Indirect CO_2 emissions from power generation for grinding cement
Secondary processes	Indirect CO_2 emissions from power generation for secondary processes such as drying of blast furnace slag or coal and for emission abatement technology

In 2010, specific CO_2 emissions amounted to a total of 0.576 tonnes of CO_2/t_{Cement}, of which 0.108 tonnes of CO_2/t_{Cement} arose from thermal-related CO_2 emissions from primary fuels (not including CO_2 emissions from secondary fuels), 0.060 tonnes of CO_2/t_{Cement} to power-related CO_2 emissions and 0.408 tonnes of CO_2/t_{Cement} to raw material or process-related CO_2 emissions. CO_2 emissions for 2010 from secondary fuels were estimated at 0.169 tonnes of CO_2/t_{Cement} (see Table D-26), resulting in total emissions of 0.745 tonnes of CO_2/t_{Cement}. An overview of the development of CO_2 emissions from the German cement industry are given in Table D-26. Please note that the figures for secondary fuels in Table D-26 include CO_2 emissions from secondary fuels of biogenic origin.

Table D-26: CO2emissions from the cement industry, own calculations

			1990	1995	2000	2005	2010
direct CO_2 emissions							
process-related		t CO_2/tclinker[248]	0.53	0.53	0.53	0.53	0.53
		0.403	0.429	0.424	0.419	0.408	
		13,776	14,682	14,840	13,315	12,488	
Fuel-related**	Primary fuels*	t CO_2/tCement	0.279	0.254	0.201	0.137	0.108
		kt	9,530	8,693	7,033	4,350	3,309
	Secondary fuels	PJ	8.1	11.0	25.5	43.3	53.7
		kt CO_2/PJ	93	93	93	93	93
		t CO_2/tCement	0.023	0.031	0.070	0.131	0.169
		kt	772	1,052	2444	4157	5163
	total	kt	10,302	9745	9478	8507	8472

		1990	1995	2000	2005	2010
indirect CO_2 emissions						
Electricity-related	t CO_2/TWh	544,000	544,000	544,000	544,000	544,000
t CO_2/tCement	0.058	0.058	0.055	0.055	0.060	
kt	1996	1980	1931	1763	1833	
Total CO_2 emissions (incl. secondary fuels and electricity	**kt**	**26,074**	**26,407**	**26,249**	**23,584**	**22,793**
incl. secondary fuels	t CO_2/tCe-ment	0.762	0.772	0.750	0.742	0.745
excl. secondary fuels**	t CO_2/tCe-ment	0.740	0.741	0.680	0.611	0.576

* regular fuels only (excluding CO_2 emissions from secondary fuels)

** Estimated CO_2 emissions for secondary fuels are not included in this figure.

Base data and assumptions for calculations

process-related CO2 emissions
(raw materials-related CO_2 emissions from calcination of limestone during clinker sintering):
The raw-material-related CO_2 emissions were calculated to take account of the production volumes from Table A23 and the specified CO_2 emission factors.

Fuel-related CO2 emissions

- Fuel inputs – source: RWI (2010, p. 153)[249].
- Emission factors for fuels – source: Umweltbundesamt (Table 281)[250].
- Emissions for 2010 were calculated on the basis of the emission factors for 2009.
- Emission factor for lignite = emission factor for lignite dust
- Emission factor for other fuels = average of the emission factors for the other fuels
- Total emissions are obtained by adding up CO_2 emissions for the individual fuels.
- In order to obtain an estimate of increased CO_2 emissions arising from a higher input of secondary fuels, for simplicity it is assumed that these fuels replaced hard coal and lignite exclusively. The emission factor for secondary fuels is calculated from the average of the emission factors for hard coal and lignite (dust).
- The product-specific emission factor t CO_2/t_{Cement} is calculated from fuel-related CO_2 emissions relating to cement production as listed in Table D-23.

Electricity-related CO_2 emissions

- Emission factor for electricity 544 g CO_2/kWh = 544,000 t CO_2/TWh (reference year 2010) – source: Umweltbundesamt[251]

The falling trend in energy consumption (see Table D-24) and the associated decrease of emissions in the cement industry (see Table D-26) can be explained to some extent by fluctuations in the economy, as well as by measures to improve energy efficiency and the trend of replacing cement clinker with other additives such as blast furnace slag. While in 1995, the share of cement types with various components was 23.2%, by 2000 it had risen to 38.2%. The trend continued over the following years. In 2010, the share of multi-component cement types was 66.2%.[252]

According to the specifications for greenhouse gas emissions reporting, greenhouse gas emissions directly associated with cement production are attributed to source categories 1.A.2.f and 2.A.1 (see Table D-27).

Table D-27: Source categories in the National Emissions Inventory[253] where greenhouse gas emissions directly associated with cement production are reported

CRF Code	Source category	Comment
1.A.2.f	Manufacturing industries and construction – other energy generation	Includes greenhouse gas emissions from the use of fuels in the cement industry for heat generation.
2.A.1	Mineral products: Cement	Greenhouse gas emissions arising from the calcination of limestone (mainly CO_2) — a subset of greenhouse gas emissions from the cement industry, which, by conventi-on, are considered to be 'process-related' (as opposed to emissions in 1.A.2.f)

When looking at how to make the cement industry greenhouse gas-neutral in the long-term, it makes sense to distinguish between energy-related and process-related emissions because different mitigation concepts will be applicable. We will therefore retain this distinction throughout the following.

D.6.2 Strategies for reducing GHG emissions in the German cement industry

From today's perspective, the following measures could be implemented to reduce greenhouse gases in the cement industry:

- Enhancing thermal energy efficiency, e.g. by increased use of waste heat or more efficient kilns
- Increasing electric energy efficiency, e.g. by using more energy-efficient mills
- Continuing to replace fossil fuels with renewable energy vectors especially in cement clinker production and further adaptations to the engineering of installations[CLXVI]
- Increasing the use of secondary raw materials in the production of cement clinker
- Development of new types of low-CO_2-cement with a low cement clinker content and
- Development of new, cement-like building materials.

D.6.2.1 Measures to improve energy efficiency

Enhancing thermal energy efficiency

Methods to improve the thermal energy efficiency of cement plants include changes to production processes, optimisation of the installation design and reducing heat loss.

CLXVI Going down the route of replacing fossil fuels with waste-derived secondary fuels in order to reduce CO_2 emissions is not considered here. The assumption is that in the long-term, no or hardly any waste materials will be burnt in the production process. However, they may have their place during a transition period on the way to GHG-neutrality and help reduce CO2 emissions.

The following steps could be taken:[254,255]

- Building in more cyclone stages:
  In principle, it is possible to reduce thermal energy requirements by 80 to 100 $kJ/kg_{Clinker}$ by building in an extra cyclone stage, if the moisture content of the raw materials permit.[256]
  Such a measure, however, could have a negative impact on the economic viability of other energy-saving measures, such as waste heat utilisation for power generation.
- Improvement of efficiency at clinker coolers:
  After sintering, the cement clinker comes out of the kiln into a cooler, releasing heat. To what extent this heat can be re-used is crucial in terms of the efficiency of the entire cement kiln system. Cooler exhaust gases that cannot be re-used in the kiln system itself are often used for drying fuel (e.g. petroleum coke, sewerage sludge) or raw materials for cement production (e.g. blast furnace slag). Modern clinker coolers can achieve an efficiency ratio of up to 80%.[257] Conversion into electric power is another option. While one plant in Germany pilots the conversion of cooler exhaust into power using ORC (Organic Rankine Cycle) technology, another German cement plant converts waste heat from the kiln into power.
- Reducing false air entry
- Oxygenising the combustion air
- Use of mineralisers
- Use of calcined raw materials
- Optimising process control
- Minimising bypass streams
- Use of suitable raw materials
- Increasing the availability of installations:
  Another general approach to improving energy efficiency is the avoidance of downtime and limited operability. In terms of industrial cement production, above all, this means avoiding heat loss caused by frequent service and repair-related disruptions to plant operations.

Systematic re-use of waste heat

In terms of waste heat efficiency, the most effective strategy would be to avoid the generation of waste heat. This could be achieved, for example, by avoiding radiation of surplus heat through kiln walls or re-using as much heat as possible in internal processes, e.g. by increasing cyclone stages. Where heat is transferred, transported, stored or transformed, as the case may be, heat loss occurs. Thus, harnessing waste heat for external processes or power generation should only be considered if the heat cannot be reused within the same installation.

The biggest sources of heat loss in a cement kiln plant are exhaust gas, off-gas from clinker coolers and heat loss through kiln walls. Any existing bypass streams for the discharge of pollutants and interfering substances may also contain a relevant amount of energy. The following list gives an overview of options for the systematic re-use of waste heat.

- Exhaust gas from kilns:
  - drying raw materials:
    Drying raw materials and fuels before use has become common practice in German cement plants. However, the available waste heat often exceeds demand for drying purposes.
  - power generation (steam processing, ORC technology)
  - cogeneration of power and heat for district heating
- Cooler exhaust gas/bypass streams
  - drying of fuels (petroleum coke, sewage sludge)

- drying of cement components (e.g. blast furnace slag)
- possibly also conversion into electric power
- Cogeneration of power and heat for district heating

Conversion of waste heat into power

From today's perspective, the energy potential of waste heat is not sufficiently exploited because energy costs are too low and return on investments required takes too much time. This makes it economically unattractive for operators to harness waste heat. One example is waste heat conversion into power using ORC technology. It could be widely applied, but its low efficiency rate, combined with slow return on investment, has prevented further acceptance in the cement industry so far.

In principle, two methods are currently available to cement plants for the conversion of waste heat into electricity – ORC or conventional steam cycle technology.

Currently, Germany has one op*-erating ORC plant that converts clinker cooler exhaust gas into electricity at the Lengfurt cement plant. The plant supplies about 10% of the cement works' own electricity demand.[258]

The year 2012 saw the commissioning of the first waste heat power station relying on conventional steam cycle technology to convert kiln exhaust gas in a German cement-producing plant. The target net electricity output is 6 MW. This is equivalent to about 30% of the cement plants' own electricity demand or a yield of 44kWh/$t_{Clinker.}$[259]

In Asia, by contrast, conventional steam cycle power generation from cement plant exhaust gas is widely used and considered state-of-the art technology. Their yield is also 30–45 kWh/$t_{Clinker}$ and can supply up to 30% of a cement plant's electricity demand.[260]

However, effective power generation based on conventional steam cycle technology generally requires higher exhaust gas temperatures and may therefore not be suitable for all cement plants. ORC technology with its various organic input media allows for a higher degree of flexibility and can be used for waste heat-to-power conversion at lower temperatures.

Other possible uses

Another way of using waste heat effectively would be to feed it into district heating systems. However, most cement plants are not connected to communal district heating grids and the infrastructure would have to be set up first. This has so far prevented the spread of this type of waste heat use. It is also true that cement plants cannot guarantee continuous feed-in all year round, which reduces its attractiveness for potential consumers.

No practically and economically viable solution has yet been found for the utilisation of the heat radiating from the rotary kiln. Priority will be given to existing tried and tested methods (mainly ORC and steam cycle-based conversion of waste heat to power). The potential is there and must be exploited in the near future.

Potentials

Although efforts have been made in the cement industry to improve energy efficiency, waste heat is largely being lost, e.g. in evaporative coolers that cool kiln exhaust gas to a temperature compatible with fabric filters for dust separation.

More intensive use of waste heat would improve the energy efficiency of cement kiln plants. In 2007, 45% of waste heat from Austrian cement plants was not utilised. This would be equivalent to 10.5% of the thermal energy input.[261] If we assume a similar additional utilisation potential in Germany, the usable waste heat potential for 2010 would amount to 2.5 TWh (9 PJ).

Increasing electric energy efficiency

Electric energy is mainly used for electric motors and pumps in all process stages. The largest proportion goes to grinding processes (e.g. raw material, cement). To make a cement plant energy-efficient in terms of electricity, using energy-saving and energy-efficient machinery is the way forward and may in some cases require investment-intensive changes in the production process. Improving individual components in the process chain, such as a single motor, is often less than effective. What is important is a holistic view of the processes involved so that they can be fine-tuned. For instance, replacing ball mills with vertical roller mills may save between 20% and 30% of electricity in raw material grinding.[262] Such changes in processing methods, however, should always be made with the properties and requirements of the mill feed material in mind.

There is also further scope for optimising power consumption in other areas, such as air compression and lighting.

Increased production of new types of low-CO_2-cement with a low clinker content

Producing types of cement with low clinker content is currently the most effective way of reducing energy demand and CO_2 emissions. This requires the development of new cements that contain several alternative components to replace clinker. The production volume of multi-component cements rose from 23.2% to 66.2% during the period between 1995 and 2010.[263] The trend is expected to continue in coming years, as considerable research is ongoing in the field. The major limiting factors for the development of new types of cement are compliance with technical standards and market acceptance.

In 2010, the clinker factor for Germany was 0.77. In other words, the production of one tonne of cement required on average 770 kg of cement clinker. The World Business Council for Sustainable Development (WBCSD) and the International Energy Agency estimate that in 2050, the global average clinker factor will be 0.71.[264] With reference to the current situation, this would mean that in Germany 60 kg of clinker per tonne of cement must be replaced by equivalent amounts of alternative admixtures. The strong position of German research in the field makes it likely that clinker factors will be considerably lower than those estimated by the WBCSD and will be around 0.6 by 2050. Assuming that this is achievable, this would be equivalent to a 22% reduction in clinker input compared to 2010, also assuming that production levels remain the same. Thermal and raw materials-related CO_2 emissions from calcination of limestone would be reduced at the same rate. Compared to the consumption and emission situation in 2010, this would mean a reduction in raw material-related emissions by 2.75 million tonnes of CO_2 and a fall in fuel-related emissions by 1.86 million tonnes of CO_2.

New production processes/development of new, cement-like binders low in CO_2

In recent years, the development of 'green' types of cements and novel cement-like building materials has been yielding promising results. The production of these materials requires less energy and is associated with lower CO_2 emissions and lower resource consumption. One example is Celitement®[265], which is expected to save at least 50% of energy and 50% CO_2 emissions compared to conventional cement clinker. This is just one of the many initiatives and developments on the 'green cement' front worldwide (e.g. Novacem®[266], Zeobond®[267]) — an area with strong innovative potential. We cannot yet predict which of these innovative approaches will make their way onto the market and will become market-relevant. However, it is very likely that these novel cement-like building materials will have a significant impact on the cement production of the future and spark off further product innovations in the sector. We can therefore assume that the 'green' cements of the future will become main contributors to GHG emission mitigation in the cement industry.

D.6.3 The German cement industry in 2050

D.6.3.1 Assumptions regarding the development of production volumes by 2050

A WWF study suggests that cement production in Germany could decrease slightly by 2050.[268] The following arguments support this view: from a resource perspective, the existing building stock must be used and fewer new buildings erected. At the same time, the need for road building will also decline after the catch-up effect of German reunification and European integration. Additionally, demand for raw materials for maintenance and repairs will also decline significantly, as more and more input material will come from recycling.

However, we can assume that cement will conquer new market segments and play a significant part in the further development of renewable energies, e.g. building foundations for wind turbines. We therefore assume for the purpose of this scenario of greenhouse gas-neutral cement production that production levels will remain the same as in 2010.

D.6.3.2 Possible structure of the German cement industry in 2050

Another technological revolution may lie ahead in the next decades. This would involve not so much adapting existing production processes as the development of new processes and novel (cement-like) binders.

Assuming that an almost greenhouse gas-neutral, highly energy-efficient cement industry is achievable only if the industry moves towards innovative production processes for cement-like materials, conventional dry and semi-dry processes in rotary kilns would become less important by 2050 as a consequence.

In the following discussion, we assume that in 2050, only 50% of the overall cement production is based on conventional production methods. The other 50% involves new production methods and novel binders (see Chapter D.6.3.3).

In traditional production, renewable methane could be used as energy vector, whereas new production processes and the production of new binders would be based exclusively on renewable power in 2050. Where raw materials need to be neutralised, this could happen in separate process steps.

The kilns will be operated with renewable methane. Energy efficiency could be further improved if pure oxygen was used in the combustion process and the arising CO_2 could be re-used (see Chapter B.3.3.6).

D.6.3.3 Energy demand and greenhouse gas emissions in the German cement industry in 2050

The International Energy Agency (IEA) estimates that efficiency improvements and substitution of compounds could reduce CO_2 emissions by approximately 15%[269] even without relying on Carbon Capture and Storage (CCS). This is a conservative estimate, based on production structures all over the world. Germany and other countries may well achieve better results.

Conventional production methods

Although the cement industry has been making efforts to improve energy efficiency, it has not yet harnessed its full potential. This is true for thermal efficiency where a lot of waste heat is still being lost. It is also true for electric power efficiency, which could be improved by the use of more energy-efficient machinery without compromising product quality, e.g. by modernising mills. In order to estimate greenhouse gas emissions from the cement industry, it is assumed that the specific thermal energy demand for the production of one tonne of cement clinker can be reduced by 10% by 2050 compared to 2010 and specific electric energy demand (e.g. by increasing the use of waste heat) can be lowered by 30%. We also estimate that the clinker factor can be reduced from 0.77 to 0.6.

New production processes/new, cement-like binders low in CO_2

Production methods for cement-like building materials that are currently discussed and developed, such as Celitement and Novacem, reduce energy consumption as well as CO_2 emissions to an extent that far exceeds the IEA's assumptions. If we add to that the expectation that the novel building materials can be mixed with other materials, the balance looks even better.

Although with these novel methods, raw material-related CO_2 emissions cannot be avoided altogether by 2050, they can be reduced to a minimum. We shall assume in our further discussion that with new production processes and new products, raw material-related CO_2 emissions can be reduced by 70% compared to conventional production methods. Specific electric and thermal energy demand per tonne of product can be halved compared to the status quo.

An estimate of energy demand and greenhouse gas emissions in the German cement industry in 2050

According to the assumptions made in Chapters D.6.3.1and D.6.3.2 energy demand and greenhouse gas emissions for the German cement industry can be estimated as shown in Table D-28.

Table D-28: Energy demand and greenhouse gas emissions from the German cement industry in the UBA THGND 2050 Scenario, own estimate

			2050			
			Total	Conventional production methods	New production methods/ novel binders	Relative change compared to 2010* in %, rounded
Cement production		million tonnes p.a.	30.6	15.3	15.3	0
Clinker factor**				0.6	0.6	- 22
Cement clinker production		million tonnes p.a.		9.18	9.18***	
Raw materials-related CO_2 emissions		million tonnes p.a.	6.33	4.87	1.46	-50
Total final energy consumption		TWh p.a.	15.35	9.75	5.6	-45
Electric energy	Electricity demand for process steps that also required electricity in 2010 (e.g. kiln motor, cement mill)	TWh p.a.	2.02	1.18	0.84	
	Additional electricity demand due to changes in the production method for novel binders	TWh p.a.	2.38		2.38	
	Total electricity demand	TWh p.a.	4.40	1.18	3.22	+ 31
Thermal energy	Demand for renewable methane	TWh p.a.	10.95	8.57	2.38	-55

* (Data for 2010 see Table A24)

** Here, the clinker factor is the ratio of cement clinker or novel binder and the finished cement product.

*** This is not cement clinker as we know it, we are referring to cement-like binders. Our esti mates suggest that 1 tonne of such novel binder replaces 1 tonne of cement clinker.

This would mean that compared to 2010, raw materials-related CO_2 emissions can be reduced by almost 50% to 6.3 million tonnes. Thermal energy demand can be reduced by 45%. Thus, assuming that total production will remain the same, average energy demand for the production of one tonne of product would be 436 $kWh/t_{product}$ (1569 MJ/t) in 2050.

D.6.4 Summary of the cement industry

Germany's cement industry has a high demand for energy vectors and, as such, is one of the energy-intensive industry sectors. Although there have been various approaches to improving the energy and resource efficiency of existing process routes, the cement industry can become (largely) GHG-neutral only if it adopts more efficient production methods and switches to renewable energy vectors.

The most promising option seems to be the adoption of new approaches to the production of cement-like building materials. The only energy vectors for the production of cement-like binders will be renewable methane and renewable electricity, while conventional cement production in rotary kilns using the dry method would become less important by 2050. However, even within existing production structures, changes such as switching to renewable energy vectors can make a major contribution to the transformation of the cement industry into a greenhouse gas-neutral industry.

It was assumed in this scenario that in 2050, only 50% of the overall cement production will be based on conventional production methods. It was further assumed that the volume of cement produced would remain more or less constant at 30 million tonnes per annum. The clinker share or share of a substitute produced with new methods in the finished cement product could be reduced to 60% by 2050. This would lead to a 22% reduction in cement clinker.

Based on these assumptions, the resulting long-term energy demand of the cement industry will be 11 TWh per annum of renewable methane and approximately 2.4 TWh of renewable power for thermal processes. Further renewable power requirements for additional process steps are estimated at 2 TWh p.a. Total electricity demand will rise by more than 30% compared with 2010, while the total energy demand can be reduced by 45% at the same time.

According to the assumptions made above, the only source of CO_2 emissions in 2050 will be the calcination of raw materials. Raw material-related CO_2 emissions can be reduced by almost 50% compared to 2010. Taking into account the above assumptions, we can conclude that CO_2 emissions directly or indirectly linked to the cement industry (including off-site electricity generation) will be reduced by almost 70%.

The above considerations did not factor in the possible availability of renewable waste for co-incineration in the cement industry in 2050. This might reduce demand for renewable methane.

Other climate-relevant gases, such as CH_4, will be equally reduced by the measures described wherever they arise.

D.7 Glass industry

D.7.1 The glass industry in Germany – its structure and economic importance

In 2010 some 53,000 employees in around 400 companies in Germany produced, processed or refined 7.3 million tonnes of various glass products. The total turnover for 2010 amounted to around 9.28 billion euros.[270]

Five sectors within the industry produce glass for a wide range of applications:

- The container glass sector produces all kinds of glass packaging for the food and beverage industry, the pharmaceutical industry and the cosmetics industry. This represents the largest sector and accounts for 52% of overall production.
- The flat glass sector produces, refines and finishes flat glass for construction, automotive and vehicle manufacturing and the furniture industry. In 2010 this sector accounted for 30% of total production.
- The special glass sector produces glass for a wide range of applications, e.g. for electrical and electronic devices, optical and precision engineering, medical, chemical and other scientific applications, as well as plant construction and communications technology.
- The domestic glass sector produces tableware and other glassware for end consumers and the catering industry.
- The mineral fibres sector produces insulating material for construction (glass and stone wool) as well as textile glass fibres for the textile industry.

D.7.2 Energy consumption and greenhouse gas emissions of the German glass industry in 2010

With its high demand for energy, the glass industry is one of the most energy-intensive industry sectors in Germany. Final energy consumption for the entire glass industry in 2010 amounted to approximately 25.47 TWh p.a. (Table D29). Of this, around 14 TWh p.a. or 55% came from fossil fuels such as heating oil (1.78 TWh p.a.), natural gas (12.22 TWh p.a.) and liquefied gas (0.028 TWh p.a.).[271] The remaining energy demand was covered by electric power (11.4 TWh p.a.).

Total energy-related CO_2 emissions in 2010 therefore amounted to 9.193 kilotonnes p.a. (fuel-related: 2.966 kt p.a.), with specific energy-related CO_2 emissions per tonne of glass produced totalling 1.251 kg (fuel-related: 405 kg/t).[272]

Table D-29: Production and final energy consumption of the German glass industry in 2010

	Production in million tonnes p.a.[CLXVII]	Total FEC in TWh p.a.[CLXVIII]	Electricity in TWh p.a.+	Primary fuels in TWh p.a.+	Including			
					Heavy fuel oil+	Light fuel oil+	Natural gas+	Liquefied gas+
Glass production 2010	7.33	25.47	11.40	14.10	1.67	0.10	12.22	0.028

In addition to energy-related CO_2 emissions, process-related CO_2 emissions are also produced from the decomposition of the carbonates in the batch. In 2010 process-related CO_2 emissions amounted to 761,563 t.[273] Total CO_2 emissions for 2010 were therefore 9,955,416 tonnes (see Table D-30).

CLXVII Data from BV Glas 2010 annual report.

CLXVIII Data from [271].

Table D-30: Glass production and associated total CO_2 emissions from glass manufacturing

	1990	1995	2000	2005	2010
Production in tonnes p.a.	6,561,849	7,621,300	7,505,000	6,948,400	7,326,700
CO_2 emissions in tonnes p.a.	10,553,880	10,304,719	11,064,366	10,043,073	9,955,416

Glass is usually melted in continuously operated gas or oil-fired furnaces. Small quantities of glass are produced in electric furnaces or discontinuously operated pot furnaces. During glass production, the greatest amount of energy is required for melting and processing the starting material. On average this accounts for 90% of the total energy consumption. A further 7% is required for auxiliary operations such as generating steam and compressed air, water treatment and cooling, plus 3% for ancillary operations (administration, maintenance, shipping, vehicle fleet, lighting, heating).[274]

The melting process itself is essentially divided into four phases: batch melting, dissolving the silica sand, fining and homogenisation.

The theoretical heat demand for the melting process is approximately 700 kWh/t_{glass}, of which 20% is required for the actual melting of the raw materials, 10% for driving off the gases, and 70% for reaching the working temperature of the molten glass.

Owing to the heat lost through the furnace walls, regenerators, waste gases and the necessary cooling, e.g. at the feeder, the actual heat demand is around 2 MWh/t_{glass}, i.e. more than double the amount theoretically required.

As a result of measures taken between 1940 and 2003, such as the improved sealing of furnaces, heat recovery from waste gases, and increasing cullet usage, it proved possible to reduce the specific energy demand in the container-glass industry by two thirds.[275]

D.7.3 Possible solutions for GHG mitigation in the glass industry

Key strategies for a future greenhouse gas mitigation policy in the glass industry include:

- Increasing cullet usage (especially in sectors other than container and flat glass)
- Enhancing energy efficiency
  - recovering heat from diffuse waste heat from downstream processes (e.g. annealing lehrs)
  - switching to electric furnaces.

D.7.3.1 Increasing cullet usage

Each 10% of cullet added to the batch reduces the energy required for melting by 2-3%. Process-related CO_2 emissions are then also reduced in direct proportion.

Currently around 60% of the batch raw materials are replaced by cullet in the container-glass industry. Owing to the high quality requirements, the proportion of cullet used in flat glass production is only approximately 30%. Up to 40% cullet or wool fibres can be used in mineral wool production. However, owing to product quality requirements or the lack of a collection infrastructure, there are some sectors in which no cullet has been used to date.

Efforts should be made to increase the amount of cullet used across the whole industry. However, where these go beyond technical optimisation of the melting processes and cullet preparation, it will entail discussions and change processes involving actors other than solely the glass manufacturers themselves. For instance, it will be necessary to discuss quality requirements with downstream processors, and discuss collection and recycling infrastructures with disposal companies.

The aim should be to increase the proportion of cullet used to an average of 60%, and consequently reduce the concomitant energy demand by around 15%.

D.7.3.2 Enhancing energy efficiency

Since they are less economic to run than gas or oil-fired furnaces, there are very few fully electric furnaces in use. In electric furnaces, the energy required is supplied via electrodes arranged in the glass bath. Gas burners are needed to start the furnaces in order to bring the batch up to the temperature required to ensure sufficient electric conductivity (approx. 1200°C). In contrast to fuel-fired furnaces, the furnace crown is cold because batch raw materials float on the glass bath and retain the rising heat.[276] As a result, significantly less diffuse waste heat is produced than with conventionally fired furnaces. Moreover, the heat loss from the waste gas is negligible, as the quantities of waste gas are very small and the waste gas temperature is low. The specific heat demand for a furnace with a capacity of 120 tonnes per day is less than 1 MWh/t_{glass}.[277]

Glass leaves the forming processes at temperatures of up to 600°C. The glass is cooled without stress on annealing lehrs, with a heat demand of 108 kWh/t_{glass} for container glass or 180 kWh/t_{glass} for flat glass.[278] The heat released during this process should be recovered and used, for example, to reach the initial annealing lehr temperatures.

D.7.4 The German glass industry in 2050

On the whole, production will remain constant up to 2050 as no new applications are anticipated in the glass industry. As a result of switching to fully electric furnaces, the average specific energy demand will be 0.8 MWh/t_{glass}, which will be reduced by an average level of cullet usage of 60% to 0.68 MWh/t_{glass} in terms of final energy. On average 150 kWh/t_{glass} will be required for annealing. This is released as heat which can be recovered. This will lead to an energy demand of approximately 1 TWh in 2050, which will be available for heat recovery from the annealing lehrs. Taken together with the production figures, the above specific energy consumption values result in a total final energy consumption for the German glass industry in 2050 of around 4.8 TWh p.a. in the form of renewable electricity (Table D-31). For the industry as a whole, therefore, final energy consumption will be reduced by 81% compared to 2010.

Table D-31: Production and final energy consumption of the German glass industry in 2010 and 2050

	Production in million tonnes p.a.	Total FEC in TWh p.a.	Including			Rel. change in final energy consumption 2050/2010 in %
			Renewable electricity in TWh p.a.	Renewable hydrogen in TWh p.a.	Renewable methane in TWh p.a.	
Glass production 2050	7.33	4.8	4.8	-	-	-81%

D.8 Lime industry

D.8.1 The German lime industry

D.8.1.1 The lime industry in Germany – its structure and economic importance

The lime industry produces burnt and unburnt lime products for numerous industrial applications. Unburnt lime products such as limestone aggregates or powders are primarily used in building and construction (roadbuilding), in the iron and steel industry, and in environmental protection applications. From the point of view of working towards achieving greenhouse gas-neutrality in the lime industry, the production of burnt lime products (quicklime products) is extremely important as this process is both responsible for the vast majority of climate-relevant gases and offers the greatest potential for reducing greenhouse gases. The main markets for quicklime products are industrial applications (e.g. in the iron and steel industry), the building materials industry and for environmental protection applications (flue-gas desulphurisation for instance); (see Figure D-5).

The main process steps for producing lime are extracting and preprocessing the raw materials, calcination (heating), and refining the burnt lime products (e.g. pulverising quicklime and producing slaked lime). In 2010 around 40 plants in Germany employing 4,000 people produced approximately 6.4 million tonnes of burnt lime products (quicklime, dolime, sintered dolomite), generating revenues of 650 million euros.[280]

Figure D-5: Uses of quicklime products[279], UBA graphic

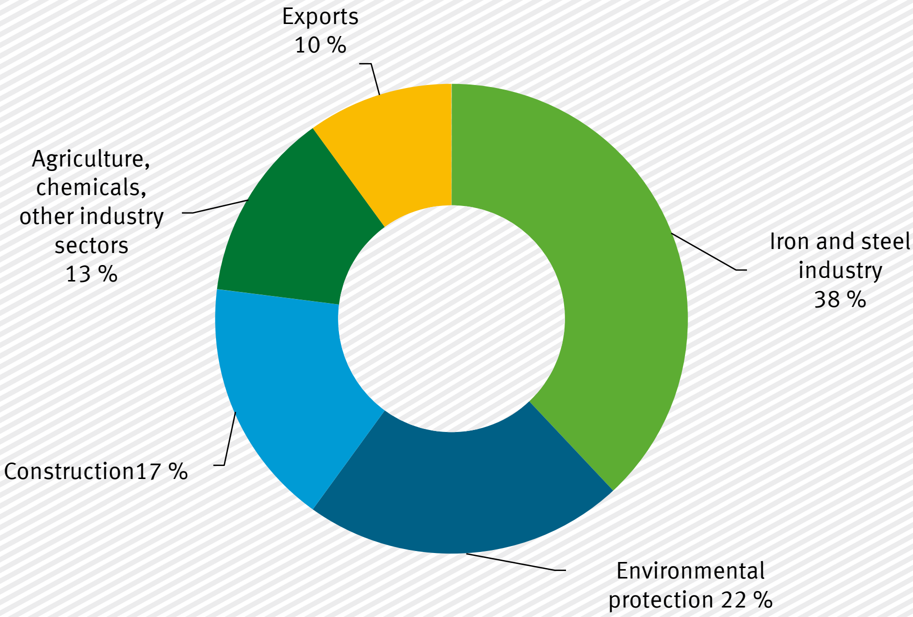


Table D-32: Lime production volumes in Germany from 1990 to 2010

		1990	2000	2005	2010
Lime production (excl. sintered dolomite)[281] [CLXIX]	[t]	7,130,000	6,800,000	6,570,000	6,320,000
Quicklime[CLXX]	[t]	6,773,500	6,460,000	6,241,500	6,004,000
Dolime[CLXXI]	[t]	356,500	340,000	328,500	316,000

D.8.1.2 Energy consumption and greenhouse gas emissions of the German lime industry in 2010

Energy consumption for lime production

Owing to its high specific energy consumption and the high total energy demand, the lime industry is one of the most energy-intensive sectors in Germany. In 2010 total energy consumption for the production of quicklime and dolime (excluding sintered dolomite) in Germany was approximately 8.25 TWh (29.7 PJ). Around 7.61 TWh (27.4 PJ), i.e. 93.3%, of this energy was derived from fossil fuels. The remaining energy was provided by electric power (0.64 TWh/2.3 PJ) — (see Table D-33).[282] This does not include energy input from secondary fuels. Based on experience, the proportion of the latter is estimated to be approximately 1% of total thermal energy consumption for 2010. Since this percentage is negligible for calculating the greenhouse gas emissions of the lime industry and its

CLXIX According to the German Lime Association (BV Kalk), the RWI Monitoring Report does not include the figures for sintered dolomite production.

CLXX It is assumed in the following discussion that on average dolime accounts for 5% of annual production and quicklime 95%. This may mean that the individual production volumes have been slightly over- or underestimated.

CLXXI It is assumed in the following discussion that on average dolime accounts for 5% of annual production and quicklime 95%. This may mean that the individual production volumes have been slightly over- or underestimated.

shift towards GHG-neutrality, the energy inputs from secondary fuels will be ignored in the rest of this chapter.

Quicklime products are produced in a variety of kiln types. Mixed-feed shaft kilns, annular shaft kilns and parallel-flow regenerative shaft kilns (PFR kilns) are the most common types of kiln used in Germany. In addition there are a further four rotary kilns producing quicklime in Germany which, owing to their relatively high production capacity in comparison with the other types of kiln, also make a significant contribution to total quicklime production.

During the production of quicklime and dolime, the greatest amount of energy is required for the calcination process itself. In 2010 the average fuel energy demand for producing one tonne of product (based on total quicklime and dolime production), excluding off-site electricity generation, amounted to 1.204 MWh/$t_{product}$ (4,335 MJ/$t_{product}$) — see Table D-34.

As a result of various measures, such as improved seals on kilns, avoiding false air intake and modernising kilns and other plant equipment, it proved possible to reduce the specific total energy demand for producing one tonne of product by over 10% between 1990 and 2010 — see Table D-34.

Table D-33: Energy input (excluding sintered dolomite) in Germany between 1990 and 2010[283]

		1990	2000	2005	2010
Fuel energy*	[PJ]	36.0	33.2	28.6	27.4
[TWh]		10.0	9.22	7.94	7.61
[%]		93.3	93.0	92.3	92.3
Off-site electricity generation	[PJ]	2.6	2.5	2.4	2.3
[TWh]		0.72	0.69	0.67	0.64
[%]		6.7	7.0	7.7	7.7
Total energy input[CLXXII]	[PJ]	38.6	35.7	31.0	29.7
[TWh]		10.72	9.92	8.61	8.25

CLXXII Excluding secondary fuels.

Table D-34: Specific energy inputs in the lime industry (excluding sintered dolomite), UBA's own calculations

Specific energy input[CLXXIII]		**1990**	**2000**	**2005**	**2010**
Total	$MJ/t_{product}$	5,414	5,250	4,718	4,699
	$kWh/t_{product}$	1,504	1,458	1,311	1,305
Fuels[CLXXIV]	$MJ/t_{produc}t$	5,049	4,882	4,353	4,335
	$kWh/t_{product}$	1,403	1,356	1,209	1,204
Electricity	$MJ/t_{product}$	365	368	365	364
	$kWh/t_{product}$	101.3	102.1	101.5	101.1

Greenhouse gas emissions

Both process and energy-related CO_2 emissions arise. Process-related CO_2 emissions are produced during the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$) or dolomite ($CaMg(CO_3)_2 \rightarrow CaO \cdot MgO + 2CO_2$). Energy-related CO_2 emissions arise both directly from fuel combustion (thermal emissions) and indirectly from generating the electrical energy required for lime production.

Assuming that the limestone or dolomite used is free of impurities and has been completely calcined, the process-related CO_2 emissions can be calculated using the stoichiometric factors of 0.785 t CO_2/$t_{quicklime}$ and 0.913 t CO_2/t_{dolime} respectively. It was assumed when calculating the CO_2 emissions in Table D35 that dolime accounted for 5% of total production. Thus, process-related CO_2 emissions for all German lime production (excluding sintered dolomite) in 2010 were approximately 5 million tonnes. Total fuel-related CO_2 emissions in 2010 amounted to approximately 2.34 million tonnes, with specific fuel-related CO_2 emissions per tonne of quicklime product averaging 371 kg.

In 2010 the CO_2 emissions generated by the production of quicklime products (excluding sintered dolomite) in Germany (excluding CO_2 emissions from off-site electricity generation) totalled approximately 7.34 million tonnes — see Table D-35.

Table D-35: CO_2 emissions from lime production in German (excluding sintered dolomite), UBA's own calculations

		1990	**2000**	**2005**	**2010**
Raw-material-related*					
Quicklime	t CO_2/$t_{quicklime}$	0.785	0.785	0.785	0.785
	t CO_2	5,317,198	5,071,100	4,899,578	4,713,140
Dolime	t CO_2/t_{dolime}	0.913	0.913	0.913	0.913
	t CO_2	325,485	310,420	299,921	288,508
Total	t CO_2	5,642,682	5,381,520	5,199,498	5,001,648

CLXXIII The specific energy input is calculated from the total energy input (see Table D-33) based on total quicklime and dolime production (see Table D-32).

CLXXIV Excluding secondary fuels.

	1990	2000	2005	2010
Fuel-related**				
t CO_2/PJ	84,342	80,219	83,247	85,546
t $CO_2/t_{product}$	0.426	0.392	0.362	0.371
t CO_2	3,036,311	2,663,255	2,380,869	2,343,950
Electricity-related***				
t CO_2/PJ	151,111	151,111	151,111	151,111
t CO_2	392,889	377,778	362,667	347,556
Total emissions				
t CO_2	9,071,882	8,422,553	7,943,034	7,693,154

Base data and assumptions for calculations:

* Raw-material-related CO_2 emissions
The raw-material-related CO_2 emissions were calculated to take account of the production volumes from Table D32 and the specified CO_2 emission factors.

** Fuel-related CO_2 emissions:

- Fuel inputs – source: RWI (2010)[284]: p. 162.
- Emission factors for fuels – source: Umweltbundesamt (2011)[285]: Table 281.
- Emission factor for other fuels = average of the emission factors for the other fuels
- Total emissions are the sum of the CO_2 emissions for the individual fuels.
- The product-specific emission factor t CO_2/tproduct is calculated from the fuel-related CO_2 emissions based on the total from quicklime and dolime production as stated in Table D32.

*** Electricity-related CO_2 emissions:

- Emission factor for electricity 544,000 t CO_2/TWh (reference year 2010) – source: Umweltbundesamt[286]

D.8.2 Possible solutions for GHG mitigation in source categories and sub-source categories

On average two-thirds of the CO_2 emissions are released as a result of calcination of the limestone during heating. These emissions are directly linked to production volumes as it is not possible to modify the limestone (apart from to a very small degree through fluctuations in impurities), and consequently a reduction of associated CO_2 emissions is not possible. Mitigation would therefore directly entail a decrease in production.

Specific thermal and electrical energy consumption can be cut by means of various efficiency measures. In recent years, in addition to modernising individual plants, the main focus has been on organisational measures (e.g. optimising kiln operations, workforce training) and introducing energy management systems.[287]

Key strategies for future increases in energy efficiency and the mitigation of greenhouse gases in the lime industry include:

- Waste heat utilisation in lime kilns
- The use of more energy-efficient machines and equipment (e.g. crushers, mills — and in particular also the use of energy-saving kilns in new plants).

In addition, energy-related emissions could be avoided by shifting to renewable energy vectors in the long term.

D.8.3 The German lime industry in 2050

Quicklime production in 2050 in particular will be greatly influenced by developments in other industries.

Especially significant is iron and steel production, which in 2010 was responsible for approximately 38% of the production of quicklime products (see Figure D-5). A virtually GHG-neutral iron and steel industry with high energy efficiency and low energy consumption is only possible following a sector-wide shift to electric steel production (see Section 2 Steel industry, Chapter D.2). This also has a direct impact on lime production in 2050.

In 2010 around a third of steel was produced in electric arc furnaces (EAF), while the other two-thirds were produced as oxygen steel from pig iron (see Section 2 Steel industry, Chapter D.2). Currently a total of approximately 6090 kg of quicklime per tonne of steel is used to produce one tonne of oxygen steel. 4050 kg per tonne of steel is required in EAF steelmaking.[288] Assuming that steel production will remain stable compared with 2010, 45,000,000 tonnes of steel will be produced using electric arc furnaces in 2050. This results in an average reduction in the amount of quicklime used of 900,000 tonnes per year, equivalent to around 15% of current quicklime production volumes.

A sharp decline in quicklime use in other sectors is also to be anticipated. As a result of the expansion of renewable energies and the closure of fossil fuel-fired power stations, less quicklime will be required for environmental protection applications in 2050. This would mean that 70% less quicklime will flow into the environmental protection sector. Based on figures for 2010, quicklime usage would fall by 980,000 tonnes in 2050. This is equivalent to approximately 16.3% of quicklime production in 2010. Taking into account the assumptions for quicklime consumption in the iron and steel industry and for environmental protection uses, but disregarding the fall in production in other sectors, production is projected to decline by around 31% to 4.12 million tonnes of quicklime in 2050. Raw-material-related and concomitant process-related CO_2 emissions for quicklime production would be reduced by the same amount and would be around 3.24 million tonnes in 2050.

Assuming that dolime production remains constant in comparison with 2010, raw-material-related CO_2 emissions would also be unchanged at 0.29 million tonnes (see Table D-35). Raw-material-related CO_2 emissions from the production of quicklime products (excluding sintered dolomite) would then amount to a total of 3.53 million tonnes in 2050. In comparison with 2010, this represents a reduction of 30%.

Taking account of the estimated production volumes and assuming that the specific fuel demand (see Table D-34) can be reduced by an average of 20% by 2050, the total energy demand of the German lime industry (excluding off-site electricity generation) would be 4.3 TWh (15.4 PJ). It is assumed that renewable methane would be a potential energy vector.

If one assumes that the specific demand for electricity generated off-site (see Table D-34) can be reduced by 10%, the German lime industry (excluding sintered dolomite) will buy in approximately 0.4 TWh of electricity in 2050. The total energy demand for producing quicklime products (excluding sintered dolomite) would then theoretically be around 4.7 TWh per annum.

Table D-36: Production and final energy consumption of the German lime industry (excluding sintered dolomite) in 2010 and in the UBA GHG-neutral Germany 2050 scenario

	Production in million tonnes p.a.	Total FEC in TWh p.a.	Electricity in TWh p.a.	Primary fuels in TWh p.a.	Raw-material-related CO_2 emissions in million tonnes
Total production 2010 (excl. sintered dolomite)	6.32	8.25	0.64	7.61	5.00
Quicklime	6.00				4.71
Dolime	0.32				0.29
Total production 2050 (excl. sintered dolomite)	4.44	4.7	0.4	4.3	3.53
Quicklime	4.12				3.24
Dolime	0.32				0.29

D.8.4 Summary

No fundamental changes to production processes in the lime industry are anticipated in the years to 2050. It is however highly probable that significant increases in the energy efficiency of the production process are achievable. Based on a projected decline in production of around 30%, and assuming that energy efficiency measures (e.g. when building new kilns) will enable the specific fuel energy demand to be cut by 20%, the total fuel energy demand of the German lime industry (excluding sintered dolomite) will be around 4.3 TWh p.a. in 2050. This represents a reduction of over 40% compared with 2010. On the basis of the above assumptions, significant reductions in the amount of electricity bought in can also be achieved. There are also further process-related CO_2 emissions of 3.5 million tonnes p.a.

D.9 Pulp and paper industry

D.9.1 Outline of the pulp and paper industry

D.9.1.1 Structure and economic significance of the pulp and paper industry

- Some 3000 different types of paper are produced in Germany. There are four main categories:
- Graphic papers
- Paper and board for packaging
- Sanitary & household papers
- Paper and board for special technical applications.

Worldwide around 394 million tonnes (2010) of paper and board are produced annually. In Germany, total production of paper and board in 2011 was 22.7 million tonnes.[289] This represented a fall of 1.6% compared with the previous year. Of this total, packaging papers accounted for 45%, graphic papers 43%, speciality papers 7% and sanitary & household papers 6%.

In 2011 the German pulp and paper industry generated sales of 14.4 billion euros. The industry comprises around 160 plants employing 41,100 people. The German paper industry is therefore Europe's largest paper producer, ahead of Finland and Sweden. Worldwide it ranks fourth after China, USA and Japan. Table D-37 lists some key data for the industry from 1990 to 2011, including production volumes, sales, number of plants and size of the workforce. Since 2005, production volumes have fluctuated around the 22 million tonne mark, depending on the economic situation. It is anticipated that overall production volumes in the paper industry will fall slightly in future. This decline is due to the increasing digitalisation of former print media such as daily newspapers for example.

Table D-37: Overview of key data for the pulp and paper industry[289]

	1990	1995	2000	2005	2009	2010	2011
Sales [€ bn]	n.a.	10.5	12.8	13	12.3	14.3	15.5
Production volume in 1000 t	12,773	14,827	18,182	21,679	20,870	23,062	22,690
Plants	291	193	184	191	169	167	167
Employees	82,600	47,500	45,800	45,900	42,000	41,500	41,100

Trends in the industry vary widely across the different paper categories. With a 45% share, packaging papers represent the largest segment and have been experiencing an upturn for a number of years, while production of graphic papers — 42.5% — has been waning since 2005. The upturn in packaging papers (+0.1% in 2011) has so far somewhat compensated for the downturn in graphic papers (-4% in 2011). Owing to the marked decline in printing papers and the low growth in packaging papers, this effect will no longer be enough across a transitional period over the coming years. The sharp decline is expected to tail off after a number of years, with production volumes settling at a lower level. The figures for the volumes produced between 1990 and 2010, where available, have been shown separately for the individual product groups in the table below.

Table D-38: Production volumes for product groups in 1000 tonnes from 1990 to 2010[290]

	1990	1995	2000	2005	2010
Graphic papers	6,065	7,454	9,134	10,545	10,038
Paper and board for packaging	4,835	5,480	6,733	8,498	10,203
Sanitary & house-hold papers	873	877	1,017	1,188	1,343
Paper and board for special purposes	4,835	5,480	6,733	8,498	10,203
Sulphate pulp prod.	0	0	0	796	924
Sulphite pulp prod.[6]	1,105	718	621	613	590
Mechanical pulp prod.	1,616	1,266	1,342	1,468	1,239

D.9.1.2 Production processes

In addition to minerals and additives, the **raw materials** for papermaking in Germany are 16 million tonnes of recycled fibres (recovered paper) and 5.9 million tonnes of virgin fibres (chemical and mechanical pulp).

In 2011 around 10,659,000 cubic meters of timber (excluding bark) were consumed in the industry. 432,000 tonnes of bark were also used for the on-site generation of energy.

Almost half of wood is made up of cellulose fibres. Other constituents are lignin and hemicellulose, which act like a cement between the cellulose fibres. There are various methods of pulping wood and using the cellulose fibres to make paper.

Pulp production, i.e. separating the individual fibres out of the wood, is the most energy-intensive step in papermaking and requires approximately 5 MWh per tonne of pulp. To produce the pulp, wood chips are cooked together with solvents such as caustic soda and sodium sulphide for several hours at temperatures of up to 190°C. This allows the lignin and hemicellulose to be removed and to be used as a fuel for the cooking process. The energy captured in this way is enough to meet the entire energy demand for pulp production.

At some 3.9 million tonnes, the most important virgin fibre for paper is sulphate pulp. 0.7 million tonnes of sulphite pulp is also used. The predominantly used sulphate process (kraft process) uses different chemicals for cooking the pulp than the sulphite process. The pulps produced have different characteristics and are used for different grades of paper.

The third virgin fibre is **mechanical pulp**, which accounts for 1.3 million tonnes or 22% of the virgin fibres used in Germany. This pulp is obtained by adding water, in some cases at high pressure, to break down the wood. In contrast to the sulphate process, lignin and hemicellulose are not removed. Although this gives a yield of virtually 100%, the quality of wood-containing papers (papers made of mechanical pulp) is lower. Mechanical pulp is therefore primarily used for products with a short life such as advertising leaflets and magazine papers for instance. Producing mechanical pulp is very energy-intensive. The pulp is processed directly afterwards to make paper. The energy used to produce one tonne of wood-containing magazine paper can be up to 3 MWh of electric power per tonne and an additional 0.8 MWh of heat per tonne.

Overall, virgin fibres account for only 27% of the fibres used. With a total of 16 million tonnes, the larger share of 73% is recycled fibres (recovered paper).

During paper recycling, the waste paper is dissolved in water, non-paper materials such as staples are removed, the paper is de-inked and is then dried again. Consuming around 2 MWh per tonne, producing recycled paper uses much less energy than paper made using virgin fibres.

Paper fibres can be recycled about six or seven times. As the quality of the fibres diminishes each time they are recycled, a continuous supply of around 20% of virgin fibres is necessary to sustain the paper cycle. It is therefore not possible to increase the proportion of recycled paper used in the German paper industry ad infinitum, but a further rise of around 10% may be feasible.

A variety of products can be produced from the raw materials described, and these differ with respect to the production processes used and their impact on the environment:

- Sulphate pulp, e.g. as a reinforcement fibre (high strength) for papers with high strength requirements
- Sulphite pulp, e.g. for papers with low strength requirements and sanitary & household papers
- Coated/uncoated mechanical papers, e.g. advertising leaflets, inexpensive magazine paper
- Coated/uncoated woodfree papers, e.g. virgin fibre graphic papers made from chemical pulp
- De-inked papers from recovered paper, e.g. recycled paper, newsprint
- Non-de-inked papers from recovered paper, e.g. board, wrapping papers

The actual process of making paper from the raw materials described is as follows: first the fibres are broken down and sorted with screens. Auxiliary chemicals and fillers are then added. Following this, on the paper machine the fibres are passed over cylinders heated using steam, as a result of which the fibres are indirectly first pressed and then dried. Depending on the paper product concerned, the paper may then pass through a coating machine. Production takes place either in integrated paper mills, i.e. where both the fibres and the paper are produced in the same plant (e.g. mechanical pulp plants and most recovered paper processing plants) or in non-integrated plants where the fibres and the paper are produced in separate mills (e.g. the German sulphate pulp mills). While the fibrous material is processed into paper in a liquid state in integrated plants, in non-integrated mills the material must first be dried before being transported to the paper mill. Additional heat is required for this.

D.9.1.3 Trends in greenhouse gas emissions and energy consumption in the pulp and paper industry up to 2011

In 2010 the final energy consumption of the pulp and paper industry was 72.4 TWh. This represents 10.3% of the total energy consumption for industry as a whole (702.38 TWh in 2010). This sector is therefore one of the five most energy-intensive industry sectors.

The 72.4 TWh consumed by the paper industry breaks down into 60.70 TWh for fuels and heat purchased from third parties, and 11.72 TWh for electricity. See Table D-39 for a more detailed list.

Table D-40 shows the trends in final energy consumption and greenhouse gas emissions for the pulp and paper industry from 1990 to 2010. It can be seen that final energy consumption rose by approximately 28.8 TWh (66%), while production rose by 80% from 12.8 million tonnes to 23.1 million tonnes during the same period. The specific energy input per tonne of paper[CLXXV] therefore fell from 3.4 MWh to 3.1 MWh.

The pulp and paper industry generates no, or only negligible, process-related GHG emissions.[146] The emissions that can be attributed to the pulp and paper industry originate from the provision of energy in the form of electricity and heat. The energy consumption data for producing pulp, paper and printed products is presented in detail in the NIR only for substitute fuels under 1A2d, and these are used to a large extent. The great majority of the substitute fuels used in the sector consist of wood fibres from chemical or mechanical pulp, and thus of biomass.

Emissions from the use of regular fuels in process combustion and emissions from on-site electricity generation are not shown separately in the NIR, but are summarised under 1.A.2.f Other. This is in line with the categories in the energy balance. On the other hand, each year the German Pulp and Paper Association (VDP) publishes statistics gathered from its members which also contain detailed energy consumption data. The figures set out below refer to the data from this association.

Table D-39: Current final energy consumption (FEC) in the pulp and paper industry[289] by energy carrier and energy demand

	Total	Fuels/ heat from third parties	Coal	Lignite	Petroleum	Gas	Renewables[CLXXVI]	Other	Electricity
FEC for 2010 in TWh	72.419	63.37	5.344	1.287	0.380	33.23	13.779	6.675	11.721
GHG emissions for 2010 in t CO_2	18,717,883	10,936,054	1,795,447	459,603	105,443	6,679,610	0	1,895,951	7,781,829

Table D-40: Final energy consumption (FEC) and GHG emissions for the pulp and paper industry 1990-2010[289]

	1990	1995	2000	2005	2010
FEC in TWh	43.594	48.395	49.564	66.12	72.419
GHG emissions[CLXXVII] in t CO_2	At least 12,198,215	14,159,785	15,181,970	18,687,300	18,717,883

CLXXV The specific energy input is calculated from the final energy consumption for the entire pulp and paper industry divided by the volume of paper produced in Germany. Chemical pulp is not stated separately as this is a raw material for paper manufacture which flows directly into papermaking. The energy consumption for the various product groups and raw materials varies widely. See also Chapter A.1.1.2.

CLXXVI Renewables here refer to: renewable fuels originating primarily from industry-specific processes, e.g. black liquor, bark, fibre sludge, biogas from anaerobic wastewater treatment, other residuals. b The following industry-specific conversion factors from the performance report of the German Pulp and Paper Association were used to calculate CO_2 volumes (MWh ⇢ t CO_2): coal 0.336; lignite 0.357; fuel oil 0.277; gas 0.201; heat from third parties 0.284; "fossil" electricity 0.670.

CLXXVII The following industry-specific conversion factors from the performance report of the German Pulp and Paper Association were used to calculate CO_2 volumes (MWh ⇢ t CO_2): coal 0.336; lignite 0.357; fuel oil 0.277; gas 0.201; heat from third parties 0.284; "fossil" electricity 0.670.

D.9.2 Possible solutions for GHG mitigation in the pulp and paper industry

Since no process-related GHG emissions are produced in the pulp and paper industry, mitigation measures for this are neither necessary nor possible. It is possible to reduce energy-related GHG emissions through a range of measures aimed at lowering consumption of live steam and electrical energy and by increasing the on-site generation of steam and electricity:

Increase energy efficiency with the following technologies:[292,293]

- Use energy-saving refiners (machines in which wood chips are broken down into fibres for pulp making)
- Dimension all machines optimally
- Control sealing water volumes with flow control regulators
- Use energy-saving drive systems in the paper machine (e.g. for driving the rollers transporting the paper web)
- Control compressed air use
- Increase production or use less steam by increasing the web temperature and improving dewatering in the press section
- Multiple heat recovery.
- Pulp mills can meet their requirements for heat and electrical energy to a large extent by utilising (waste) biomass[CLXXVIII] in the form of black liquor from the pulping process, bark and wood waste, as well as fibre sludge. In integrated mills, however, there is a need for additional steam and additional electrical energy, generated either on-site or off-site.
- Increase the proportion of recovered paper in the pulp by a further 10% to 83%.

Very little solid fuel is used in the sector. Most of the energy is provided in the form of gas and electricity (see Table D-39) so this will allow the sector to switch over entirely to renewable energy vectors such as methane and renewable hydrogen or renewably generated electricity. Furthermore, at almost 20%, the amount of renewable fuels used, such as black liquor, bark, fibre sludge or biogas, is already very high. In the long term, further significant increases in this percentage are expected.

D.9.3 The pulp and paper industry in 2050

Table D-41 shows the forecast energy demand for the pulp and paper industry in 2050. A factor of 2 was selected for the increase in energy efficiency, that is to say energy demand will be halved. The annual growth rate is assumed to be 0%. It is also assumed that in the long term, once the current trends have levelled out, growth in the packaging, hygiene and speciality paper grades will in future offset falling production volumes for graphic papers, resulting in at least zero growth for the sector. Within Germany, the level of demand is expected to remain stable, or possibly decline slightly due to the falling population. These figures are based on data from the VDP performance report. It is further assumed that, owing to the diminishing fibre quality, only a small increase in the proportion of recovered paper will be possible. As a consequence, and also due to a slight increase in efficiency, the demand for 10,659,000 cubic metres of wood and 432,000 tonnes of bark could fall slightly. For the most part the demand for wood can be met by roundwood and small-diameter wood in accordance with the potential set out in 0.[CLXXIX]

CLXXVIII This (waste) biomass is obtained from the non-cellulose constituents of the wood raw material or from low-grade fibres discarded during waste paper treatment. These materials will still be available to the pulp and paper industry in 2050 for sourcing fibres.

CLXXIX Given an average calorific value of 15.5 MJ/kg for air-dried wood, this results in an annual demand of around 172 PJ.

D.9.4 Summary of the pulp and paper industry

In the long term the pulp and paper industry will emit almost no GHG emissions at all. Already today no relevant process-related emissions are released. Over the long term a complete shift to renewable fuels and electricity is possible, so no energy-related GHG emissions will be produced either.

If the assumptions with respect to increasing energy efficiency by a factor of two, an annual growth rate of 0% and a slight increase in the amount of recovered paper to 83% prove correct, the pulp and paper industry will require approximately 37.6 TWh energy in 2050.

Table D-41: Forecast final energy consumption in the pulp and paper industry in the UBA GHG-neutral Germany 2050 scenario by energy carrier and energy demand[CLXXX]

Year	Total FEC in TWh	Fuels	Ren. met-hane	Waste biomass[CLXXXI]	Ren. electri-city
2050	37.6	31.7	16.6	15.1	5.9

D.10 Food industry

D.10.1 Outline of the food industry

In this section the term 'food industry' is used to cover the production of both food and beverages. Tobacco processing is sometimes also included in this sector, but owing to the lack of available information about the technology/production processes used, energy demand and GHG emissions, it is not considered here.

The food industry processes a substantial proportion of agricultural produce. The products are sold on the domestic market or are exported. In 2010 the sector generated revenues of 164.9 billion euros. Of this, around 17% or 28.78 billion euros were earned abroad. 551,280 people were employed in some 5882 companies in the industry[294], mainly in small and medium-sized enterprises. The three subsectors with the highest turnover in 2011 were meat and meat products (23.02% of total turnover of 163.3 billion euros), milk and dairy products (15.91% of total turnover), and bakery products (9.03% of total turnover). Growth in the industry is due to a rise in exports, while the market within Germany is expected to remain stable over the long term.[295] Table D42 lists some key data for the industry between 1995 and 2010 such as sales, number of companies and size of the workforce.

Table D-42: Overview of key data for the food industry, source: Federal Statistical Office 2011[296]; Federal Statistical Office 2012[297]

	1995	2000	2005	2010
Sales [€ bn]	128	137	153	164.9
Companies	5,126	6,167	5,956	5,882
Employees	539,154	566,386	532,945	551,280

CLXXX The calculations are based on data from association members and assume an increase in efficiency by a factor of 2, annual average growth of 0%, and a slight increase in usage of recovered paper.

CLXXXI Waste biomass here refers to: renewable fuels originating primarily from industry-specific processes, e.g. black liquor, bark, fibre slurry, biogas from anaerobic wastewater treatment, other residuals.

Trends in production volumes for the individual subsectors between 1990 and 2010 vary. Particularly notable is that production volumes of bakery products more than doubled between 1990 and 2010, meat processing increased by a third between 2000 and 2010, while trends in starch production and milk processing fluctuated somewhat. Production volume trends for meat and meat products as well as milk and dairy products are primarily dependent on the level of exports. These two subsectors account for the biggest share of the totals for 2011.[298]

Table D-43: Production volumes for selected subsectors from 1990 to 2010[CLXXXII]

	1990	1995	2000	2005	2010
Meat processing [1000 t][299]			6553.7	7216.5	8726.3
Milk deliveries to dairies [1000 t][300]	28,722	26,966	27,211	27,663	29,076
Production of starch [Mt][301,302]				1.51	1.41
Prod. of bakery products [t][303]	2,498,981	3,131,453	4,163,933	4,972,587	5,356,104
Prod. of sugar[304] (processed beet) [305] [Mt]	3.45 (30.5)	4.40 (26.1)	4.53 (27.9)	4.24 (25.3)	3.50 (24.8)
Prod. of beer [1000 hl][306]	104,284	116,900	110,429	107,678	95,683

D.10.2 Production processes in the food industry

Some examples of production processes in various sectors are described analogously to Chapter 2 of the 'Reference Document on Best Available Techniques in the Food, Drink and Milk Industries'.[307]

D.10.2.1 Meat processing

Meat processing encompasses the slaughtering of animals and the production of further products from the meat, such as bacon, ham and sausages as well as other prepared and ready-to-eat products. Large amounts of energy are required to refrigerate the meat, process the meat (for example chop it to make sausage meat), and for the heating processes during further processing.

D.10.2.2 Milk processing

In addition to various forms of milk for drinking, milk is also used as a raw material for the production of butter, yoghurt, desserts, milk powder and other dairy products.

CLXXXII Volumes produced between 1990 and 2010 stated separately by subsector where available; subsector categories as used in Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008) (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008), Climate Change 07/2012, Dessau-Roßlau, data from the stated sources.

In most cases the raw milk is separated into cream with a high fat content and skimmed low-fat milk. Depending on the end product, these streams are then subsequently mixed again in different proportions. During homogenisation, the fat globules in the milk are broken down into small particles of a uniform size. To destroy bacteria and inactivate enzymes, the milk is either pasteurised or subjected to ultra-heat treatment.

The energy-intensive parts of these processes are the heating of milk to extend its shelf life followed by subsequent cooling, and producing milk powder, by spray drying for example.

D.10.2.3 Production of starch

Starch is manufactured from potatoes, wheat or maize. Depending on which raw material is used, a slightly different process is used to obtain the starch. However, the fundamental process steps are milling the raw material, extracting the starch using water, and finally washing and drying the starch. The process of evaporation/condensation of the water in order to dry the starch requires a lot of heat, while the grinding mills, transport operations and separation processes (using centrifuges for example) require electrical energy.

D.10.2.4 Production of bakery products

The production of bakery products can be divided into the phases of dough preparation (kneading) and subsequent baking. These require energy in the form of heat. Some products are then deep-frozen, which also requires a great deal of energy. In some cases air-conditioned rooms with defined air humidities and temperatures are used during dough preparation. Energy is also required for this, primarily in the form of electricity.

D.10.2.5 Production of sugar

In Germany sugar is produced from sugar beet in 20 sugar factories. This is done by extracting the sugar stored in the beet from the rest of the plant. This process can be divided into the following six phases:

1. Washing the supplied beets
2. Slicing the beets into thin chips called cossettes
3. Extracting the sugar content from the cossettes with hot water
4. Removing the non-sugar solids (carbonatation)
5. Evaporation of the water and crystallisation of the sugar
6. Separating and drying the sugar crystals.

In particular, the evaporation of water to increase the sugar content and initiation of crystallisation are very energy-intensive processes. A large amount of energy in the form of fuel is required by the process for burning the limestone to produce milk of lime and CO_2, which are used to remove the non-sugar components. Although not directly used to produce sugar, another process with a high energy demand which is frequently performed at the same time is drying the extracted pulp. This is then used as animal feed. The sugar industry thus has a high demand for energy in the form of heat. This is usually provided by steam. For the most part, electricity generated by a cogeneration process is used in the factory itself, with any surplus being fed into the grid.

D.10.2.6 Production of beer

Beer production can be generally broken down into the following process steps:
1. Milling the malted grain supplied
2. Mashing the milled malt
3. Lautering (separating the liquid wort from the residual grain)
4. Boiling the wort extracted during lautering
5. Clarifying the wort
6. Cooling the wort
7. Fermenting and conditioning
8. Filtration
9. Filling

Processes in the brewhouse (mashing to produce the wort then heating and cooling the wort), plus the bottling and cooling systems are the areas that consume the most energy.

D.10.3 Trends in greenhouse gas emissions and energy consumption in the food industry up to 2008

In 2008 the final energy consumption of the food industry was 55.80 TWh. This represents 8% of the total energy consumption for industry as a whole (702.38 TWh).

Table D-44: Final energy consumption and GHG emissions for the food industry 1990–2010

	1990	1995	2000	2005	2010
Final energy consumption [TWh][308]	63.16	52.07	51.51	56.69	(2008: 55.80)[309]
GHG emissions [t CO_{2eq}][310]	2,018,600				462,800
Process-related[CLXXXIII]	NMVOC				NMVOC

Table D-44 shows the trends in final energy consumption and greenhouse gas emissions for the food industry from 1990 to 2010 (or final energy consumption for 2008). Process-related cooling and heat demand account for a large proportion of the energy consumption in the food industry.[311,312,313] It can be seen that final energy consumption fell by approximately 7 TWh (11.7%) between 1990 and 2008. There are however clear fluctuations between the years. This is due in part to fluctuations in production. The food industry generates no, or only negligible, process-related GHG emissions (see National Inventory Report for the German Greenhouse Gas Inventory 1990-2010 (NIR)[314]). The emissions that can be attributed to the food industry originate from the provision of energy in the form of electricity and heat. These are reported in the NIR in CRF sector 1 (Energy). Only the data for sugar production are reported separately. The other subsectors are grouped together with other industries in the NIR under '1.A.2.f Other'. Table D-44 shows the available sugar production data. However, only some of the total emissions are reported here.[CLXXXIV]

CLXXXIII No concrete data are available since the NMVOC emissions are listed in the NIR, but no emission factors have been specified for them.

CLXXXIV The RWI Monitoring Report (2011), which is based on data supplied by the German Sugar Industry Association (VdZ), reports significantly higher values. The variances are primarily attributable to the different categorisation of energy consumption data used in the NIR methodology.

The 55.80 TWh of energy consumed by the food industry breaks down into 37.94 TWh for fuels and district heating, and 17.86 TWh for electricity.[315] Table D-45 shows the energy consumption data by energy carriers for the various subsectors of the food industry.

Table D-45: Energy consumption in 2008 in the food industry with subsectors, broken down by energy carriers; based on Umweltbundesamt (2012)[316]

Final energy consumption in TWh										Elec-tricity
Total		Fuels/ district hea-ting	Of which:							
			Coal	Lignite	Petro-leum	Gas	Rene-wable-s[CLXXXV]	Other	District hea-ting	
Food industry	**55.8**	37.94	0.97	1.21	5.76	26.91	0.75	0.4	1.94	17.86
Of which:										
Meat processing	**4.29**	2.45	0	0	0.43	1.82	0.11	0.01	0.09	1.84
Milk processing	**7.48**	5.3	0	0	0.4	4.19	0.01	0.22	0.48	2.18
Production of starch	**2.32**	1.62	0	0	0	1.47	0	0	0.16	0.7
Prod. of bakery products	**5.07**	3.18	0	0	0.8	2.35	0	0	0.03	1.89
Prod. of sugar	**4.83**	4.09	0.69	1.16	1.83	0.37	0.02	0	0.03	0.74
Prod. of beer	**3.7**	2.61	0.05	0.05	0.38	2.06	0.03	0	0.06	1.08
Rest (not reported in sectors)	**28.11**	18.68	0.24	0	1.94	14.66	0.59	0.17	1.09	9.43

Calculating the energy-related greenhouse gas emissions based on the final energy consumption data in Table D-45 and the emission factors stated in the NIR gives the values shown in Table D-46. As expected, the total of 7.8 million tonnes is significantly higher than the emissions reported in the NIR solely for sugar production.

CLXXXV Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau, does not provide any information about the sources of renewable energy so it is unclear whether the energy vector is biomass, biogas or renewable electricity.

Table D-46: Fuel-related CO_2 emissions in the food industry, calculated from Umweltbundesamt (2012)[163] with emission factors from NIR, reference year 2008[CLXXXVI]

Fuel-related CO_2 emissions in tonnes p.a.	Of which:			
	Coal (coke)	Lignite	Petroleum	Gas (natural gas)
7,797,229	367,906	469,197	1,534,895	5,425,231

D.10.4 Possible solutions for GHG mitigation in the food industry

Since no process-related GHG emissions are produced in the food industry, mitigation measures are not possible.

It is possible to reduce greenhouse gases indirectly emitted by the food industry as a result of its energy consumption by means of various energy-saving measures and increased efficiency, as well as through the substitution of fossil fuels.

The greatest potential for savings is in the area of energy for cooling and heating. As yet untapped savings potential can be utilised by, for instance, improving the efficiency of refrigeration units and heat recovery. Such measures have already been taken in some cases. In the sugar industry for example, the specific energy consumption[CLXXXVII] was reduced by approximately 40%[317] between 1990 and 2010. This reduction was achieved in part by the closure of old production facilities and subsequent building of new modern plants, for instance in the new federal states after 1990. In addition the industry invested more heavily in energy-efficient technologies. Energy savings were achieved for example by improving evaporators and setting up a pulp press. Further reductions in CO_2 emissions were achieved by converting fuels to lower-carbon natural gas.[318] However, physical limits mean that further reductions on this scale are unlikely in future in this industry.
Another example in the beer production subsector is described in the Handelsblatt supplement entitled ‘Topic – Energieeffizienz’ (energy efficiency) dated 18.09.2012.[319] The Weihenstephan Bavarian State Brewery invested in improving the energy efficiency of its production. By replacing an old boiler that ran on heavy oil with a modern one powered by natural gas, it succeeded in reducing emissions of nitrogen oxide, sulphur oxide and dust. In addition it installed a flue gas heat exchanger to preheat the feed water. Further improvements in energy efficiency were achieved by utilising the waste heat from the refrigeration system and optimising the combustion installation controls.
In other subsectors, however, potential efficiencies have not yet been implemented, or only partially implemented.

Very little solid fuel is used in the food industry (see Table D-45), most of the energy is provided in the form of gas and electricity. Since electricity generated from renewable sources constitutes the more favourable form of energy in the long term and, with few exceptions, gaseous or liquid forms of fuel are not essential for the production processes in the food industry, it would be possible for the industry to switch over almost entirely to renewable electricity. One exception is the burning of limestone in the sugar industry as this will probably still require the use of a gaseous fuel in future.

CLXXXVI Emission factors: Coal (coke) 105 t CO_2/TJ (377,997 t CO_2/TWh), lignite: 108 t CO_2/TJ (388,797 t CO_2/TWh), petroleum: 74 t CO_2/TJ (266,398 t CO_2/TWh), gas (natural gas): 56 t CO_2/TJ (201,598 t CO_2/TWh); from NIR Table 281 (reference year 2009)

CLXXXVII KWh per decitonne of beet.

D.10.5 The food industry in 2050

Table D-47 shows the energy demand for the food industry for the various scenarios. These scenarios differ with respect to conversion from gaseous, solid and liquid fuels to renewable electricity. A factor of 2 was assumed for the increase in energy efficiency, that is to say energy demand will be halved. The annual growth rate is assumed to be 0.7%. Within Germany, the level of demand is expected to remain stable, or possibly decline slightly due to the falling population (see Chapter D.10.1). This may be offset by, among other things, a higher volume of processed foods, such as the production of convenience products for the food service market and ready meals for the retail market. This may lead to increased sales for the companies and possibly higher energy consumption, but exactly how much is difficult to quantify.

Growth in production volumes will therefore depend mainly on whether there is higher demand from abroad. However, this is difficult to estimate as, among other things, it also depends on political circumstances and on unforeseeable events (such as other countries imposing import bans following animal epidemics for example).

Table D-47: Energy demand in the UBA GHG-neutral Germany 2050 scenario given an efficiency factor of 2[CLXXXVIII,CLXXXIX]

Final energy consumption in TWh	Total FEC	Scenario 1		Scenario 2
		Gas (CH_4)	Electricity	Electricity
Food industry	37.4	24.9	12.5	37.4
Of which:				
Meat processing	2.9	1.6	1.3	2.9
Milk processing	5.0	3.5	1.5	5.0
Production of starch	1.6	1.1	0.5	1.6
Prod. of bakery products	3.4	2.1	1.3	3.4
Prod. of sugar	3.2	2.7	0.5	3.2
Prod. of beer	2.5	1.8	0.7	2.5
Rest (not reported in sectors)	18.84	12.1	6.7	18.8

D.10.6 Summary of the food industry

In the long term the food industry will emit almost no greenhouse gas emissions at all. Already today no process-related emissions are released. In future the fuels required to provide energy will be replaced by renewable energy vectors so the resulting greenhouse gas emissions will consequently be offset. With very few exceptions, it is expected that a complete switchover to electricity in production will be possible.

Assuming energy efficiency is increased by a factor of 2 and the annual growth rate is 0.7%, the food industry will require approximately 37.4 TWh energy in 2050.

CLXXXVIII 0.7% growth per year, fossil energy carriers distributed over renewable sources.

CLXXXIX These figures are based on data from Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau.

D.11 Textile industry

D.11.1 Industry overview

The textile and clothing industry is one of the most important consumer goods industries in Germany. In 2011 the textile industry alone (excluding the clothing industry) employed around 64,400 people in 727 mainly small and medium-sized enterprises. Total turnover for the textile industry in 2011 was approximately 11,651 million euros.[320] The textile industry has been undergoing structural change for over 30 years and has seen an enormous decline in production. Between 1991 and 2010 (price-adjusted) production fell by a total of almost 50%.[321] Around 50% of the textiles manufactured in Germany are technical textiles. These are textiles destined for use, for example, in the automotive industry, in construction and landscaping, in medical applications and in environmental protection.

The textile industry encompasses the manufacture of yarns and plied yarns from various types of fibre, the manufacture of textile fabrics, and textile finishing processes, during which the fabrics are, for example, dyed, printed and endowed with special properties.

Yarns are manufactured by spinning raw fibres. The raw fibres used in the textile industry comprise plant fibres such as cotton, animal fibres such as wool, and synthetic fibres such as polyester. Between 1990 and 2011 the proportion of synthetic fibres in global fibre production increased from 47% to 65%. Globally, around 0.8% of petroleum extracted is used in the production of synthetic fibres.[322] The manufacturing of synthetic fibres is categorised as part of the chemical industry, while the primary production of natural fibres is assigned to the agricultural sector.

To manufacture fabrics from yarn, the textile industry uses processes such as weaving, knitting and warp knitting. Non-woven fabrics are made of fibres bonded together through their intrinsic adhesion and by the interlocking of the fibres.

Various process steps involving the use of water, chemicals and energy are used for textile finishing. These primarily encompass pretreatment (scouring, bleaching, washing, mercerising), dyeing, printing and finishing (including lamination and coating).

At 1013% of production costs, energy consumption accounts for a relatively large proportion of the costs of textile finishing.[323] Energy-intensive processes and systems in textile finishing operations include washing, dyeing and bleaching processes, during which it may be necessary to heat water to temperatures of up to 95°C, as well as stentering processes for drying and fixation.

D.11.1 Trends in greenhouse gas emissions and energy consumption in the textile industry up to 2010

The textile industry does not rank among the industrial sectors with a high energy consumption. In 2009, the textile industry accounted for barely 1% of the total energy input for the manufacturing industry. Between 1990 and 2010 energy consumption fell by 66.3% from 24.87 TWh to 8.39 TWh.

Energy-related CO_2 emissions dropped by 71.9% to 3,434 kt p.a. from 1990 to 2010. There are no process-related greenhouse gas emissions.[CXC]

The main reason for the big reduction in energy consumption and CO_2 emissions is the continuing decline in textile production in Germany. Overall, between 1990 and 2010 the consumption of primary fuels decreased from 12.31 to 3.47 TWh and net purchased electricity fell from 12.56 to 4.92 TWh (see Table D-48).

In the textile industry energy is primarily used for supplying low-temperature heat to heat process water, for use in steam-heated machines, and for operating gas-heated stenters. Process heat is required in virtually all areas of textile processing. The main focus for energy efficiency measures is therefore on heat recovery from process wastewater or from stenter exhaust air.

As a result of energy-saving measures, specific energy consumption fell by 28.8% between 1990 and 2010:[324]

Table D-48: Greenhouse gas emissions and energy consumption (by energy carrier) in the textile industry 1990-2010.[CXCI325]

	1990			2010		
	FEC in TWh p.a.	E-factor in t CO_{2eq}/TWh	CO_{2eq} in tonnes p.a.	FEC in TWh p.a.	E-factor in t CO_{2eq} TWh	CO_{2eq} in tonnes p.a.
Primary fuels	**12.31**		**2,893,740**	**3.47**		**757,360**
Hard coal	0.00			0.22	339,120	75,360
Hard-coal briquettes	0.94	334,800	316,200	0.00		
Hard-coal coke	0.03	378,000	10,500	0.00		
Raw lignite	0.08	391,680	32,640	0.00		
Lignite briquettes	0.22	356,400	79,200	0.00		
Heavy fuel oil	2.22	280,800	624,000	0.11	280,800	31,200
Light fuel oil	1.33	266,400	355,200	0.28	266,400	74,000
Natural gas	6.94	201,600	1,400,000	2.86	201,600	576,800
Coke-oven gas	0.53	144,000	76,000	0.00		
Net purchased electricity	**12.56**	743,750	**9,341,500**	**4.92**	544,144	**2,677,188**
Total	**24.87**		**12,235,240**	**8.39**		**3,434,548**

CXC Calculated on the basis of the fuel-related emission factors and the emission factors for the German electricity mix, source: German National Inventory Report 2012, Table 310 (www.uba.de/uba-info-medien/4292.html) and Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011 (Development of specific carbon dioxide emissions in the German electricity mix in 1990-2010 and first estimates for 2011) (www.umweltbundesamt.de/energie/archiv/co2-strommix.pdf).

CXCI Emission factors from the German National Inventory Report 2012, Table 310.

D.11.3 Possible solutions for GHG mitigation in the textile industry

Currently energy demand in the textile industry is met primarily by natural gas and electricity. If a switch were made to renewable energy vectors such as methane or electricity from renewable sources, it would be possible for the textile industry to be GHG-neutral.

- Among other things, the following energy consumption measures are necessary to increase efficiency by a factor of 2:
- Total heat utilisation concepts with heat recovery from the process wastewater and from stenter exhaust air
- Insulation of pipes, stenters, machines
- Measures to reduce the quantity of system liquor
- Use of low-energy textile finishing methods (e.g. atmospheric pressure plasma treatment of textiles)
- Further energy-saving measures on stenters (regulating exhaust air humidity and residual humidity, frequency-controlled ventilators, temperature-controlled processes)
- Use of energy-saving motors
- Replacement of compressed air and steam generators.

It is anticipated that in Germany the proportion of technical textiles in overall production will continue to increase, and that production volumes are likely to be smaller in future. Since this will result in an above-average energy demand, other measures — as yet unknown in the industry — may be required to increase energy efficiency by a factor of 2.

D.11.4 The textile industry in 2050

The potential long-term energy demand for the textile industry is set out in Table D49. It is assumed that hard coal, natural gas and petroleum will be replaced completely by methane gas or hydrogen. Electricity will be generated from renewable energy sources. A factor of 2 was selected for the increase in energy efficiency, that is to say energy demand will be halved. An average annual growth rate of 0% is assumed, as the following assumptions have been made:

- The decline in production can be halted as a result of growth in the production of technical textiles
- The demand for clothing as well as home and furnishing fabrics will decrease due to the falling population
- Germany will continue to import clothing, home and furnishing fabrics, e.g. from Asia.

The figures are based on data from the RWI 2010 Monitoring Report.[326]

D.11.5 Summary of the textile industry

In the long term GHG emissions from the textile industry can be avoided altogether. Current emissions are due to the use of fossil fuels. In future these will be replaced by renewably generated energy sources.

Assuming energy efficiency is increased by a factor of 2 and the annual growth rate is 0%, the textile industry will require approximately 4.3 TWh energy in 2050.

Table D-49: Energy demand in the UBA GHG-neutral Germany 2050 scenario given an efficiency factor of 2 and 0% growth per annum in relation to 2010 baseline data

	Total energy consumption in TWh	Relative change from 2010	Renewable methane in TWh	Electricity from renewable sources in TWh
2050	4.3	-50%	1.8	2.5

D.12 Emissions of fluorinated greenhouse gases

Fluorinated greenhouse gases (F-gases) include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Although F-gas emissions currently account for just under 2%[327] of overall greenhouse gas emissions, this substance group is particularly important because most F-gases are deliberately produced for use in applications, and in ever increasing quantities.

Fluorinated gases have a long atmospheric lifetime and are a major contributor to the greenhouse effect. Global warming potential (GWP) is the index used to measure the greenhouse effect. This index indicates the effectiveness of the respective gases in comparison with carbon dioxide (CO_2) as reference substance (GWP = 1), usually over a period of 100 years (GWP_{100}). The GWP_{100} values of the most important fluorinated greenhouse gases range between 140 and 23,900. At 23,900, SF_6 has the highest GWP of all the greenhouse gases. With the exception of HFC-152a (GWP_{100} = 140), all other F-gases have high GWP values over 150.

D.12.1 Application areas with F-gas emissions

The areas of application for fluorinated greenhouse gases are many and various. A basic distinction may be made between their use in largely enclosed cycles (e.g. as refrigerants), in open applications (e.g. as propellants), and as a process gas (e.g. in semiconductor manufacture). The type of application determines the amount and timing of the emissions. In the case of open applications, all the gases used are released during the application, whereas with mainly enclosed applications some of the gases contained in the systems and products are emitted over their entire lifetime. Emissions are additionally generated during the production and disposal of systems and products.[328]

The main application areas for HFCs are:

- Stationary and mobile refrigeration and air conditioning systems (as a refrigerant)
- Insulating materials/foams (as a blowing agent)
- Aerosols (as a propellant)
- In addition, HFC emissions arise as an unwanted by-product during the production of hydrochlorofluorocarbons (HCFCs) and when used as fire extinguishing agents, solvents, and as an etching gas in semiconductor manufacture.

PFCs are used selectively in:

- Semiconductor manufacture (as an etching gas)
- Circuit board production (as an etching gas)
- Refrigeration technology (as a refrigerant).

PFC emissions also arise during production processes in the aluminium industry. In this case PFCs are not produced deliberately, but are released as a side effect of the electrolytic reduction of aluminium oxide to aluminium.

The many applications of SF_6 include its use in:

- Electrical equipment (as an insulating gas and quenching gas)
- Magnesium foundries (as a cover gas)
- Aluminium foundries (as a cleaning gas)
- Semiconductor manufacture (as an etching gas)
- Production of photovoltaic cells (as an etching gas)
- Production of optical glass fibres (as a process gas for fluorine doping)
- High-voltage electronic devices (e.g. X-ray equipment).

SF_6 was and also continues to be used as an insulating gas in car tyres, soundproof windows and soles for sports shoes, as well as in airborne radar systems, as a cover gas during welding, and as a tracer and leak detection gas.

D.12.2 Emission trends 1990-2010

Overall, emissions of F-gases have increased by 22% since 1990 (see Table D-50). However, the individual trends for HFCs, PFCs and SF_6 were very different: HFC emissions in Germany have increased sharply since 1990, while emissions of PFCs have fallen steadily since then. SF_6 emissions reached an all-time high in the mid-nineties, but have remained at approximately the same level since 2002.[329]

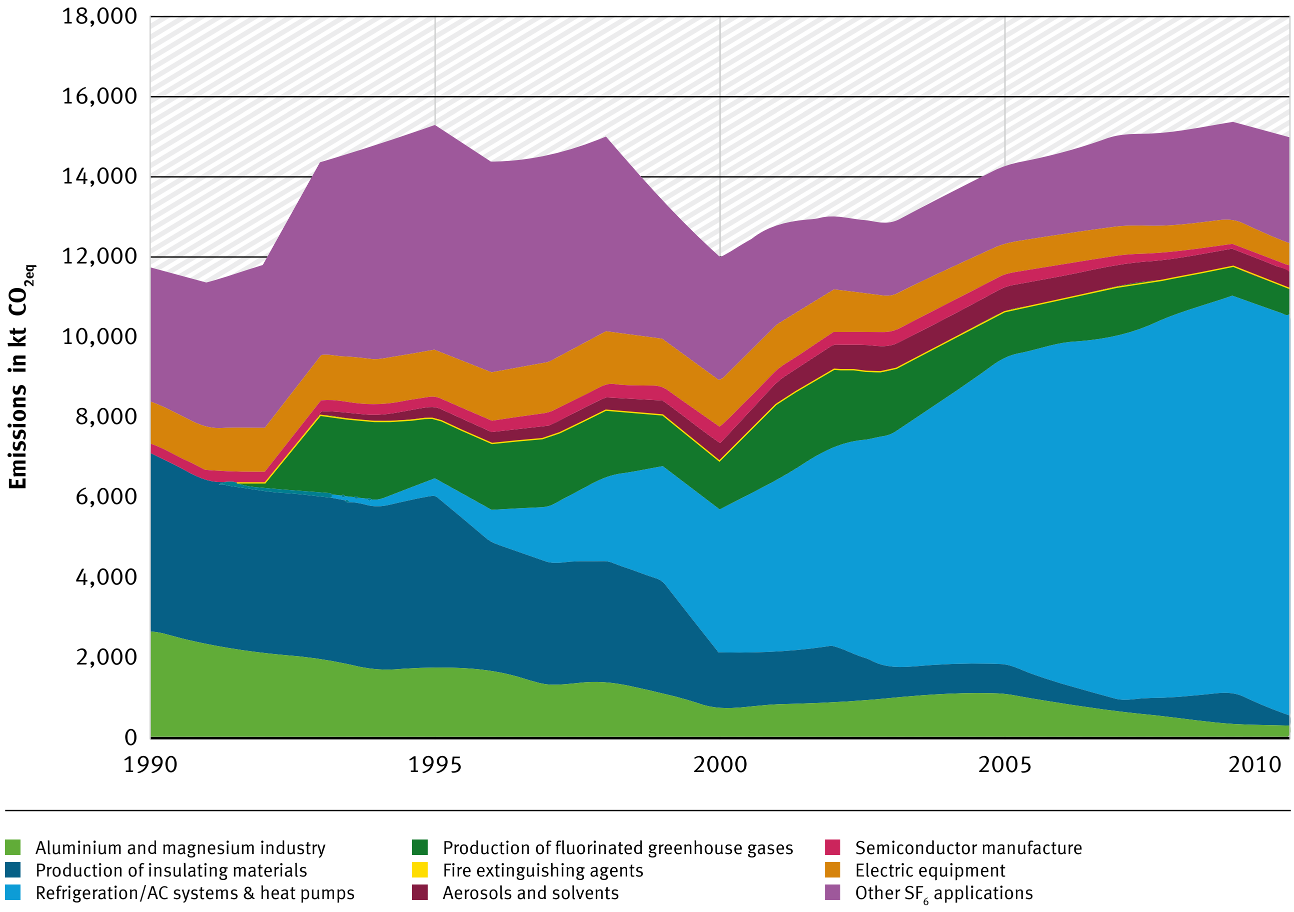
Table D-50: Trends in F-gas emissions in kt CO_{2eq} from 1990 to 2010 for selected applications[330]

Application	1990	1995	2000	2005	2010
Aluminium and magnesium industry	2,678	1,749	686	1,067	262
Production of fluorinated greenhouse gases	4,529	4,386	1,422	755	256
Refrigeration & air conditioning systems and heat pumps	-	407	3,643	7,799	10,139
Production of insulating materials	-	1,534	1,206	1,163	670
Fire extinguishing agents	-	-	2	7	24
Aerosols and solvents	-	304	487	618	458
Semiconductor manufacture	266	276	419	339	148
Electrical equipment	1,034	1,148	1,158	762	543
Other SF_6 applications	3,354	5,659	3,067	1,924	2,655
Total	**11,861**	**15,464**	**12,091**	**14,436**	**15,155**

In 1990 the main emission sources were the production of fluorinated greenhouse gases, and especially the production of HCFCs, as well as the many applications of SF_6, the most potent greenhouse gas. SF_6 emissions arose primarily from its use in electrical equipment, in metal production, especially in the aluminium industry, as well as in car tyres and soundproof windows (Other SF_6 applications in Table D-50).

In 2010, 67% of Germany's total F-gas emissions were attributable to HFC emissions from refrigeration and air conditioning systems and heat pumps. At 17.5%, other SF_6 applications accounted for the second largest share of F-gas emissions, primarily the disposal of soundproof windows containing SF_6 (see Table D-50).

Figure D-6: F-gas emissions from 1990 to 2010[331]



The emission reduction measures taken in recent years in individual applications were rapidly offset by rising emissions in other areas (see Figure D-6). Emissions of HFCs rose above all as a result of their increased use as refrigerants and higher disposal rates for refrigeration and air conditioning systems containing F-gases. This more than offset the emission reductions gained from less use in polyurethane one-component foams and the decline in HFC emissions as an unwanted by-product during the production of HCFCs.

Reductions in the emissions of PFCs were achieved mainly as a result of the efforts of the producers of primary aluminium and semiconductors.

The decline in SF_6 emissions up to 2002 is primarily attributable to decreased use in car tyres. A successful environmental awareness campaign resulted in lowering emissions by almost 3,000 kilotonnes of CO2eq here. The same also applies to soundproof windows, for which the use of SF_6 during production was likewise reduced to virtually zero following a successful campaign and an EU-wide ban imposed from July 2008. Current and future emissions arise primarily from the open disposal of old windows. Emissions for electrical equipment have also fallen significantly since 1990. However, over the same period SF_6 was increasingly used in new applications, as a cover gas for welding and in the production of photovoltaic cells and optical glass fibres.

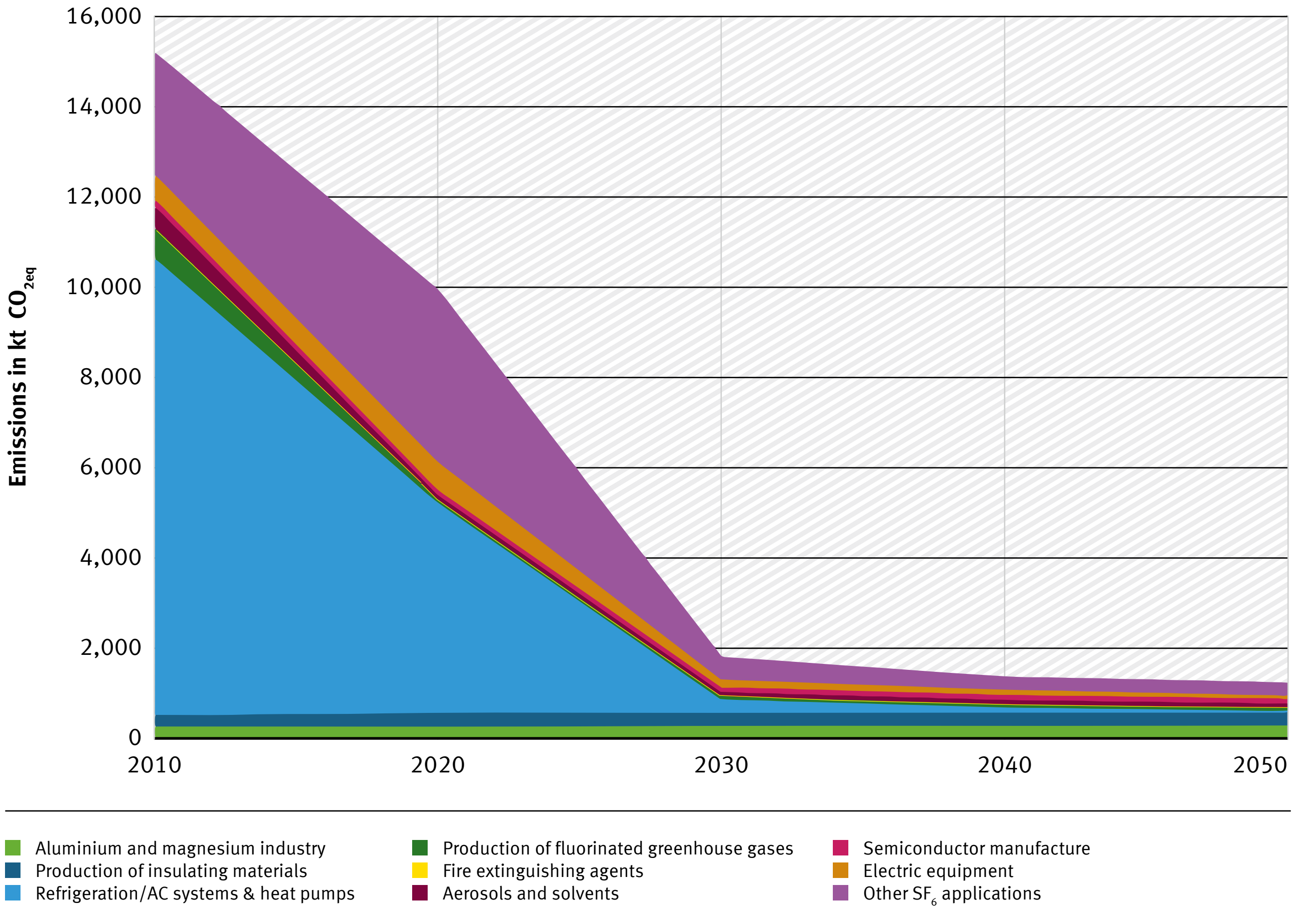
D.12.3 Potential emission reductions by 2050

It is possible to use substitutes for F-gases in virtually all application areas. The most important substitutes are: carbon dioxide, hydrocarbons, ammonia, dimethyl ether and nitrogen. All these substances are relevant to refrigeration and air conditioning systems, and some are relevant to the foam and aerosol industries, as well as to fire extinguishing agents and solvents. Air and 'vacuum' are also important 'substitutes'.[332] All the above-mentioned substitutes have a low global warming potential (GWP_{100} < 20) or none at all.

The use of substitutes usually requires changes to processes, or possibly even the development of new equipment and processes. These new developments often go hand in hand with technical advances that also enable energy savings or improved performance of the equipment or the process.

In comparison with 2010, emissions of fluorinated greenhouse gases can be reduced by 92% by 2050 (see Figure D-7).

Figure D-7[CXCII] Projected figures for fluorinated greenhouse gas emissions up to 2050 assuming a 'with additional measures' scenario[333]



To achieve significant substitutions of F-gases by 2050, a large number of measures are required which are already technically possible, and some of which have already been put into practice. These measures go beyond the current legislation and also the new provisions[189] of the amended European F-Gas Regulation.[CXCIII] The most important are:

- Using only natural refrigerants in all stationary refrigeration and air conditioning systems and heat pumps by 2050
- Substituting HFCs with refrigerants having a GWP_{100} of less than 150 in all mobile air conditioning systems
- Dispensing almost entirely with the use of F-gases in the manufacture of insulating materials and one-component foams
- Dispensing with the use of HFCs in new fire protection systems
- Doubling the market share of dry-powder inhalers and similar HFC-free systems in medicinal metered dose inhalers by 2020
- Substituting SF_6 in electrical equipment with an alternative insulating medium from 2020

CXCII The data on which the projections were based have since been adjusted downwards and the total is now around 12,000 kt $CO_{2eq.}$

CXCIII Proposal for a Regulation (EU) of the European Parliament and of the Council on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006 (www.europarl.europa.eu/meetdocs/2009_2014/documents/envi/dv/envi20140130_f-gases_agreed_v2_/envi20140130_f-gases_agreed_v2_en.pdf).

- Completely replacing fluorinated greenhouse gases with elementary fluorine for chamber cleaning in photovoltaic cell production by 2020.

The measures set out above result in the projected F-gas emission figures up to 2050[335] as shown in Table D-51.

Table D-51: Projected F-gas emissions in kt CO_{2eq} from 2010 to 2050 for selected applications[336]

Application	2010	2020	2030	2040	2050
Aluminium and magnesium industry	262	273	277	279	283
Production of fluorinated greenhouse gases	256	300	300	300	300
Refrigeration & air conditioning systems and heat pumps	10,139	4,659	293	114	28
Production of insulating materials	670	69	69	69	69
Fire extinguishing agents	24	10	-	-	-
Aerosols and solvents	458	96	98	101	100
Semiconductor manufacture	148	109	109	109	109
Electrical equipment	543	614	166	115	65
Other SF_6 applications	2,655	3,771	464	250	250
Total	**15,155**[CXCIV]	**9,901**	**1,176**	**1,331**	**1,204**

D.12.4 F-gas emissions in 2050

The current measures required by legislation are not enough to achieve a significant reduction in F-gas emissions.[337] After the proposed amendment to the European F-Gas Regulation comes into force on 1 January 2015, many of the potential emission reductions will already have been achieved by 2030 as a result of the planned bans, and in particular as a result of the quota system for placing HFCs on the market. Assuming the further measures described above are implemented, it is possible to achieve a reduction in emissions to a minimum of 1,204 kilotonnes CO_{2eq} by 2050. The following 'residual emissions' would remain:

- SF_6 emissions from magnesium foundries, old electrical equipment, particle accelerators and the production of optical glass fibres
- PFC emissions from aluminium production and semiconductor manufacture
- HFC emissions from stocks (e.g. insulating materials) and medicinal metered dose aerosols (asthma sprays for children and the elderly).

At this point in time, these emissions are unavoidable.

CXCIV The data on which the projections were based have since been adjusted downwards and the total is now around 12,000 kt CO2eq.

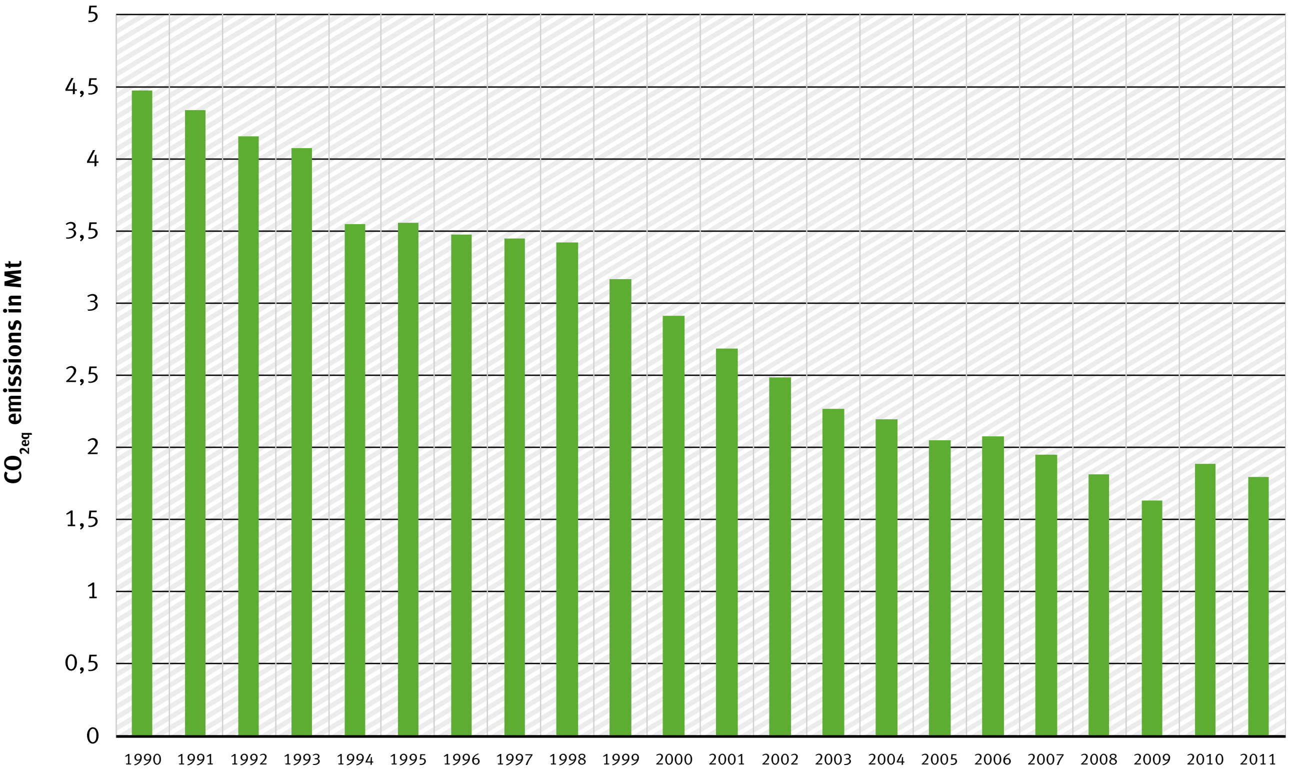
D.12.4.1 Summary of fluorinated greenhouse gas emissions

With the technology already available today it is possible to substitute F-gases in many applications, but this is not yet happening to a sufficient extent, above all due to the inadequacy of current legislation. This applies in particular to the use of natural refrigerants in refrigeration and air conditioning systems, the use of alternative blowing agents in the production of insulating materials, or the substitution of SF_6 with an alternative insulating medium in electrical equipment. If all the measures that are already technically possible were implemented by 2050, F-gas emissions could be reduced by 92% to a minimum of 1,204 kilotonnes of CO_{2eq} in 2050.

D.13 Emissions from solvents and other product uses

The 'Emissions from solvents and other product uses' category (CRF 3) is an umbrella category for emissions from the use of chemical products in industry, trade and private households. It is divided into four subcategories 'Paint application' (CRF 3.A), 'Degreasing and dry cleaning' (CRF 3.B), 'Chemical products, manufacture and processing' (CRF 3.C) and 'Other' (CRF 3.D). Source category 3.D includes nitrous oxide emissions as well as all other emissions from solvent use not included in source categories 3.A to 3.C.

Figure D-8: Greenhouse gas emissions from solvent and other product uses — 1990 to 2011, UBA's own representation[338] and calculations[CXCV]



CXCV For 2011.

D.13.1 Solvent use in Germany (CRF 3.A-D)

D.13.1.1 Source category description

In the family of volatile organic compounds, only methane is a greenhouse gas within the meaning of the Kyoto Protocol. Emissions from all other organic compounds excluding methane, collectively referred to as 'non-methane volatile organic compounds' or NMVOCs for short, are not direct greenhouse gases. As a result of photochemical processes in the atmosphere, however, they can contribute to the formation of the secondary greenhouse gas ozone, or to the formation of GHG-relevant aerosols. The emissions of non-methane volatile organic compounds are consequently referred to as 'indirect' greenhouse gases, and the source category should more properly be called 'Indirect CO_2 from NMVOC emissions from *solvent and other product use*'.

The source category *Other* encompasses the following applications and activities:

- Glass wool and mineral wool enduction
- Printing industry (printing applications)
- Extraction of oils and fats
- Application of glues and adhesives
- Preservation of wood
- Underseal treatment and conservation of vehicles
- Domestic solvent use (other than paint application)
- Vehicle dewaxing
- Manufacturing of pharmaceutical products
- Domestic use of pharmaceutical products
- Other

The definition of 'NMVOC' is in line with the definition of VOC in the EC Solvent Emissions Directive.[CXCVI] The term 'solvent use' is also as defined in the EC Solvent Emissions Directive.[CXCVII]

It should be noted that some of these non-methane volatile organic compounds are used both as solvents and as chemical reactants. Toluene, for instance, is used as a solvent in coatings and adhesives and as a reactant in the production of toluene diisocyanate (TDI). Another example is methyl ethyl ketone (butanone) which is used as a solvent in printing inks and as a starting material for synthesising methyl ethyl ketone peroxide. NMVOCs (or more accurately substances or fractions of substances or products) used as chemical reactants are accordingly not included in this source category.

Delimiting the source category as outlined above results in the inclusion of a wide variety of processes that produce emissions. This applies to:

- the concentrations and volatility of the VOCs used
  (the range covered includes the use of individual volatile substances as solvents, for example in cleaning processes, the use of products with solvent mixtures, in paints and varnishes for example, as well as in applications in which only small parts of a mixture (also) have solvent properties,

CXCVI Volatile organic compounds (VOCs) are defined as any organic compound having at 293.15 K a vapour pressure of 0.01 kPa or more, or having a corresponding volatility under the particular conditions of use.

CXCVII An organic solvent is defined as any VOC which is used alone or in combination with other agents, and without undergoing a chemical change, to dissolve raw materials, products or waste materials, or is used as a cleaning agent to dissolve contaminants, or as a dissolver, a dispersion medium, a viscosity adjuster, a surface tension adjuster, a plasticiser, or a preservative.

as is the case in polystyrene foam production for example), and
- the widely differing emission conditions.

Solvent uses may be open to the environment, as is the case when cosmetics are used, or they may be largely closed to the environment, as in the extraction of essential oils or cleaning in chemical dry-cleaning systems.

D.13.1.2 Methodology used to calculate the emissions inventory

NMVOC emissions are calculated on the basis of product consumption. In this approach, the inputs of volatile organic compounds, from solvents or solvent-based products, allocated to these source categories are determined and the NMVOC emissions are then calculated from these inputs using specific emission factors for each source category. This methodology requires reliable information — differentiated by individual source categories — on the following input variables:

- The quantities of VOC-containing precursors, products and agents used in the reporting year
- The VOC concentrations in these products (substances and mixtures)
- The relevant application and emission conditions (or the resulting specific emission factor).

As a result of the wide variations in how solvents and solvent-based products are used in industry, trade or private households, the structure of the source category is extremely heterogeneous. To take account of this, inputs are determined at the level of 37 differentiated source processes (analogous to CORINAIR SNAP Level 3), and the NMVOC emissions calculated are then aggregated. The product/substance quantities used are determined at the product group level with the aid of production and foreign-trade statistics. Where possible, these domestic consumption figures are then further verified by cross-checking against industry statistics. The values used to calculate the average VOC concentrations of the input substances and the emission factors are based on experts' estimates (from expert reports and dialogues within the industry) for the individual source categories or source category sectors.

Since conformity with EU emissions reporting is the principal methodological premise for converting NMVOC emissions into indirect CO_2 emissions, for the present report we have used the reference approach proposed in Chapter 7 Precursors and Indirect Emissions of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories:

Equation D-2: $EM_{indirect\ CO2} = EM_{NMVOC} * \text{molar mass } CO_2 / \text{molar mass C} * 60\%$

This calculation method gives a conversion factor of 2.20; 1 tonne of NMVOC emissions is thus equivalent to 2.20 t CO_{2eq}.

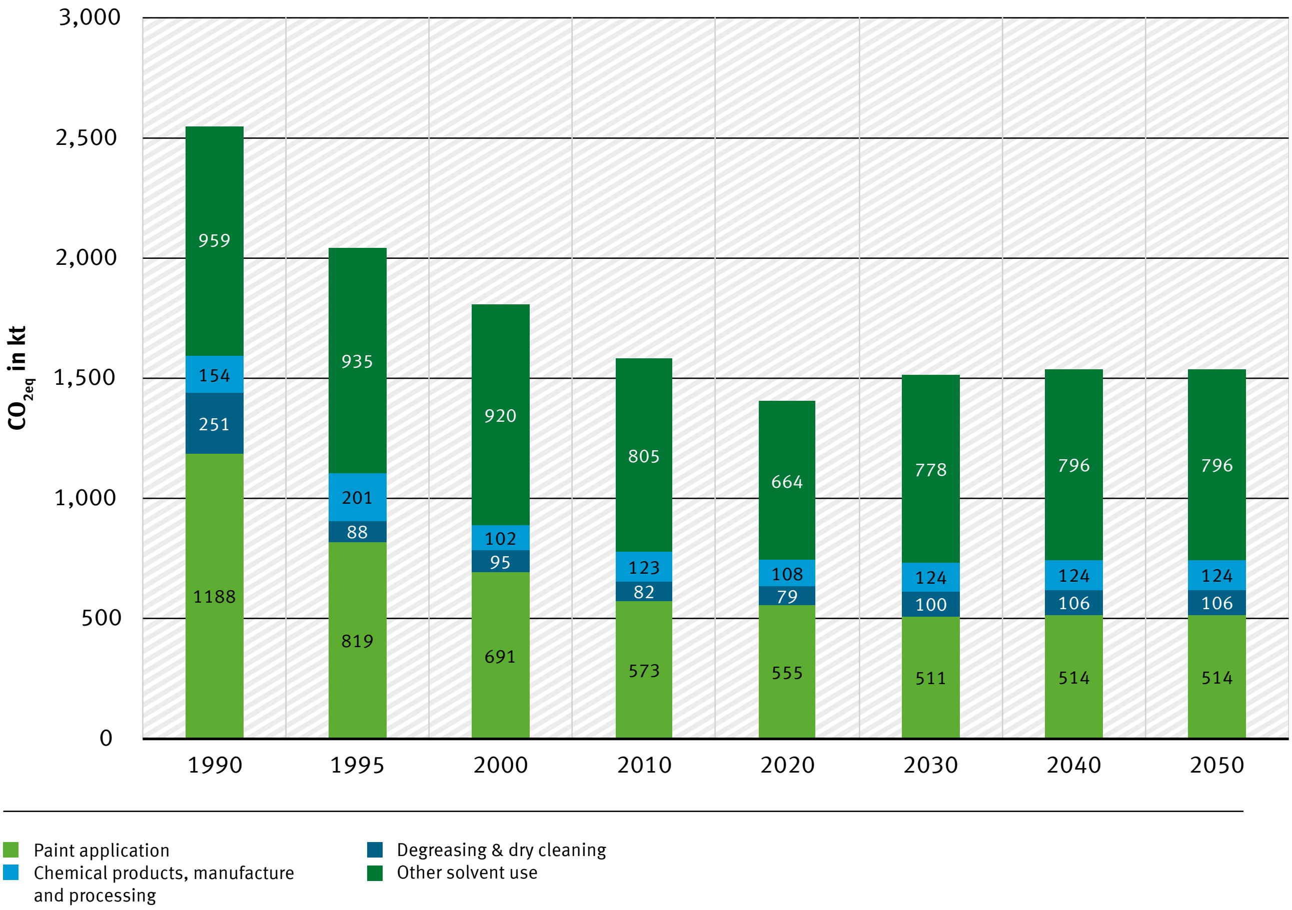
D.13.1.3 Emission trends 1990-2010

At approximately 1,500,000 t CO2eq (in 2011), emissions from NMVOCs arising from the use of solvents and solvent-based products contribute 0.17% to German greenhouse gas emissions.

NMVOC emissions from this source category have fallen overall by approximately 41% since 1990. Most of this reduction in emissions has been achieved since 1999. The reductions achieved have been due in particular to the introduction of statutory regulations such as the solvent-based paint and varnishes ordinance (*Lösemittelhaltige Farben- und Lack-Verordnung, ChemVOCFarbV*), the 2nd and 31st ordinances implementing the Federal Immission Control Act (*Verordnung über Emissionsbegrenzung von leichtflüchtigen halogenierten organischen Verbindungen* (ordinance limiting the emissions of halogenated VOCs) and *Verordnung zur Begrenzung der Emissionen flüchtiger organischer Verbindungen bei der Verwendung organischer Lösemittel in bestimmten Anlagen* (ordinance limiting the emissions of VOCs from the use of organic solvents in certain installations)), as well as the Technical Instructions on Air Quality Control (TA Luft). The use of the German 'Blue Angel' environmental label, for example on low-solvent paints, varnishes and adhesives, has also been a major contributing factor.

Although product sales rose in individual areas — in some cases even over a period of several years — and consequently contributed to an increase in emissions, the above-mentioned measures have largely succeeded in offsetting this trend. These successes, especially those in recent years, are reflected in the latest emission calculations. Thanks to optimisation of the methodology, these calculations now take account of more differentiated VOC concentrations and emission factors.

Figure D-9: NMVOC emissions from solvent and other product uses — 1990 to 2010 — and CLE scenario[CXCVIII] for 2020 to 2050, stated as CO2eq, UBA's own representation[339] and calculations[CXCIX]



CXCVIII CLE scenario (Current LEgislation): Scenario based on current regulations and legislation, with no further measures taken into account when estimating emissions.

CXCIX Data 2020-2050 estimated by UBA.

D.13.1.4 Potential reduction in emissions by 2050

As outlined above, the voluntary and statutory measures undertaken since 1990 have resulted in a substantial reduction in NMVOC emissions.

The product-related regulations are primarily aimed at reducing the concentrations of emissions-relevant constituents in the various products. On the other hand, legally speaking, product-related measures such as limiting the manufacture and use of solvent-based products in Europe can no longer be implemented at a national level. Such product-related measures constitute an infringement of the free movement of goods within the EU which is one of the fundamental freedoms enshrined in European Law. It is therefore up to the European Parliament or the Member States (via the Council of the European Union) to ask the European Commission to propose suitable European regulations in order to establish a basis for product-related measures.

In order to identify possible ways of achieving reductions by 2050 in an MFR scenario[CC] which includes a comprehensive range of technically feasible reduction options, we have made the following assumptions:[340]

- Product and process-related measures such as the replacement of solvent-based formulations by low-solvent or solvent-free products in all four source categories 3.A to 3.D (reductions of approximately 200,000 t CO_{2eq});
  including for example
  - limiting VOC content in aerosol packaging,
  - further reducing the use of VOCs in printing inks and processes in the printing industry,
  - limiting VOC content in paints and varnishes in previously unregulated application areas;
- Increased use of GHG-neutral solvents from renewable resources from waste and residues, for example from renewable methane or bioethanol (additional reductions in all four source categories 3.A to 3.D up to 2050: 33%);[341,342] Further increased efficiency in the use of solvents and solvent-based products (additional reductions in all four source categories 3.A to 3.D up to 2050: 10%).

The table below summarises the results of the reduction scenario. Overall, the reduction scenario measures result in a lowering of emissions by over 50% compared with the base scenario for 2050.

Table D-52: Trends in NMVOC emissions arising from solvents and other product uses in t CO2eq for source categories 3.A to 3.D, UBA's own representation[343] and calculations[CCI]

CRF	Source category	Emissions 2010 in t CO_{2eq}	Emissions 2050 Base scenario (CLE) in t CO_{2eq}	Emissions 2050 + measures (MFR) in t CO_{2eq}	Reduction 2050 compared with base scenario in %
3.A	Paint application	572,860	513,913	255,310	55.4%
3.B	Degreasing & dry cleaning	82,474	105,834	47,785	42.1%
3.C	Chemical products, manufacture and processing	123,000	124,453	70,938	42.3%

CC MFR scenario: Maximum (Technically) Feasible Reduction scenario.

CCI 2050 data estimated by UBA.

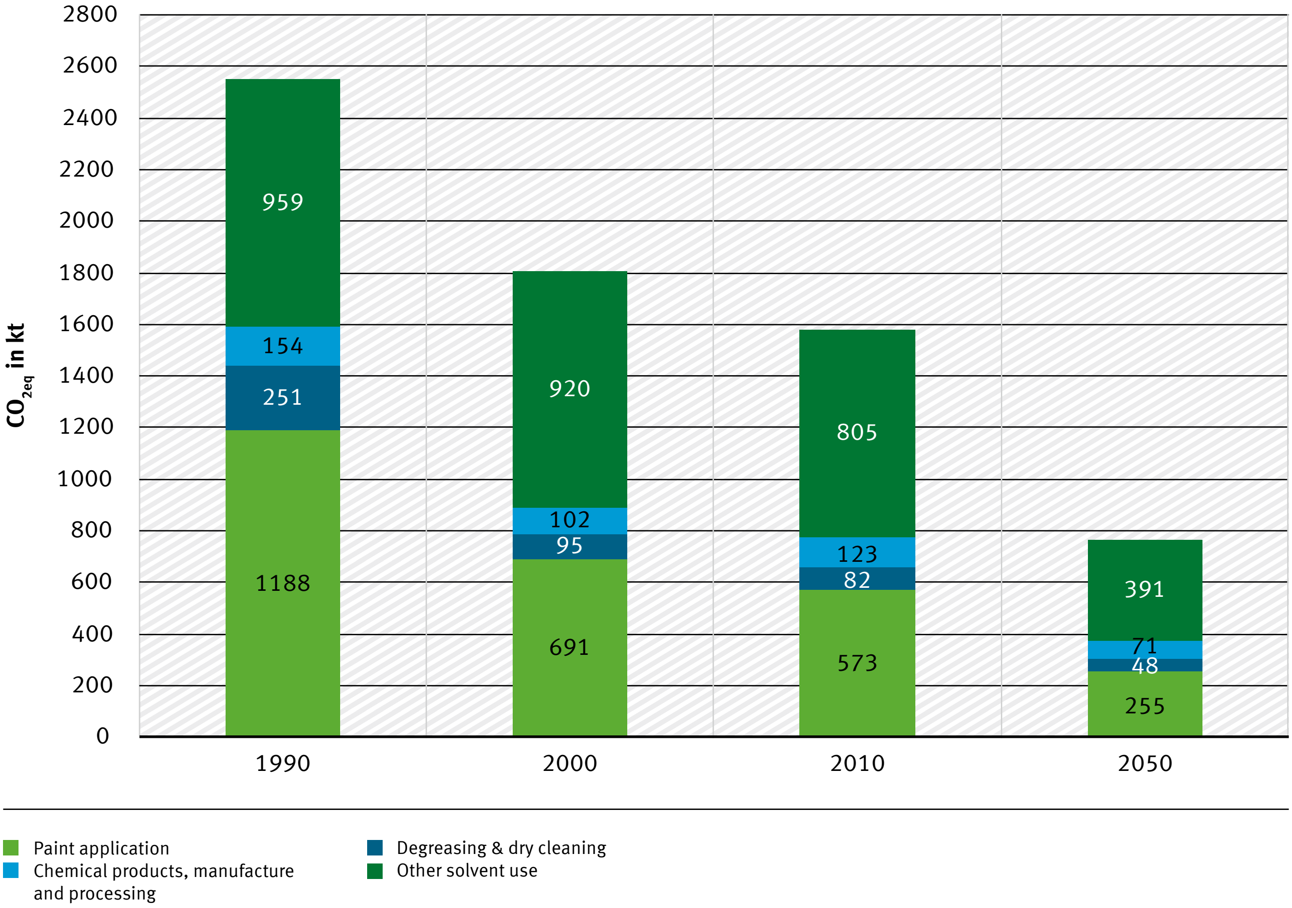
CRF	Source category	Emissions 2010 in t CO_{2eq}	Emissions 2050 Base scenario (CLE) in t CO_{2eq}	Emissions 2050 + measures (MFR) in t CO_{2eq}	Reduction 2050 compared with base scenario in %
3.D	Other solvent use	804,690	795,655	390,824	51.4%
3	**Total**	**1,583,024**	**1,539,855**	**764,857**	**52%**

At first glance the reductions achieved as a result of the assumptions in the MFR scenario may not appear very significant and the methodology of the scenario would therefore be seen as tending to the conservative. However, the opposite is in fact true: the assumptions made extend far beyond the measures that are currently feasible or are foreseeable in the near future.

We expect renewable resources to become a much more important source of raw materials for the chemical synthesis of solvents for products. This will reduce the consumption of fossil resources accordingly. It should also be noted that over the past decade, the use of renewable resources as raw materials in the chemical industry has stagnated or has increased only very slightly. For instance, the proportion of GHG-neutral solvents from renewable resources on the European solvent market is currently less than 1.5%.

Accounting for only around 0.17% of total German greenhouse gas emissions (as at 2010)[344], solvent and other product use is not a key source category. In comparison with overall trends in greenhouse gas emissions, its contribution will increase in future, without however attaining a significant percentage in the overall balance.

Figure D-10: NMVOC emissions from solvent and other product uses — 1990 to 2010 — and MFR scenario[CCII] for 2050, stated as CO2eq, UBA's own representation[345] and calculations[CCIII]



D.13.2 Nitrous oxide use in Germany (CRF 3D)

D.13.2.1 Source category description

At just 0.03% of total greenhouse gas emissions in 2010, emissions from the use of nitrous oxide (CRF 3D) were relatively low. The German nitrous oxide market is dominated by Air Liquide, Linde AG and Westfalen AG. These firms are both leading producers as well as importers. No nitrous oxide emissions occur during nitrous oxide production and filling into cylinders. Emissions occur solely when the gas is actually used. Medical applications are the most important source of N_2O emissions. In 2010, 95% of N_2O emissions in the 3D category emanated from the use of nitrous oxide in anaesthesia. Further emission sources are the use of nitrous oxide as a propellant in whipped cream aerosol cans and applications in the semiconductor industry. Small amounts of N_2O are also released from the use of explosives.

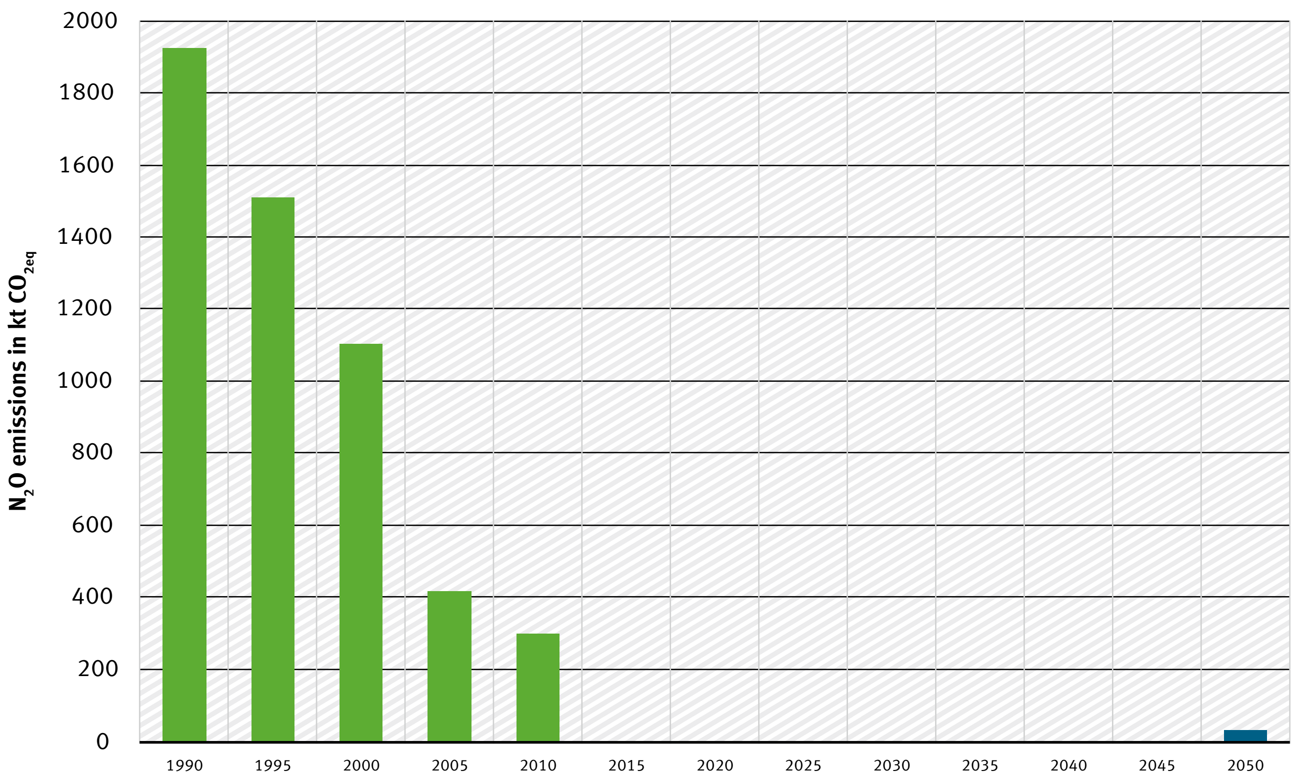
Emissions have fallen sharply by 84.5% since 1990. The most important contributing factor here is the decreasing use of nitrous oxide in anaesthesia owing to increasing opposition to the use of nitrous

CCII MFR scenario: Maximum (Technically) Feasible Reduction scenario.

CCIII 2050 data estimated by UBA.

oxide in medical circles in Germany. Its other applications in the semiconductor industry, in whipped cream aerosol cans and in explosives are relatively insignificant and they are therefore disregarded below. (NIR 2012)[346]

Figure D-11: N_2O emissions from the use of nitrous oxide in anaesthesia, semiconductor industry, whipped cream aerosol cans and explosives — 1990 to 2010 and scenario for 2050, UBA's own representation[347] and calculations



D.13.2.2 Possible solutions for GHG mitigation

In the field of anaesthesia, other anaesthetics are increasingly being used for medical reasons. However, this application is unlikely to disappear entirely, as the companies concerned are attempting to find other markets for their products. For example, they are marketing numbing sprays containing nitrous oxide to dental practitioners. It is difficult to counter this trend with further measures, as purported medical benefits will outweigh environmental concerns.

D.13.2.3 GHG mitigation scenario for 2050

Owing to the strong pressure to further reduce the use of nitrous oxide in anaesthesia, a further fall in emissions can be expected in future. However, a GHG-neutral endpoint is unlikely, as gas dealers will target other niche applications, such as the use of nitrous oxide in dentistry for example. We therefore estimate that in 2050 emissions will still be around 100 t N_2O or 31 kt CO2eq respectively (see Figure D-11). This estimate assumes that the quantities of nitrous oxide used in other applications will not rise significantly.

D.13.2.4 Summary of emissions from solvents and other product uses

Both NMVOC emissions from solvent and other product uses as well emissions from the use of nitrous oxide have fallen sharply in recent years: from 4 million tonnes CO_{2eq} in 1990 to 2 million tonnes CO_{2eq} in 2009.

As a result of product and process-related measures, the use of solvents obtained from renewable resources, and increased efficiency in the use of solvents, NMVOC emissions can be further reduced by over 50% to 0.765 million tonnes CO_{2eq} in 2050.

As regards emissions from the use of nitrous oxide, we assume that discontinuation of their use in anaesthesia would automatically reduce emissions to 0.031 million tonnes CO_{2eq}.

In this case total emissions in 2050 would be just under 1 million tonnes CO_{2eq}.

D.14 Summary

Overall, within the framework established for the study (see Chapter A Introduction), it was possible to develop a scenario for a greenhouse gas-neutral and energy-efficient industrial sector in Germany in 2050. In this scenario, energy-related greenhouse gas emissions are reduced to zero through the use of renewable electricity, renewable methane and renewable hydrogen, thereby achieving a 100% reduction in comparison with 2010. To enable renewable energy vectors and renewable electricity to be used, some fundamental changes will need to be made to production processes in many sectors, as well as the use of suitable technologies in plants. For instance, in this scenario, the blast furnace/oxygen steel process is no longer a method of primary steel production. Instead, electric arc furnace steel production based on scrap and directly reduced iron (DRI) will have been massively expanded, and renewable methane or renewable hydrogen will be the only energy vectors used for direct reduction. In addition, electric arc furnaces and rolling mill furnaces will be powered exclusively by renewable electricity.

Although increases in production are expected in many sectors by 2050, the scenario shows that industry can reduce its final energy consumption to approximately 373 TWh p.a., a reduction of around 50% compared with the baseline year 2010 (Table D-53). In many industries, this is on average equivalent to a per-tonne reduction in specific energy input by a factor of 2 to 4. This can often be achieved by optimising material and energy efficiency in production processes, coupled with the systematic utilisation of waste heat and the use of highly efficient technologies. The scenario assumes that many technological innovations will emerge over the coming four decades. Accounting for approximately 50% (199 TWh p.a.) of final energy consumption, renewable methane will be the primary energy vector, followed by renewable electricity with a share of around 45% (159 TWh p.a.). In addition, the paper industry will use around 15 TWh p.a. generated from biowaste (lignin etc.) created as a by-product of the production process.

Furthermore, the scenario assumes that in future, 282 TWh p.a. of renewable methane will be used as a non-energy carbon source for synthesis in the chemical industry. This will also enable process-related GHG emissions to be avoided altogether in many parts of the chemical industry, such as in ammonia production for example. By 2050, the entire industrial sector will see process-related greenhouse gas emissions fall to approximately 14 million tonnes p.a., a reduction of 75% in comparison with 2010 (Table D54). Along with the measures outlined for the chemical industry, savings can also be achieved by product changes — such as in the cement industry — and substantial reductions in the use of fluorinated greenhouse gases as a result of substitution.

Table D-53: Final energy data for the industrial and manufacturing sectors in the UBA GHG-neutral Germany 2050 scenario

	Total FEC in TWh p.a.	Renewable methane in TWh p.a.	Renewable electricity in TWh p.a.	Use of internal biogenic waste streams in TWh p.a.	Changes in total FEC comp. with baseline year in %
Steel industry[CCIV]	104.7	66.7	38.0		-42.19
NFM industry	16.5	6.3	10.2		-35.29
Foundry industry	6.5	1	5.5		-49.31
Chemical industry[CCV]	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 included in report)[CCVI]	60.2	30.1	30.1		
Total	373.1	198.8	159.2	15.1	

CCIV It is assumed that it will be technically feasible to replace the majority of demand for renewable methane by the more favourable form of energy renewable hydrogen.

CCV Methane and hydrogen are equivalent in their use so the total comes to 61 TWh p.a. The range is based on the assumption that, given an annual reduction rate of 1.5% for all energy vectors from now until 2050, 61 TWh of methane/hydrogen and 20 TWh of electricity will be required. In addition, 282 TWh of methane will be required as a renewable raw material or carbon source for chemical synthesis.

CCVI For the other industries not included in the report, it was assumed that total FEC will be reduced by 50% compared with 2010, and that there will be a 50/50 split between renewable methane and renewable electricity in 2050.

Table D-54: Greenhouse gas emissions from the industrial and manufacturing sectors in the UBA GHG-neutral Germany 2050 scenario

Greenhouse gas emissions(GHG-EM) in t CO_{2eq} p.a.	Energy-related	Process-related	Changes in total emissions compared with baseline year in %
Steel industry[CCVII]	0	162,000	-99.7
NFM industry	0	0	-100.0
Foundry industry	0	0	-100.0
Chemical industry[CCVIII]	0	500,000	-98.7
Cement industry[CCIX]	0	6,330,000	-79.8
Glass industry	0	761,563	-94.1
Lime industry[CCX]	0	3,530,000	-64.8
Paper and pulp industry	0	0	-100
Food industry	0	0	-100
Textile industry	0	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/AC systems and heat pumps		28,000	-99.7
Production of insulating materials		69,000	-89.7
Fire extinguishing agents		0	-100.0
Aerosols and solvents		100,000	-78.2
Semiconductor manufacture		109,000	-26.4
Electrical equipment		65,000	-88.0
Other SF_6 applications		250,000	-90.6
Emissions from solvents and other product uses*			
Paint application		255,310	-55.4
Degreasing & dry cleaning		47,785	-42.1
Chemical products, manufacture and processing		70,938	-42.4

CCVII The only source of CO_2 emissions will be the burn-up of graphite electrodes in electric arc furnaces.

CCVIII Process-related GHG emissions will arise only as N_2O in the production of adipic acid and nitric acid because in 2050 the only sources of carbon used for chemical synthesis will be based on renewable methane.

CCIX Assuming that new production methods and products will enable raw material-related CO_2 emissions in cement production to be reduced by 80% in comparison with 2010, approximately 2,500 kt CO_2 will still be produced from the calcination of raw materials in 2050.

CCX Due to decreased production levels, raw material/process-related CO_2 emissions will be reduced by 30% by 2050.

CCXI Including 31,000 tonnes of CO2eq from the use of nitrous oxide.

Greenhouse gas emissions(GHG-EM) in t CO_{2eq} p.a.	Energy-related	Process-related	Changes in total emissions compared with baseline year in %
Other solvent use		390,824	-51.4
Other industries (not included in report)	0		
Total	**0**	**13,783,420**[CCXI]	

E. Waste and wastewater

E.1 Description of the sector

Before Germany's first waste disposal law came into force in 1972, each municipality had its own rubbish tip. There were around 50,000 in total.

Today there are only 160 landfill sites for municipal waste in operation in the whole of Germany (category II landfill sites for non-hazardous waste with a low organic content). At the same time, the waste disposal sector – driven since the 1980s by the 'avoid, recycle, dispose' hierarchy – has been transformed from a sector focused purely on waste disposal to a multifaceted sector with advanced technical facilities. The number of waste sorting, processing and recycling facilities has risen dramatically. As a result of this development, since 2005 – when it became illegal in Germany to send untreated waste to landfill – waste has been sent for processing in systems that protect resources and avoid greenhouse gases.

Today, Germany's recycling and waste industry employs around 250,000 people. The sector generates annual turnover of over 50 billion euros.[348] Germany's waste sector has therefore become an important branch of the economy and its expertise and systems engineering are sought after by many other countries keen to develop environmentally friendly waste management systems.

E.1.1 Calculating greenhouse gas emissions

The National Inventory Report (NIR) provides figures for methane emissions from landfill sites. Since 2004 it has reported on emissions from composting and mechanical-biological waste treatment, since these have become increasingly important for the treatment of biodegradable waste fractions, as well as emissions from landfill sites and wastewater treatment. Methane and nitrous oxide emissions are reported for the wastewater sector.

A total of 43.1 million tonnes of CO_{2eq} was reported for the solid waste and wastewater sector in 1990. Nearly 90 % of this came from landfill sites. 10.3 % stemmed from the wastewater sector. The proportion from composting plants is very low, at 0.1 %. Mechanical-biological treatment (MBT) plants were not in operation in 1990.

E.1.2 Emissions 1990 to 2010

According to NIR 2012,[350] the solid waste and wastewater source category contributed 1.3 % to Germany's total emissions in 2010. In 1990 it contributed 3.5 %. The waste sector has seen the greatest reduction in emissions of any sector (~72 %) and has therefore made a exceptionally high contribution to Germany's greenhouse gas reductions so far.

Figure E-1: Breakdown of greenhouse gas emissions in 1990 (43.1 million tonnes CO_{2eq})[349]

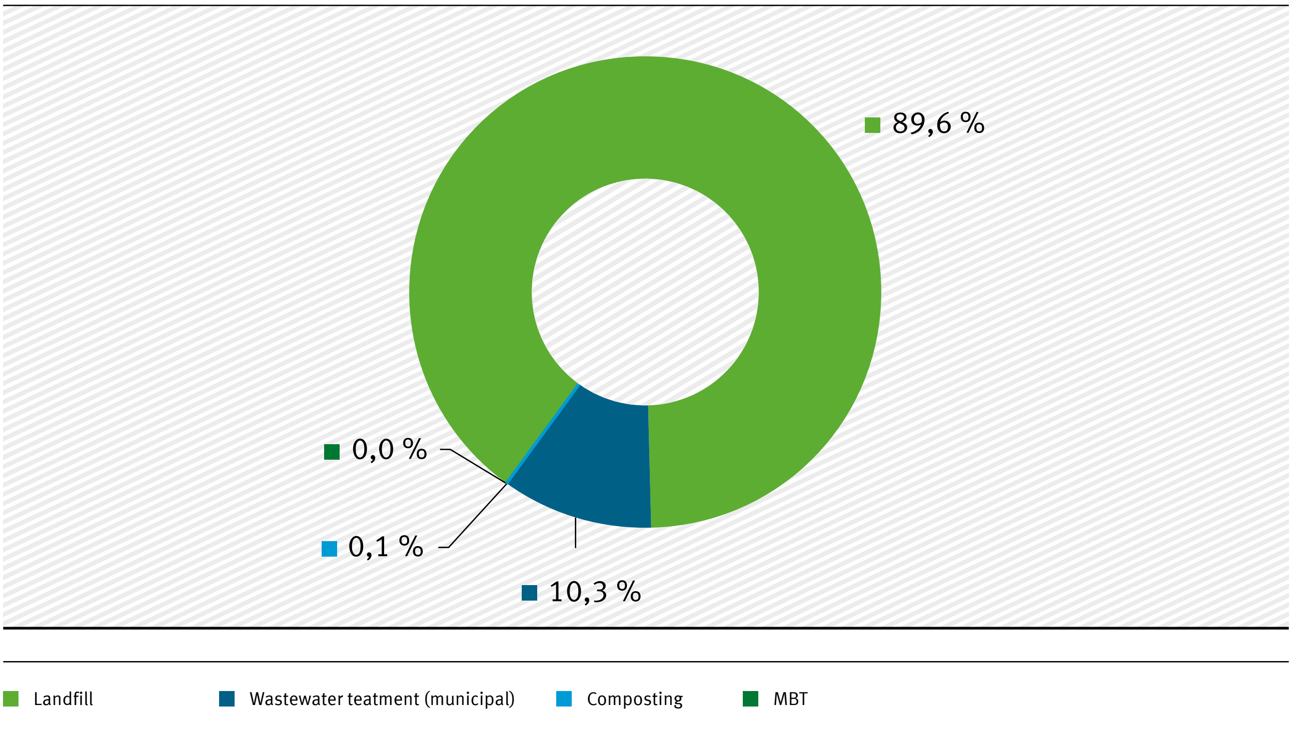
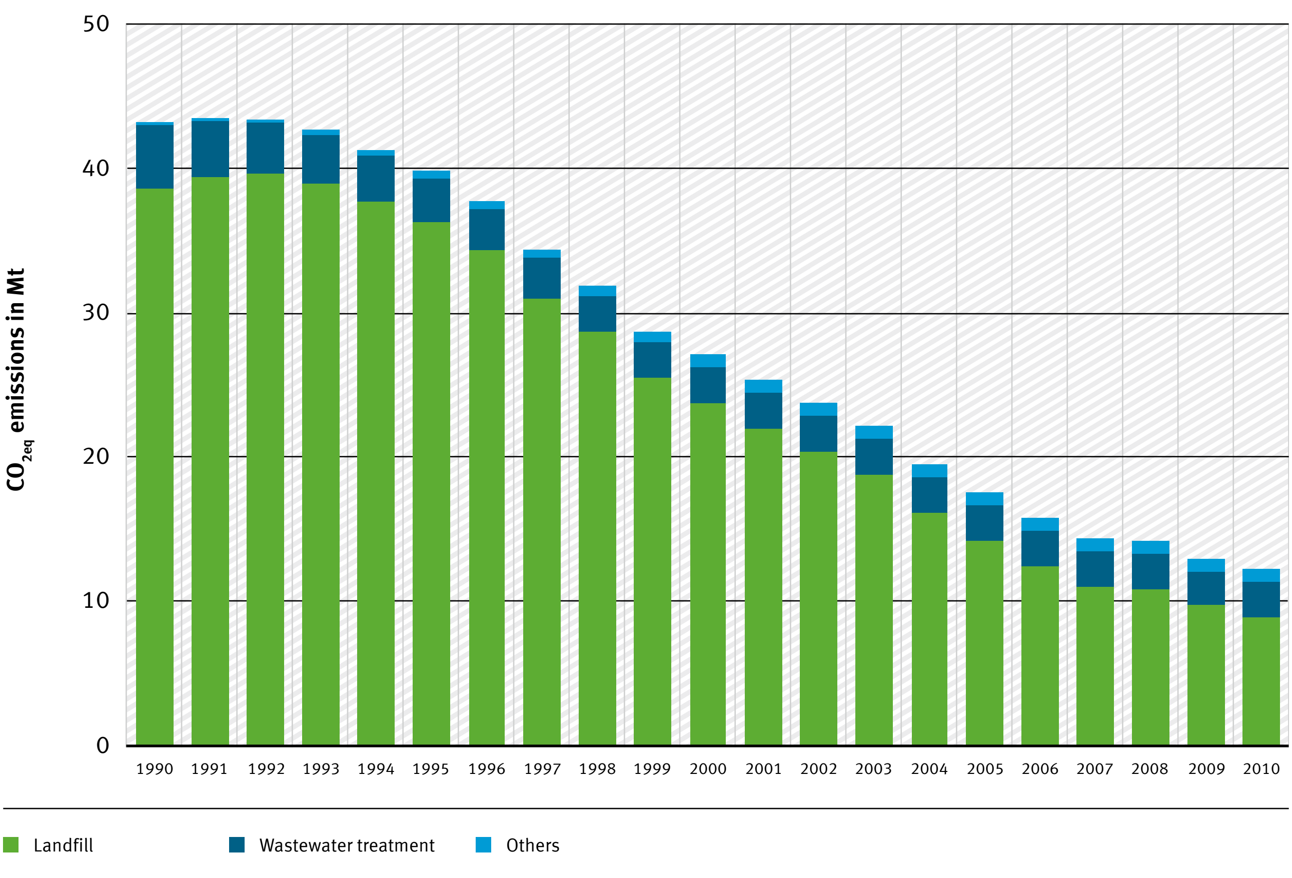


Figure E-2: Greenhouse gas emissions in Germany from waste and wastewater (excluding CO_2 from the LULUCF sector)[CCXII] 1990–2010[351]



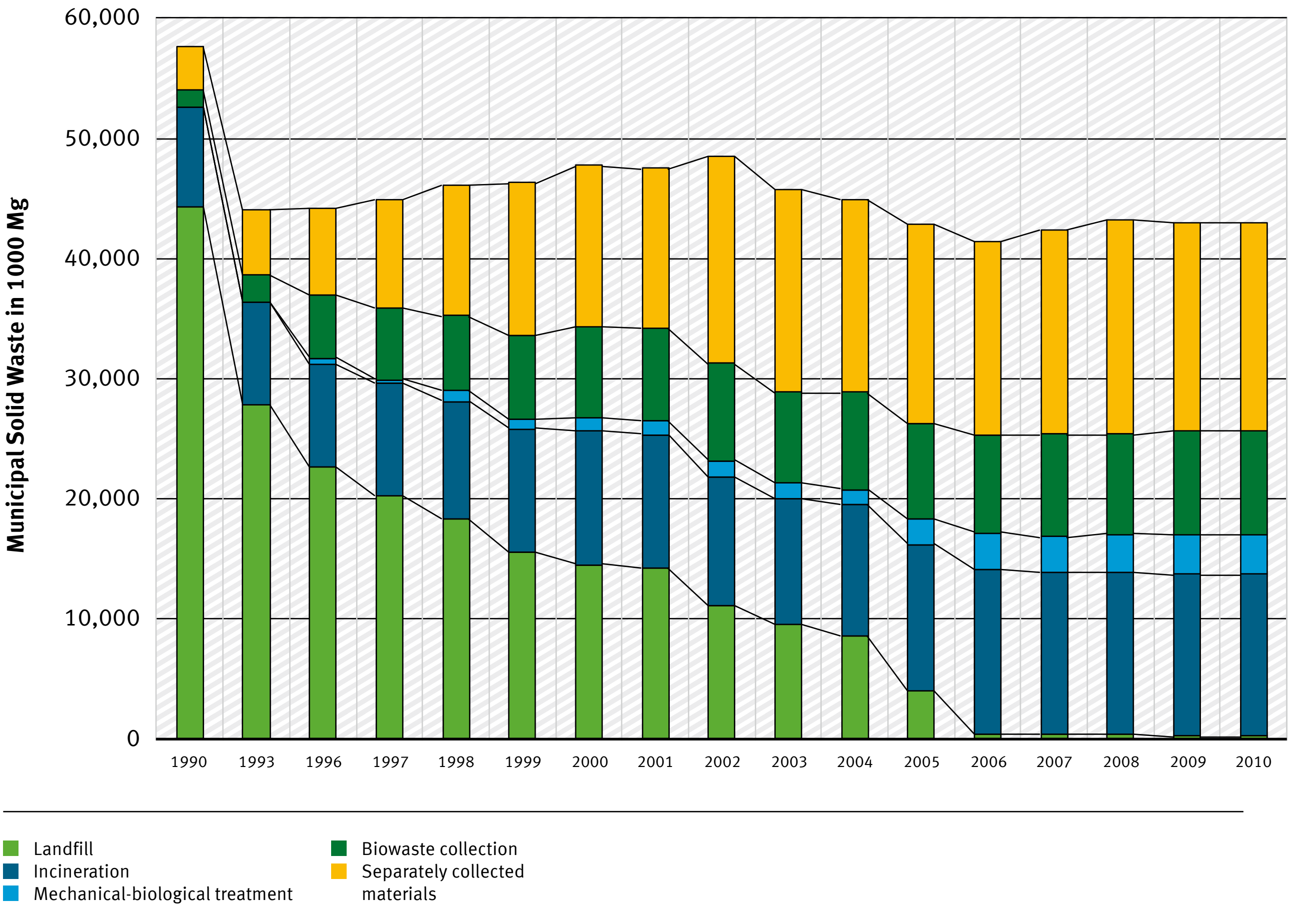
CCXII The 'others' category comprises emissions from composting plants and MBT plants.

E.1.2.1 Landfill sites

Under anaerobic conditions the organic fractions of waste in landfill sites produce methane, some of which can be captured by technical means. The rest leaks out over several decades and disperses in the atmosphere.

A number of laws have been passed concerning waste management in Germany since 1990 and organisational measures have been introduced that have had a big impact on emissions from landfill sites. These include increased collection of biowaste from households and businesses, increased collection of other valuable materials, such as glass, paper and card, metal and plastics, and separate collection and recycling of packaging. Since June 2005, under the provisions of the Landfill Ordinance *(Abfallablagerungsverordnung)*, municipal waste in Germany can no longer be sent to landfill without pre-treatment. To meet the criteria for disposing of waste in landfill sites, the waste has to go through thermal or mechanical biological treatment. These measures have led to a sizeable shift in waste flows. Far more than half of household waste – particularly waste paper, glass, packaging and biowaste – is now recovered.

Figure E-3: Change in pathways for management of municipal solid waste between 1990 and 2010[352]



The quantity of municipal waste sent to landfill has fallen steeply since the middle of 2005. Now it makes only a very small contribution to gas emissions because it contains only a few components with low methane-forming potential (e.g. MBT residues and small amounts of timber in processed construction waste).

Emissions are reduced still further by capturing and utilising landfill gas. The 1993 Technical Instructions on Municipal Waste (TA Siedlungsabfall) made gas capture a prerequisite for obtaining approval for municipal landfill sites. The captured methane can be used by district heating plants, either for internal consumption or for supplying energy to third parties. Some methane is also oxidised in the landfill cover layer.

According to the NIR 2012[353] calculations, in 2010, Germany's landfill sites produced around

821,000 tonnes of methane, of which
347,000 tonnes were captured and used for energy purposes or flared off, and
47,000 tonnes were biologically oxidised. The emissions released into the atmosphere amounted to around
427,000 tonnes of methane (8,970,000 tonnes of CO_{2eq}).

This means that methane emissions from landfill sites have been reduced from 1.8 million tonnes in 1990 to around 0.4 million tonnes in 2010.[354] These reductions in methane emissions represent 30 million tonnes of CO_{2eq} per year, and reduce Germany's total greenhouse gas emissions by around 2.5 %.

E.1.2.2 Composting and mechanical-biological waste treatment

The quantity of biowaste and garden and park waste collected separately has risen over the past few years and is due to increase further from 2015 onwards as a result of a nationwide mandatory separate collection of biowaste.[CCXIII] Greenhouse gas emissions from composting amounted to approximately 726,000 tonnes of CO_{2eq} in 2010. These emissions were the result of composting just under 9 million tonnes of biowaste.[355]

Methane:	25,300 tonnes	~ 531,000 tonnes of CO_{2eq}
Nitrous oxide:	630 tonnes	~ 195,000 tonnes of CO_{2eq}
Total		~ 726,000 tonnes of CO_{2eq}

Since the 1990s, mechanical-biological processes have been used extensively in Germany for processing residual waste. Initially, most plants were simple, with no facilities for collecting and treating waste gas. As processes have improved, however, closed systems with biofilters for waste gas scrubbing have become the norm. These have reduced the plants' odour emissions but have not reduced greenhouse gas emissions. Since March 2001, under the provisions of the 30th Federal Immission Control Act Ordinance,[CCXIV] new MBT plants have to meet stringent technical conditions and comply with demanding emissions standards. Compliance with these emissions limits requires a combination of acid waste gas scrubbing and thermal treatment.

CCXIII Section 11 of the Closed Substance Cycle Management Act (*Kreislaufwirtschaftsgesetz* – KrWG), 24 February 2012.

CCXIV 30th ordinance for the implementation of the Federal Immission Control Act (ordinance on facilities for the biological treatment of waste – 30. BImSchV), 20 February 2001.

MBT plants emit methane and nitrous oxide as a result of biodegradation processes. According to NIR 2012,[356] emissions in 2010 amounted to

Methane:	280 tonnes	~ 6000 tonnes CO2eq
Nitrous oxide:	500 tonnes	~ 155,000 tonnes CO2eq
Total		~ 161,000 tonnes CO2eq

E.1.2.3 Municipal wastewater treatment

In Germany, municipal wastewater treatment is usually carried out under aerobic conditions (at municipal wastewater treatment plants and small-scale wastewater treatment plants), which means there are no methane emissions. The open sludge digestion systems used until the early 1990s in East Germany for sludge stabilisation, which resulted in methane emissions, were phased out and eventually abandoned in 1994. However, methane can be produced in septic tanks if households are not connected to the public sewer network or to small wastewater treatment plants. 573,500 people were still disposing of wastewater in septic tanks in 2010.[357] The organic load sent to cesspools and septic tanks has been reduced dramatically since 1990, resulting in a steep decline in methane emissions (reduction from around 180 kt p.a. in 1990 to around 13 kt p.a. in 2009[358]).

Nitrous oxide emissions can occur as a by-product of municipal wastewater treatment, especially in connection with denitrification, in which gaseous end products – primarily molecular nitrogen – are formed from nitrate. The level of nitrous oxide emissions (N_2O) in the wastewater sector depends on per-capita protein intake and is therefore directly linked to lifestyle and consumption habits.

According to the NIR 2012[359] calculations, municipal wastewater treatment in 2010 produced

3370 tonnes of methane (70,800 tonnes of CO_{2eq}) and
7430 tonnes of nitrous oxide (2,303,300 tonnes of CO_{2eq})

resulting in total emissions of nearly **2.4 million tonnes of CO_{2eq}**.

Methane emissions from wastewater treatment have fallen by 93.8 % since 1990; nitrous oxide emissions have risen by 3.6 %.

E.2 Options for reducing greenhouse gas emissions in the source categories and subcategories

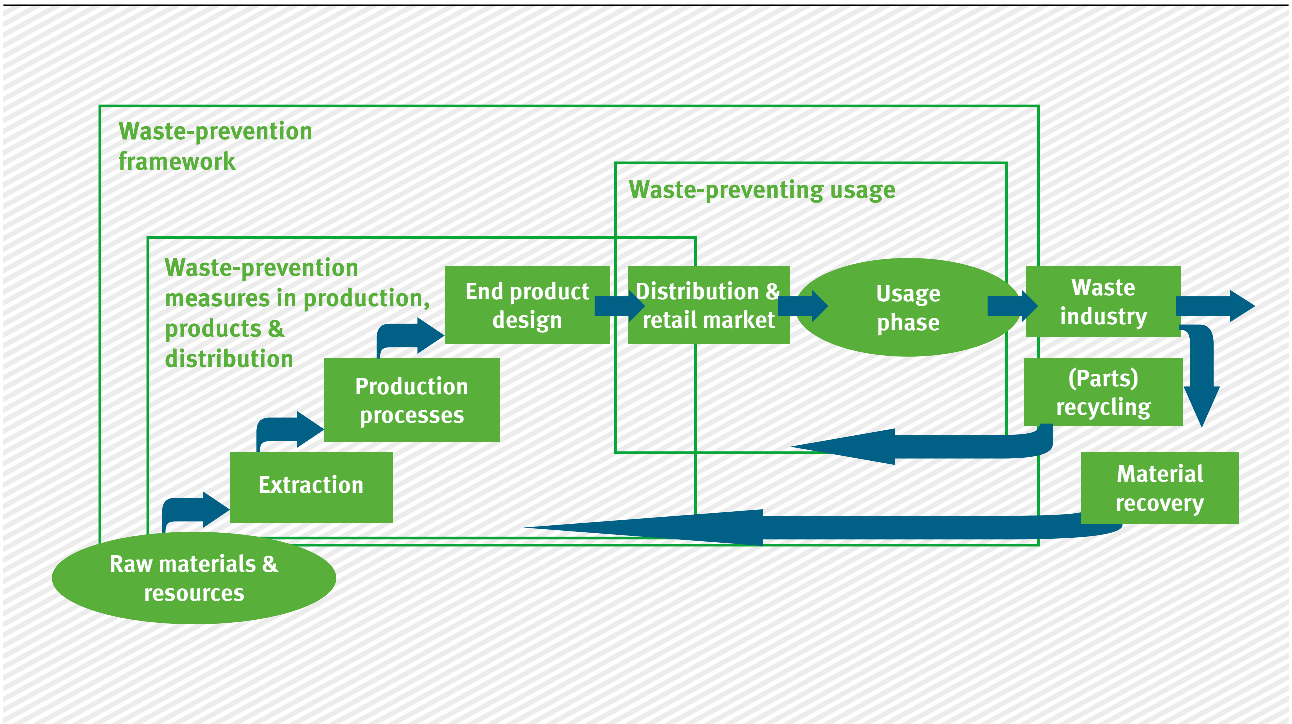
The main factors affecting greenhouse gas emissions in the waste sector are the quantities of waste generated and its composition, and the way in which waste is recycled or treated. Waste prevention is the top priority in the five-step waste-reduction hierarchy described in Section 6 of the Closed Substance Cycle Management Act,[CCXV] which came into force in June 2012 to implement the European Waste Framework Directive. The German government plans to pass a waste prevention programme by the end of 2013.

However, only a small proportion of waste prevention activities can be influenced by measures taken within the waste sector itself. To make significant progress in preventing waste, we need to look at the

CCXV Section 11 of the Closed Substance Cycle Management Act (*Kreislaufwirtschaftsgesetz* – KrWG), 24 February 2012.

entire product life cycle – from raw materials extraction to production, product use and waste generation (see Figure E-4).

Figure E-4: Waste prevention along the product life cycle[360]



Germany's population is predicted to fall between now and 2050, which will lead to a reduction in waste. In the absence of effective waste-prevention measures, the predicted rise in single-occupancy households could produce a counter trend, with an increase in per-head waste volumes. The eventual waste quantities and waste composition will be closely linked to consumption patterns and lifestyles in 2050 and are difficult to predict.

However, we assume that there will be a sharp decrease in residual waste as a result of changes along the entire product life cycle, since dwindling resources and more stringent climate protection standards will limit the production and consumption of products that waste raw materials and energy. Legislation, financial incentives, e.g. internalising environmental costs, and changes in consumer behaviour (not investigated in greater detail here), can contribute to this process.

Figure E-5: Conserving resources along the product life cycle[361]

Product design has major repercussions on the use of resources and waste generation as well as on the useful life and versatility of products. Products that conserve resources and avoid waste are characterised by sparing use of materials and by secondary raw materials that take account of upstream material requirements (ecological rucksack). These products have a long useful life, use resources efficiently and at the end of their lifetime they can be dismantled and their components reused or recycled.

The entire life cycle of a product or system must be considered in order to conserve natural resources, prevent waste and relieve pressure on the environment as a whole (including reducing greenhouse gas emissions).

Ink-jet printers (as used in households) can be used to illustrate these aspects. There are a number of synergies that apply here when it comes to reducing environmental impacts:

- Most of today's ink-jet printers are multi-function printing, faxing, scanning and copying devices. This reduces product diversity, which in turn cuts materials use and waste generation.
- In usual household usage patterns for ink-jet printers (as opposed to commercial use), the energy required to manufacture a printer (including the energy used to obtain the materials) is about twice as high as the energy it consumes during its useful life. When printers or multi-function devices have a long useful life, fewer devices are used and materials and energy (and therefore GHG emissions) can be saved.
- The useful life of a product must not be restricted by wearing parts, like the cartridge or the pad used to absorb excess ink when the print head is cleaned (obsolescence). Consumers must be able to replace worn parts themselves and the appropriate spare parts need to be available.
- Energy consumption for paper production is somewhat higher than the energy used for printing (taken over the entire life of the product). Functions for double-sided printing and printing several sides per sheet of paper make it possible to save paper and the resources used to produce it.
- By using recycled materials it is possible to conserve resources and reduce the costs involved in obtaining materials. Using 30 % recycled plastic, for instance, leads to a 10 % reduction in GHG emissions over the lifetime of a printer.

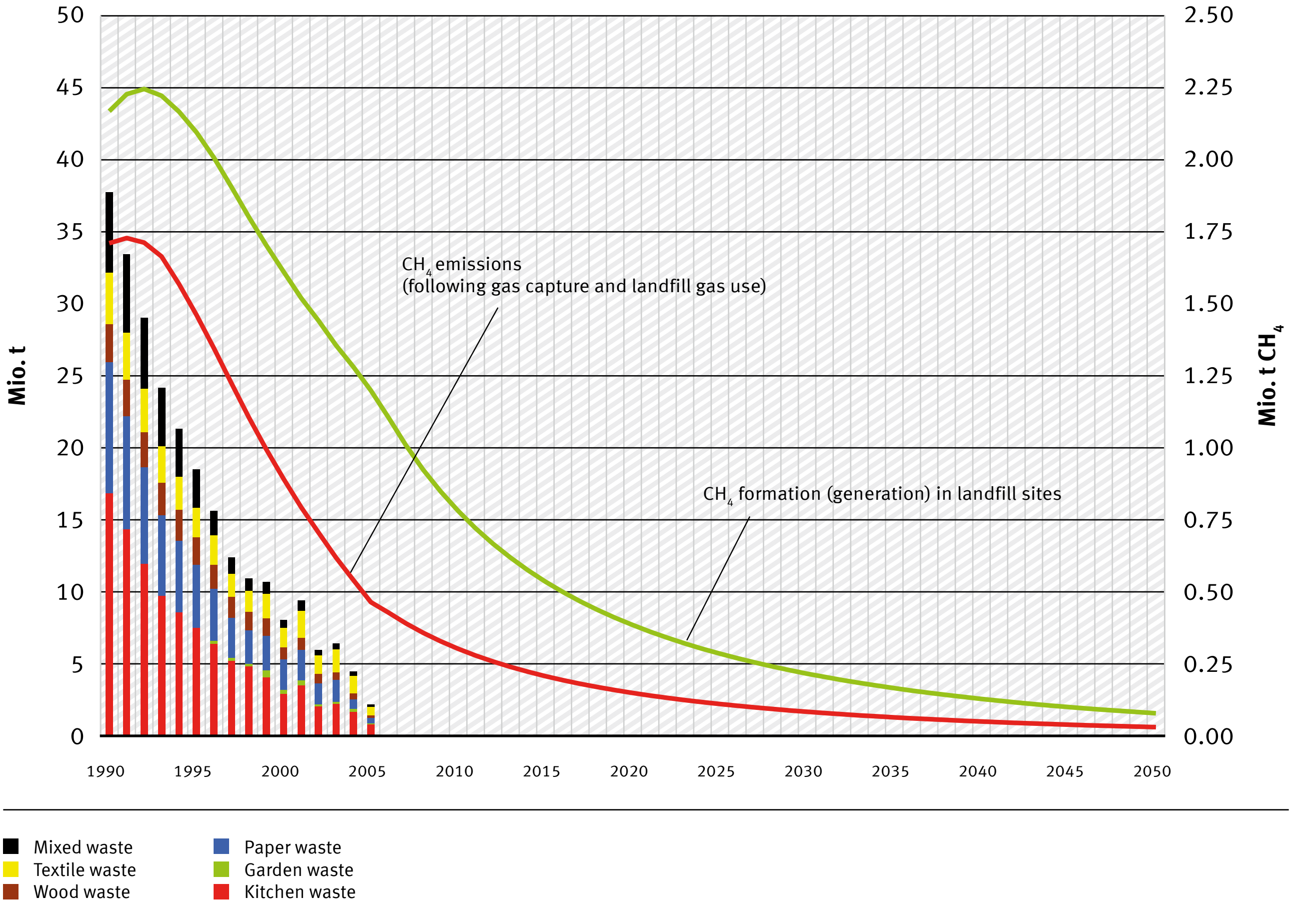
Where other products are concerned, however, there may be a conflict of aims. For instance, energy-efficient electric motors need more copper than more power-hungry motors.

In the narrower sense, waste industry measures that could contribute to waste prevention include promoting product reuse, e.g. through swap sites or furniture donations. Recycling can be encouraged through legislation, supported by financial incentives at local authority level, e.g. waste charges based on the amount of waste produced, which reward waste prevention. Voluntary agreements with industry that set minimum recycling quotas, for instance, can also help achieve waste targets.

E.3 Greenhouse gas mitigation in the waste and wastewater sector 2050

In Germany, the key measures for reducing greenhouse gas emissions associated with the disposal of waste have already been implemented. By changing the waste streams, significantly reducing the amount of municipal waste sent to landfill and ensuring that it passes through thermal or mechanical-biological treatment beforehand, Germany has dramatically reduced methane emissions from landfill sites. This trend will continue, since the pre-treatment of waste will lead to a sharp decline in the methane produced by landfill sites.

Figure E-6: Trends in methane emissions from landfill sites in Germany 1990–2050[362]



In the long term, the majority of the gas emitted will still come from the slow-degrading organic fractions of waste sent to landfill before 2005. It can be assumed that the volume of MBT waste sent to landfill will fall steeply over the coming decades. The 2050 scenario assumes an 80 % decrease in MBT waste sent to landfill (from 650,000 tonnes to 130,000 tonnes). However, the impacts on methane emissions are small compared with the emissions from waste sent to landfill before 2005.

Based on these assumptions, German landfill sites in 2050 will still produce 80,000 tonnes of methane (1.7 million tonnes of CO_{2eq}).

The dismantling and aerobic stabilisation of landfill sites can be expected to increase between now and 2050. Assuming that these measures are deployed at 30 % of landfill sites, annual methane emissions will be reduced to 56,000 tonnes (1.2 million tonnes of CO_{2eq}).

We assume that landfill gas will be captured and undergo biological oxidation, which will reduce methane emissions by 50 % by 2050. As a result, methane emissions are expected to amount to 28,000 tonnes in 2050 (0.6 million tonnes CO_{2eq}).

We assume that waste undergoing mechanical-biological treatment (MBT) will remain constant between 2010 and 2050. As MBT plants are converted into mechanical-biological stabilisation (MBS) plants, the quantities of off-gas and the nitrous oxide produced in the biological process will fall. Greenhouse gas emissions from MBT plants are therefore expected to fall by around 40 % (i.e. around

100,000 tonnes of CO_{2eq}). The conversion of MBT plants to MBS plants will also lead to a reduction in the volume of treatment residues sent to landfill, since MBS treatment results in a much higher proportion of treated waste being used for heating or material purposes.

In the long term, it is assumed that around 13 million tonnes of biowaste can be recycled. A large proportion will be treated in fermentation plants. Technical and organisational measures to prevent methane and nitrous oxide emissions in composting and fermentation plants (e.g. fitting plants with thermal scrubbing systems) will reduce greenhouse gas emissions from these plants to around 460,000 tonnes of CO_{2eq}. There are already plans for legislation (a biogas plant regulation) that will achieve some of this reduction.

Approximately 25 million tonnes of waste is currently sent for thermal treatment or energy recovery. In future, such volumes will no longer be available. This study assumes that the petroleum-based industry will switch to renewable or renewably sourced raw materials in the long term. Furthermore, it assumes that a large proportion of petroleum-based products will have been disposed of by 2050, which will reduce fossil-based carbon dioxide emissions from incinerators to negligible quantities.

Further emissions reductions can also be expected in the area of wastewater treatment in the long term. As more households are connected to the central wastewater system and the population in rural areas declines, methane gas emissions from septic tanks will fall further. We can assume a potential reduction of 50 %, which equates to total methane emissions of around 35,000 tonnes of CO_{2eq} from septic tanks.

We assume that the proportion of nitrous oxide (N_2O) will fall by 2050, provided there is a switch to lower-protein diets in line with the recommended protein values for Germany, Austria and Switzerland.[CCXVI] There will be a further reduction as a result of the population decline.

The National Nutrition Survey II (2008)[363] found that current protein intake in Germany is around 130 % of the recommended value. If German consumption patterns change as recommended in the nutrition survey, and protein intake is reduced by around 30 % over the long term, nitrous oxide emissions will fall by around 690,000 tonnes of CO_{2eq}. This represents total GHG emissions from N_2O of just over 1.6 million tonnes of CO_{2eq}.

Based on the foregoing assumptions, we can expect emissions from the wastewater sector to amount to around 1.65 million tonnes of CO_{2eq} in 2050.

E.4 Summary

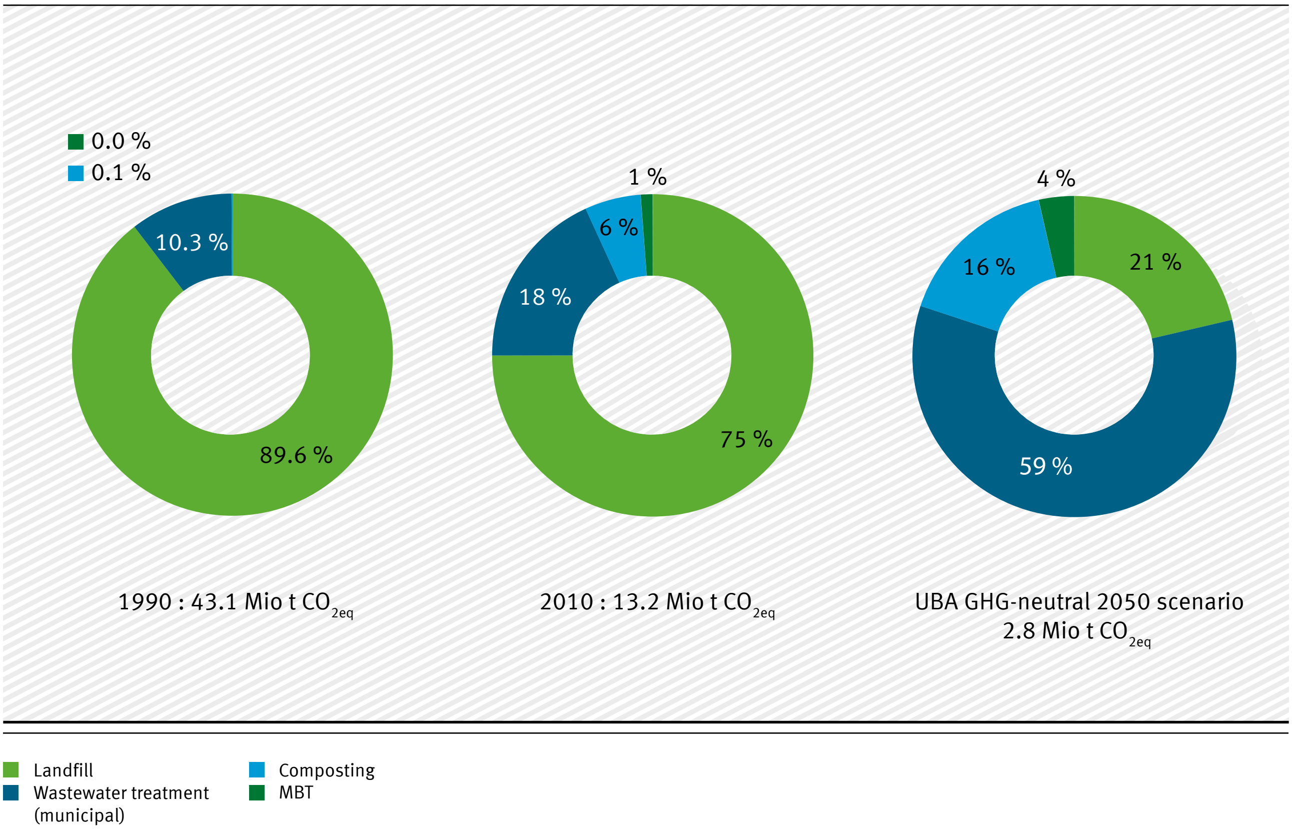
Emissions in the waste and wastewater sectors fell considerably between 1990 and 2010, and are set to decrease further by 2050 to around 2.8 million tonnes of CO_{2eq}. This is a reduction of over 90 % compared with 1990.

Most of this reduction can be attributed to the fall in methane emissions from untreated waste sent to landfill before 2005. In terms of total emissions, the proportion of emissions from the wastewater sector will increase, since emissions in this sector are not expected to fall by as much. Whereas nearly

CCXVI Reference values for nutrients recommended by the German Nutrition Society (Deutsche Gesellschaft für Ernährung e.V. – DGE), the Austrian Nutrition Society (Österreichische Gesellschaft für Ernährung – ÖGE), the Swiss Society for Nutrition Research – SGE) and the Swiss Nutrition Association – SVE).

90 % of total emissions from the waste and wastewater sectors in 1990 could be attributed to methane from landfill sites, this proportion will fall to around 20 % by 2050. By contrast, the proportion of emissions from the wastewater sector will increase from around 10 % to around 60 %.

Figure E-7: Changes in greenhouse gas emissions in the waste and wastewater sector 1990–2050. Own representation based on data from NIR 2012[364] and own calculations.



The main changes that have an impact on waste volumes relate to upstream areas: production and product use. By 2050 we can expect to see a change in production, towards methods that consume far fewer resources and much less energy, and a change in consumption patterns and lifestyles. The quantity of residual waste requiring disposal will fall sharply.

F. Agriculture

F.1 Introduction

The presentation in this chapter is based on an expert opinion[365] written by the Thünen Institute and commissioned by the Federal Environment Agency. This chapter describes current agricultural production and resulting greenhouse gas emissions, mitigation measures and greenhouse gas reduction scenarios for 2050.

Within the source category "Agriculture", as defined by the IPCC, total greenhouse gas emissions from agricultural production in Germany amounted to 67.5 million tonnes of CO_{2eq} in 2010. These include methane (CH_4) emissions from enteric fermentation (digestive processes) and manure management and nitrous oxide (N_2O) emissions from manure, fertilisation and agricultural soils. The Thünen Report identifies technical mitigation potential for these greenhouse gases and outlines different scenarios that illustrate how Germany's agricultural sector can reach the emission reduction target of 35 million tonnes of CO_{2eq} by 2050.

According to the scenarios in this study, by 2050 the source category "Agriculture" will account for more than half of Germany's total greenhouse gas emissions.

F.2 Current agricultural production in Germany in the global context of food and farming

Agricultural production in Germany is described below in a global context with the aim of identifying starting points for GHG mitigation options. The chapter provides an overview of Germany's main agricultural products and draws comparisons with the EU and the rest of the world. Data analysis is based on three-year averages wherever possible. Since only preliminary data, or no data at all, are currently available for later years, the year 2007 was chosen as the baseline (average of 2006, 2007 and 2008). Agricultural production is primarily aimed at producing food for human consumption. However, non-food crops for the production of energy and raw materials also play a significant role. The different uses are described individually and then compared on the basis of the supply balance sheet for agricultural products in Germany. Data on the underlying agricultural structures, resource and land use, the impact of agriculture on the environment and biological diversity can be found in the UBA publication '*Daten zur Umwelt*' (Data on the Environment)[366].

F.2.1 The German agricultural sector in an international context

Due to favourable site conditions, German agriculture is very productive and generates high yields. Around 50 % of Germany's total land area is farmland, of which as much as 60 % is used to produce animal feed.[367] Around half of the land used for fodder production is grassland, which can only be harnessed for the production of food for human consumption through livestock farming. Less than 6 % of agricultural land is farmed organically.

Table F-1 compares land area and production levels of the main agricultural products in Germany with the EU and the rest of the world.

Table F-1: Land areas, production levels and yields of key agricultural products in Germany, the EU and the world[368]

2007 (3-year average)			Germany	EU	World	G share of EU	G share of world
Population	Inhabit-ants	in 1000	82,509	495,064	6,661,733	17 %	1.2 %
Total land area	area	1000 ha	34,867	418,122	13,004,612	8 %	0.3 %
Agricultural land	area	1000 ha	16,939	189,414	4,898,507	9 %	0.3 %
Organically farmed land	area	1000 ha	800	6,111	30,713	13 %	2.6 %
Arable land	area	1000 ha	11,892	109,000	1,376,535	11 %	0.9 %
Permanent crops	area	1000 ha	199	12,206	148,138	2 %	0.1 %
Permanent grassland and pasture	area	1000 ha	4,849	68,208	3,373,834	7 %	0.1 %
Cereals (total)	area	1000 ha	6,771	58,397	695,782	12 %	1.0 %
	production	1000 t	44,737	282,576	2,372,007	16 %	1.9 %
	yield	dt/ha	66	48	34	137 %	194 %
Wheat	area	1000 ha	3,107	25,417	217,110	12 %	1.4 %
	production	1000 t	23,082	132,447	632,907	17 %	3.6 %
	yield	dt/ha	74	52	29	143 %	255 %
Potatoes	area	1000 ha	270	2,209	18,417	12 %	1.5 %
	production	1000 t	11,014	60,772	318,618	18 %	3.5 %
	yield	dt/ha	409	275	173	148 %	236 %
Oilseed rape	area	1000 ha	1,449	6,021	29,299	24 %	4.9 %
	production	1000 t	5,271	17,821	52,395	30 %	10 %
	yield	dt/ha	36	30	18	123 %	204 %
Legumes	area	1000 ha	112	1,373	73,122	8 %	0.2 %
	production	1000 t	320	3,323	61,387	10 %	0.5 %
	yield	dt/ha	28	24	8	116 %	338 %
Vegetables	area	1000 ha	114	2,533	52,500	5 %	0.2 %
	production	1000 t	3,535	65,217	960,427	5 %	0.4 %
	yield	dt/ha	310	258	183	120 %	169 %
Fruit	area	1000 ha	175	6,243	54,230	3 %	0.3 %

2007 (3-year average)			Germany	EU	World	G share of EU	G share of world
	production	1000 t	2,806	62,136	566,197	5 %	0.5 %
	yield	dt/ha	161	100	104	161 %	154 %
Livestock (total)	stocking density	1000 animals	168,342	1,763,584	24,043,989	10 %	0.7 %
		1000 LSU	17,056	129,374	1,975,348	13 %	0.9 %
Livestock density		LSU /ha AL	1,0	0,7	0,4	147 %	250 %
Meat (total)	production	1000 t	7,387	43,269	273,972	17 %	2.7 %
Pigs	stocking density	1000 animals	26,778	159,476	925,952	17 %	2.9 %
		1000 LSU	3,481	20,732	120,374	17 %	2.9 %
	production	1000 t	4,923	22,381	101,601	22 %	4.8 %
	yield	kg/ animal	93	88	79	107 %	117 %
Cattle	stocking density	1000 animals (=LSU)	12,801	90,970	1,579,743	14 %	0.8 %
	production	1000 t	1,193	8,113	65,276	15 %	1.8 %
	yield	kg/ animal	316	279	205	113 %	154 %
Poultry	stocking density	1000 animals	126,071	1,392,105	19,568,725	9 %	0.6 %
		1000 LSU	504	5,568	78,275	9 %	0.6 %
	production	1000 t	1,130	10,806	87,810	10 %	1.3 %
	yield	kg/ animal	1,7	1,8	1,6	98 %	106 %
Milk	production	1000 t	28,386	153,339	681,216	19 %	4.2 %
	yield	kg/ animal	6,877	6,034	2,302	114 %	299 %

Cereals, especially wheat, dominate crop production. Potatoes and oilseed rape also play an important role in comparison with EU and global production. German growers account for 30 % of oilseed rape production in the EU and 10 % of global production. This high proportion is linked to significant yield increases which have been achieved over the last two decades and rising demand for rapeseed oil for biodiesel production. German fruit and vegetable production each account for 5 % of total EU production. Crop yields are above EU and global averages. Yields from animal products are also above

EU and global levels, with the exception of poultry, which is at roughly the same level as the EU and the rest of the world. At 1.0 livestock unit (LSU) per hectare of agricultural land (AL), the stocking density is higher than the EU average (0.7 LSU/hectare AL) and the rest of the world (0.4 LSU/hectare AL). Milk production in Germany is three times higher than the global average.

F.2.2 The use of agricultural products for human consumption in Germany

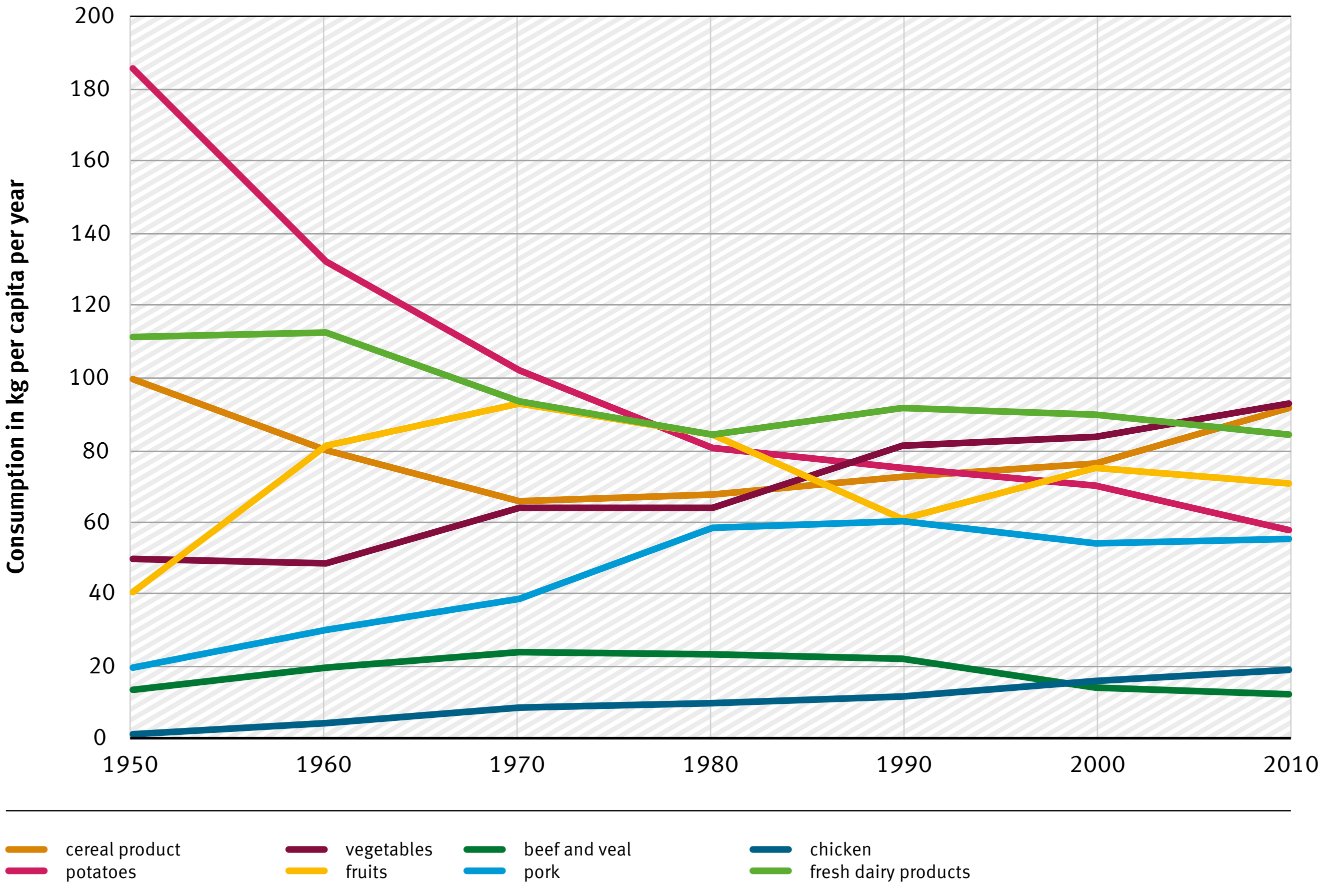
The majority of agricultural products are used for the production of food for human consumption. The dietary behaviour of the German population is determined by a number of factors. An increasingly diverse range of food, changing and varied lifestyles and social structures, greater consumption of ready-made meals and the growing tendency to "eat out" are changing the dietary composition of our food.[369]

Per capita consumption of different foodstuffs provides insights into German eating habits and trends. Potato consumption has declined dramatically from 186 kg in 1950 to 57.8 kg in 2010, whilst cereal products are gaining in popularity again following a severe downturn. Fruit and vegetable consumption has increased overall since 1950, despite major fluctuations, although vegetables have yet to reach the levels recommended by the German Nutrition Society (Deutsche Gesellschaft für Ernährung, DGE). Meat consumption has roughly doubled since 1950 with pork showing the greatest increase. The German appetite for chicken also appears to be undiminished and is now approaching 20 kg per head. Meat consumption has increased less rapidly in recent years and is now virtually stagnant. Consumption of fresh dairy products is in decline, whilst that of processed dairy products such as cheese, yoghurt and cream products is increasing. It should also be mentioned that consumption of legumes, which even in 1950 was relatively low at 1.7 kg per head per year, is continuing to decline. In 2010 demand had fallen to just 0.5 kg/head.[370]

Food consumption refers to the amount of food available for human consumption. However, actual food consumption is significantly lower since the quantity shown does not reflect wastage and losses arising from food processing, storage and preparation as well as industrial use. There is a substantial difference between reported food consumption and actual consumption of perishable goods such as meat and sausage products, bakery products, dairy products and fresh fruit and vegetables since their limited shelf life leads to high loss rates (see Chapter 0).

Germany's current average consumption of some food groups differs widely from DGE nutritional recommendations (see Chapter 0). It advocates greater consumption of plant-based foods which have undergone as little processing as possible, high intake of fibre from cereal products, especially wholegrain products, and secondary phytochemicals. DGE recommendations are aimed at encouraging a healthy, balanced diet.

Figure F-1: Trends in annual per capita consumption of important foodstuffs in kg since 1950[371]



F.2.3 The use of non-food crops for the production of energy and raw materials in Germany

F.2.3.1 The use of renewable energy crops for bioenergy production

In addition to food, the agricultural sector also produces raw materials for energy production (energy crops). The main biofuels are biodiesel, vegetable oils and bioethanol. Biogas produced from arable feedstock and agricultural waste is used mainly to generate electricity. In 2007 feedstock for biogas production was grown on approximately 400,000 hectares of agricultural land (xiv, see Table F-4). The share of land claimed by biogas production has further increased in recent years. The Fachagentur Nachwachsende Rohstoffe (Agency for Renewable Resources) (2012) estimates that over 950,000 hectares of land were under feedstock cultivation in 2012. The more detailed examination of biodiesel, biofuels and ethanol which follows is based on data taken from analyses of material flows in the German biofuel sector for the year 2007.[372] Up until 2010 biofuel consumption in Germany increased by 25 % compared with 2007 due to changes in government funding, with biodiesel and vegetable oil consumption falling and ethanol consumption increasing.[373]

Biodiesel and vegetable oils

In 2007 5.37 million tonnes of oilseed rape and sunflower were grown in Germany. A further 6.75 million tonnes of oleaginous plants were imported (mainly oilseed rape and soya) and 0.63 million tonnes were exported. This yielded a total of 3.75 million tonnes of vegetable oil, of which 2.9 million tonnes was rapeseed oil (see Table F-2). In addition, 4.6 million tonnes of vegetable oil were imported and 1.4 million tonnes were exported. Palm oil and rapeseed oil were of prime importance. Rapeseed oil accounted for the largest share of domestic use (3.1 million tonnes). Almost ⅔ of this was used for biodiesel production. Unfortunately the data available for plant oil statistics are patchy,[374] and import and export figures for oil seeds, vegetable oils, oil cake and meal are sometimes difficult to understand.

Vegetable oils can be used to produce biodiesel, used directly as biofuel or converted to electricity in a combined heat and power plant (CHP plant). Rapeseed oil and soya oil are used mainly for biofuel production, whilst palm oil is predominantly used to generate electricity. All three types, especially rapeseed oil, are used for biodiesel production. In 2007 Germany produced a total of 2.89 million tonnes of biodiesel and consumed 3.264 million tonnes. Since biodiesel streams are difficult to measure, it was only possible to determine the net import (0.37 million tonnes) from the quantities of biodiesel produced and consumed.

Table F-2: Quantity of raw materials used for ethanol production and quantity of ethanol produced in Germany in 2007[375] [376]

Oils[CCXVI] and fats in [1000 t]	Production	Import	Export	Energetic use	including		
					Biofuel	Biodiesel	Electricity generation in CHP plant
Sonnenblumenöl	/	341	80	/	/	/	/
Sunflower oil	/	341	80	/	/	/	/
Rapeseed oil	2,959	1,237	363	3,079	689	2,320	70
Soya oil	646	483	212	597	83	504	10
Palm oil	0	1,230	219	656		66	590
Palm kernel oil	0	290	3	/	/	/	/
Coconut oil	0	314	22	/	/	/	/
Miscellaneous	/	667	461	/	/	/	/
Total	3,605	4,562	1,360	4,332	772	2,890	670

In 2007 Germany used 0.46 million tonnes of ethanol as fuel. Of this, 0.31 million tonnes were derived from domestic production, whilst net imports accounted for 0.15 million tonnes. Table F-3 describes the quantity of raw materials used for ethanol production and the resulting amount of ethanol obtained. Wheat is the principal energy crop used for ethanol production, with a share of 57 %. In other words, 0.6 million tonnes of wheat were used to produce 0.18 million tonnes of ethanol. Rye

CCXVII Indicated as crude oil, excluding imports of pre-processed biodiesel.

accounted for 13 % of the total volume of ethanol, whilst oats/barley, molasses and beets each contributed around 7 %.

Table F-3: Quantity of raw materials used for ethanol production and quantity of ethanol produced in Germany in 2007[377]

Ethanol production	Domestic use in 1000 t	Quantity of ethanol in 1000 t	Quantity of ethanol in %
Wheat	603	179	57
Rye	186	56,4	13
Oats/barley	89.0	26.3	6.7
Maize	10.0	2.89	0.8
Triticale	42.4	13.5	3.7
Other non-floury crops	42.0	12.6	3.6
Molasses/beets	77.4	23.6	7.0
Total		314.4	100

Biofuels of all types should only be used in Germany and in the EU if they have been sustainably produced. The German Biofuel Sustainability Ordinance was passed in 2009 to provide for this,CCXVIII and corresponding certification systems have also been introduced (REDcert, ISCC). Section 37a of the Federal Immission Control Act (Bundesimmissionsschutzgesetz, BImSchG) stipulates a minimum share of biofuel that must be present in the total quantity of fuel placed on the market (with the aim of reducing greenhouse gas emissions), with the additional proviso that this biofuel is produced only by sustainable means.

Despite this requirement for sustainability, biofuels are regarded less positively from an environmental perspective because they often fail to achieve the required GHG reductions whilst making comparatively inefficient use of land. Solar and wind energy provides significantly higher energy yields in terms of land use than energy crops.

F.2.3.2 Use of renewable non-food crops for the production of raw materials

Alongside its use for energy generation, biomass from renewable sources is also used to produce raw materials. Biomass for raw materials is currently grown on around 300,000 hectares of land. The cultivation of biomass for the production of energy has increased substantially in the last 10 years due to wide-ranging incentive schemes.

Table F-4 shows that energy crop cultivation accounts for approximately 87 % of the total area of land used for renewable resources, with raw material production making up just 13 %. Industrial crop cultivation is used predominantly to produce starch, sugar and rapeseed oil. In Germany starch is extracted mainly from maize, wheat and potatoes.[378] Sugar, on the other hand, is obtained almost exclusively from sugar beet. As well as oilseed rape, sunflowers and flax are grown for commercial oil

CCXVIII BGBl I No. 65, pp. 3182–3212.

extraction. Crops cultivated for the production of fibre and dyes or for medicinal use play only a minor role in terms of land use.

Table F-4: Land use for the cultivation of sustainable resources (excluding timber) in 2007 in Germany, divided into industrial raw material and energy crop cultivation[379]

Raw material	Area	Area
	1000 ha	%
Raw material use		
Industrial starch	128	6.26
Industrial sugar	22	1.08
Technical rapeseed oil	100	4.89
Technical sunflower oil	8.5	0.42
Technical linseed oil	3.1	0.15
Fibrous plants	2	0.10
Plants for dyes and medicinal use	10	0.49
Total industrial plant cultivation	**273.6**	**13.4**
Use for energy production		
Oilseed rape and biodiesel/vegetable oil	1,120	54.8
Sugar and starch for bioethanol	250	12.2
Crops for biogas	400	19.6
Miscellaneous	1	0.05
Total energy crops	**1,771**	**86.6**
Total	**2,045**	

There is a limited supply of arable land available and it can be increased only with disproportionately high environmental costs. Consequently there is only a limited amount of land available for the cultivation of renewable resources. Since the world population is continuing to grow and putting food on the table takes priority over putting fuel in the tank, the UBA recommends that in future biomass should be cultivated for cascade use and bioenergy should be produced only from residual and waste materials.[380]

F.2.4 Supply balance sheets

Supply balance sheets have been produced for key agricultural products to describe the agricultural sector and to help develop the scenarios. The data is obtained from the German Statistical Yearbook for Food, Agriculture and Forestry.[381] Information about the use of renewable resources has additionally been obtained from the data in Chapter A.2.3.shows utilisation according to food, animal feed, energy and raw materials production, as well as production levels. Net imports and exports and self-sufficiency ratio can also be deduced from the figures in the table. Net exports are indicated as positive values, and net imports as negative values. Net trade flows for the products and product groups are indicated because the gross import and export flows make it more difficult to evaluate the findings.

The proportion of food consumed in a given country that is also produced in that country is defined as the self-sufficiency ratio. This figure indicates the ratio of certain commodities produced domestically to their overall consumption. It is therefore an indicator of import rates. In Germany, the self-sufficiency ratio for animal products is higher than for plant products. However, it should be noted that Germany is highly dependent on imports of protein feeds for animal production. Fruit, vegetables, oil seeds and fish have a particularly low self-sufficiency ratio of below 50 %, as a result of which demand for these products is largely met by imports. At 150 %, potatoes have the highest self-sufficiency ratio, followed by sugar and wheat at over 120 %. Germany is self-sufficient in most foodstuffs of animal origin with the exception of poultry and butter.

Cereals and oils are used as food, and also as fodder and renewable resources. The self-sufficiency ratio for cereals is over 100 %, especially in the case of wheat. This means that some of domestic production can be exported. The same applies to potatoes and sugar. Self-sufficiency ratios of over 100 % also apply to milk and beef. Pork production has increased since 2007 and the self-sufficiency ratio in pork has now risen to over 100 %. Other products such as oils, oilcake, fruits, vegetables and poultry meat are imported to satisfy demand in Germany.

Table F-5 shows utilisation according to food, animal feed, energy and raw materials production, as well as production levels. Net imports and exports and self-sufficiency ratio can also be deduced from the figures in the table. Net exports are indicated as positive values, and net imports as negative values. Net trade flows for the products and product groups are indicated because the gross import and export flows make it more difficult to evaluate the findings.

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Table F-5: Supply balance sheet for 2007[383] [384] [385]

	Production	Food consumption	Fodder	Renewable resources		Net imports (–) and exports (+)	Self-sufficiency ratio
				raw materials	energy crops		
	in million tonnes						%
Cereals (total)	45.0	115 %	25.4	3.1	1.2	6.0	115 %
Wheat	23.0	126 %	10.3	0.7	0.6	4.7	126 %
Rye	3.0	117 %	1.4	0.0	0.3	0.4	117 %
Barley	11.4	124 %	6.9	2.1	0.1	2.2	124 %
Other cereals	7.6	84 %	6.8	0.3	0.2	−1.4	84 %
Legumes	0.3	102 %	0.3	no data available	no data available	0.01	102 %
Oilseed rape and other oilseeds	5.3	k.A.	no data available	no data available	no data available	no data available	k.A.
Vegetable oils, margarine	2.3	32 %	0.0	1.5	4.3	−4.9	32 %
Oilcake	3.0	39 %	7.9	no data available	no data available	−4.8	39 %
Energy rich fodder	3.3	107 %	3.1	n.a.	n.a.	0.2	107 %
Other fodder	2.5	67 %	3.7	n.a.	n.a.	−1.2	67 %
Potatoes	11.0	154 %	0.7	1.5	no data available	3.9	154 %
Sugar beet	23.3	124 %	n.a.	0.6	no data available	4.5	124 %
Vegetables	3.2	43 %	n.a.	n.a.	n.a.	−4.2	43 %
Fruit	1.3	13 %	n.a.	n.a.	n.a.	−9.0	13 %
Grape must	0.8	k.A.	n.a.	n.a.	n.a.	no data available	no data available
Milk	28.1	120 %	no data available	n.a.	n.a.	4.6	120 %
Meat (total)	6.4	87 %	n.a.	n.a.	n.a.	−0.9	87 %
Beef	1.1	111 %	n.a.	n.a.	n.a.	0.1	111 %

	Production	Food consumption	Fodder	Renewable resources		Net imports (–) and exports (+)	Self-sufficiency ratio
				raw materials	energy crops		
Pork	4.0	90 %	n.a.	n.a.	n.a.	–0.4	90 %
Lamb	0.04	48 %	n.a.	n.a.	n.a.	0.0	48 %
Chicken	1.0	65 %	n.a.	n.a.	n.a.	–0.5	65 %
Eggs	0.8	100 %	n.a.	n.a.	n.a.	0.0	100 %

F.3 Greenhouse gas emissions in the agricultural sector

This chapter focuses on GHG emissions from the source category Agriculture in 2010. Information is based on the 2010 submissions for the National Inventory Report 2012,[386] with additional information taken from inventory data published by the European Environment Agency[387] and the Thünen Institute[388]. All figures are quoted in CO_{2eq}.

Emissions in the source category Agriculture are generated by the following sub-source categories:

- Fermentation: digestion-related CH_4 emissions largely associated with ruminants (cattle, sheep and goats)
- Manure management: CH_4 and N_2O emissions from storing farmyard manure
- Agricultural soils: N_2O emissions from fertiliser, decomposing crop residues, gaseous N loss and N contamination of ground and surface water. The mineralisation of wetlands is a further source of N_2O emissions.

In 2010, GHG emissions from agriculture amounted to around 67.5 million tonnes of CO_{2eq} (see Of this, 29.9 % was attributable to methane (CH_4) emitted during digestion (20.3 million tonnes of CO_{2eq}), a further 8.2 % to CH_4 and 3.3 % to nitrous oxide (N_2O) caused by manure management (7.8 million tonnes CO_{2eq} in total), whilst 58.5 % in the form of N_2O was related to the application of nitrogen fertiliser to the soil (39.4 million tonnes of CO_{2eq}). Cattle farming accounts for 95 % of methane emissions arising from digestion. It is also responsible for the largest share of GHG emissions (CH_4 and N_2O) from manure management (66 %), followed by pig farming (30 %). However, these figures do not yet take into account the mitigation potential of anaerobic digesters (biogas plants) which convert manure into biogas. 40 % of N_2O emissions from agricultural soils originates from fertilisation (including grazing and leguminous nitrogen fixation, which together account for 15.8 million tonnes of CO_{2eq}), 14 % comes from the decomposition of crop residues (5.5 million tonnes of CO_{2eq}) and 34 % from indirect nitrogen emissions to air and water. A further 12 % or 4.8 million tonnes of CO_{2eq} is attributable to N_2O emissions resulting from wetland mineralisation.

Table F-6). Of this, 29.9 % was attributable to methane (CH_4) emitted during digestion (20.3 million tonnes of CO_{2eq}), a further 8.2 % to CH_4 and 3.3 % to nitrous oxide (N_2O) caused by manure management (7.8 million tonnes CO_{2eq} in total), whilst 58.5 % in the form of N_2O was related to the application of nitrogen fertiliser to the soil (39.4 million tonnes of CO_{2eq}). Cattle farming accounts for 95 % of methane emissions arising from digestion. It is also responsible for the largest share of GHG emissions (CH_4 and N_2O) from manure management (66 %), followed by pig farming (30 %). However, these figures do not yet take into account the mitigation potential of anaerobic digesters (biogas plants) which convert manure into biogas. 40 % of N_2O emissions from agricultural soils originates from fertilisation (including grazing and leguminous nitrogen fixation, which together account for 15.8 million tonnes of CO_{2eq}), 14 % comes from the decomposition of crop residues (5.5 million tonnes of CO_{2eq}) and 34 % from indirect nitrogen emissions to air and water. A further 12 % or 4.8 million tonnes of CO_{2eq} is attributable to N_2O emissions resulting from wetland mineralisation.

Table F-6: GHG emissions from the source category Agriculture in 2010 in million tonnes of CO_{2eq} [389 390 391]

	4.A. Digestion	4.B. Manure management		4.D. Soils	Total
	CH_4	CH_4	N_2O	N_2O	
	in million tonnes CO_{2eq}				
Cattle	19.19	3.51	1.67		24.37
dairy cows	*10.90*	*2.32*	*0.84*		*14.06*
other cattle	*8.29*	*1.19*	*0.84*		*10.32*
Sheep	0.35	0.01	0.02		0.38
Goats	0.02	0.00	0.00		0.02
Horses	0.16	0.03	0.06		0.25
Pigs	0.55	1.93	0.46		2.95
Poultry		0.09	0.05		0.14
semi-liquid-manure systems			*1.32*		*1.32*
solid manure systems			*0.95*		*0.95*
Direct N_2O emissions				24.76	24.76
from using mineral fertilisers				*9.13*	*9.13*
from using farmyard manure				*4.68*	*4.68*
from leguminous plant cultivation				*0.47*	*0.47*
from crop residues				*5.51*	*5.51*
from organically farmed soils				*4.79*	*4.79*
from spreading sewage sludge				*0.17*	*0.17*
Direct N_2O emissions from grazing				1.33	1.33
Indirect N_2O emissions				13.27	13.27
from reactive N deposition				*2.21*	*2.21*
from nitrogen leaching and run-off				*11.05*	*11.05*
Total	**20.28**	**5.57**	**2.27**	**39.36**	**67.48**

GHG emissions of CH_4 and N_2O from the source category Agriculture fell by 15.8 million tonnes of CO_{2eq} (−19 %) between 1990 and 2010, and by 2.4 million tonnes of CO_{2eq} between 2005 and 2010 (−3.4 %). Emissions trends since 1990 are shown in Table F-7 These reductions in emissions can primarily be attributed to the decline in both livestock numbers and the use of nitrogen-based mineral fertilisers. Between 1990 and 1992 the reduction in GHG emissions was particularly pronounced due to the structural changes which took place in the former East German states after 1990; annual reductions during this time reached −3.2 million tonnes of CO_{2eq}. In contrast, during the period from 1993 to 2010, average annual reductions amounted to just 0.36 million tonnes of CO_{2eq}. Even after the sharp drop in livestock numbers in the early 90s, cattle stocks continued to decline due to increasing milk yields per cow and the limits on milk production imposed under quota regulations. In contrast, poultry numbers have risen by 13 % since 1990 to over 128 million. However, this livestock category makes a relatively minor contribution to agricultural emissions, accounting for 2 % of GHG emissions associated with manure management.

Figure F-2: Trends in livestock numbers since 1990[392]

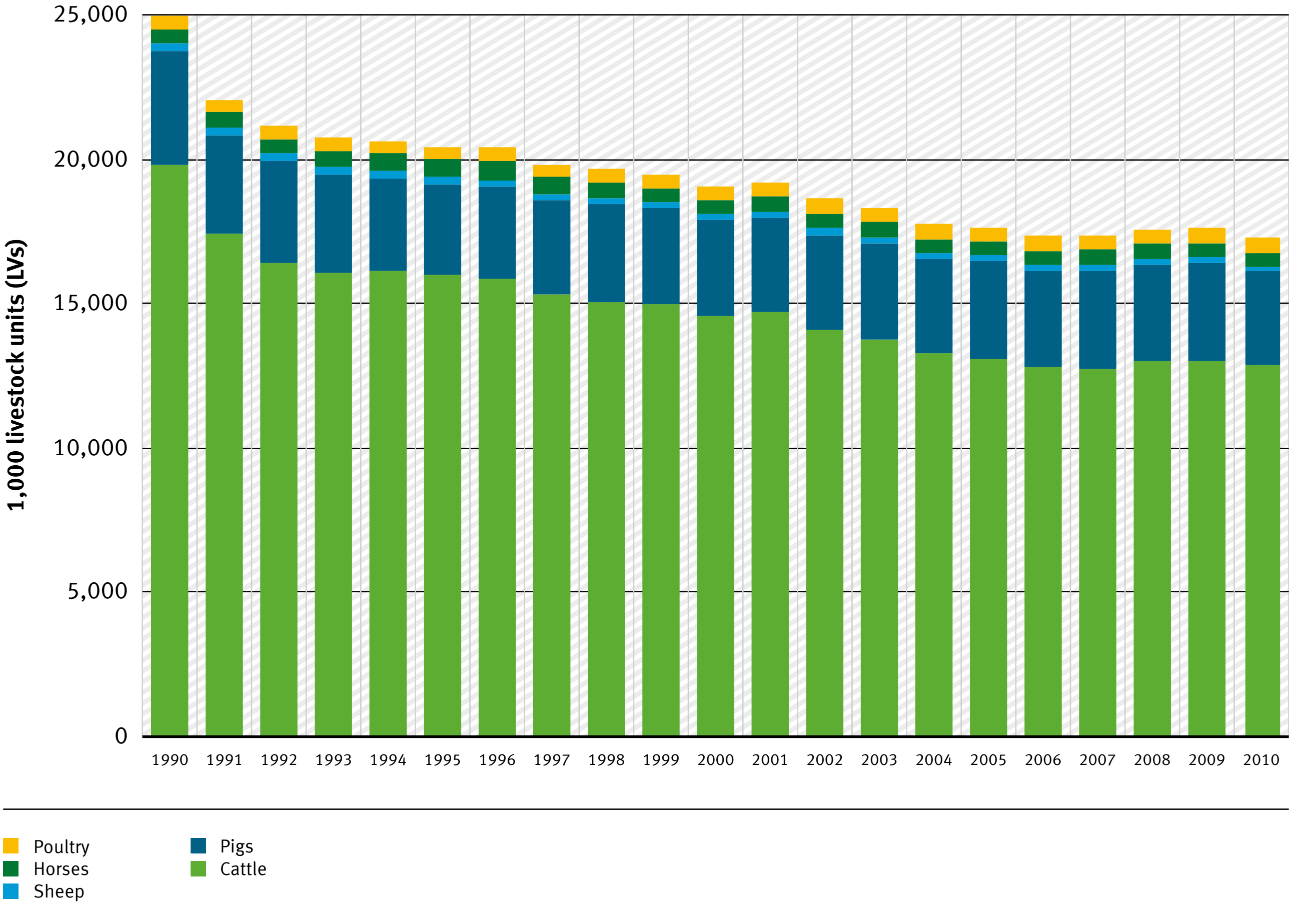


Table F-7: GHG emissions trends in source category 4 Agriculture between 1990 and 2010 in million tonnes of CO_{2eq}[393]

GHG emissions/sinks	1990	1995	2000	2005	2010
	in million tonnes CO_{2eq}				
4. Agriculture	83.21	73.14	73.86	69.85	67.48
A. Fermentation (CH_4)	26.67	23.37	21.97	20.48	20.28
B. Fertiliser and manure management (CH_4)	6.32	5.83	5.73	5.62	5.57
B. Fertiliser and manure management (N_2O)	2.57	2.35	2.27	2.25	2.27
D. Agricultural soils (N_2O)	47.64	41.60	43.89	41.50	39.36
	Percentage change compared with 1990				
4. Agriculture		*−12 %*	*−11 %*	*−16 %*	*−19 %*
A. Fermentation (CH_4)		*−12 %*	*−18 %*	*−23 %*	*−24 %*
B. Fertiliser and manure management (CH_4)		*−8 %*	*−9 %*	*−11 %*	*−12 %*
B. Fertiliser and manure management (N_2O)		*−9 %*	*−12 %*	*−13 %*	*−12 %*
D. Agricultural soils (N_2O)		*−13 %*	*−8 %*	*−13 %*	*−17 %*

It makes sense to deviate from UNFCCC conventions and look at the entire agricultural sector, including upstream services (fertilisers, pesticides, fuel for machines and vehicles) and affected areas (changes of land use through agriculture). Germany's emissions in the source category Agriculture as calculated according to UNFCCC and Kyoto Protocol methodology make up no more than around 43 % of the total direct GHG emissions from the wider agricultural sector including upstream and downstream impacts. The remaining GHG emissions are either recorded in other source categories in the National Inventory (mainly Energy, Transport and LULUCF) or they occur abroad (and are assigned to their country of origin in accordance with UNFCCC guidelines). For instance in 2010, 36.3 million tonnes of CO_{2eq} attributed to the agricultural use of wetlands was recorded in the LULUCF sector (Land Use, Land Use Change and Forestry) and is consequently dealt with in the LULUCF section of this report. Upstream services such as the production of nitrogen-based mineral fertilisers and the direct use of energy have a major impact, as do imports of animal feed. In 2010 Germany imported around 3.5 million tonnes of soya meal and a further 3.5 million tonnes of soya beans[394] for processing into soya oil and soya meal, which is mainly fed to fattening pigs. The majority of German soya imports come from Argentina and Brazil. In these countries soya cultivation is associated with land use changes which can account for more than 90 % of total GHG emissions for this commodity.[395] However, since there is no reliable information about the share of newly established soya plantations and because the complex reasons behind land use changes make it difficult to categorise them, emissions from land use changes are not included in the calculations for up- and downstream sectors. Food processing and transport make roughly equivalent contributions to GHG emissions in the downstream sector.

F.4 GHG mitigation in the German agricultural sector

Selected measures aimed at reducing GHG emissions are described and evaluated here in terms of their mitigation potential, feasibility, cost and impact on other areas.

F.4.1 Improving nitrogen efficiency in fertilisers and animal feed

The use of nitrogen fertilisers makes a major contribution to greenhouse gas emissions in the source category Agriculture. A distinction is made between direct and indirect nitrous oxide emissions (N_2O). Direct nitrous oxide emissions are caused by N inputs from organic and mineral fertilisers, the atmosphere (N deposition), soil, plant residues and biological N fixation, whereas indirect nitrous oxide emissions are caused by the release of reactive nitrogen compounds, such as nitrate and ammonia, into the environment. These reactive N compounds produce nitrous oxide as a byproduct during nitrification and denitrification processes. The severity of greenhouse gas emissions is determined not only by the level of N input, but also by factors such as site conditions, climate (e.g. rainfall), temperature (e.g. ground frost and especially thawing), top soil characteristics and land management practices.

The intensity of GHG emissions, for example per grain equivalent unit, can be reduced by improving nitrogen efficiency in agricultural systems. This involves either reducing nitrogen inputs whilst maintaining yields (outputs), or maintaining inputs (upstream services) whilst increasing yields. The amount of nitrogen not taken up by crops is thus reduced and hence the input/output ratio. To achieve this, fertilisation schedules must be carefully planned with regard to timing, application rates and spreading techniques and ensuring that they are suitably adapted to the climatic and site conditions.[396]

One of the principal aims of plant and animal breeding programmes is to improve nitrogen and protein efficiency. Past progress in this field has led to average yield improvements of between 1.0 and 1.5 % a year. However, it is not clear whether this continuous rise can be sustained until 2050 or whether we can expect a decline in yield improvements.

Nitrogen surpluses can be reduced by determining the crop's fertiliser requirement, paying closer attention to sources of supplemental nitrogen provided by organic soil substances during the growing season and analysing the nutrient contents of organic fertilisers. The savings potential depends on the initial nitrogen surplus. According to the federal government's strategy for sustainable development, the total quantity of excess nitrogen, calculated as the national farm gate balance, should have fallen to 80 kg N/hectares of agricultural land (AL) by 2010. In recent years, however, the nitrogen surplus has exceeded this figure.[397] The Federal Environment Agency recommends a long-term goal of 50 kg N/ha per year (as national farm gate balance surpluses). A reduction in nitrogen balance surpluses will mitigate the risk of nitrate leaching to groundwater and is therefore necessary to achieve the objectives of the Water Framework Directive (good status of all water bodies). However, this is only associated with a reduction in GHG emissions if the total quantity of nitrogen used is also reduced.

Based on IPCC emission factors (1996),[398] emissions of 17.5 kg of CO_{2eq} per kg nitrogen can be saved by improving the productivity of nitrogen fertilisation. This figure includes 7.5 kg of CO_{2eq}/kg N cut from the preparation of synthetic chemical nitrogen fertilisers (although these savings are allocated to the energy and industrial emissions sectors), as well as 6.1 kg of CO_{2eq}/kg N from direct and 3.9 kg of CO_{2eq}/kg N from indirect nitrous oxide emissions from fertilised soil.[399] Reducing the nitrogen application rate by 20 kg/ha whilst maintaining yields would reduce GHG emissions by 5.77 million tonnes of CO_{2eq} per year. Of this, 43 % would be cut from nitrogen-based mineral fertiliser production in the chemical industry – these savings would be recorded in the source categories Energy and Industrial Processes in the greenhouse gas inventory, so this is where their impact would be felt. At 57 %, direct and indirect nitrous oxide emissions from soil caused by agricultural fertilisers would deliver the greatest share of savings.

F.4.2 Farmyard manure for biogas production

Greenhouse gas emissions from manure storage can be avoided and fossil fuels saved by converting farmyard manure and other agricultural waste and residues to biogas. Biogas generation from farmyard manure is thought to have strong potential, although this is yet to be fully exploited. Germany produces approximately 200 million tonnes of farmyard manure annually, which could be used to produce around 3.46 billion m^3 of methane. This would meet 2 % of Germany's electricity needs. However, the majority of biogas in Germany is currently obtained from biomass crops.[400]

The use of farmyard manure for biogas production reduces greenhouse gas emissions not only by providing an alternative to fossil fuels, but also by reducing GHG emissions associated with the uncovered storage of farmyard manure. To achieve this, the fermentation residues must be stored under gas-tight conditions. Farmyard manure thus offers greater GHG mitigation potential than biomass crops.[401]

Despite lower methane yields per tonne of substrate, electricity generating costs may fall as the proportion of farmyard manure used increases. At present, however, generating costs for slurry cannot compete with those of silage maize. Therefore it would make sense to promote the use of farmyard manure for biogas production, for example through the Renewable Energy Sources Act (Erneuerbare Energien-Gesetz, EEG). However, any such scheme should be based not on the proportion of slurry in the feedstock, but rather its share of the renewable energy generated. Substantial costs and emissions may arise during transport from the farm to the biogas plant, depending on the distance, so small to medium-sized plants are more appropriate for farmyard manure than very large ones.[402]

GHG mitigation costs are lower for biogas production from farmyard waste than from biomass crops. An increase in the percentage of slurry in the feedstock brings about a corresponding fall in GHG mitigation costs. Transporting farmyard manure from farm to biogas plant increases GHG mitigation costs. Transport distances should therefore be kept to a minimum to retain the benefits of lower mitigation costs compared with silage maize. It is also important to bear in mind that high volumes of traffic do not endear the public to the use of farmyard manure for biogas production, and that road maintenance costs may also increase.[403]

The use of farmyard manure as feedstock for biogas production also has a positive impact on other environmental goals. These benefits stem from the fact that farmyard manure can to some extent replace energy crops such as maize. This, in turn, reduces the environmental impact of maize cultivation. Maize crops are intensively fertilised, which can increase nitrogen and pollutant inputs to water and soil. Maize is also a humus-depleting crop that is planted with wide row spacings and takes a long time to cover the ground. These three factors increase the risk of erosion, which poses a further threat to soil and water.[404] Dispensing with energy crop monocultures would reduce this risk and also help protect biodiversity.[405] Ploughing up grassland for maize cultivation breaks down the humus, leading to further harmful emissions (CO_2, nitrous oxide). These effects are particularly pronounced on carbon-rich soils, such as reclaimed fenland. In the annual National Inventory Report issued by the UBA these GHG emissions are allocated to Land Use, Land Use Changes and Forestry (LULUCF). Largely dispensing with energy crop monocultures would go a long way towards reducing these adverse effects.

F.4.3 Milk production

ncreasing the milk yield per cow reduces product-related GHG emissions per kg of milk because the cow's energy demand (energy metabolism) and associated GHG emissions are distributed over a larger volume of product.[406] This effect is particularly pronounced where initial yields are lower. Where milk yields are already high, the ongoing reduction in milk-related GHG emissions diminishes. By reducing the rate of introduction of heifers into a dairy herd to replace ageing cows (replacement rate), fewer replacement heifers (sexually mature females that have not yet produced a calf) are required, thereby reducing GHG emissions. The effectiveness of this approach is based on the fact that less feed is used for animal growth.

Between 1990 and 2010 the milk yield per cow increased by 48 %, whilst GHG emissions per dairy cow increased by only 23 % during the same period.[407] According to model calculations performed at the Thünen Institute based on dairy cow and heifer numbers, the replacement rate in dairy herds in recent years has been around 0.3. If the herd replacement rate is lowered, cows will be replaced by higher yielding heifers less frequently, as a result of which milk yield increases may rise more slowly than in the past.

Increasing milk yields and lowering replacement rates are both in the farmers' commercial interest since unit costs of milk production fall as yields rise, and reducing the rate of introduction of heifers cuts down on heifer-rearing costs. However, these two goals appear incompatible, as modern, high-performance dairy cows are not associated with longevity and a large number of lactations. From the point of view of climate protection, this means that in the case of high-performance dairy cows, the time until the first lactation, when methane emissions from the cow are not offset by product (milk), is even more critical if the total productivity of the cow (total milk produced) is lower. On the other hand, assuming that beef consumption remains the same, whilst the lifespan and overall productivity of dairy cows increases, demand for beef cattle would increase, as would their emissions.[408] The parameters under consideration and the chosen system boundaries play an essential role in comparisons of life-cycle assessments.

It is beyond the scope of this document to examine the animal welfare problems that may arise through further attempts to increase milk yields. Greater attention will be paid to this in future in view of the revised Art. 20a of German Basic Law (putting animal welfare on an equal footing with environmental protection) and its implementation through legislation. It seems likely that this will result in relatively tight restrictions being placed on strategies aimed at tackling climate protection through increased milk yields.

Milk yield increases place greater demands on herd management practices since poor husbandry or feeding regimes can quickly lead to health problems and performance losses in dairy cows. A growing demand for feed concentrates is reducing the ratio of roughage (silage maize, green fodder, hay and silage) in the feed. At the same time, roughage quality requirements are increasing, which is compelling farmers to manage grassland more intensively (cutting earlier in the season to obtain more digestible, energy-rich basic fodder). These changes to the fodder ration of dairy cows and the reduction in the number of replacement heifers can adversely affect the use and management of grassland at a time when farm practices which maintain and encourage soil protection and biodiversity should be promoted. If the grassland is additionally ploughed, ensuing humus degradation substantially increases GHG emissions (allocated to the LULUCF source category rather than agriculture in the emission inventory).

F.4.4 Organic farming

A substantial proportion of GHG emissions caused by conventional farming can be cut by switching to organic farming. A review of the literature by Flessa et al.[409] shows that organic farming emits fewer greenhouse gases per hectare of agricultural land than conventional farming; only 0.92 tonnes of CO_{2eq} per hectare on average instead of 2.67 tonnes.[410] However, the results of such comparisons vary enormously since the farms included in the study are comparable only to a limited extent.

Since organic farming generally produces lower yields per hectare, a comparison of GHG emissions based on unit of product produced on the land rather than unit of land itself could reduce, if not entirely wipe out, the climate-friendly benefits of organic farming compared with conventional farming. A well-managed conventional farm would then be just as good as or even better than a poorly managed organic farm.[411] This suggests that both conventional and organic farmers should be aiming for climate-friendly best practices.

Research shows that in most cases organic crop cultivation emits fewer or at least comparable greenhouse gas emissions to conventional cultivation when the two systems are compared on both area and product basis.[412] Organic farming considerably reduces energy consumption and greenhouse gas emissions by not using manufactured nitrogen fertilisers and pesticides.

Product-related emissions per kg are considerably higher for animal products than plant products. The findings of different studies of animal products vary even more widely than those of plant products. The level of product-based greenhouse gas emissions largely depends on the productivity of the respective organic farm.[413] However, lower livestock numbers, longer replacement cycles and correspondingly lower replacement rates can reduce emissions in organic farming.

Organic farming practices mainly use solid manure systems (deep litter with straw) on animal welfare grounds.[414] The aerobic conditions present in solid systems result in fewer methane emissions than liquid manure systems. At the same time, however, the amount of N_2O emitted during storage increases. Further indirect N_2O emissions are caused by the release of ammonia.

Organic land management promotes the temporary storage of carbon in the soil. Organic farming practices such as the use of farmyard manure, green manure, cover crops and undersowing, improved crop rotations and the return of crop residues to the soil promotes humus formation in agricultural soils.[415] Organic farms capture on average around 400 kg CO_2 /ha per year.[416] However, carbon sequestration after switching from conventional to organic farming can be regarded only as a temporary CO_2 sink.[417] Once the soil achieves a (new, higher) humus balance, no more CO_2 can be absorbed. Gattinger et al.[418] were able to show in a meta-analysis that organically farmed soil ultimately contains no more than approx. 2–3 tonnes of C per hectare more organic soil carbon than conventionally farmed soil. A significant difference in sequestration rates was observed only in the first 20 years of organic farming. These CO_2 sinks are also highly vulnerable. Further cultivation of the land without continuing to return organic matter to the soil would lead to renewed release of CO_2. When switching back to conventional farming, the same processes take place in reverse, i.e. humus is partially broken down again and stored CO_2 is released. After a number of years the land returns to the starting point before the switch to organic farming took place, i.e. the conversion processes are fully reversible.

The cost of converting to organic farming and of maintaining this form of land management is largely reflected by the level of government subsidy. In addition to other agricultural subsidies, organic farms receive a special, area-based agri-environmental subsidy. This takes account of the fact that organic farming helps protect the environment in a variety of ways. It also acts as an incentive for organic production and offers more security to those intending to switch, as this process is not without risk.

Due to fewer livestock, a smaller proportion of cereals in the crop rotation and lower yields, organic farms on average had lower revenues as well as higher personnel and operating costs during the 2005/06–2009/10 financial year.[419] However, the authors found that organic farms achieved higher profits than comparable conventional farms due to reduced expenditure on upstream services combined with agri-environmental subsidies amounting to 148 euros per hectare. Despite this, it must be borne in mind that profitability varies considerably across organic farms.[420]

Subsidies should ensure that the expansion of organic farming in Germany keeps pace with the rising demand for organic products. In this way Germany will reap the environmental benefits of organic farming for rural development rather than relying on imports to fill the gap between supply and demand. The UBA thus recommends that Germany's agri-environmental programme provides for a well-funded 'second pillar of the Common Agricultural Policy' (rural development) backed up by a willingness of individual federal states to provide co-financing (because under EU law, Brussels and national governments much each pay half of the costs of subsidising the switch to organic farming).

The federal government's sustainability strategy aims to increase to 20 % the proportion of Germany's farmland that is used for organic farming (this is a long-term goal for which no timeframe has been set). A corresponding scenario is described and analysed below. To achieve this goal by 2050 the current switching rate will have to be at least maintained. Since subsidies are provided not only for switching to organic farming, but for continuing to farm organically, this means that the budget earmarked for organic farming will have to be gradually but continuously increased over the next decades.

As well as promoting climate-friendly production, organic farming reduces other **external environmental costs**. Better soil fertility and the avoidance of mineral nitrogen fertilisers protect water bodies and surface water from harmful inputs. Furthermore, existing grassland is retained as forage areas and may even be expanded as more farms switch to organic land management. Supplies of carbon stored in grassland are not released. Numerous studies also confirm the benefits of organic farming on biodiversity.

F.4.5 Reducing production levels

Reducing production levels in the German agricultural sector is a means of mitigating GHG emissions associated with production. However, this is only a viable climate protection option if productivity restrictions do not cause production to increase outside Germany, giving rise to the same or even higher production-related GHG emissions. The objectives of grassland use and management must be taken into account when restricting ruminant numbers (which have high GHG emissions per animal and product unit due to enteric CH_4 emissions). It should be borne in mind that in Germany large areas of land are still used for field forage cropping e.g. silage maize or clover grass. A reduction in ruminant numbers could concentrate the remaining ruminant herds on grassland areas whilst restricting forage crop cultivation in favour of other arable crops. The objectives of grassland management can then be implemented with parts of the dairy herd (heifers, dry cows).

The scenario analyses described below for reducing GHG emissions from agricultural land use and changes to land use are based on the assumption that grassland will not be turned into arable land and agriculturally used wetlands will be restored and re-wetted (see Chapter Error! Reference source not found.). Whilst the preservation of grassland allows farming to continue, largely by providing a food supply for ruminant livestock, wetland restoration would require these areas to be taken out of agricultural production entirely or at least to a very large extent. More information about these measures, which also help protect water bodies, soil and biodiversity, can be found in Flessa et al. (2012).[421]

F.4.6 Measures in the food consumption sector

Measures that can be implemented outside the agricultural sector to reduce or modify the consumption of agricultural products (in Germany) are considered below. These measures have no direct impact on emissions in the German agricultural sector. Agricultural production in general does not necessarily have to be curbed as demand for food in Germany falls; instead exports of agricultural products can be increased.

F.4.6.1 Reducing food waste

Food waste occurs along the entire value-added chain. If it could be avoided, this would make a substantial contribution to reducing greenhouse gas emissions. Downstream, food waste occurs in the food processing industry, in the wholesale and retail sector and at consumer level, especially in private households. It is estimated that half of this waste is avoidable. Cutting down on food waste has huge potential and raises the question of what level of emission reductions could be achieved by this means.

In agricultural production alone, losses account for around 3 % of overall production in Germany.[422] Products may be deemed unfit for sale due to defects and damage, or losses caused by incorrect storage. By the same token, quality requirements exist which must be met. In the case of commonly occurring cereal varieties, these losses amount to around 1 % of total production. Three percent of the potato harvest is non-marketable. Fruit and vegetables have the highest loss rates among plant products, at 5 and 10 % respectively. This is attributable to their highly perishable nature and limited shelf life.[423]

The FAO estimates that one third of food produced globally is not used for human consumption. This equates to 1.3 billion tonnes of food a year lost during the course of production processes, or simply thrown away. In developing countries most food losses occur during production, while in industrialised countries the retail and consumption stage is responsible for the majority of food waste.[424] Public awareness of this issue has increased in recent years. However, as yet no reliable data are available about the quantity of food waste, and statements made in this regard are therefore based only on estimates. In the downstream sector food waste is generated by stakeholders in the food chain, from the food processing industry, the wholesale and retail trade to consumers (large-scale consumers and private households). It is estimated that 10,970,000 tonnes of food per year goes to waste in Germany.[425]

shows the proportion of waste generated by different areas of the value-added chain.

Overproduction, poor planning, technical problems, legal restrictions and retained samples for quality assurance purposes constitute sources of food waste in industry. Careful, forward-looking operational planning can reduce waste, but never eliminate it entirely since the demand for products is not consistent.[426] Furthermore, a large amount of waste is unavoidable. In the case of animal products in particular, the proportion of non-edible constituents (e.g. bones), is very high.[427]

Table F-8: Food waste in Germany by areas of the food value-added chain[428]

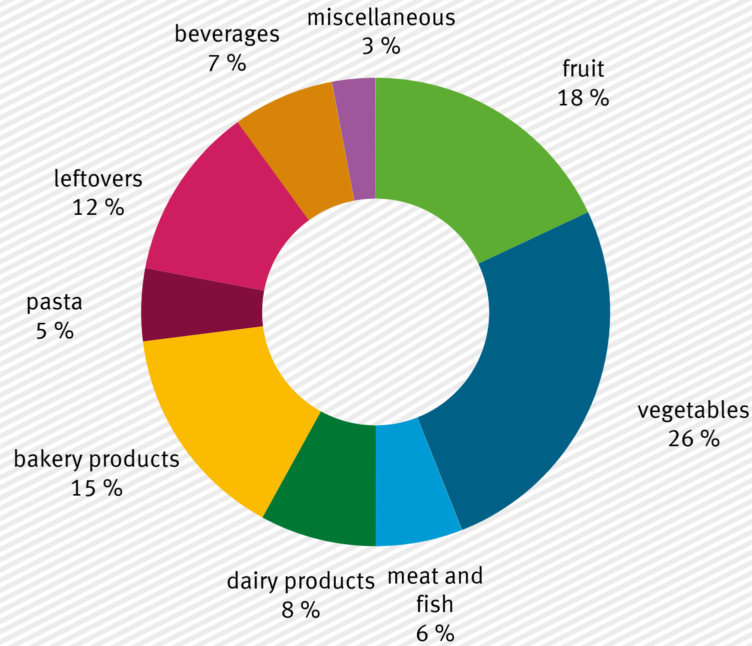
Food waste	in million tonnes	percentage share
Food processing and industry	1.85	17 %
Wholesale and retail trade	0.55	5 %
Large-scale consumers	1.9	17 %
Private households	6.67	61 %
Total	10.97	100 %

Food waste from the trade sector is comparatively low, accounting for 5 % of the total share. Waste is generated by oversupply as retailers aim to stock a huge variety of goods. Unmarketable or unsaleable products (best-before or use-by date expired) and products that do not meet strict requirements for quality, freshness and appearance have to be rejected. Organisational difficulties or inadequate storage of perishable goods also generates waste. A substantial proportion of this food is passed on to charitable organisations such as food banks. This approach is a sensible way to avoid food waste and could be intensified.

Large-scale consumers, including the catering and hospitality industry, in-company catering and institutions such as retirement and care homes, hospitals and schools, are responsible for 17 % of food waste. Waste arises due to internal organisational procedures in the kitchen, incorrect storage, processing or miscalculation. Failure to adapt portion sizes and menu choices to customer needs can also create waste. It is assumed that around 48.5 % of waste in this area is avoidable.

Private households account for the majority of food waste. An estimated 5.05 million tonnes of food waste is discarded via the municipal waste collection system each year. This corresponds to 75 % of household food waste, or around 62 kg per capita. Around 70 % of this ends up in the residual (non-recyclable) household waste bin and 30 % is disposed of as green waste (compostable). Some ⅔ of this waste is regarded as avoidable or partially avoidable. Food waste is also disposed of via other routes such as self-composting, feeding to pets or pouring down the drain, but it is difficult to estimate the additional amounts being disposed of in this way. Avoidable waste can be attributed to various causes such as inadequate storage, lack of knowledge of stocks, expiry of best-before date and use of special ingredients required only in certain dishes. Partly avoidable food waste covers mixtures of avoidable and unavoidable waste, for instance leftovers or waste generated due to different consumer habits (e.g. apple peel, bread crusts). Since no data are available on the composition of food waste by product group, the information below is based on estimates by Hafner et al.[429] The main product groups are shown in the diagram below.

Figure F-3: Share of avoidable and partially avoidable waste by principal food groups[430]



Fruit and vegetables account for the largest share of avoidable food waste, followed by bakery products and leftovers. Each year German households discard food to the value of 16 to 21.6 billion euros. This corresponds to between 10 and 14 % of total expenditure on food and non-alcoholic beverages; in other words, 200 to 260 euros per capita and per year of avoidable spending on food.[431]

In order to reduce waste, the food industry is advised to optimise operations and processes and implement more resource-efficient management systems. The UK has taken the promising step of setting up a voluntary agreement with the grocery sector, saving around 1.1 million tonnes of food and packaging waste a year. The food retail sector can avoid waste by actively promoting products that are nearing their best-before date. Similarly, regional and unpackaged goods which encourage consumers to buy smaller quantities can help to reduce waste. Large-scale consumers can be encouraged to avoid waste and optimise material flow management through the awarding of certificates, which, in turn, highlight their green credentials. It is particularly important to raise awareness of the issue of food waste in private households and encourage households to use food more efficiently.[432]

However, it is not enough to consider food waste purely from the point of view of the downstream sector, since resources intended for agricultural production can also be lost, leading to unnecessary environmental pollution. Consequently, reducing food waste can also help to conserve resources and prevent environmental pollution. The needless wastage of material flows in the upstream chain cause considerably higher losses. A North Rhine Westphalia waste study[433] investigated the relevance of the upstream chain for selected products using the material footprint and carbon footprint as indicators. The material footprint indicates the cost of material resources required by a product or activity across the entire added-value chain. The carbon footprint indicates the amount of direct and indirect GHG emissions generated by a product or activity.

The results of this study show that the environmental impact of different food groups cannot be linked to their share of food waste alone. For example, fruit and vegetables account for 44 % of food waste, yet their environmental footprint is lower; 28 % for the material footprint, falling to 18 % for the carbon footprint. The relevance of cereal products is also lower than their share of food waste suggests. Animal food products, on the other hand, have a significantly higher environmental footprint, which is not evident from their smaller share of waste.

Deriving assumptions about food waste in 2050

Calculations about food consumption in the year 2050 are based on the assumption made in a UBA study on 2050 energy targets[434] that the population will fall to 87.9 % of its current level. If eating patterns remain the same, food consumption will also fall to this level. However, if eating habits were to change in line with DGE recommendations, consumption levels would change accordingly. Consumption of cereal products and vegetables would rise above current levels, despite a declining population, whilst meat consumption would fall to around a quarter of current levels.

It is assumed that consumption will be reduced by cutting down on household food waste, in addition to following DGE (German Nutrition Society) guidelines. Calculations are based on the study by Hafner et al.,[435] which analysed the proportion of food waste allocated to certain product groups. The total quantity of domestic food waste by product group identified in the study is shown in column 1.

Table F-9: Domestic food waste by product group, own calculations[CCXIX]

	Total food waste	Avoidable share of waste	
		as percentage of total	assuming: 50 % avoidable
Fruit	18 %	35 %	6 %
Vegetables	26 %	45 %	12 %
Meat and fish	6 %	55 %	3 %
Dairy products	8 %	75 %	6 %
Bakery products	15 %	75 %	11 %
Pasta	5 %	75 %	4 %
Leftovers	12 %	60 %	7 %
Beverages	7 %		0 %
Miscellaneous	3 %	30 %	1 %

Around 50 % of all food waste is considered to be avoidable. The proportion of avoidable food waste varies according to different product characteristics such as perishability and amount of inedible constituents (e.g. bones, leaves). Assumptions about relevance were made on the basis of the study's estimates of the proportion of avoidable food waste by product group. Dairy products and bakery products are already sold in consumable form. Thus it can be assumed that the majority of food waste in these product groups (around 75 %) is avoidable. It is further assumed that 60 % of leftover food waste is avoidable. In contrast, meat, fruit and vegetables have a larger amount of non-consumable parts which are disposed of as unavoidable waste or used for secondary purposes, e.g. animal feed. Calculations are based on the assumption that 55 % of food waste from meat is avoidable, 45 % from vegetables, 35 % from fruit and 30 % from miscellaneous sources. Food consumption levels will be

CCXIX Based on 435.

further reduced by cutting avoidable food waste by 50 %. Consequently, consumption of products with a higher proportion of avoidable waste (e.g. dairy products and bakery products) will differ more greatly.

The shares of avoidable food waste in the "leftovers" and "miscellaneous" categories are allocated to potatoes (4 %), fats and oils (3 %) and eggs (1 %), since consumption data is available for these products, but no waste data. The beverages share was distributed across the remaining product groups.

F.4.6.2 Climate-friendly food and nutritional guidelines recommended by the DGE (German Nutrition Society)

The food sector in Germany is currently responsible for around 16 to 22 % of total greenhouse gas emissions. This figure covers food production, processing, distribution and sales.[436] Consequently, it is important to consider potential GHG savings along the entire added-value chain. Changing the dietary habits of the German population has the potential to mitigate substantial GHG emissions. The production of animal-based food and the growing trend to consume highly processed foods in particular cause high emissions. Reduced consumption of these foods would promote climate-friendly eating whilst at the same time complying with DGE nutritional recommendations. The origin of food is also an important factor, since imported goods have longer transit times which are generally associated with higher greenhouse gas emissions.

The table below compares the average food consumption and intake of the German population with nutritional guidelines recommended by the DGE and the Vegetarian Alliance Germany (VEBU), which advocates a vegetarian diet. The national consumption survey found that around 1.6 % of Germans are vegetarian whilst a further 8 to 9 % are semi-vegetarian, eating a low-meat diet.[437] Both dietary practices are based on the principles of a balanced wholefood diet. Nutritional recommendations are generally given in grams of food per day or week and have been extrapolated to annual consumption values. Germany's current average consumption of some food groups differs widely from DGE nutritional guidelines.

Meat consumption in particular is considerably greater than recommendations. High meat consumption is linked to increased health risks. This is attributed to high levels of saturated fatty acids and cholesterol, and also to preparation methods such as smoking, frying, grilling and curing. However, evidence also suggests that insufficient consumption of foods containing protective ingredients, such as fruits, vegetables and whole grain products, could play a greater role in the development of disease.[438] Nevertheless, it is important to emphasise that diseases associated with nutrition may have several causes and that food is only one of many factors.

Table F-10: Food consumption (2007) and nutritional guidelines recommended by the DGE and the German Vegetarian Alliance (VEBU)[439, 440, 441, 442]

Product	Consumption (amount purchased)	Consumption (amount actually consumed)	Recommendation		Percentage share of	
			DGE	VEBU	DGE guidelines	VEBU guidelines
	in kg per capita and year				%	
Cereals, bakery products, rice	93	100.7	166.1	146	78 %	89 %
Potatoes	61.4	29.6				
Vegetables	90.1	85.0	146	at least 146	58 %	58 %
Fruit	125.1	92.7	91.3	at least 109.5	102 %	85 %
Protein products						
legumes	0.5			10.4		
soya products and other meat substitutes		0.9		36.5		3 %
Nuts and seeds				16.4		
Vegetable oils and fats	26.1	8.9	12.8	11	70 %	82 %
Meat	88.2	60.5	15.6–31.3	0	388 %	
veal	12.4	8.5				
pork	54.3	39.1				
chicken	17.8	10.7				
Milk and dairy products	130.4	92.9	91.3	opt. 91.25	102 %	102 %
cheese	22.2	15.3	20.1	opt. 18.25	76 %	84 %
Eggs	9.5	23.5	6.3	opt. 6.24	110 %	111 %
Fish	15.5	9.5	11.0	0	87 %	

FAO projections assume that global demand for animal-based foods will have increased substantially by 2050. In emerging economies in Asia and Latin America in particular, consumption is rapidly approaching per capita consumption levels of industrialised nations. In Germany there is a growing interest in vegetarianism, but uptake still remains at a very low level.[443] The rise in the number of vegetarians is especially noticeable among the younger members of the population, and women in particular.[444]

Compliance with DGE nutritional guidelines will entail a shift in consumption habits in German society away from animal-based products and towards plant-based products. This would reduce meat consumption by half, and sausage products by almost three quarters. At present, around 40 % of nutritional protein in Germany is derived from plant sources and around 60 % from animal sources. Protein-rich legumes provide an alternative to animal proteins. Another option is to consume tofu and seitan (wheat gluten) products, which are often used as meat substitutes. According to Goodland and Anhang[445] these are healthy, cheap and ecologically sound alternatives to animal-based foods. They maintain that these products have great potential to reduce GHG emissions in the agricultural sector.[446]

However, a meat-free diet is not per se more climate friendly than a non-vegetarian one. For instance, greenhouse gas emissions may rise if meat is replaced with rice (paddy fields are a major source of methane emissions; this is not the case with upland rice) or greenhouse-grown vegetables (high heating energy consumption, unlike seasonal outdoor vegetables). The same can be said of the consumption of regional products. Importing products from overseas, particularly by air, causes substantial GHG emissions. Regional products, however, are often transported in smaller vehicles that are not fully loaded, which has the disadvantage of greater logistical inefficiency. Grünberg et al.[447] maintain that southern Europe's more favourable growing conditions for certain varieties of vegetable, for instance, may offset higher transport emissions compared with regionally produced food grown under less favourable conditions. Furthermore, upstream services of regional products may also be imported, for instance animal feed.[448]

The recommended guideline for milk and dairy products more or less corresponds to actual consumption in Germany. The DGE recommends a daily allowance and stresses the importance of dairy products for providing protein, vitamins and calcium. Dairy farming accounts for around 1/3 of agricultural greenhouse gas emissions. We have to consider how it might be possible to reduce emissions by 50 % if we are to continue consuming high levels of dairy products. Furthermore, we are advised to eat more vegetables, cereal products, potatoes and rice. Germany's self-sufficiency ratio for fruit and vegetables is comparatively low (vegetables: 40 %, fruit: 21 %) and consequently a substantial amount is imported. If we increase vegetable consumption and maintain fruit consumption at current levels, imports would presumably increase, as conditions in Germany do not facilitate self-sufficiency on the basis of current consumption habits. Food imports are associated with increased greenhouse gas emissions due to longer transport routes. Consumption of regional and local products generally emits fewer greenhouse gas emissions and could be extended. Increased demand for carbohydrate-rich foods (cereals, potatoes and rice) could largely be met by boosting potato production. Potato cultivation produces more food on less land than cereal production, although potatoes have high post-harvest losses associated with storage. Around 5 % of the potato harvest is lost due to respiration, evaporation, germination and rot.

F.5 Greenhouse gas reduction scenarios for 2050

The aim of the scenario analyses is to indicate ways in which the GHG emissions target of 35 million tonnes of CO_{2eq} per year for the source category Agriculture can be achieved.

The scenario analyses focus on three areas of action relating to climate protection policy which are relevant to GHG emissions in the German agricultural and food industry:

- The focus lies on agricultural climate protection measures aimed at reducing direct emissions in the source category Agriculture to 35 million tonnes of CO_{2eq}. Common cross-scenario assumptions are made about the availability of agricultural land and the use of agricultural products in Germany.
- Irrespective of the individual scenarios, the area of agricultural land will decline substantially by 2050 due to the restoration of wetlands currently used for agriculture (motivated by climate change policy) and the conversion of agricultural land to residential land and transport infrastructure.
- Figures for the domestic use of agricultural products to provide food for the German population and as renewable non-food crops are also standardised across all scenarios. The production volumes described in the agricultural scenarios provide a basis for calculating supply balance sheets and agricultural imports and exports.

Although these three areas of action are related, they require specific, individual climate protection measures. For instance, although changes in eating habits and the prevention of food waste will improve the ecological footprint of food in Germany, this will not necessarily lead to a corresponding adaptation of German agricultural production, because agricultural products are tradable commodities and the demand for food is increasing globally. Accordingly, changes at the level of production or use primarily affect the self-sufficiency ratio and import and export volumes of agricultural products. For this reason the scenarios are evaluated not only on the basis of the extent of direct agricultural emissions, but also on the basis of the use of upstream services, the supply balance sheet and the resulting assessment of cumulative emissions and resource use.

The scenarios are based on an extrapolation of the baseline year 2007, since a complete set of data is available for this year. Scenario calculations are shown in a spreadsheet which draws on agricultural statistics to present German agriculture in terms of crop and livestock categories together with all resource and service requirements. The data are sourced from Germany's regionalised agricultural and environmental information system RAUMIS, the report on integrated environmental and economic accounting[449] (compiled by the German Federal Statistical Office) and the National GHG Inventory for 2010.[450]

The GHG inventories are calculated using the methodologies described in the 1996 UNFCCC reporting guidelines.[451]

The new 2006 UNFCCC reporting guidelines apply from 2013.[452] They contain methodological changes which alter the results of GHG emissions calculations. This report does not take into account the impact of these new calculation methods. Important changes concern the omission of previously included, direct N_2O emissions from leguminous nitrogen fixation and a proposed 70 % reduction in the emission factor for indirect N_2O emissions resulting from leaching. Since the assumption that N2 fixation by leguminous plants is a direct source of N_2O emissions has been proved incorrect, the direct emissions previously reported can be omitted in future. Emissions from the conversion of nitrogen fixed by leguminous plants which is present in the soil in crop residues and roots will continue to be included in emission calculations. This change in the way GHG emissions are calculated will make leguminous nitrogen fixation a more attractive climate protection option in future.

The scenarios are developed initially on the basis of a continuation of yields and livestock performance. Future yield increases are conservatively estimated (because of the potential consequences of climate change). A growth rate for the period from 2007 to 2050 is derived from this. Trends are not carried forward on the basis of percentage annual yield increases, in order to avoid overestimating growth during this extensive period.

The **framework conditions for agricultural** production will change dramatically between now and 2050. According to the results of an FAO publication 'World agriculture towards 2030/2050', demand for agricultural products will have risen dramatically by 2050 due to population growth and rising incomes in emerging and developing countries, combined with changing dietary habits. According to the study, from 2005/2007 to 2050 the average global per capita consumption of meat will increase by 25 % or 10 kg per person per year, whilst milk consumption is expected to increase by 10 %. Global meat production will increase by 75 % during this period. At the same time, the amount of arable land available per capita globally (hectares per person) is set to decline from its current level of 0.24 to around 0.18 hectares by 2050.[453]

In the face of limited availability of agricultural land, this rapidly increasing demand for food on the world agricultural market will create strong market incentives to increase agricultural production. For environmental protection in general and climate protection in particular it is crucial that any such increase is sustainable (i.e. stable in the long term) and does not overburden the carrying capacity of the agricultural ecosystems in question, resulting in subsequent damage to natural resources. The FAO coined the phrase 'sustainable intensification' (increasing production and simultaneously conserving resources); the International Assessment of Agricultural Knowledge, Science and Technology for Development, or World Agricultural Council (IAASTD) suggests that our natural resources account is now overdrawn due to a fundamental flaw in the previous generation's economic development strategies, and recommends promoting and practicing more sustainable methods of land cultivation which focus on avoiding deforestation, soil erosion, water wastage and pollution, and a high dependency on fossil fuels for the production and use of agrochemicals and machinery. The details cannot be covered in this report.[CCXX]

GHG mitigation measures that involve reducing production will become more expensive. As prices for agricultural products increase, opportunity costs of limiting production will rise as a consequence. However, as fertiliser and fodder costs increase, GHG mitigation measures that raise fertiliser and fodder efficiency will become more affordable and may prove to be a winning formula.

Measures to curb production conflict with the aim of addressing food security and, in situations where there is increased competition for land use, may cause indirect land use change effects leading to increased emissions in other areas of the world. In order to evaluate such measures, it is important to estimate the net effect on GHG balances, taking into account unintended 'leakage' effects (relocation of emissions). It should also be borne in mind that extensification measures are often designed primarily to achieve other environmental goals such as water and biodiversity conservation.

F.5.1 Description of the scenarios

The scenarios are designed to test whether and how the GHG emissions reduction target for the agricultural sector of 35 million tonnes of CO_{2eq} can be achieved. The Federal Environment Agency assumes that a scenario which envisages at least 20 % organic farming by 2050 is achievable (meeting the Federal Government's sustainability target). The possible effects of increasing organic farming to 100 % have also been discussed.

CCXX Zukunftsstiftung Landwirtschaft (Hrsg., 2010) (Foundation for the Future of Agriculture): 'Wege aus der Hungerkrise – Die Erkenntnisse des Weltagrarberichts und seine Vorschläge für eine Landwirtschaft von morgen.' (Possible solutions for the hunger crisis – the insights of the 2008 IAASTD report and its proposals for tomorrow's agriculture).

F.5.1.1 Assumptions

The scenarios, which are described in more detail below, are based on the following common basic assumptions:

Assumptions about land use

The aim of reducing GHG emissions in the source category LULUCF can be achieved only by restoring wetland areas currently used for agriculture. These GHG hotspots are responsible for releasing over 40 million tonnes of CO_{2eq} (see Chapter Error! Reference source not found.). This means that such areas could no longer be used as arable land or intensive grassland, although it would still be possible to manage them very extensively as wet grassland. It is therefore assumed that wetlands will be taken out of agricultural production and restored. This withdrawal of over one million hectares of agricultural land will have a significant impact on the foundations of agricultural production in Germany. The scenario calculations take into account the ensuing reduction in the availability of agricultural land. It is assumed that by 2050, 85 % of wetland areas will have been restored by re-wetting and halting agricultural production. Drained wetland currently accounts for approximately 600,000 hectares of arable land and 633,000 hectares of grassland. Of this, 420,000 hectares of arable land and 633,000 hectares of grassland will be taken out of production. It is assumed that the remaining 180,000 hectares of cropland will not be reconverted to wetland, due to their proximity to human settlements and infrastructure or because of irreversibly damaged peat stocks. Instead, these areas will become extensively managed grassland. Since grassland will no longer be converted into cropland, no further GHG emissions will arise due to land use changes to agriculture.

Lime will continue to be used on agricultural land to stabilise the soil pH and maintain soil fertility; this generates emissions amounting to approx. 1.5 million tonnes of CO_2 per year across all scenarios which are reported in the source category LULUCF.

The remaining extensively managed wetland is responsible for releasing approximately 4 million tonnes of CO_{2eq} in the form of CO_2 and N_2O. Added to this are settlements in wetland areas, which released 2.5 million tonnes of CO_2 in 2010, and a further 1.5 million tonnes of CO_2 from the use of agricultural lime. Given these assumptions, total emissions for the source category LULUCF (agricultural land and residential use) should amount to 8 million tonnes of CO_{2eq} in 2050. These emissions may be partially offset by restored wetlands, which act as sustainable long-term carbon sinks. A study of peatland carbon fluxes[454] showed that intact wetlands can store between 0.7 and 2 tonnes of CO_{2eq} per hectare per year, depending on climatic conditions, wetland type and vegetation. Assuming, somewhat optimistically in terms of climate protection, that the wetland areas taken out of agricultural production in Germany can be restored to a near-natural condition in the long term, it is thought that they could store between 1 and 2 million tonnes of CO_{2eq} per year. However, there is a great deal of uncertainty regarding the extent to which peat can act as a long-term carbon sink, particularly in terms of the feasibility of renaturalisation and the impacts of future climate change.

It is assumed that there will be a linear decline in land lost to residential and transport areas from 80 hectares per day in 2007 to 30 hectares per day in 2020, with a further linear decline in loss to residential use from 2020, reaching the zero target by 2050. This assumption is based on the implementation of the federal government's strategy for sustainable development, which aims to restrict the growth of residential and transport areas.[455] The growth of residential and transport areas will reduce agricultural land (AL) by 434,500 hectares by 2050, which amounts to a decrease of around 8 %. This figure assumes that no further agricultural land is taken out of use for mitigation and compensation measures or nature conservation. In the scenario calculations, agricultural land is reduced proportionally across all forms of use and crops.

Set-aside (fallow farmland), which in 2007 amounted to approx. 700,000 hectares, will fall to 200,000 hectares (due to the abolition of compulsory set-aside). Arable crops will increase proportionally. On organic farms fallow land will be used to grow clover-grass leys, a nitrogen-fixing leguminous clover and grass mix which is fed to cattle.

Increasing the amount of carbon stored in agricultural soil is not regarded as GHG mitigation because it is not possible to further increase these sinks in the long term beyond 2050 and the process is reversible, e.g. in the context of climate change. Technical methods of carbon sequestration such as hydrothermal carbonisation (HTC) are still not properly understood. Uncertainty remains regarding the extent to which HTC processes can capture carbon in the soil in a form which is protected from degradation in the long term and make it available for soil improvement and carbon enrichment.

Assumptions about the use of agricultural products originating in Germany

In the scenario analyses, domestic demand for food, marketable animal feed (cereal, protein in the form of oilcake) and non-food crops for industrial purposes has no direct impact on production in the German agricultural sector. Instead, assumptions about the domestic consumption of agricultural products are used to compile supply balance sheets, which compare domestic production and use, as well as recording exports and imports. Import and export data are used to calculate a 'foreign trade balance' of emissions and resource requirements for evaluating the scenarios.

The domestic use of agricultural products will continue at the same level on the basis of the following assumptions:

- In 2050 no biomass will be grown in Germany for the sole purpose of producing energy. However, residual and waste products from crop and livestock production, e.g. manure, will continue to be used. Land used for silage maize production will be restricted to the amount required for providing cattle feed; at present silage maize is also used as a feedstock for biogas plants. Large areas of other crops such as wheat, oilseed rape and sugar beet, which are also used for biofuel production, will continue to be cultivated as food crops. Bringing an end to the cultivation of energy crops will increase the supply of these products for other uses.
- The use of agricultural products as industrial raw materials will continue at 2007 levels.
- Farmyard manure will be used for biogas production, cutting GHG emissions from manure storage by up to 80 %. However, energy generation is not the main aim of this measure. A decline in livestock production will also cut the amount of waste available for biogas production.
- The estimated domestic demand for food assumes that Germany's population will have dropped by approximately 12 % by 2050 based on a UBA publication.[456] Per capita food consumption is calculated on the basis of German Nutrition Society (DGE) recommendations to reduce meat consumption significantly. It is also assumed that food waste can be reduced by around 50 % and that this potential will be exhausted by 2050 (see Chapter0). This will lead to a decline in domestic food consumption.

The scenarios take into account the effects on animal feed, (fertiliser) nutrient and product supply balance sheets. In the model calculations, supply balance sheets for young livestock, animal feed and nutrients are 'equalised', i.e. supply of these services must equate with their use. Balances for young livestock (calves and yearlings for breeding and fattening) are equalised in all scenarios. For example, if cow numbers fall, yearling numbers will also be reduced. Calf rearing and finishing will increase as a result of reducing bullock and heifer rearing. Staple feed balances are also equalised due to the use of less transportable and therefore less marketable amounts of roughage (silage maize, other field forage crops and grassland). Staple feed and roughage (grazing, hay and silage) for cattle is supplied from domestic sources, whilst cereal, oilcake and other animal feed can also be imported.

Consideration is given to the provision of primary plant nutrients – nitrogen (N), phosphorus (P_2O_5 and P) and potassium (K_2O and K) – since changes to agricultural production systems and livestock levels also change the fertiliser balance. In terms of nitrogen provision, the degree of uptake of the nitrogen input (or 'nitrogen efficiency': the ratio of N in the harvested crop to N in the fertiliser applied) varies in order to illustrate the potential of making more efficient use of this input. Ultimately, any change in land use must be offset by the land footprint/balance. If forage cropping is reduced, wheat cultivation will expand, since wheat is a dominant and highly commercial crop. An expansion of forage cropping, or other crops, will reduce barley cultivation. It is assumed that the remaining grassland areas will be retained and not converted to arable land or woodland.

F.5.1.2 CONV scenario: Continuation of the status quo plus climate protection

This scenario is based on a continuation of existing agricultural structures in Germany. 'CONV' is an abbreviation for 'conventional agriculture'. The baseline projection of the modelling system developed by the Thünen Institute forms the basis for this approach.[457] Organic farming is not explicitly highlighted in this scenario, but is an element of the overall portrayal of the German agricultural system. The development and analysis of the scenarios involved the following stages:

- Calculating the anticipated production volumes and the corresponding GHG emissions in 2050 based on the baseline year 2007.
- Progressively adapting activities to the GHG emissions reduction target of 35 million tonnes of CO_{2eq} in the source category 4: Agriculture:
  1. Adapting intensity and emissions (proportional rise with increased yields, except in the case of dairy cows: disproportionately low rise, here a 30 % yield increase generates only a 15 % increase in direct GHG emissions)
  2. Optimising nitrogen fertilisation: Increasing the nitrogen efficiency of nitrogen in mineral fertiliser from 80 to 90 %, nitrogen in farmyard manure from under 30 to 60 % and nitrogen fixed by legumes from 20 to 40 %. The term nitrogen efficiency refers to the ratio of nitrogen in the harvested crop to nitrogen in the fertiliser applied.
  3. Maximising the anaerobic digestion of slurry in biogas plants to control GHG emissions arising from farmyard manure management (CH_4 and N_2O). It is assumed that this measure will reduce these emissions by 80 %.
  4. Lowering the dairy cow replacement rate (from approx. 0.3 to 0.2). The replacement rate refers to the proportion of cows in the dairy herd replaced each year by young heifers.
  5. Where necessary, the effect of lowering livestock numbers is calculated until the emissions target of 35 million tonnes of CO_{2eq} is reached, starting with production systems with very high GHG emissions per euro of production value: initially targeting suckler cows and sheep, then bullock and heifer rearing for fattening, then dairy herds and finally pigs. The rearing of suckler cows and bullocks and heifers for fattening will have to cease completely to achieve the reduction target.

Table F-11 shows the assumptions for yields remaining at current levels and shows the yields and performance for the 20 % organic agriculture scenario, in comparison with conventional agriculture.

Table F-11: Estimated yields and performance (in t per hectare or 'animal place') for organic and conventional farming scenarios, compiled by the authors[458, 459]

	Growth rate	Yield	Yield ratio	Yield
Crop production method	**2007–2050 (conv)**	**conv. (t)**	**to conv.**	**eco (t)**
Winter wheat, spelt	1.2	8.9	0.45	4.0
Spring wheat, durum	1.2	7.0	0.45	3.1
Rye, winter mashlum	1.2	5.6	0.6	3.4
Winter barley	1.2	7.5	0.5	3.7
Spring barley	1.1	5.0	0.6	3.0
Oats and spring mashlum	1.1	4.8	0.6	2.9
Maize (incl. CCM)	1.2	11.1	0.7	7.8
Other cereal (triticale)	1.2	6.1	0.5	3.1
Legumes	1.2	3.4	0.75	2.6
Oilseed rape and turnip rape	1.3	4.8	0.6	2.9
Non-food (industrial) oilseed rape on set-aside	1.3	4.7	0.6	2.8
Other oil crops	1.3	3.9	0.6	2.3
Early potatoes	1.1	34.5	0.6	20.7
Late potatoes (mid-season, late)	1.1	45.7	0.6	27.4
Sugar beet	1.3	80.4	0.8	64.3
Vegetables, strawberries and garden plants	1	24.2	0.7	16.9
Fruit (excluding strawberries)	1	18.8	0.8	15.0
Vineyards	1	8.3	0.8	6.6
Clover and clover/grass leys	1	33.8	1	33.8
Lucerne and lucerne/grass leys	1	34.3	1	34.3
Grass leys and other field forage crops	1	32.1	0.7	22.4
Fodder and silage maize	1.2	52.9	0.7	37.0
Fodder beet	1	91.8	0.7	64.3
Pastureland and hay meadows	1	28.8	0.7	20.1
Permanent grassland	1	31.7	0.7	22.2
Rush pasture (litter meadows) and rough grazing	1	4.4	1	4.4
	Growth rate	**Yield**	**Yield ratio**	**Yield**
Livestock production method	**2007–2050 (conv)**	**conv.**	**to conv.**	**eco**
Dairy cows	1.3	9	0.9	8

Crop production method	Growth rate 2007–2050 (conv)	Yield conv. (t)	Yield ratio to conv.	Yield eco (t)
Suckler cows	1	0.047	1	0.047
Calf rearing for fattening	1	0.247	1	0.247
Heifer fattening (› 6 months)	1	0.155	1	0.155
Bullock fattening (› 6 months)	1	0.282	1	0.282
Sow keeping	1.2	18.2	0.8	14.6
Pig fattening	1.1	0.251	0.8	0.200
Pullets	1	1.94	0.8	1.55
Laying hens (six months and older)	1.1	0.022	0.8	0.018
Chickens and broilers	1.1	0.011	0.8	0.008
Ducks, geese and turkeys	1.1	0.030	0.8	0.024
Sheep (breeding and fattening)	1.1	0.029	1	0.029

F.5.1.3 ECO-20 % scenario: Increase in organic farming to 20 % of agricultural land

This scenario adopts the targets of the German strategy for sustainable development (2002), in which it is assumed that organic farming will expand to 20 % of agricultural land. The existing 1:1 ratio of arable land to grassland on organic farms will be maintained. In this scenario approx. 1.5 million hectares of arable land, including permanent crops, and 1.5 million hectares of grassland will be converted to organic farming. This corresponds to a more or less linear continuation of the current growth trend up till 2050.

The land use and livestock levels are based on organic farming structures recorded in 2010. For instance, compared with conventional farms, there will be more rye and vegetable cultivation, but significantly less pig and poultry rearing on organic farms. However, since organic farming relies on grassland to grow nitrogen-binding crops such as clover and other legumes, cattle numbers would not need to be reduced to enable grassland to be used for food production. Silage maize is not an important fodder crop in organic farming. It is assumed that organic farming would require lower cattle densities per hectare of grassland compared with conventional agriculture. In a change from current organic farming structures, dairy cows would account for a higher proportion of the total number of organically reared cattle.

Organic yields are based on the analyses of structures and yields in organic agriculture compared with conventional reference farms referred to in Chapter 0. The underlying data were compiled by comparing similar farms. The resulting yield ratios have been transferred to the ratios in the agricultural sector as a whole for this scenario. In the case of milk yields, the difference between organic and conventional agriculture was assumed to be slightly greater (than the data suggested), as below-average milk yields were also recorded for the conventional reference group in the farm comparison.

In this scenario legumes and grassland are grown on approximately 60 % of the organic farmland.

Uncertainties remain about the areas required for nitrogen-fixing legumes, both in terms of the level of nitrogen fixation and the nitrogen efficiency that different crops can achieve. In the baseline situation in 2010, 68 % of land farmed organically is potentially available for leguminous nitrogen fixation. This includes grassland, clover-grass leys and other fodder mixes and legumes. White clover is largely responsible for nitrogen fixation in grassland.

The stages involved in developing and adapting the scenario for reducing GHG emissions are outlined below:

1. Developing the structures of organic agriculture and adapting yields and performance based on the difference from conventional agriculture in 2010 (see Table F-11).
2. Nitrogen fertilisation: No mineral nitrogen fertiliser; nitrogen balance equalised by leguminous nitrogen fixation with nitrogen efficiency of just under 60 %
3. Maximising the anaerobic digestion of slurry in biogas plants to save 80 % of emissions arising from farmyard manure management.
4. Reducing livestock numbers (suckler cows, sheep, bullocks and heifers for fattening).

Conventional farming on the remaining 80 % of agricultural land is structured as described in the CONV scenario. Adaptations will be made in line with the CONV scenario to meet the GHG emissions reduction target of 35 million tonnes of CO_{2eq}. Numbers of organically reared beef cattle will be reduced just as dramatically as conventionally raised stock. The rationale underlying this decision is that agricultural production methods with the highest emission per euro of production value should be restricted to cut GHG emissions.

F.5.1.4 Digression: Structures and yields in organic agriculture

Organic farming is considered to be an environmentally friendly and sustainable agricultural system which differs from conventional farming in a number of ways. Due to its efficient use of resources and synergies with other environmental goals such as soil and water conservation and animal welfare,[460] organic farming should be expanded to 20 % of agricultural land in line with the target of the federal government's sustainability strategy.[461] The extent to which an expansion of organic agriculture can contribute to reducing greenhouse gases is still being debated. Emission reductions at the level of upstream services are the principal benefit, since synthetic mineral fertilisers containing nitrogen and chemical plant protection products are not used, and the majority of animal feed is home-grown (see Chapter 0).

When switching from conventional to organic farming, the differences between the two land management systems must be considered. Without the use of synthetic nitrogen fertilisers and pesticides, yields per hectare are lower, which is why organic farms generally require more land to produce similar volumes. To maximise yields, nitrogen-based mineral fertilisers must be replaced with nitrogen from other sources such as farmyard manure and leguminous plants. When determining yield differences between organic and conventional farming, it is important to compare only farms and land with similar operational and site conditions. Factors which limit plant growth are particularly significant. On land with a limited supply of water, the yield differences between conventional rain-fed agriculture and organic agriculture are relatively minor due to the superior soil quality of organically farmed land. Furthermore, organic practices have a positive impact on the soil's infiltration capacity.[462] During heavy rainfall, the water can infiltrate the soil more quickly, thereby reducing the intensity of floods. In low-nutrient systems, on the other hand, yields differences can be far greater due to the reduced intensity of fertiliser applications. In this case the choice of crop plays an important role. For instance, legume growth is not limited by nitrogen so these plants can achieve high yields without the addition of mineral fertilisers.[463]

Organic fruit, vegetable and sugar beet yields are between 70 and 80 % of conventional yields. Organic yields are most likely to approximate conventional yields in livestock production. At 5879 kg per cow per year, organic milk yields are only 9 % below conventional yields, although milk yields in the conventional reference farms are 10 % below the industry average. For this reason it was decided to base the scenario calculations on a 20 % difference between organic and conventional milk yields. This also takes account of the fact that opportunities to further increase milk yields in the organic sector are limited.

Table F-12 shows yield differences observed on farms in Germany's Farm Accountancy Data Network. Where available, this was based on data spanning a three-year period[465], although, in the case of fruit and vegetable yields, AMI[464] data were available for 2010 only. Reference data from the Thünen Institute are based on a comparison with conventional farms of a similar structure. Organic fruit, vegetable and sugar beet yields are between 70 and 80 % of conventional yields. Organic yields are most likely to approximate conventional yields in livestock production. At 5879 kg per cow per year, organic milk yields are only 9 % below conventional yields, although milk yields in the conventional reference farms are 10 % below the industry average. For this reason it was decided to base the scenario calculations on a 20 % difference between organic and conventional milk yields. This also takes account of the fact that opportunities to further increase milk yields in the organic sector are limited.

Table F-12 clearly shows that conventional agriculture produces substantially higher yields per hectare in some cases. Organic cereal yields in particular are lower than conventional yields (47 % of conv. yields, see Organic fruit, vegetable and sugar beet yields are between 70 and 80 % of conventional yields. Organic yields are most likely to approximate conventional yields in livestock production. At 5879 kg per cow per year, organic milk yields are only 9 % below conventional yields, although milk yields in the conventional reference farms are 10 % below the industry average. For this reason it was decided to base the scenario calculations on a 20 % difference between organic and conventional milk yields. This also takes account of the fact that opportunities to further increase milk yields in the organic sector are limited.

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Table F-12: Comparison of yields between comparable organic and conventional farms selected from Germany's Farm Accountancy Data Network (FADN) database[465, 466]

Product	Unit	Average yield 2008/09–2010/11		Organic yield as percentage of conventional (=100)
		Organic	Conventional**)	
Cereals	t/ha	2.9	6.1	47 %
of which: wheat	t/ha	3.0	6.7	44 %
barley	t/ha	3.0	6.0	51 %
Vegetables*)	t/ha	20.8	29.4	71 %
Fruit*)	t/ha	14.0	18.1	78 %
Oilseed rape	t/ha	2.1	3.8	56 %
Potatoes	t/ha	21.6	36.9	58 %
Sugar beet	t/ha	52.0	62.8	83 %
Milk production	kg/cow	5908	6513	91 %
Piglets (born)	piglets/sow	17.8	22.0	81 %

*) Data based on the AMI dataset for 2010 (AMI 2012a)

**) Conventional reference groups are composed of individual conventional farms with similar site conditions and factor endowments.
Exception: Values for fruit and vegetables are based on AMI (2012a).

Organic farms in Germany tend to be located at present on fairly poor sites and in regions with lower production intensity.[467, 468] prevent site differences from distorting the results, the organic farms are compared with conventional farms on similar sites. If organic farming expands to include more productive sites, the yield differences may become even greater, since conventional farms on these sites produce very high yields.

Since certain organic crops produce lower yields, organic agriculture requires different farm structures from conventional agriculture. These differences are illustrated in Table F-13. An expansion of organic farming would thus result in a different range of crops.

Table F-13: Breakdown of land use for different crops in organic and conventional farming (based on data from 2010)[469]

Share of agricultural land AL [%]	Organic	Conventional
Arable land	44.5	71.4
Grassland	52.7	25.7
Orchards	1.65	1.76
Permanent crops	1.23	1.16

Share of agricultural land AL [%]	Organic	Conventional
Share of arable land [%]		
Cereal	47.6	56.0
Wheat	12.4	28.4
Rye	13.1	4.99
Barley	5.29	14.17
Spelt	5.06	0.00
Oats (winter and spring)	4.94	1.04
Maize	1.01	3.99
Set-aside/ green manure	1.95	2.12
Forage crops	36.1	21.2
Silage maize & CCM	1.49	16.0
Mashlum	2.41	0.65
Legumes	19.8	1.41
Grass leys on arable land	6.21	3.13
Legumes	6.21	0.66
Root crops	2.21	5.38
Industrial crops	1.91	13.4
Oil seeds harvested for seed production	1.56	13.1
Vegetables	2.76	0.86
Flowers and ornamental plants	0.03	0.38
Fruit	1.31	0.52
Vineyards	1.20	0.80
Tree nurseries	0.09	0.16

Organic farming uses almost twice as much grassland as conventional farming, since it relies on the nitrogen-binding properties of white clover in the grass. If a higher proportion of conventionally farmed land switched to organic farming, however, considerably less grassland would be available than at present. Consequently, more arable land would have to be set aside for the cultivation of legume crops to provide a supply of nitrogen.

Livestock production on organic farms is also structured differently to conventional farms. Overall, organic farming has a higher proportion of livestock farms.[470] Cattle play a greater role because the production of farmyard manure is vital to organic land management. The number of cows based on total land area is similar in both systems (org: 0.26 head per hectare AL; conv: 0.29 head per hectare AL)[CCXXI], but organic farming supports about the same number of suckler cows as dairy cows, whilst conventional farming has a far higher proportion of dairy cows. Organic milk production per hectare

CCXXI Calculated by the authors as per [469].

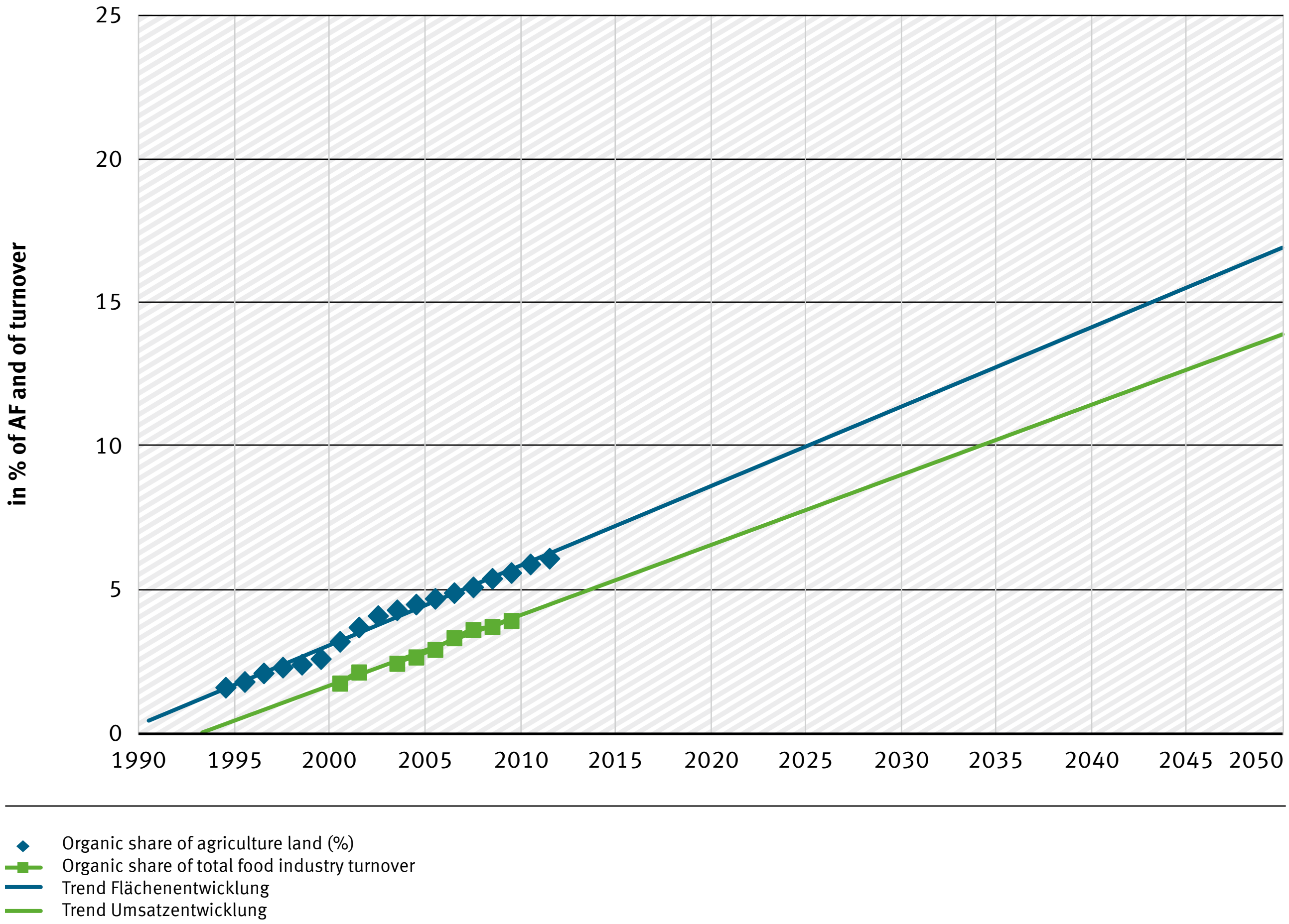
of agricultural land is only just over a third of conventional milk production. Large differences also occur with fattening pigs and broilers. Here, conventional farming supports more than eight times as many animals per hectare of agricultural land. An expansion of organic agriculture would lead to a significant decline in production volumes of pork and chicken. In contrast, there are no differences in terms of egg production.

Despite lower production volumes, organic farming does not appear to be less profitable than conventional farming. A comparison of similarly structured organic and conventional farms indicate that organic farms generate a higher income per hectare.[471] This can be explained by higher product prices, reduced expenditure on fertilisers and plant protection and the subsidies available to organic farming as it constitutes an agri-environmental measure.

Rising turnover figures confirm that the demand for organic products is continuously increasing. Organic farming generated just 2.1 billion euros in 2000, but by 2007 this figure had more than doubled to 5.3 billion euros.[472] Figure 5-1 illustrates the percentage share of organically farmed land and turnover. Actual figures may deviate slightly from this since the turnover figures for organic products compiled by Schaak et al.[473] do not include luxury food items *(Genussmittel)* and food consumed outside the home. The trend lines clearly show that the government target of expanding organic farming to 20 % of agricultural land cannot quite be achieved by 2050 if growth continues at its present rate. The proportion of agricultural land farmed organically is continuously rising, but since grassland makes up a high proportion of organic farmland, this trend alone does not provide reliable data about the growth of production volumes. The percentage of the food industry‘s turnover generated by organic farming is also rising, albeit less rapidly than the growth in organic farmland.

Despite the fact that Germany produces more organic products than any other EU country, at present it cannot meet rising demand. So clearly there is still potential for further conversion to organic farming in order to cover domestic demand. It must be borne in mind, however, that German organic production is less competitive than external production, giving rise to an increase in organic imports in recent years. Egg production is a good example. To cover the domestic shortfall, 20 % of organic eggs consumed in Germany are imported from Italy and the Netherlands.[475] Germany produces most of the organic cereal it consumes (with the exception of rice), although it relies on imports in years when harvests are poor. Imports accounted for 15 % of overall organic cereal consumption in 2009/2010, amounting to 70,000 tonnes. Other products have to be imported because they cannot be produced in Germany (bananas, rice, sesame), or at least not competitively. This includes in particular fruit, vegetables and oilseeds. For instance, 50 % of apples are imported, as well as a most of the tomatoes, peppers and cucumbers. In 2009/2010 Germany imported 82 % of tomatoes and 91 % of peppers mainly from Spain, Israel and the Netherlands.[476] The majority of oilseeds also comes from abroad (76 %). Almost 100 % of soya beans, linseeds and sunflower seeds are imported, whereas oilseed rape imports amount to just 33 %. In contrast, Germany is largely self-sufficient in dairy products such as cream and yoghurt, although butter and cheese are imported. Approximately 16 % of milk is imported.[477]

Figure F-4: Trends in organic agriculture's percentage shares of agricultural land and total turnover (food retail sector).[474]



F.5.1.5 The effects of a complete conversion to organic farming

Throughout the project, the question of whether to include a third scenario involving a complete conversion to organic farming was intensively discussed. Since a scenario of this kind would be based on very extensive and therefore tenuous assumptions, it was decided not to take it any further. In such a scenario, organic farming would lose its economic basis, because the dramatic increase in the supply of organic products would far outstrip the demand that higher-priced organic food can command.

Simply transferring current organic farming structures and yields to the entire agricultural sector is not feasible, because it is largely beef farms that convert to organic farming. Grassland makes up around half of the organically farmed land in Germany. In addition, over a third of organic arable land is used to produce green fodder and at the same time to fix atmospheric nitrogen using clover and other legumes. Since no mineral nitrogen fertilisers are allowed, organic farming is dependent on providing nitrogen in this form to improve the soil. Increasing the amount of arable land used for green fodder production would reduce the amount available to grow other arable crops. It must also be borne in mind that organic arable farming produces lower yields than conventional agriculture, so a complete conversion to organic farming would lead to a dramatic decline in production output in the German agricultural sector. This course of action should be seen in a critical light in terms of climate protection, since it could result in leakage effects (more production from abroad). The evaluation of a scenario based on 100 % organic farming depends not only on the underlying assumptions, but also on the approach and the chosen system boundaries.

It cannot be assumed that the market share of organic farming in Germany will increase to 100 % in the future. If the supply of organic products were to increase so dramatically, far outstripping demand, the higher prices currently commanded by organic products compared with conventional products would no longer be achievable. This would remove the income basis for organic farming. The viability of organic farming is largely dependent on the ability to charge higher prices. In the 2005/06 to 2008/09 financial years, for instance, organic cereal prices were 80 % and in some cases over 100 % higher than conventional prices, and milk prices 20–40 % higher. From this it is clear that a further expansion of organic farming should be linked to the trend in demand for organic products. This was the basis for developing the ECO 20 % scenario - an expansion of organic farming to 20 % of agricultural land (see Chapter F.5.1.3).

F.5.2 Results of modelling exercises

F.5.2.1 Greenhouse gas reduction

Greenhouse gas reduction illustrates the gradual adaptations required in the individual scenarios to reduce GHG emissions. A continuation of the status quo produces agricultural GHG emissions of almost 60 million tonnes of CO_{2eq}. In both the CONV and ECO 20 % scenarios a key primary measure is to substantially increase nitrogen efficiency in order to save energy and cut N_2O emissions. A further measure is the fermentation of farmyard manure in anaerobic digesters (biogas plants) which provide leakproof storage for the digestates. These reduction measures combined can save over 10 million tonnes of CO_{2eq}. Since the primary focus of this section is the reduction of emissions in the source category Agriculture, the impact on the upstream production of mineral nitrogen fertiliser is not addressed at this stage.

Lowering the dairy herd replacement rate is another means of reducing GHG emissions, provided that the follow-on heifers no longer required are slaughtered as veal calves and not reared as heifers. Livestock numbers will have to be reduced to achieve the maximum emissions target of 35 million tonnes of CO_{2eq}. In the CONV scenario, as well as lowering beef cattle numbers and cutting sheep by 50 %, dairy herds will have to be reduced to a level sufficient to meet domestic needs under optimistic conditions. The German dairy industry currently has a self-sufficiency ratio well in excess of 100 %. The final measure is to substantially reduce pig rearing – here Germany's self-sufficiency ratio is over 110 %, so exports would initially decline, at least in absolute terms.

In the ECO-20 % scenario, conventional agriculture, which accounts for 80 % of the agricultural land, will be subject to the same measures as in the CONV scenario. On the remaining 20 % of agricultural land which is organic, nitrogen efficiency will be further increased and farmyard manure will be used in biogas plants. It is assumed that beef cattle numbers will fall in both conventional and organic agriculture. Due to the lower GHG emissions associated with organic farming, conventionally reared pig stocks will not have to be reduced as drastically as in the CONV scenario in order to achieve the emission target.

The different scenarios show that lowering livestock numbers is the only way to get below the reduction target of 35 million tonnes of CO_{2eq}. This will remain the case until we have a reliable method of reducing enteric CH_4 emissions – which is currently the subject of a number of research projects. If the research proves successful, this approach could make a substantial contribution to reducing GHG emissions by 2050.

Table F-14 illustrates the gradual adaptations required in the individual scenarios to reduce GHG emissions. A continuation of the status quo produces agricultural GHG emissions of almost 60 million tonnes of CO_{2eq}. In both the CONV and ECO 20 % scenarios a key primary measure is to substantially increase nitrogen efficiency in order to save energy and cut N_2O emissions. A further measure is the fermentation of farmyard manure in anaerobic digesters (biogas plants) which provide leakproof storage for the digestates. These reduction measures combined can save over 10 million tonnes of CO_{2eq}. Since the primary focus of this section is the reduction of emissions in the source category Agriculture, the impact on the upstream production of mineral nitrogen fertiliser is not addressed at this stage.

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In the ECO-20 % scenario, conventional agriculture, which accounts for 80 % of the agricultural land, will be subject to the same measures as in the CONV scenario. On the remaining 20 % of agricultural land which is organic, nitrogen efficiency will be further increased and farmyard manure will be used in biogas plants. It is assumed that beef cattle numbers will fall in both conventional and organic agriculture. Due to the lower GHG emissions associated with organic farming, conventionally reared pig stocks will not have to be reduced as drastically as in the CONV scenario in order to achieve the emission target.

The different scenarios show that lowering livestock numbers is the only way to get below the reduction target of 35 million tonnes of CO_{2eq}. This will remain the case until we have a reliable method of reducing enteric CH_4 emissions – which is currently the subject of a number of research projects. If the research proves successful, this approach could make a substantial contribution to reducing GHG emissions by 2050.

Table F-14: GHG reduction measures in agriculture in the scenarios for 2050[478]

	N_2O	CH_4	Total THG	Reduction per step
	in million tonnes of CO_{2eq}			
Scenario 1: Conventional agriculture (CONV))				
Baseline situation extrapolated to 2050	37.2	22.6	59.8	
N-efficiency increased	30.7	22.6	53.3	−6.5

CCXXII Increased efficiency of N-based mineral fertilizers from 80 % to 90 %; organic N from 26 % to 60 %; leguminous N-fixation from 20 % to 40 %.

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

below shows GHG emissions from different sub-sources in the German agricultural sector based on the two scenarios. It also illustrates the impact of changing both nitrogen supply and removal and livestock numbers on the nitrogen balance in German agriculture. The nitrogen balance is determined from the land balance by calculating the difference between nitrogen added to an agricultural system in the form of mineral nitrogen fertilisers, animal manure, other organic fertilisers, leguminous nitrogen fixation and non-agricultural depositions and nitrogen removed via harvested crops. Nitrogen deposition is estimated to be approx. 10 kg N/ha.

In the scenarios, the nitrogen balance per hectare of agricultural land in 2050 falls by around 50 % compared with the baseline year 2007. In conventional agriculture this reduction is brought about largely by greater nitrogen efficiency. Whilst a very high level of efficiency can be achieved with the mineral nitrogen fertilisers used in conventional agriculture, the level of efficiency attainable with other sources of nitrogen is generally lower due to losses that are difficult to control. The somewhat higher nitrogen balance depicted in the ECO 20 % scenario is due to higher livestock numbers and nitrogen surpluses arising from farmyard manure.

Table F-15 below shows GHG emissions from different sub-sources in the German agricultural sector based on the two scenarios. It also illustrates the impact of changing both nitrogen supply and removal and livestock numbers on the nitrogen balance in German agriculture. The nitrogen balance is determined from the land balance by calculating the difference between nitrogen added to an agricultural system in the form of mineral nitrogen fertilisers, animal manure, other organic fertilisers, leguminous nitrogen fixation and non-agricultural depositions and nitrogen removed via harvested crops. Nitrogen deposition is estimated to be approx. 10 kg N/ha.

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Table F-15: GHG emissions and nitrogen surpluses in the baseline year 2007 and in the scenarios for 2050[479]

		2007	CONV	ECO- 20 %
GHG source category 4 Agriculture	million tonnes of $CO_{2eq.}$	62.6	35.0	35.0
of which N_2O				
... from nitrogen-based mineral fertiliser	million tonnes of $CO_{2eq.}$	9.3	9.0	6.9
... from organic N	million tonnes of $CO_{2eq.}$	6.0	2.6	3.4
... from leguminous N	million tonnes of $CO_{2eq.}$	0.5	0.4	0.8
... from crop residues	million tonnes of $CO_{2eq.}$	5.4	5.2	4.9
... from N leaching	million tonnes of $CO_{2eq.}$	11.1	8.6	8.4
... from N deposition	million tonnes of $CO_{2eq.}$	2.3	1.3	1.5

		2007	CONV	ECO- 20 %
... from manure storage	million tonnes of $CO_{2eq.}$	2.3	0.2	0.2
Of which CH_4				
... from digestion	million tonnes of $CO_{2eq.}$	20.1	7.3	8.2
... from manure storage	million tonnes of $CO_{2eq.}$	5.6	0.4	0.7
Nitrogen balance	kg/ha AL	98	45	51

F.5.2.2 Production volumes

shows production volumes for different crop and livestock production methods. In the CONV scenario, wheat cultivation expands compared with the baseline year 2007 despite a reduction in the amount of arable land, increasing the share of cereal crops to over 70 %. A decline in cattle numbers reduces the need to grow forage crops (silage maize, clover and grass). Livestock numbers fall to less than a third of 2007 levels – especially cattle, pigs and sheep, while poultry and horses remain at current levels. Due to an increase in dairy cattle performance, milk production will not decline to the same extent as meat production.

Land use in the ECO-20 % scenario is similar to the CONV scenario, although slightly less wheat is grown. In terms of livestock production, however, cattle and pig numbers will not have to be reduced as drastically to achieve the maximum GHG emissions in the agricultural sector. More rye, legumes and grass/clover leys will be grown on the organic arable land and less wheat and oilseed rape. Pig and poultry rearing in particular will decline in comparison with conventional structures.

Table F-16 shows production volumes for different crop and livestock production methods. In the CONV scenario, wheat cultivation expands compared with the baseline year 2007 despite a reduction in the amount of arable land, increasing the share of cereal crops to over 70 %. A decline in cattle numbers reduces the need to grow forage crops (silage maize, clover and grass). Livestock numbers fall to less than a third of 2007 levels – especially cattle, pigs and sheep, while poultry and horses remain at current levels. Due to an increase in dairy cattle performance, milk production will not decline to the same extent as meat production.

Land use in the ECO-20 % scenario is similar to the CONV scenario, although slightly less wheat is grown. In terms of livestock production, however, cattle and pig numbers will not have to be reduced as drastically to achieve the maximum GHG emissions in the agricultural sector. More rye, legumes and grass/clover leys will be grown on the organic arable land and less wheat and oilseed rape. Pig and poultry rearing in particular will decline in comparison with conventional structures.

Table F-16: Arable and livestock production in the baseline year 2007 and in the scenarios for 2050[480]

	2007	CONV	ECO-20 %	CONV (Eco 20 %)	*Eco (Eco-20 %)*
	Baseline year	CONV	ECO-20 %	ECO-20 %	
	2007	2050	2050	*(conv)*	*(eco)*
	in million hectares				
Wheat	3.10	4.67	4.01	3.77	0.24
Rye	0.65	0.60	0.63	0.41	0.22
Barley	1.97	1.82	1.73	1.72	0.01
Other cereals	1.05	0.97	1.00	0.75	0.26
Legumes	0.11	0.10	0.47	0.17	0.31
Oilseed rape and other oil crops	1.47	1.36	1.38	1.28	0.10
Potatoes	0.27	0.25	0.26	0.20	0.06
Sugar beet	0.38	0.35	0.35	0.30	0.05
Vegetables, strawberries	0.13	0.12	0.12	0.07	0.05
Orchards	0.07	0.06	0.06	0.05	0.02
Vineyards	0.10	0.09	0.09	0.07	0.02
Clover/grass leys	0.59	0.00	0.14	0.00	0.14
Silage maize	1.46	0.10	0.28	0.25	0.02
Set-aside	0.25	0.20	0.17	0.17	0.00
Total arable and permanent crops	11.72	10.81	10.82	9.30	1.51
Grassland	4.85	4.27	4.27	2.76	1.51
Agricultural land	16.57	15.08	15.08	12.07	3.02
Cereal share of arable land	*59 %*	*76 %*	*69 %*	*72 %*	*50 %*
Legume share of arable land	*5 %*	*3 %*	*6 %*	*4 %*	*21 %*
Legume + grassland share of agricultural land	*33 %*	*30 %*	*33 %*	*26 %*	*60 %*
	in million 'animal places'				
Cattle	12.75	3.63	4.11	2.98	1.13
of which dairy cows	4.12	1.97	2.18	1.61	0.57
of which other cattle	8.63	1.67	1.92	1.37	0.56
Pigs	19.66	6.16	14.82	14.09	0.72
Poultry	127.8	127.8	123.4	115.0	8.4

	2007	CONV	ECO-20 %	CONV (Eco 20 %)	*Eco (Eco-20 %)*
	Baseline year	CONV	ECO-20 %	ECO-20 %	
	2007	2050	2050	*(conv)*	*(eco)*
	in million hectares				
Sheep	1.58	0.79	0.79	0.63	0.16
Horses	0.54	0.54	0.54	0.43	0.11
Livestock units/ hectare AL	*0.82*	*0.33*	*0.45*	*0.47*	*0.37*

shows production volumes in the agricultural sector. The figures indicated are gross volumes including cereals, legumes and oil cakes used for domestic animal feed. Due to yield improvements and an expansion of cereal cultivation, cereal production in the CONV scenario increases by 45 % compared with 2007. Yield increases also boost oilseed and sugar production by around 20 %. Milk production declines by almost 40 % compared with 2007, and meat production by over 50 %. The ECO-20 % scenario shows a less marked increase in cereal production, a slightly lower decline in milk production and substantially lower drop in meat production.

Table F-17 shows production volumes in the agricultural sector. The figures indicated are gross volumes including cereals, legumes and oil cakes used for domestic animal feed. Due to yield improvements and an expansion of cereal cultivation, cereal production in the CONV scenario increases by 45 % compared with 2007. Yield increases also boost oilseed and sugar production by around 20 %. Milk production declines by almost 40 % compared with 2007, and meat production by over 50 %. The ECO-20 % scenario shows a less marked increase in cereal production, a slightly lower decline in milk production and substantially lower drop in meat production.

Table F-17: Production volumes for the baseline year 2007 and the scenarios for 2050[481]

	Baseline year	CONV	ECO-20 %		
	2007	2050	2050	(conv)	(eco)
	in million tonnes				
Cereals (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
Misc. cereal	2.2	2.4	2.1	1.8	0.4
Legumes	0.3	0.4	1.4	0.6	0.8

	Baseline year	CONV	ECO-20 %		
	2007	2050	2050	(conv)	(eco)
	in million tonnes				
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	0.04	0.02	0.02	0.02	0.00
Chicken	1.0	1.1	1.0	0.9	0.0
Eggs	0.8	0.9	0.8	0.8	0.1

F.5.2.3 Domestic use of agricultural products and supply balance sheets

The supply balance sheets are analysed below in order to evaluate the scenarios. In terms of use, all scenarios are based on the same figures for domestic food consumption and industrial use of non-food crops. The scenarios differ only in terms of animal feed consumption, which varies depending on livestock numbers and fodder rations. hows predicted domestic food consumption in million tonnes per annum. Column 1 indicates food consumption based on 2007 consumption data (in other words, per capita consumption remaining at this level) and a 12 % reduction in the population. The figures in Column 2 are based on the assumption that eating habits shift in favour of the healthy, balanced diet recommended by the German Society for Nutrition (DGE) (essentially, more vegetables, more complex carbohydrates and less meat). This level of food consumption can be further reduced if we optimistically assume that 50 % of food waste can be avoided (as the latest literature suggests). These reduced levels are shown in Column 3. The figures in Column 3 are then broken down in Column 4 on the assumption that preferences for certain types of cereal and meat do not alter (i.e. although we eat less meat overall, the proportion of beef, pork and chicken remains the same).

Table F-18 hows predicted domestic food consumption in million tonnes per annum. Column 1 indicates food consumption based on 2007 consumption data (in other words, per capita consumption remaining at this level) and a 12 % reduction in the population. The figures in Column 2 are based on the assumption that eating habits shift in favour of the healthy, balanced diet recommended by the German Society for Nutrition (DGE) (essentially, more vegetables, more complex carbohydrates and less meat). This level of food consumption can be further reduced if we optimistically assume that 50 % of food waste can be avoided (as the latest literature suggests). These reduced levels are shown in Column 3. The figures in Column 3 are then broken down in Column 4 on the assumption that preferences for certain types of cereal and meat do not alter (i.e. although we eat less meat overall, the proportion of beef, pork and chicken remains the same).

Table F-18: Assumptions concerning domestic food consumption in 2050[482]

	(1)	(2)	(3)	(4)
	Food consumption			
	extrapolated from 2007 levels	as per DGE recommendations	DGE plus reduction in food waste	from (3) based on (1)
	in million tonnes			
Cereals (total)	8.2	10.5	9.0	9.0
Wheat	6.0			6.5
Rye	0.8			0.8
Barley	0.0			0.0
Other cereals	1.5			1.6
Legumes	0.03			0.1
Oilseed rape and other oilseeds	0.1			0.1
Vegetable oils, margarine	1.2	1.3	1.2	1.2
Potatoes	4.3	5.4	5.1	5.1
Sugar beet	16.0			16.0
Vegetables	6.5	11.1	9.5	9.5
Fruit	9.0	8.9	7.6	7.6
Milk	20.6	20.3	17.2	17.2
Meat (total)	6.4	1.6	1.4	1.4
Beef	0.9			0.2
Pork	3.9			0.9
Lamb	0.08			0.02
Chicken	1.3			0.3
Eggs	0.7	0.6	0.6	0.6

Figures for the domestic use of non-food crops for industrial purposes shown in Column 2 are based on statistical data for the baseline year 2007. The remaining columns show the results for the two scenarios in terms of production volume (columns 3 and 6), animal feed (columns 4 and 7) and self-sufficiency ratio (columns 5 and 8). The self-sufficiency ratio is calculated from the ratio of production to the three domestic types of usage (food, animal feed and raw materials).

Table F-19 shows the consumption balance sheets for the calculated scenarios. The food consumption figures shown in Column 1 are taken from Column 4 inbelow shows GHG emissions from different sub-sources in the German agricultural sector based on the two scenarios. It also illustrates the impact of changing both nitrogen supply and removal and livestock numbers on the nitrogen balance in German agriculture. The nitrogen balance is determined from the land balance by calculating the difference between nitrogen added to an agricultural system in the form of mineral nitrogen fertilisers, animal manure, other organic fertilisers, leguminous nitrogen fixation and non-agricultural depositions and nitrogen removed via harvested crops. Nitrogen deposition is estimated to be approx. 10 kg N/ha.

In the scenarios, the nitrogen balance per hectare of agricultural land in 2050 falls by around 50 % compared with the baseline year 2007. In conventional agriculture this reduction is brought about largely by greater nitrogen efficiency. Whilst a very high level of efficiency can be achieved with the mineral nitrogen fertilisers used in conventional agriculture, the level of efficiency attainable with other sources of nitrogen is generally lower due to losses that are difficult to control. The somewhat higher nitrogen balance depicted in the ECO 20 % scenario is due to higher livestock numbers and nitrogen surpluses arising from farmyard manure.

Table F-15. Figures for the domestic use of non-food crops for industrial purposes shown in Column 2 are based on statistical data for the baseline year 2007. The remaining columns show the results for the two scenarios in terms of production volume (columns 3 and 6), animal feed (columns 4 and 7) and self-sufficiency ratio (columns 5 and 8). The self-sufficiency ratio is calculated from the ratio of production to the three domestic types of usage (food, animal feed and raw materials).

Table F-19: Supply balance sheet for 2007[483]

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Food consum. DGE plus less food waste	Renewable raw materials	CONV			ECO-20 %		
		as in 2007	Production	Animal feed	(3)/(1+2+4)	Production	Animal feed	(6)/(1+2+7)
	in Mio. t							
Cereals (total)	9.0	3.1	65.1	13.1	259 %	56.7	20.7	173 %
Legumes	0.1		0.4	0.3	100 %	1.4	1.3	100 %
Oilseed rape and other oilseeds	0.1		6.4			6.3		
Vegetable oils, margarine	1.2	1.5	2.2		84 %	2.2		82 %
Oilcake			4.2	4.8	86 %	4.1	5.7	72 %
Energy-rich animal feed				1.6			2.2	
Other animal feed				2.2			3.3	

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Food consum. DGE plus less food waste	Renewable raw materials	CONV			ECO-20 %		
		as in 2007	Production	Animal feed	(3)/(1+2+4)	Production	Animal feed	(6)/(1+2+7)
	in Mio. t							
Potatoes	5.1	1.5	11.2		169 %	10.5		158 %
Sugar beet	16.0	0.6	28.0		169 %	27.7		167 %
Vegetables	9.5		2.9		31 %	2.6		27 %
Fruit	7.6		1.2		16 %	1.2		15 %
Milk	17.2		17.4		101 %	18.3		106 %
Meat (total)	1.4		2.9		207 %	4.8		345 %
Eggs	0.6		0.9		134 %	0.8		132 %

Variations in production volumes and volumes used as animal feed lead to very varied self-sufficiency ratios and consequently different import and export volumes. Large quantities of cereal are available for export in both scenarios and we are considerably more self-sufficient in vegetable oils compared with 2007. However, the milk self-sufficiency ratio falls to just over 100 %. Assuming that domestic meat consumption will fall dramatically, meat exports are likely to increase significantly. Because more pig rearing takes place in the ECO-20 % scenario than in the CONV scenario, meat exports are substantially higher. From this assumption it follows that oilcake imports (e.g. soya meal) will increase to feed the conventional pig stocks, which are subject to less drastic reductions.

Energy-rich and other animal feeds derived from the food processing industry are shown as imports to the German agricultural sector despite the fact that they are processed domestically. This mainly involves molasses and beet pulp from sugar processing, as well as residues from the beverage industry. It is assumed that domestic production will largely meet the demand for these animal feeds even in 2050. In the following evaluation, however, these animal feeds are treated as imports because they are produced from commercial agricultural products and replace other commercial animal feeds such as cereals.

Table F-20: Net imports and exports in the scenarios in 2050[484]

	2007	CONV	ECO-20 %
	Net imports (–) and exports (+) in million tonnes		
Cereals (total)	6.0	40.0	23.9
Legumes	0.0	0.0	0.0
Oilseed rape and other oilseeds			
Vegetable oils, margarine	–4.9	–0.4	–0.5

	2007	CONV	ECO-20 %
	Net imports (–) and exports (+) in million tonnes		
Oilcake	−4.8	−0.7	−1.6
Energy-rich animal feeds[CCXXIII]	−3.1	−1.6	−2.2
Other animal feeds[CCXXIV]	−3.7	−2.2	−3.3
Potatoes	4.6	4.6	3.9
Sugar beet	4.5	11.4	11.1
Vegetables	−4.2	−6.5	−6.9
Fruit	−9.0	−6.4	−6.4
Milk	4.6	0.2	1.1
Meat (total)	−0.9	1.5	3.4
Eggs	0.0	0.2	0.2

F.5.2.4 Balancing GHG emissions

There is no difference between the two scenarios under consideration in terms of the extent of direct GHG emissions in the source category Agriculture: both achieve the reduction target of 35 million tonnes per annum. However, as shown in the previous section, their level of productivity does differ. Whilst domestic consumption remains the same in both scenarios, import and export volumes of agricultural commodities produced in Germany vary. The two scenarios also differ with regard to upstream services (e.g. energy, fertiliser, imported animal feeds) due to their different production structures. For this reason upstream services, supply balance sheets and the resulting assessment of cumulative emissions should be taken into account in evaluating the scenarios in this chapter. This approach allows for an assessment of German agricultural production and its contribution to supplying the German population. At the same time, a cross-sector and cross-border assessment will indicate whether undesirable shifts in global land use, agricultural production and food supply (leakage effects) might occur.

The scenarios are evaluated according to the balances for cumulative GHG emissions produced annually in the German agricultural sector to cover domestic demand for food and non-food crops for industrial purposes (Table F-11). Imported products which are not produced in Germany, such as rice, coffee and tea, are not included in this assessment.

The total balance at the end (bottom lines Table F-11) gives an initial indication of GHG emissions based on the IPCC classification system (‘Source Category 4 Agriculture’ line). In addition, the last line ‘Total of lines 1+2+3+4’ shows the total GHG balance including upstream services and ‘GHG rucksacks’ for imports and exports. However, by 2050 GHG emissions associated with upstream services will be marginal, as already mentioned, since it is assumed that by then Germany will have switched to 100 % renewable energy (making mineral fertiliser production virtually climate-neutral). The ‘Upstream services and energy’ line therefore contains only minimal values for the 2050 scenar-

CCXXIII Consumption is shown for energy-rich and other animal feeds largely originating from the food processing industry.

CCXXIV Consumption is shown for energy-rich and other animal feeds largely originating from the food processing industry.

ios. Import 'GHG rucksacks' are largely linked to plant-based animal feeds, for which we are liable, and so they are indicated with a plus sign. In 2007 the export GHG rucksacks are largely linked to refined animal products; these GHG rucksacks are allocated to the importing countries (such as China, which imports German poultry products) and are therefore indicated in the German balance by a minus sign. In 2050, however, rising yields combined with a declining population will allow us to export substantial amounts of cereals and virtually halt imports of animal feed. Consequently, we will be able to export GHGs in the form of 'rucksacks' for plant products as well, so they are also shown as negative. Further explanations and analysis can be found in the Thünen Report 'Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050'[485].

It is assumed that in 2050 there will no longer be any direct or indirect land use changes resulting from German agriculture. Consequently, no additional GHG emissions will be produced in the source category LULUCF as a result of land-use changes. In 2050 both scenarios will generate annual emissions of over 5 million tonnes of CO_2 (cf. Chapter G.4.2) in the LULUCF sector from the use of agricultural lime and the remaining extensively farmed wetland areas.

Along with direct CH_4 and N_2O emissions in the agricultural sector (IPCC source category 4), this gives a total balance which provides a basis for evaluation. The total GHG emissions indicated are generated directly and indirectly by the German agricultural sector to meet domestic demand.

Bearing in mind that agricultural exports have a very positive impact on this balance, cumulative GHG emissions arising from the domestic consumption of agricultural products thus amount to 20.9 million tonnes of CO_{2eq} in the CONV scenario and 18.5 in the ECO-20 % scenario – substantially below the target of 35 million tonnes of CO_{2eq} of direct GHG emissions from the agricultural sector.

Table F-21: Foreign trade balance and total balance of GHG emissions from the German agricultural sector in 2007 and in the scenarios for 2050[486]

	2007	CONV	ECO-20 %
	million tonnes CO_2		
Upstream services			
Energy	9.46	0.00	0.00
of which direct consumption	6.42	0.00	0.00
of which electricity	3.05	0.00	0.00
Nitrogen-based mineral fertiliser	9.57	0.05	0.04
Phosphate-based mineral fertiliser	0.16	0.00	0.00
Potassium-based mineral fertiliser	0.18	0.00	0.00
Lime	0.41	0.38	0.38
Plant protection products	0.22	0.00	0.00
Repairs	0.37	0.00	0.00
Other miscellaneous costs	0.59	0.00	0.00
Vet	0.11	0.00	0.00
Depreciation	2.76	0.29	0.32

	2007	CONV	ECO-20 %
	million tonnes CO_2		
Agricultural imports and exports			
Cereals (total)	−3.93	−10.48	−8.74
Legumes	−0.01	0.00	0.00
Oilseed rape and other oilseeds			
Vegetable oils, margarine	5.22	0.28	0.31
Oilcake	4.03	0.55	1.35
Energy-rich animal feed [CCXXV]	1.61	0.42	0.60
Other animal feed [CCXXVI]	1.93	0.60	0.91
Potatoes	−0.38	−0.18	−0.15
Sugar beet	−0.39	−0.66	−0.64
Vegetables	1.38	0.71	0.75
Fruit	1.76	0.23	0.24
Milk	−5.86	−0.18	−1.10
Meat (total)	2.26	−5.70	−10.39
Eggs	0.00	−0.43	−0.40
Subtotals			
(1) Upstream services and energy	23.84	0.72	0.73
(2) Imports/exports of plant products	11.23	−8.52	−5.37
(3) Imports/exports of animal products	−3.61	−6.31	−11.89
Total	31.47	−14.11	−16.53
Total balance			
(4) Source category 4 Agriculture**) [CCXXVI]	62.6	35.0	35.0
Sum of lines (1) + (2) + (3) + (4)	94.1	20.9	18.5

F.5.3 Summary of the results from the scenario analyses

The scenario analyses show that if the status quo is continued and substantial areas of agricultural land are lost to wetland restoration, residential areas and transport zones, production levels in the German agricultural sector can be largely maintained based on assumed – conservatively estimated – yield improvements. Climate protection measures with no restrictions on production could cut GHG emissions to approximately 45 million tonnes of CO_{2eq} (a 27 % reduction;illustrates the gradual adaptations required in the individual scenarios to reduce GHG emissions. A continuation of the status

CCXXV Consumption is calculated for energy-rich and other animal feeds largely originating from the food processing industry.

CCXXVI Consumption is calculated for energy-rich and other animal feeds largely originating from the food processing industry.

CCXXVII Excluding N_2O emissions from organic soil.

quo produces agricultural GHG emissions of almost 60 million tonnes of CO_{2eq}. In both the CONV and ECO 20 % scenarios a key primary measure is to substantially increase nitrogen efficiency in order to save energy and cut N_2O emissions. A further measure is the fermentation of farmyard manure in anaerobic digesters (biogas plants) which provide leakproof storage for the digestates. These reduction measures combined can save over 10 million tonnes of CO_{2eq}. Since the primary focus of this section is the reduction of emissions in the source category Agriculture, the impact on the upstream production of mineral nitrogen fertiliser is not addressed at this stage.

Lowering the dairy herd replacement rate is another means of reducing GHG emissions, provided that the follow-on heifers no longer required are slaughtered as veal calves and not reared as heifers. Livestock numbers will have to be reduced to achieve the maximum emissions target of 35 million tonnes of CO_{2eq}. In the CONV scenario, as well as lowering beef cattle numbers and cutting sheep by 50 %, dairy herds will have to be reduced to a level sufficient to meet domestic needs under optimistic conditions. The German dairy industry currently has a self-sufficiency ratio well in excess of 100 %. The final measure is to substantially reduce pig rearing – here Germany‘s self-sufficiency ratio is over 110 %, so exports would initially decline, at least in absolute terms.

In the ECO-20 % scenario, conventional agriculture, which accounts for 80 % of the agricultural land, will be subject to the same measures as in the CONV scenario. On the remaining 20 % of agricultural land which is organic, nitrogen efficiency will be further increased and farmyard manure will be used in biogas plants. It is assumed that beef cattle numbers will fall in both conventional and organic agriculture. Due to the lower GHG emissions associated with organic farming, conventionally reared pig stocks will not have to be reduced as drastically as in the CONV scenario in order to achieve the emission target.

The different scenarios show that lowering livestock numbers is the only way to get below the reduction target of 35 million tonnes of CO_{2eq}. This will remain the case until we have a reliable method of reducing enteric CH_4 emissions – which is currently the subject of a number of research projects. If the research proves successful, this approach could make a substantial contribution to reducing GHG emissions by 2050.

Table F-14CONV scenario, total GHG). In order to achieve this, the level of nitrogen efficiency has to be continuously increased and farmyard manure has to be fermented in biogas plants which store the fermentation residues (digestate) under gas-tight conditions. Reducing herd replacement rates, on the other hand, has only a limited impact on GHG emissions in this sector.

Further reductions in GHG emissions can be achieved only by restricting production volumes. In this regard we have focused on ruminants due to their high GHG emissions per capita and per unit of product. Severely restricting ruminant numbers, however, conflicts with the aims of grassland conservation and management. The resulting reduction in emissions is not equivalent to the reduction in livestock numbers because declining amounts of manure are substituted by more mineral fertiliser or legume cultivation, and areas no longer required for forage production are still used for crop cultivation. These feedback effects lessen the impact of reducing livestock numbers on GHG mitigation. To achieve the (specified) GHG reduction target of 35 million tonnes per annum in the conventional scenario, the livestock restrictions listed in illustrates the gradual adaptations required in the individual scenarios to reduce GHG emissions. A continuation of the status quo produces agricultural GHG emissions of almost 60 million tonnes of CO_{2eq}. In both the CONV and ECO 20 % scenarios a key primary measure is to substantially increase nitrogen efficiency in order to save energy and cut N_2O emissions.

A further measure is the fermentation of farmyard manure in anaerobic digesters (biogas plants) which provide leakproof storage for the digestates. These reduction measures combined can save over 10 million tonnes of CO_{2eq}. Since the primary focus of this section is the reduction of emissions in the source category Agriculture, the impact on the upstream production of mineral nitrogen fertiliser is not addressed at this stage.

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Table F-14 would be required: no suckler cows, sheep down 50 %, no fattening of bullocks and heifers, dairy herds down 38 %, pigs down 55 %.

Widespread extensification of agricultural production that could be achieved by switching completely to organic farming would certainly reduce direct GHG emissions in the agricultural sector due to reduced livestock numbers (less methane) and no nitrogen-based mineral fertilisers (less nitrogen fertilisation therefore less nitrous oxide from agricultural soil). However, when upstream services and agricultural imports and exports are taken into consideration, a 100 % organic farming scenario would fare less well than the scenarios which include a share of conventional agriculture due to lower production volumes combined with the cumulative GHG emissions of the GHG rucksacks brought into the country with the imports, but not included in the GHG inventory – at least if the exporting country does not apply the same strict climate protection standards as in this study. One reason for the low cumulative GHG emissions in the scenarios with conventional agriculture is the assumption that in 2050 GHG-neutral, renewable energy will be used to manufacture mineral nitrogen fertilisers.

The scenario with 20 % organic agriculture is the best option by far in terms of balancing cumulative GHG emissions plus imports and minus exports. The combination of conventional and organic farming clearly produces synergies that result in a less drastic reduction in overall agricultural production. This benefits livestock farming in particular. At the same time, the overall use of mineral nitrogen fertilisers and pesticides is lower compared with the conventional scenario. The synergies result from organic farming's reliance on the use of grassland to grow nitrogen-binding crops such as clover and other legumes. In the ECO-20 % scenario no mineral nitrogen fertilisers are used on organic grassland, which reduces N_2O emissions and enhances the nitrogen-binding properties of clover. Nitrogen bound in this way is then fed to cattle, turned into manure and reused in organic farming. Thus, less agricultural land must be set aside for cultivating clover/grass leys and other legumes.

A further expansion of organic farming beyond the 20 % target without a corresponding increase in grassland would result in more land being used for cultivating nitrogen-fixing legumes. This could be achieved either by expanding forage production on arable land or cultivating 'nitrogen-fixing biomass crops' that are not used as fodder. Both options directly compete with conventional food production based on mineral nitrogen fertiliser, for example cereal cultivation.

Direct N_2O emissions previously attributed to leguminous nitrogen fixation will in future be omitted from GHG emission calculations in the national inventory. This reflects the fact that previous methods appear to have overestimated direct N_2O emissions from biological nitrogen fixation. This makes biological nitrogen fixation an even more interesting proposition from the point of view of climate protection, especially on land which can be used without displacing other forms of agricultural production. As a result, nitrogen fixation by grassland clover should lie at the heart of Germany's legume strategy. At the same time this could reduce the demand for imported protein-based cattle feed.

F.6 Conclusion

This study is concerned with the technical GHG mitigation potential in the agricultural sector in 2050. Our analysis of the scenarios is based on the current best available technology in accordance with the assumptions of the UBA study "Energieziel 2050: 100 % Strom aus erneuerbaren Quellen" (Energy target 2050:100 % electricity from renewable sources).[487] Unlike the energy sector, which has the potential to cut up to 100 % of GHG emissions by expanding the use of renewable energy, it is impossible to completely prevent greenhouse gas emissions in the source category Agriculture since methane and nitrous oxide emissions arising from natural conversion processes are extremely difficult to control. Consequently, as the use of renewable, GHG-neutral energy continues to rise, so too does agriculture's share of the remaining overall GHG emissions, although these are now considerably lower.

As wind, solar and geothermal energy increasingly replace fossil fuels to become the renewable energy sources of choice in many sectors, the use of agricultural energy crops will no longer be a climate-friendly option. The UBA study[488] cited above therefore assumes that biomass crops will no longer be grown for this purpose. Furthermore, the UBA does not deem it justifiable to grow biomass crops for energy production because of competition with food and feed production and potential conflicts with other environmental goals. Accordingly, biomass used for energy production in 2050 will be sourced from waste and residues. These include woodchip and pellets from thinnings, landscape management and agroforestry systems as well as straw pellets, provided that they can be produced without adversely affecting the humus balance. Bioenergy therefore plays only a minor role in energy provision compared with other renewable energy sources. The use of renewable energy crops for bioenergy production is to a large extent a "bridging" (interim) technology which will become less relevant as a climate protection measure by 2050 under the conditions described in the scenarios.

To reduce GHG emissions in the agricultural sector caused by land use, grassland areas must no longer be turned into arable land and agriculturally used wetlands must be taken out of production and restored. Technical and socio-economic limitations mean that emissions from drained wetlands cannot be entirely avoided. However, restored wetland areas could be used for a form of wetland biomass production known as "paludiculture" (sedge and reed cultivation), provided that this did not clash with environmental aims such as groundwater protection. In this way, biomass crops could be cultivated without competing with food production, since fully restored wetland sites are not suitable for food and fodder crops.

Having exhausted the potential for increasing efficiency and reducing emissions, the only way to achieve a 50 % reduction in direct GHG emissions in the agricultural sector compared with 2010 is to curb livestock production. But as the results from the two scenarios under investigation show, even with ambitious climate protection targets, there is considerable leeway when it comes to deciding which production structures and ensuing production volumes will achieve these targets. In terms of restricting livestock production, we have focused on ruminants due to their high enteric methane emissions. Very tough climate protection targets and a more drastic reduction in cattle numbers, however, could to some extent call into question the benefits of using grassland for food production if low stocking densities resulted in surplus grass growth. In this case there would be increasing pressure to plough up the grassland and use it for other purposes.

However, the Federal Environment Agency estimates that in terms of climate protection it makes sense for ruminants to continue grazing natural grassland areas, because this adds value to the grassland and prevents it from being ploughed (this is humus-depleting and therefore damaging to the environment). The practice of keeping livestock indoors all year round and the correspondingly high animal feed imports are far more questionable. If livestock farming has to be restricted, the Federal Environment Agency recommends rethinking this form of animal husbandry as a priority and retaining the grassland. If livestock 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 global climate protection effect by increasing livestock numbers abroad. This relocation of emissions is known as "carbon leakage". In the scenarios we therefore assume that changes in land use and agricultural production are underpinned by changes in eating habits. These assumptions are based on the recommendations of the German Society for Nutrition (DGE), which, if followed, would contribute to a more sustainable diet and at the same time reduce health care costs, since they would halt the harmful effects of overeating and poor nutrition. We will not pursue this issue further in this report, but would like to point out that assumptions in the agricultural and food sector are based on changes to current eating habits.

The consumption of animal products has a significant impact on cumulative land and energy requirements and GHG emissions arising from feeding the German population. The same applies to food waste and spoilage. However, potential changes in animal product consumption and food waste 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 trade on international markets. The targeted changes in the food sector should therefore be seen as a separate initiative which may not necessarily bring about the intended changes in land use and the agricultural sector. The latter improvements can only be achieved through land-use policies and sector-related agri-environmental policies.

A change in current eating habits which leads to a decline in consumption of animal products and cuts down on food waste, in conjunction with an end to the cultivation of energy crops, will significantly reduce domestic demand for agricultural products.

Both scenarios under investigation achieve the defined emissions target of 35 million tonnes of CO_{2eq} in the source category Agriculture in Germany.

In addition to considering domestic GHG emissions, emissions reporting logistically calls for us to determine what effects agricultural production and demand for agricultural products in Germany have on resource use and emissions outside Germany. A reduction in livestock numbers will reduce the amount of land required for feed cultivation outside Germany, thereby further reducing resource use and emissions in the German agricultural and food sector. At the same time, agricultural exports will rise, especially cereal exports. Consequently, according to the "polluter pays principle", cumulative GHG emissions will be exported to other countries. The ultimate question is to what extent we should exhaust the potential for agricultural production in Germany. In view of the global rise in demand for food by 2050, a severe restriction on production would place greater pressure on agricultural land outside Germany.

The self-sufficiency ratios (i.e. surpluses that are exported) calculated in the scenarios in some cases exceed 100 %. Further productivity gains combined with a declining population will boost this trend. However the Federal Environment Agency also recognises an opportunity to reduce intensive land use and thus production volumes, for instance by switching to organic farming. It refers to a study by Seemüller,[489] based on optimistic assumptions about yields, who calculated back in 2001 that even if we converted fully to organic farming, we would be able to ensure food security by deriving 24 % of our calories from animal products and 76 % from plant products (the current values are 39 % and 61 %). Compared with Italian eating habits, where animal calories account for 26 % of total calories consumed, this would not, in his view, constitute an "unusual diet".

The Thünen Institute suggests that, compared with more recent data used in our study of the scenario analyses for agriculture (see Table F-12), Seemüller's yield assumptions place organic farming in a far more favourable light. Furthermore, Seemüller does not investigate the amount of land required for leguminous nitrogen fixation. Consequently, his findings differ fundamentally from the results of the scenario analyses presented here, although both studies assume a sharp decline in the consumption of animal products.

The Thünen Report[490] contains a more detailed study of the balance of foreign trade (external accounts) in the agriculture and food sector based on cumulative land and energy use and GHG emissions. Due to lack of space it has been greatly simplified in this report and reduced to "ecological rucksacks". This analysis uses the final consumption of goods within Germany's borders and their cumulative resource requirements and emissions as the basis for evaluation (consumption-based reporting). By including international trade flows, it deviates from an analysis of greenhouse gas source categories based on territorial emissions (as advocated by the IPCC).

Analysing the impact of imported goods on total land and energy requirements and GHG emissions generated by economic sectors is pointless if exports are excluded from the equation. Exports must be included because the carbon budget (balance) is calculated by adding emissions associated with imports to production emissions and subtracting emissions due to exports. This relationship can be illustrated by the current, total volume of GHG emissions and primary energy demands in the German economy as indicated in the 2007 System of Environmental-Economic Accounting (SEEA).[491] Total GHG emissions arising from the agriculture, food, animal feed and beverages sectors in Germany, including raw material imports, amounted to 185 million tonnes of CO_{2eq}, with exports making up at least 42 million tonnes of this figure. Exports accounted for approximately 280 of the 1190 petajoules of total primary energy consumption in these sectors, including imports. In both cases the export share, which refers to the aggregated value of exported goods, corresponds to 23 % of the total amount.

SEEA data can be used to estimate total German imports and exports of cumulative GHG emissions and primary energy demands for all sectors of the economy combined. In 2007 in total approx. 1 billion tonnes of CO_{2eq} were emitted within Germany in the form of greenhouse gases; however, including imports, the German economy, caused emissions amounting to 1.65 billion tonnes of CO_{2eq}. In other words, 0.65 billion tonnes of CO_{2eq} of cumulated GHG emissions from these goods were exported. Germany's primary energy consumption in 2007 stood at 14,128 petajoules, rising to 23,735 petajoules when imports are included. The cumulative primary energy demand of exported goods accounted for approx. 11,000 petajoules of this. The share of cumulative GHG emissions and the primary energy demand of imports and exports alike was around 40 %.

These figures show that imported goods and sector-based upstream services should be included in the analysis if we are to gain a better overall understanding of economic activities in Germany and the exported cumulative GHG emissions and primary energy demands. Any such analysis of these economic interrelationships must also incorporate the consumption and production of goods, including exports. Due to the importance of the use of upstream services, the global interconnectedness of the agricultural market and its relationship with land use, climate protection policies in the agricultural sector should not be evaluated solely on the basis of direct, territorial GHG emissions. Therefore we have developed an approach to evaluation based on cumulative land and energy requirements combined with GHG emissions arising from domestic goods usage which takes into account the foreign trade balance.

G. Land use, land use change and forestry

G.1 Introduction

The category land use, land use change and forestry (LULUCF[CCXXVIII]), groups together all anthropogenic emissions, as well as greenhouse gases[CCXXIX] captured by forests, cropland, grassland, wetlands, settlements and other areas.

Due to the highly intensive land use established in Germany over centuries, the entire country is considered to be cultural landscape. Given this definition, when an area such as a military training ground or an area of agricultural land subsequently becomes populated with shrubs or gradually turns into woodland, this is a development directly caused by humans. Thus all greenhouse gas emissions and removals from LULUCF areas are anthropogenic.

G.2 Greenhouse gas emissions

G.2.1 System and definitions

Emissions reporting follows a binding international system as set out in the United Nations Framework Convention on Climate Change (UNFCCC). National Inventory Reports[492] and Common Reporting Format tables for all countries must be transparent, complete, accurate, internally consistent and comparable with one another.

In order to ensure this, the UNFCCC[CCXXX] states that the calculation methods for emissions and removals must comply with the IPCC[CCXXXI] Guidelines. These Guidelines provide standard values and calculation methods for each category in which national data is unavailable.

The 2003 IPCC Good Practice Guidance is binding until reporting takes place in 2014. From that point in 2014, the updated 2006 IPCC Guidance will apply. Errors and omissions in the 2003 Guidance have been rectified in the 2006 Guidance, the underlying data have been improved and the scientific knowledge base updated.[493]

Since this reporting process is subject to constant developments and data gathering, the greenhouse gas inventory is constantly improving. The LULUCF category is very dynamic compared to the other categories in the inventory, mainly due to the ongoing gathering of data (for example in National Forest Inventories). Although the emissions data in this report have been calculated in accordance with the IPCC 2003 Good Practice Guidance, we deem it wise to apply the IPCC 2006 Guidelines when considering predictions for developments on the emission pathway to 2050. If these are considered, it will produce a more realistic picture of the emission situation, especially in the subcategories for forests and wetlands.

CCXXVIII Land use, land use change and forestry

CCXXIX Small amounts of methane and nitrous oxide are released during forest fires and when land use changes to cropland. However, unless otherwise stated, the observations below on potential emission reductions will be restricted to CO_2.

CCXXX United Nations Framework Convention on Climate Change.

CCXXXI Intergovernmental Panel on Climate Change (IPCC):

The emissions and removals, calculated according to the IPCC method, are approved with the relevant German Ministries, then forwarded to the United Nations Climate Change Secretariat in accordance with Germany's responsibilities under the UNFCCC and the Kyoto Protocol.

To make it easier to understand the observations made in relation to this category, the main terminology will be presented below and used in accordance with Article 1(paragraphs 7, 8 and 9) of the UNFCCC.

'Reservoir' means a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored.

'Sink' means any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere.

'Source' means any process or activity which releases a greenhouse gas, an aerosol or a precursor of a greenhouse gas into the atmosphere.

When transposed onto the LULUCF category, this means: possible carbon reservoirs can be found in soil, biomass above or below ground, dead wood, litter and wood products. These reservoirs arise because plants remove CO_2 from the atmosphere through photosynthesis (removals by a sink) and sequester it for a limited period in biomass such as wood or grass. If the biomass is harvested and used in wood products over the long term, the release of carbon dioxide is postponed. If however the biomass enters the soil and is bound in humus or — in the absence of oxygen — peat, the carbon may be removed for hundreds or even thousands of years. Respiration, decomposition, cutting or harvesting, burning and other processes will then once again release the carbon stored in the biomass (emissions by a source).

If removals of CO_2 by sinks are greater than emissions from sources, then the area under consideration (whether forest, cropland or grassland) is said to be a net CO_2 sink, and if the opposite is true it is said to be a net source of CO_2.

It must be noted that a reservoir will always remain a potential source of emissions, and it is vital to protect it.

G.2.2 Developments in emissions

Figure G-1 shows the developments in greenhouse gas emissions (positive numerical values) as well as removal by sinks (negative numerical values) in million tonnes of CO_{2eq} between 1990 and 2010. The bars to the far right of the chart encompass the entire LULUCF sector, with the subcategories shown in different colours.

According to this table, land use by agriculture, settlement and wetlands are all sources of greenhouse gases, although emissions are decreasing slightly. In Germany, only forests act as a sink. After 2000, CO_2 removal fell by over 40 million tonnes CO_2[CCXXXII], and as a result CO_2 emissions from cropland and grassland are no longer balanced out by the sink effect of the forest. Thus taken as a whole, the category LULUCF is a net source of emissions. Section B.1.1.1 explains the reasons for this.

CCXXXII This Chapter uses the terms CO_2 and CO_{2eq}. Where the term CO_{2eq} is used, this means that other greenhouse gases are included — but these have been converted into equivalent units of CO_2 according to their warming effect. Where it is not used, we are specifically referring to CO_2.

Figure G-1: Greenhouse gas emissions and removals in Mt CO_{2eq} in the LULUCF sector, broken down according to subcategory[494]

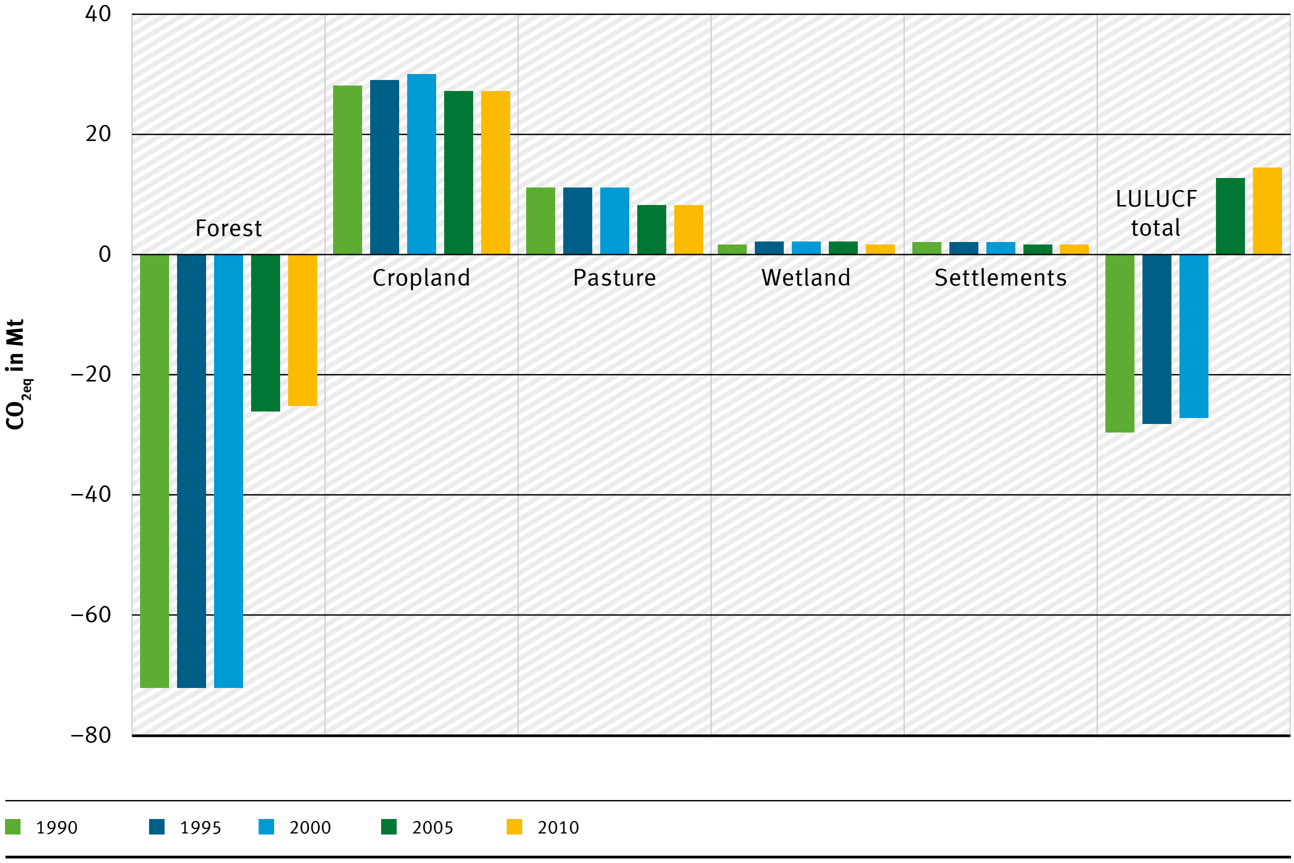


Table G-1 encompasses emissions and removals of CO_{2eq} in the LULUCF category, as well as land use trends for the period from 1990 to 2010.

According to the UNFCCC system, each subcategory is further subdivided into a 'Land remaining' category (e.g. Forest Land remaining Forest Land etc.) and a 'Land converted to' category (e.g. Cropland converted to Forest Land, Grassland converted to Forest Land). Changes in land use can cause the 'source' or 'sink' status of the land to change. Hence for instance emissions fall when cropland on organic sites is converted to grassland, and when cropland is converted to forest, it actually sequesters CO_2.

Table G-1: Developments in greenhouse gas emissions and removals, and areas identified as belonging to the LULUCF sector[495]

Land Use, Land Use Change and Forestry (LULUCF)	1990	1995	2000	2005	2010
Overall emissions in million tonnes of CO_{2eq} [CCXXXIII]	-27.70	-27.20	-26.53	15.80	17.28
A. Forest (inc. CO_2 from forest liming and CH_4 and N_2O from forest fires)					
CO_{2eq} in million tonnes	-73.22	-73.47	-73.77	-26.4	-24.93
Area in 1000 hectares	10,767	10,831	10,896	10,926	10,934
B. Cropland [CCXXXIV]					
CO_{2eq} in million tonnes	28.96	29.60	30.41	28.64	28.46
Area in 1000 hectares	14,397	14,439	13,713	14,318	14,203
C. Grassland					
CO_{2eq} in million tonnes	11.56	11.48	11.39	9.11	9.05
Area in 1000 hectares	6,663	6,532	6,400	6,307	6,268
D. Wetlands					
CO_{2eq} in million tonnes	2.25	2.43	2.64	2.47	2.16
Area in 1000 hectares	597	596	595	614	631
E. Human settlement					
CO_{2eq} in million tonnes	2.75	2.77	2.8	2.0	2.55
Area in 1000 hectares	3,275	3,309	3,342	3,551	3,681
F. Other land					
CO_{2eq} in million tonnes	-	-	-	-	-
Area in 1000 hectares	63	56	48	41	38

G.2.2.1 Forest

In Germany in 1990, forest was a significant carbon sink, removing over 70 million tonnes of CO_2. In 2010, annual carbon removal ran to only a third of that amount.

A report by Johann Heinrich of the Thünen Institute, who is responsible for modelling and the forest inventories,[496] names the following environmental and economic causes for this reduction in carbon removals:

CCXXXIII As in the case throughout the present document, the figures have been taken from the NIR 2012. A National Forest Inventory was taken in 2011/2012; however, we were not able to consider the results ofthis in the present study. The figures for the 2014 submission showed that in 2010 the forest had a sink effect of 52.11 million tonnes of CO_{2eq} and the LULUCF sector overall had a sink effect of 5.17 million tonnes of CO_{2eq}.

CCXXXIV Organic soil is a further source of N_2O emmisions reported in the agriculture sector.

- A high proportion of mature trees (ready to be harvested; large-scale planting following the First and Second World Wars, mainly of conifers, produced forests with an even age-class structure comprising a significant majority of mature trees ready for felling).[CCXXXV]
- Increased market demand for wood

Both factors have contributed to almost a doubling of the intensity with which forests are used since 2002 (compared to the period between 1989 and 2001; see also Figure G-2).

The following factors have reinforced the reduction in sink effect:

- From 2001, more trees in younger age classes have been felled than in previous years
- Trees which are now 80 years old are currently being felled at a rate far exceeding the increment in other age groups
- The proportion of the forest area taken up by very young trees, which grow more slowly in the first 10 to 20 years, is increasing

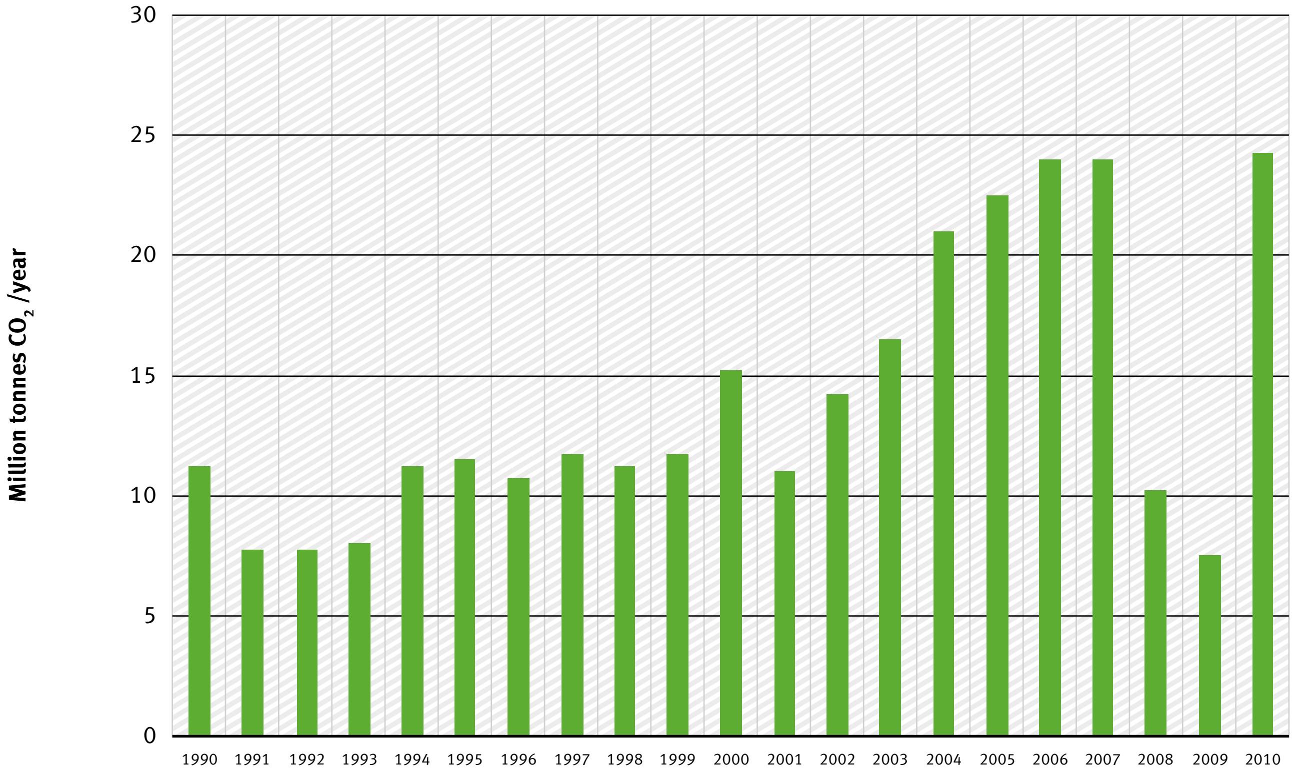
Figure G-1 shows the changes in the above ground and below ground biomass, soil, dead wood and litter pools, as required for reporting purposes. The carbon pool for wood products is not shown. It is assumed instead that the carbon stored in the wood is emitted immediately after a tree is felled, so that the sink effect of the forest is not overestimated. However, this conservative assumption does not reflect reality, as it actually only applies to energy wood. In fact, when wood is used as a raw material the carbon is still stored in the wood products. While carbon storage in forests decreases due to increased tree felling, the carbon stored in wood products grows, as more wood is being used as a raw material.

In May 2011, Germany reported details on annual net CO_2 removals in wood products to the Climate Change Secretariat for the first time; these were subsequently published in the report by the Thünen Institute.[497] They are shown in Figure G-2. It is worth noting that the volume for the period between 2002 and 2010 is double that for the period between 1990 and 2001, and this increase is clearly in line with the increase in tree-felling. Ultimately, it is fair to assume that the release of carbon from wood products is postponed, and CO_2 is released according to these products' half-life[CCXXXVI].

CCXXXV On the forests' age-class structure, see also Section G.3.1.

CCXXXVI Half-life of wood products: timber 35 years, wood-based materials 25 years, paper and cardboard 2 years.

Figure G-2: Net CO_2 removals by wood products, according to Rüter[498]



G.2.2.2 Agricultural areas: Cropland and grassland

Emissions from agricultural areas have remained consistently high since 1990. This is due to the historical use of drained peatland sites. Peatlands store around three times as much carbon per unit area as forests, including biomass. As a result, peatlands and organic soils represent both an enormous carbon pool and an enormous potential source of carbon emissions. Depending on the thickness of the peat in the peatland, drained peatlands can emit CO_2 over several centuries. Work on this land, especially ploughing, accelerates the release of the carbon stored in the soil.

The majority of emissions in the LULUCF sector, almost 28.5 million tonnes of CO_{2eq} in 2010, come from the subcategory 'cropland'. Over 25.1 million tonnes of CO_2 emissions arose in 2010 from the use of organic soils to grow crops. Other sources of emissions included the application of lime to agricultural land (1.6 million tonnes of CO_2) and conversion to cropland. Mineral soils both emitted CO_2 (1.4 million tonnes CO_2) and emitted N_2O (0.2 million tonnes CO_{2eq}) due to the loss of humus. The most frequent conversion is from grassland to cropland.

All areas covered in grass are classed as grassland, as are areas with woody growth and hedges which do not (yet) meet the definition of a forest. The grassland subcategory caused a total of 9 million tonnes of CO_2 emissions, the second-highest figure in the LULUCF sector. As with crop growing, the agricultural use of organic soils as meadows and pasture causes CO_2 emissions. However, grasslands on organic soils emit less than half as much carbon per unit area as cropland on the same soil. In 2010, just under 11.2 million tonnes of CO_2 were released in this way. Since 1990, more grassland areas have been used more extensively and populated with bushes and woody growth. This has caused a reduction in emissions from the organic grassland soils in question, as well as capturing more carbon in the vegetation. In 2010, grassland areas removed 2.2 million tonnes of CO_2 which could be offset against emissions.

A total of 36.6 million tonnes of CO_{2eq} was entered into the inventory for 2010 in the LULUCF category due to the agricultural use of organic soils. In addition, a further 4.8 million tonnes of CO_{2eq} were emitted as N_2O from organic soils subjected to agricultural use, which the reporting guidance states should be attributed to the agriculture sector. We assume in our observations below that the agricultural use of peatland sites emits a total of 41.1 million tonnes of CO_{2eq}. Thus 6% of the agricultural area is responsible for over 86% of soil emissions for the whole area of Germany.

G.2.2.3 Wetlands

Emissions from this category are almost exclusively limited to those areas where industrial peat extraction occurs. The extracted peat is used in landscape management and horticulture. Emissions have remained relatively constant since 1990 (in 2010 they were around 2 million tonnes of CO_2). The category also covers areas with undrained, semi-natural peatland sites and bodies of water from which no anthropogenic emissions are released.

In the case of semi-natural peatlands with natural fluctuations in water level, dependent on both seasonal and climate related events, research indicates that the sink/source balance at least evens out. Over long periods, peatlands are in effect carbon sinks, and the peat increases in depth. These pools can continue to grow for as long as the prevailing water levels allow. If the water table falls below ground level as a result of human influence, the peat decomposes due to oxygenation and CO_2 is emitted. Depending on the use to which the land is put, these emissions are often reported in the categories for cropland and grassland, but also the categories for forest, peatland sites and settlements. Methane emissions from anthropogenic wetland restoration are not currently considered under IPCC calculation rules (the 2003 GPG); nor is the CO_2 removed by naturally growing restored peatlands. Thus the emission figures for wetlands stated in the Inventory do not paint the whole picture. This is of particular relevance for the restoration of wetlands in peatland areas used for agriculture in Germany. As described in Section B.1.1.2, these are hotspots in terms of emissions from land use and accordingly also major sources of potential emission reductions.

G.2.2.4 Settlements

In addition to land with settlements on it, this category includes roads and railways, greenswards and parks, fallow land, glades, cemeteries and recreational facilities. Almost all the emissions in this category were released from the organic soils used (around 2.5 million tonnes of CO_2). Mineral soils emitted around 0.58 million tonnes of CO_2, and the decomposition of dead organic matter around 0.03 million tonnes of CO_2. The biomass present in parks, trees in urban areas, gardens etc. represented a sink of around 0.57 million tonnes of CO_2. Since the type and density of vegetation in settlements varies widely, simplified, conservative estimates have been made in the Inventory. As a result, actual carbon removal by green areas in settlements has probably been underestimated. Since 1990, the emissions from human settlement appear to have fallen, although no clear trend can be identified.

G.2.2.5 Other land

The subcategory 'other land' is for areas not used or managed by humans. As this does not apply to any land in Germany, the only land areas included here – in order to provide a complete picture of the country's area – are those with no emissions (for example rocky areas, sand and ice). Consequently there are no emissions from this category.

G.3 Solution spaces for reducing GHGs and increasing carbon removals

LULUCF is the only category in the National Inventory Report for the German Greenhouse Gas Inventory which is not only a source of emissions but also a sink.

However, for all types of land use (forest, cropland, meadow, wetland, settlement) the accumulation of carbon only occurs slowly, whereas the release of stored carbon occurs very quickly.

Unsustainable use of land normally causes high emissions. In terms of climate protection, the sustainable use of land aims primarily to avoid emissions, enhance sinks and preserve stored carbon. It is not possible to significantly increase carbon removals without any land use change, even if the present land use is sustainable. However, human activity is not the only cause of greenhouse gas emissions. Drought, lightning strikes, storms, changes in water levels in peatlands and other factors can all give rise to greenhouse gas emissions.

It follows that a carbon pool is also a potential source of carbon emissions. All land-specific pools (soil, above ground and below ground biomass) have an upper limit on the amount of carbon they can remove, which depends on their natural characteristics. Even the wood product pool cannot be expanded indefinitely.

It is only possible to significantly increase carbon sequestration per unit area of land in cases where the land in question is not used sustainably prior to the change in question. Examples of this include: soil which has, through cultivation, constantly released carbon that was not replaced using green manure or similar; and forest which has been cleared or degraded compared to its natural state. In this case, the application of green manure (leaving the remains of plants on the field), wetland restoration, afforestation of non-wooded areas, and leaving land to lie fallow can all increase the carbon stored in the soil and biomass. Geoengineering methods are also currently being discussed, such as a massive introduction of biochar into the soil or the planting of cloned or genetically modified trees.

G.3.1 Forest

The characteristics of land-based carbon sources and sinks set out above (in Section B.2), i.e. their limited, slow sequestration capacity and the risk of their releasing stored carbon rapidly, also apply to forest.

Climate protection measures must therefore focus on protecting carbon stocks, and increasing them as far as possible within the capacity of the ecosystems. In 2010 an additional 2 net tonnes of CO_2 were sequestered per hectare of forest in Germany.

Sustainable forest management is an essential criterion by which measures must be assessed; it is described as follows in a proposal for a Regulation of the European Parliament and of the Council on support for rural development by the European Agricultural Fund for Rural Development (EAFRD)[499]:

"'sustainable management' means the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems".

Thus sustainable forest management means optimising many parameters: just focusing on a single one, such as increased carbon stocks, runs counter to the idea of sustainability. That narrow focus would damage both economic aspects (for example no use of wood) and environmental ones (only planting trees that can sequester the most CO_2).

A sustainably managed forest is always in a state of flux, containing both newly-planted young stands of trees which absorb large amounts of CO_2, and older stands which are in balance or even in decline.

It should be noted that now forests are coming under increasing pressure to adapt as climate change manifests itself, they can no longer achieve optimal growth and changes must be made.

The following are possible climate protection measures:

- Increasing the area of forest:
  - Afforesting non-wooded areas

- Optimising sustainable use, which means reducing emissions from forest management and the use of wood:
  - Increasing the length of rotation cycles[CCXXXVII]
  - Cascading[CCXXXVIII] use of wood
  - Replacing more energy-intensive products with wood products[500]
  - Restoring riparian forests to wetland

Table G-2 provides an overview of the possible greenhouse gas emission savings for each of the potential measures.

Table G-2: Potential reduction of emissions from/growth in the forest pool

Measure	Potential removals
Wetland restoration of riparian forests	2.5t/ha/year[501]
Afforestation of pastures	18t/ha/year[502]
Wood products replace other materials[CCXXXIX]	67.8 million tonnes/year to 2020[503]
Wood products replace other energy sources	37.7 million tonnes/year to 2020[504]

CCXXXVII The rotation cycle is the length of time between planting and harvesting a tree.

CCXXXVIII Cascading use of wood means that the wood, once harvested, is first used as a raw material (in wood products with long lifespans such as timber for construction or furniture, or short lifespans such as paper). Only at the end of the products' lifespan will the wood or wood product be used for energy.

CCXXXIX It is ony possible to state the substitution effects to 2020, and then only after Rüter[498]. This is because Rüter et al. have modelled developements in the wood product market, and therefore the distribution of making different wood products, to 2020. Without additional modelling of the distribution of the different wood products, it is not possible to calculate their substitution effect to 2050. The figures given in the table are aligned with WEHAM Scenario A, 'business as usual' because this is the scenario which provides the optimum GHG distribution between the forest pool, the wood pool and the substitution effect.

The implementation of the proposed measures will face a variety of obstacles:

- The afforestation of new areas will be competing with other types of land use (see Table G-2). The net growth in forest area halved between 1990 and 2010 because an ever-decreasing area was available for afforestation. This clearly illustrates the difficulty of mobilising the sink potential quoted in the literature.[505] Faced with an increase in agricultural area of almost 1.5 million hectares by 2050, we assume that no additional area will be available for afforestation.
- Extending rotation cycles can only bring a limited increase in the carbon pool (see Figure G-5, Scenario D). However, assuming demand from German consumers remained the same, this increase would be accompanied by a decrease in storage in forests outside Germany, and would not therefore result in an overall reduction in emissions.
- The sink potential from wetland restoration of riparian forests is limited and can only be realised slowly. A (conservative) estimate results in an emission avoidance/sink potential of 2.5 tonnes of CO_2 per hectare per year (see Table G-2).
- Greenhouse gas emissions can also be reduced and delayed by strictly using all wood as a material before using it for energy – also known as cascading use. Depending on the intensity with which the forests in Germany are used, an annual saving of 54.6 to 67.8 million tonnes of CO_2 has been calculated to 2020,[506] purely due to the material substitution of wood for energy-intensive products (see Table G-2). No projections are available for the period from 2020. However, we assume that in 2050 the manufacture of energy-intensive products will be greenhouse gas-neutral, and the substitution effect will therefore cease to apply.
- In the context of the present study, short-rotation plantations – which count as cultivated biomass – are not considered as having climate protection potential.

No scenarios or projections are available to help calculate the impact of the proposed measures and the possibilities for implementing them (including any necessary incentives for the sector). Furthermore, the influence of the consequences of climate change on forests in Germany can only be estimated roughly. Yet such an estimate would be required for a precise assessment of the potential developments in the pool as a result of such measures. Further research will be required on these aspects in order to achieve robust results.

Figure G-3: Substitution and cascading use for greater resource conservation

If wood products from proven sustainable forestry replace energy-intensive products, then this will be a significant step towards a sustainable supply of raw materials as well as contributing to environmental conservation. Energy-intensive products are often made of metals or petroleum, or contain other mineral raw materials such as pebbles, sand or rocks. It often takes a lot of energy to extract and process these raw materials, and the processes involved can be significantly detrimental to the environment.[507] Equally, large volumes of material are extracted from their natural environments, although only a small proportion actually ends up in the finished product.

If wood products from sustainable forest management are used, and the proportion of cascading use increased – which means more wood is reused in other products after the initial product lifespan is over – this can result in a significant increase in resource efficiency[CCXL] and conservation[508]. In terms of volume, wood is already the most significant of all the renewable resources used as raw material or for energy in Germany[509]. It is used in many traditional ways for building, furniture, window frames, freight palettes, paper and cardboard. An increased revival of traditional uses and the development of innovative products and processes using wood mean that, for example, wood could increasingly replace steel, concrete and plastic in the construction industry. The 'ÖkoPot' project illustrated the environmental potential of substituting construction industry products with wood[510]. The BRIX[511] research project showed that an eight-storey tower block built with wood reduces raw material consumption (including for energy) by almost half over the entire life cycle of the building compared to conventional concrete and steel construction. This construction method would also significantly reduce negative environmental impact.

Yet the extent to which the substitution potential can be exploited depends crucially on the availability of the relevant raw materials. Even the availability of renewable resources like wood is limited, against the backdrop of limited land availability, other uses taking priority and adherence to sustainable and environmentally friendly production.

Besides environmentally friendly production, the efficient use of our limited raw material resources is therefore of primary importance. In other words, wood should be increasingly used for high-grade purposes and then re-used wherever possible. Furthermore, the efficient use of resources also means being sparing with energy, other materials and water. Cascading use is an important component of this approach.[CCXLI]

G.3.1.1 Wood flows and use

In order to provide a better understanding of the product flows in terms of climate protection, we have used high-profile studies and expert opinions to present the possible uses of wood from forests. These include in particular use as a raw material and cascading use.

For the period between 2005 and 2009, the Thünen Institute of Wood Research has analysed information on wood use and the material flow for wood through the forestry and wood processing chain in Germany, using the example of timber from conifers.[512] This analysis is not comprehensive, since

CCXL In terms of resource strategies, as well as sufficiency and consistency, increasing efficiency helps reduce resource use in relative or absolute terms. Resource conservation is the careful use of natural resources with the aim of preserving both the volume and function of available resources. For a more detailed explanation, see the UBA glossary (available in German: Glossar zum Ressourcenschutz, UBA 2012 a).

CCXLI See footnote CCXXXVI.

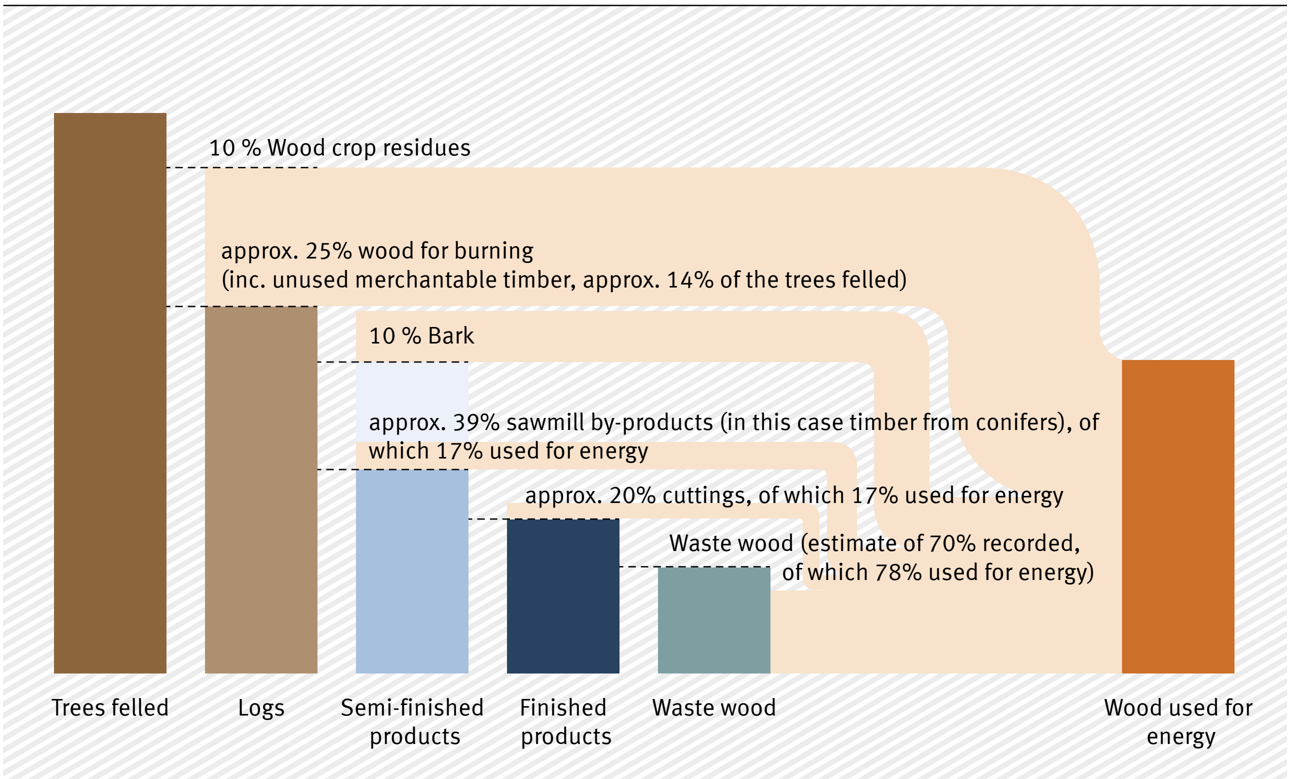
deciduous trees are not accounted for and the period covered needs to be extended. However, the data thus supplied does provide an initial indication of developments in the harvested wood products (HWP) pool. Figure G-4 provides an overview of this data. From this illustration and the assumptions made in it, we can establish that throughout its life cycle, from the time the wood is harvested through processing to its status as a waste/residual product, the majority of material produced is used for energy. Taking timber from conifers as an example, this figure stands at around 45% of all the trees felled, not including waste wood. Yet the proportion of wood used directly for energy is smaller (around 25%), with another share (around 20%) being used for energy in the course of its processing and use.

The burning of merchantable timber and smallwood cannot be avoided altogether (the 25% stated in Figure G-4 above as fuel wood). This is because it consists of thinnings and offcuts of low quality, and not (or not in significant amounts) of wood suitable for use as a raw material. The alternative to giving this wood as firewood to small scale, household users with wood collecting permits would be to let the wood decompose in the forest, in which case it would release the same amount of greenhouse gases. Naturally, an increased amount of dead wood would require closer scrutiny in respect of other goals. For example, on the one hand more dead wood is important for promoting biodiversity, but on the other it presents a greater forest fire risk, especially in view of the hotter, drier summers expected in many parts of Germany due to climate change. This could release, in a short space of time, carbon that had been stored for several centuries.

If wood is not used for energy until it has been employed as a raw material, this can further improve the reduction in greenhouse gas emissions. Unfortunately, the material flows leading to the use of industrial waste wood for energy or as a raw material are mainly determined by supply and demand, and are hard to influence. In particular, the current conditions on generating energy from biomass affect the extent to which sawmill by-products can be used to manufacture chipboard or wood pellets.

The impact of any potential shift from use as raw material towards increased use for energy, or towards the increased use of sawmill by-products as a raw material, cannot be assessed here since the study described above[9] only provides a snapshot of timber from conifers between 2005 and 2009. It would therefore be worth investigating how the material flow for wood has developed in the past, and what the different options are for changing the flows throughout the processing chain with a view to optimising their impact on the sector's CO_2 balance.

Figure G-4: Wood flows throughout the processing chain between 2005 and 2009[513]



(Rüter 2011)

G.3.2 Agricultural areas: Cropland and grassland

Organic soil used for agriculture makes up only 6% of the area used for agriculture in Germany, at 1.2 million hectares, but is responsible for 86% of the overall emissions from soil, or 4.3% of overall German greenhouse gas emissions, at 41.1 million tonnes of CO_{2eq}[CCXLII]. It follows that ceasing to use even a comparably small area for agriculture and rewetting it holds great potential to reduce greenhouse gas emissions. Besides ceasing to use land for agriculture, alternatives to conventional agriculture can provide varying degrees of emission reductions:

- Extensive use of flooded grassland as pasture for hardy breeds of livestock
- Paludiculture: planting wetland-type vegetation such as reeds, alders, sphagnum moss, fungi and berries for use as either food or raw materials

Although it is preferable for rewetting to take place without resuming use of the land, alternative uses may be worthwhile in individual cases. The primary considerations when deciding this should be conflicting use and financial disadvantage. The agriculture scenarios in GHG-neutral Germany 2050 do not take into account paludiculture.

Section G.2.3 investigates in further detail the limits set by the inventory for considering methane (CH_4) emissions from rewetted organic soils and carbon removal by restored wetlands[CCXLIII].

CCXLII Overall emissions, including CO_2 from LULUCF.

CCXLIII Organic soils reported under cropland and grassland are, once restored as wetland, entered into the inventory as (Land converted to ...) wetland.

G.3.3 Wetlands

According to the inventory system, almost all the emissions from wetlands can be traced back to industrial peat extraction. Organic soils used for agriculture are discussed in Section G.2.2.

As mentioned in Section G.2.2.3, the aim when preparing inventories is to implement international regulations on considering CH_4 emissions from restored wetlands and CO_2 removal by growing wetlands. Following years of use and drainage, high levels of CH_4 may be emitted temporarily once a drained wetland area has been restored, and these may even significantly exceed the previous CO_2 emissions. This is because of the anaerobic decomposition of vegetation which is not suited to the wetland environment. Regulated, monitored wetland restoration can largely avoid these peaks in methane emissions. Yet over the whole year, even growing wetlands emit methane and carbon dioxide due to fluctuations in the water table. Growing wetlands are carbon pools with a slow, steady build-up of carbon.

Since there is insufficient data, we are unable to produce a final estimate of the contribution and potential of existing wetlands, beyond predicting the potential for minimising emissions by stopping industrial peat extraction. In some regions of Germany, climate change means that the extent to which wetlands depend on the availability of water will become more of an issue. Further research is needed into the flows of greenhouse gases to and from wetlands and into the additional comprehensive recording of data over periods spanning multiple years.

G.3.4 Settlement

The potential for sequestration lies in expanding green spaces in urban areas, especially planting trees in industrial zones and greening the inner cities. Projects are underway to improve the existing estimates in the inventory and reflect the true sink effect of today's urban green spaces. Further investigations should build on this work, looking into the potential for an extensive greening of current land use patterns. In addition to this, any further use and sealing of organic soils should be avoided.

G.4 GHG reduction and carbon removal scenarios

Compared to other sectors, the 'land use, land use change and forestry' sector plays a special role because: it has the potential to act as a sink; there are large natural carbon pools in the soil and biomass; it takes a long time for measures to come into effect; and it depends directly and heavily on natural factors (such as climate and therefore climate change). In addition, action taken in the LULUCF sector will affect not only GHG emissions and removals, but also the supply of food and raw materials. The interconnected nature of the globe means such action will have an impact beyond national boundaries. This makes it more difficult to assess future possibilities, potential and developments regarding GHG emissions and sequestration in LULUCF in general and the forest sector in particular.

G.4.1 Forest

There are no projections available for any of the climate protection measures listed in Section G.3.1.1.

We have therefore applied the projections made by the Thünen Institute (Figure G-5) to future woodland development and wood production (WEHAM[CCXLIV]) in Germany using three different scenarios, showing results to 2040.

The forest development and timber resource model[CCXLV] calculates the potential availability of roundwood and the development in forests associated with that, especially the increment over the next 40 years. WEHAM projects the growth of single trees and consists of three parts: a growth simulator, a management simulator and a grading module.[514] The growth simulator is based on the two German forest inventory datasets from 1987 and 2002 and the 2008 Inventory Study. It is used to extrapolate increments for regions and species. The management simulator uses assumptions about parameters such as the frequency and intensity of pruning, and the trees' age and their basal area when harvested. The WEHAM model can also evaluate the increments in the main tree species. General conditions such as climate, selection of species or forest area cannot be included as parameters; nor can legal use restrictions. The model also excludes economic parameters, technical conditions (such as the steepness of slopes and distribution of forest paths) and tree mortality. The figures for the years 1990 to 2007 come from the European Commission's Framework for Integrated Environmental and Economic Accounting of Forests – IEEAF.

The Thünen Institute's WEHAM model can supply data for the years between 2003 and 2040. The figures shown in Figure G-5 for the period 2003–2007 were calculated from the mean average of IEEAF figures and of figures from the relevant WEHAM scenario. A figure on the positive axis (in black) represents CO_2 emissions released into the atmosphere; negative (red) figures mean CO_2 captured from the atmosphere (a sink). Wood products are not included in the model; the assumption made is that trees release the carbon they embody immediately after they are harvested. The WEHAM model does not take into account the climate, or any potential changes in it.

Scenario A means continuing to manage forests in the same way (BAU, business as usual). Scenario D assumes a 20% longer rotation cycle, which means slower use (of German forests), and Scenario F assumes a shorter rotation cycle, meaning more intensive use. Once again, wood products are not considered.

It emerges that, regardless of the choice of scenario and the difference in development in the intervening period, by 2040 the balance between emissions and removals by German forests will vary little, with all scenarios fluctuating around the zero mark.

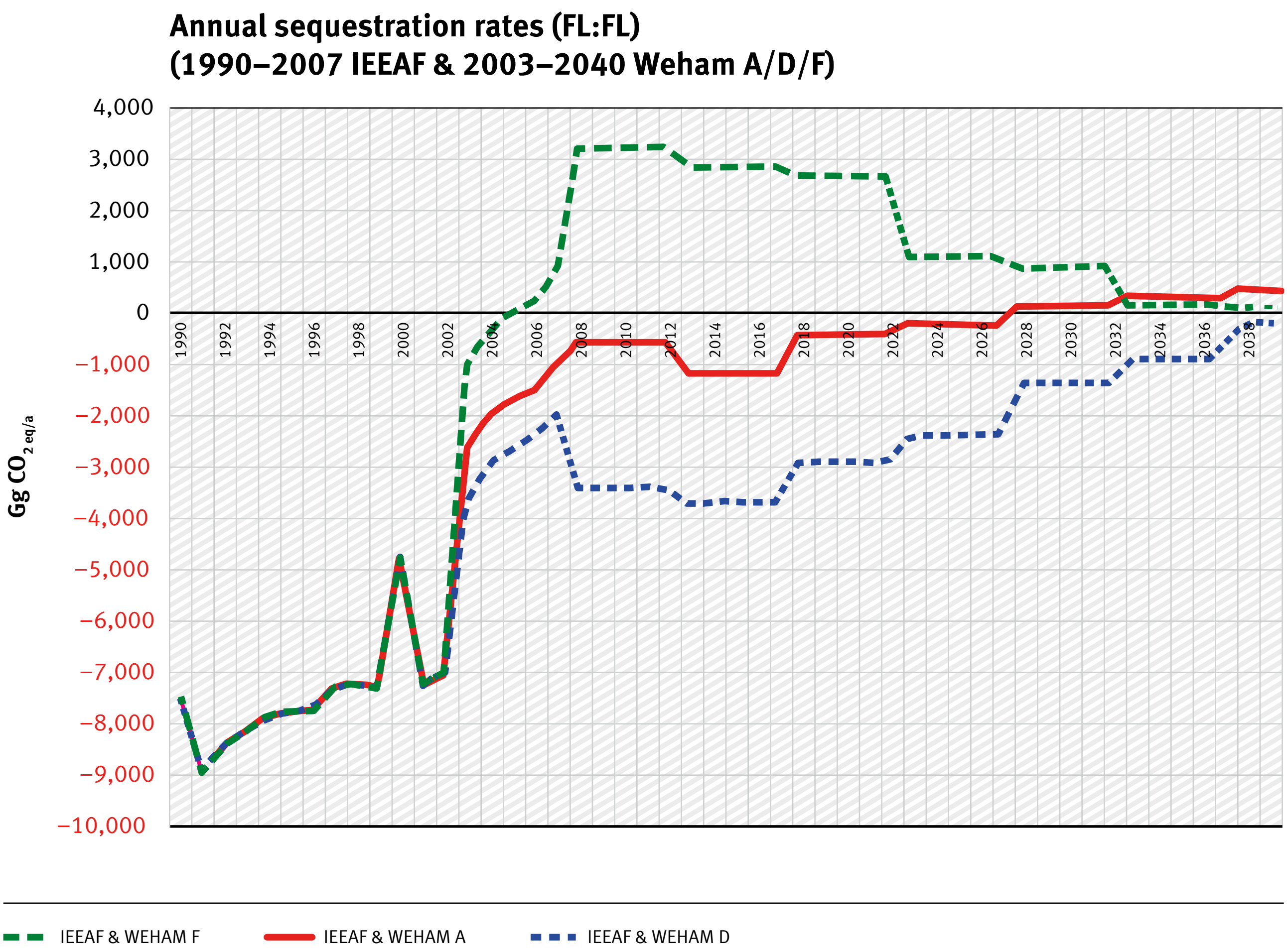
With no changes to current forest management (Scenario A), German forests would be a slight net source of emissions from the end of the 2020s.

Extending rotation periods, combined with reduced harvest intensity, would lead in the interim to around 30 years of increased carbon removal, but the increase in the age at which trees are felled would ultimately just delay emissions. In the long term, no net emissions reduction would be achieved. Furthermore, such a reduction in wood use is not realistic. It would translate to Germany importing increasing amounts of wood, which would mean carbon leakage as emissions shifted to other countries, possibly countries already struggling to counter deforestation and other environmental problems. (Germany‘s carbon footprint would remain at least as big).

CCXLIV WEHAM: WaldEntwicklungs- und HolzAufkommensModellierung, forest development and timber resource modelling

CCXLV For further information, see: http://www.ti.bund.de/en/startseite/institutes/forest-ecosystems/research-projects/greenhouse-gas-inventories/subprojects-ghg/weham.html.

Figure G-5: Annual emissions and removals from forest management in kt (Gg) CO_{2eq}[515]



The Thünen Institute[516] has calculated that, according to the scenario applicable, between 84 (WEHAM Scenario D) and 118 (WEHAM F) million tonnes of CO_2 can be saved by 2020 through the use of wood for energy and material substitution. The majority of CO_2 thus saved is linked to the use of wood as a material.

However, looking at the WEHAM scenarios and the requirement to comply firmly with the principle of sustainable use of forests, the UBA believes it is plausible and realistic for the German forestry sector to maintain zero net emissions in the long term. In reality, this means emissions and removals will fluctuate, around the zero mark. It is not likely that exact adherence to zero emissions will be achieved in 2050, but nor is it especially important. It is more important that mean emissions in the long term remain at 0 or below and that safeguards are established to ensure that the amount of wood harvested does not exceed the amount of regrowth.

Given the basic assumptions underlying the overall report, the BAU Scenario is the key one for future development. The increased use scenario contradicts our basic assumptions, and the reduced use scenario cannot be selected or recommended because the continued demand for wood would merely shift emissions to other countries (carbon leakage).

No scenario is available for 2050 and there is no scenario that takes into account carbon sequestration in wood products. It is therefore currently not possible to provide reliable figures for 2050.

G.4.2 Agricultural areas: Cropland and grassland

In the expert report 'Minderungspotenzial von Treibhausgasemissionen in der Landwirtschaft', the Thünen Institute investigates the potential for rural areas to save 37.1 million tonnes of CO_{2eq} across 1.05 million hectares of organic soils in agricultural use.[517] Of these, 633,000 hectares of grassland and 420,000 of cropland on drained organic soils could be set aside and restored. According to estimates, due to their proximity to human settlements and infrastructure or because peat stocks would be irreversibly damaged, the remaining 180,000 hectares of cropland cannot be converted back into wetland. We assume that these areas will become extensively managed grassland. These areas will continue to emit 4 million tonnes of CO_{2eq}. Withdrawing almost 6% of the agricultural area from production represents a significant restriction of the basis for production in the agriculture sector, and this is considered in the Thünen Institute's scenarios for agriculture (see Section G)[CCXLVI]. Since in 2050 no further land will be converted into cropland, there will be no emissions from conversion to cropland. According to the current results from the Greenhouse Gas Inventory, no emissions will be assumed to arise from mineral soils in agricultural use (NIR 2012 Section 7.3.4.3).

Including the 1.5 million tonnes of CO_2 emissions assumed to arise from the use of agricultural lime in 2050, total emissions from agricultural soils will be 5.5 million tonnes of CO_{2eq}.

G.4.3 Wetlands

Further reductions of up to 2 million tonnes of CO_2 could be made by putting an end to peat extraction and largely (wherever possible) substituting peat used in horticulture with alternative material such as coir or terra preta. However, a complete ban on peat extraction in Germany could result in carbon leakage if not underpinned by a simultaneous import ban on peat.[CCXLVII]

G.4.4 Settlements

According to the Thünen Institute's expert opinion, no additional land will be converted to settlement or transport use in 2050. It is assumed that there will be a linear decline in conversion to these uses, from 80 hectares per day in 2007 to 30 hectares per day in 2020 (Federal Government 2002), reaching the zero target by 2050. GHG emissions from settlements in 2010 are assumed to fit this pattern, which would mean 2.5 million tonnes of CO_2 in 2050. Due to a lack of data, no estimates can be made about expanding the sink potential of green areas within settlements.

G.5 Summary

Given the assumptions described in Section G.3 above, total emissions for the sector should amount to 8 million tonnes of $CO2_{eq}$ for land use excluding forestry. It is assumed that the potential exists for rural areas to save 37.1 million tonnes of CO_{2eq} over 1.05 million hectares of organic soils in agricultural use. In order to achieve this, 633,000 ha of grassland and 420,000 ha of cropland on drained organic soils must be set aside and restored.[518] Further reductions of up to 2 million tonnes of CO_2 could be made by ending peat extraction and largely (wherever possible) substituting peat used in horticulture with alternative material such as coir or terra preta.

CCXLVI [475], Section 5.1.

CCXLVII Imports of peat to Switzerland at the time of a ban on extraction: http://www.parlament.ch/d/suche/seiten/geschaefte.aspx?gesch_id=20103106

None of the scenarios for the forestry sector considers the complex implications, both ecological (natural and anthropogenic cycles, effects of climate change, and conservation targets) and economic (source of raw materials, ecosystem services). It is conceivable for the German forestry sector to achieve zero net emissions in the long term if the principle of sustainability is applied firmly.

However, it must be noted when assessing the impact of measures to reduce emissions and enhance sinks that carbon is only sequestered in land and biomass very slowly, whereas it is released rapidly.

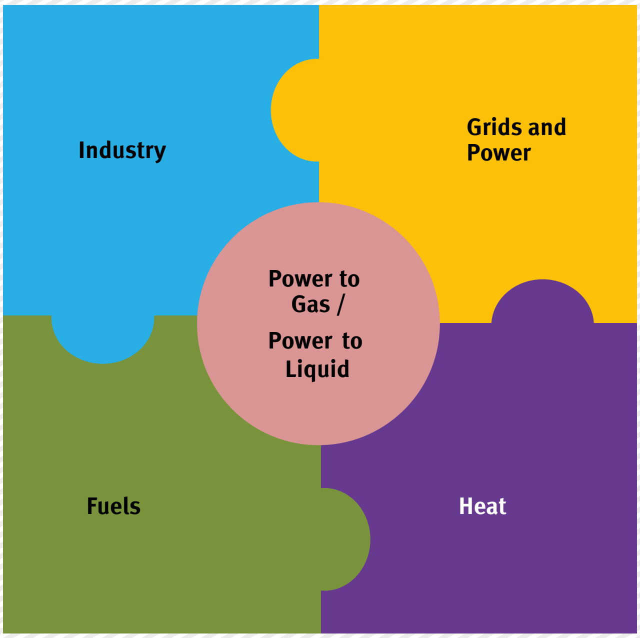
H. Conclusion/Discussion

It is technically possible to achieve a greenhouse-gas neutral Germany with annual per capita emissions of one tonne of CO_{2e} in 2050, and thus a 95% reduction in emissions. We describe one possible option within a solution space.

Renewable energy can cover not only our electricity, but also our fuel requirements. The key component is converting electricity generated using renewables into hydrogen, methane and relatively long-chain hydrocarbons (power to gas and power to liquid technology). This results in a strong increase in power demand.

Our scenario is based on switching the entire energy supply to renewable sources, and extensive exploitation of the potential for efficiencies. Thus emissions from the energy sector would drop to almost zero and the other sectors could also significantly reduce their emissions. The key component for our scenario is converting electricity generated using renewables into hydrogen, methane and long-chain hydrocarbons. This is the only way in our scenario that the demand for fuel and raw materials in the industry, transport and heat sectors can all be covered. The result is a major increase in power demand, far beyond what could be called excess power.

Figure H-1: Overview the potential scope of application of power-to-gas/power-to-liquid technology in the UBA GHG-neutral Germany 2050 scenario



The technical potential to generate this volume of electricity at national level is indeed available, but since for environmental and economic reasons, among others, only part of this potential can reasonably be harnessed, we assume that some of the electricity required in Germany will be generated abroad. PtG and PtL conversion could occur at the place where the electricity is generated and the resulting fuels could then be imported. Assuming electricity supply nationwide was on the same scale as it is today (466 TWh), the proportion of primary energy imports[CCXLVIII] would be of the same order of magnitude.

In order to make a greenhouse gas-neutral Germany a reality by 2050, technological innovations and the further development of current technologies will be required in some areas. Hence there is a need for research and development.

Our study is based on the best technology currently available. However, we have also assumed that new technologies and technical applications which have so far only been tested on a small scale will by 2050 have been introduced to the mainstream market. We are aware that, for this to be achieved, many technological innovations will be required over the next four decades. For example, power to gas and especially power to liquid conversion are only just market-ready and only beginning to be implemented commercially. Several pilot plants are currently running in Germany, and in Iceland a power to liquid installation is now operating on a commercial basis.

It is becoming increasingly clear that there is considerable room for manoeuvre with regard to converting the energy system to achieve a greenhouse-gas neutral economy. Yet it is also clear that converting the energy system to renewables will occupy a key position. Thus the energy transition and the implementation of ambitious climate protection targets are a task to be tackled by policymakers and society at large by first considering the desired outcome: an economy and way of life which are almost entirely greenhouse-gas neutral.

Further analysis is needed to broaden the solution space and identify suitable routes towards transformation. The reduction of high electricity consumption levels is one such research area – especially in the transport sector. We need to find out whether it would be possible to further expand the use of both hydrogen and electricity from renewable sources, and how more can be done to avoid traffic and initiate a shift in modes of transport.

Hydrogen is not yet used as a source of final energy, either for conversion to electricity or for transport. Hence there is a great need for research and development. Compared to methane and liquid fuels, hydrogen has major advantages (lower conversion losses), but also disadvantages (it is less energy-dense).

Further research is required as to whether more electricity can be used directly in transport and/or whether gases such as methane or hydrogen might replace liquid fuels. When looking at the potential use of hydrogen, the necessary infrastructure must be considered in depth and in great detail. Hydrogen would have the potential to reduce high conversion losses significantly, which would also reduce the demand for electricity.[CCXLIX] There is also a need to assess several suggestions currently under discussion – including the installation of overhead electric cables above motorways, accompanied by switching heavy goods vehicles to hybrid propulsion – in terms of the efficiency of the overall system and the costs involved.

We also assumed that in 2050 energy could be saved by avoiding travel and through a modal shift in transport. Our assumptions are based purely on moderate development which appears realistic from our present point of view. More far-reaching measures such as driving restrictions could be imposed, or extensive voluntary changes in behaviour and lifestyle made, which would lead to greater avoidan-

CCXLVIII According to our study, net electricity generation for 2050 will be at the same level as primary energy.

CCXLIX Net electricity demand.

ce effects and modal shifts. However, thorough debate would be required before the public accepted any such changes.

The scope of the present study does not encompass a cost-benefit analysis. Our aim is purely to prove, as an initial step, that it is technically feasible to achieve a climate-neutral Germany. We are therefore unable to predict the cost of reducing emissions by 95%, or what economic benefit will flow from this transformation. Further research is required to show the cost and benefit in detail. We must also identify the economic and regulatory framework which will be required to promote the development and diffusion of the necessary technological innovations.

Long-term economic analysis is fraught with uncertainty. Little is known as yet about the cost of the individual technologies, such as power to gas and power to liquid. Each step in the conversion from hydrogen to liquid fuel involves additional energy losses, and thus increases cost – not least because it requires high electricity consumption. Once again, further research is required. Assessments of costs for the various drive and fuel technologies in the transport sector, which also take into account learning curves, will be vital for a thorough evaluation, but are not included in the present study.

This study does not consider the framework conditions which must be in place for a particular technology to be introduced. Such conditions apply for example to the use of methane as a source of carbon for the chemical industry. It is clear that the oil industry will not switch to methane as long as oil is cheaper than renewable methane, especially since this would require a major investment in technology. Targeted policies could create the requisite conditions for this shift.

On its route to becoming greenhouse gas-neutral, Germany must be guided by additional sustainability criteria and in particular study the interaction between sustainability and resource productivity.

As mentioned in the introduction, for reasons of sustainability we have excluded from our scenario the cultivation of biomass crops solely to generate energy. In contrast to other studies, we have not considered Carbon Capture and Storage (CCS), partly because storage capacity in Germany is limited. The use of nuclear energy is no longer an option in Germany.

Unfortunately, we have not been able to illustrate here the interaction between sustainability and resource productivity. Further research on this should focus on how climate protection objectives and resource efficiency can complement one another and how any possible points of conflict between them can be resolved.

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

A comprehensive assessment must take into account the potential displacement of emissions abroad, i.e. carbon leakage – a problem which the present study has only begun to investigate. We only looked at emissions arising within Germany, in line with the method for emissions reporting. In other words, we have not included emissions arising abroad, but for which Germany is responsible because it imports the goods produced. Conversely, we have included emissions from products manufactured in Germany which are then exported. The relevant energy and material flows in conjunction with imports and exports have been accounted for as part of the UN System of Environmental-Economic Accounting (SEEA) and in life cycle analyses, but because of the complexity of assumptions that would be required with regard to 2050, these could not be considered here (cf. Ein treibhausgasneutrales Deutschland in europäischer und internationaler Perspektive (A greenhouse gas-neutral Germany in a European and international context), p. 28/29). There were, however, a few exceptions where the connection was very clear. Thus we assumed that there would be no imports of biofuel, as this would involve competition for farmland and emissions caused by growing the relevant biomass, primarily due to indirect land use change. Carbon leakage was also mentioned in the Agriculture chapter, and discussed in more detail in the context of ecological rucksacks. Although we have been mainly looking at technical solutions in this study, we assume in the context of agriculture that in 2050 the population will have a healthier diet – for example eating less meat. This would lead to a significant decrease in livestock – this is the only way agricultural emissions could be reduced sufficiently without leakage effects[CCL] due to a large-scale increase in meat imports.

We are presenting this scenario as a means of stimulating discussion in the scientific community about the possible solution spaces for a greenhouse-gas neutral Germany, as well as for greenhouse-gas neutrality in other industrialised countries. Thus research, development and modelling can combine to provide a platform on which the necessary policy decisions can be made. This will in turn help spark a timely discussion, provide the requisite tools and measures, and ensure they are implemented appropriately to make Germany a greenhouse gas-neutral country.

CCL ‘Leakage effects’ means displacing emissions outside the country’s borders.

I. References

1 Umweltbundesamt (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau p.16

2 Federal Environment Agency, national trend tables for German reporting on atmospheric emissions since 1990, http://www.umweltbundesamt.de/emissionen/publikationen.htm

3 BMWi (Federal Ministry for Economic Affairs and Energy) (2012): Ausgewählte Grafiken zu Energiegewinnung und Energieverbrauch (selected energy production and energy consumption charts), s.l.

4 BMWi (Federal Ministry for Economic Affairs and Energy) (2012): Energie in Deutschland (Energy in Germany), s.l.

5 BMWi (Federal Ministry for Economic Affairs and Energy) (2012): Energie in Deutschland (Energy in Germany), s.l.

6 AGEB (2012): Evaluation Tables on the Energy Balance for the Federal Republic of Germany 1990 to 2011, s.l.

7 AGEB(2012): Bruttostromerzeugung in Deutschland von 1990 bis 2011 nach Energieträgern (Gross electricity generation in Germany from 1990 to 2011 by energy source), s.l.

8 AGEB (2012): Bruttostromerzeugung in Deutschland von 1990 bis 2011 nach Energieträgern (Gross electricity generation in Germany from 1990 to 2011 by energy source), s.l.

9 BMU (German Federal Environment Ministry) (2012): Renewables in Figures 2012, s.l.

10 AGEB (2012): Evaluation Tables on the Energy Balance for the Federal Republic of Germany 1990 to 2011, s.l.

11 BMU (German Federal Environment Ministry) (2012): Renewables in Figures 2012, s.l.

12 AGEB (2012): Evaluation Tables on the Energy Balance for the Federal Republic of Germany 1990 to 2011, s.l.

13 SEDLACEK, R. (2009): Underground Gas Storage in Germany, Erdöl Erdgas Kohle 125, 2009, Issue no. 11, p. 412 et seq.

14 Erdölbevorratungsverband (2008): Mineralölpflichtbevorratung in der Bundesrepublik Deutschland (Compulsory petroleum stockholding in the Federal Republic of Germany), s.l.

15 German Energy Agency (2008): Untersuchung der elektrizitätswirtschaftlichen und energiepolitischen Auswirkungen der Erhebung von Netznutzungsentgelten für den Speicherstrombezug von Pumpspeicherwerken (Investigation of the impacts on the electricity industry and energy policy of charging system usage fees for the purchase of electricity from pumped storage plants). Study commissioned by Vattenfall Europe Transmission, Berlin.

16 German Energy Agency (2008): Untersuchung der elektrizitätswirtschaftlichen und energiepolitischen Auswirkungen der Erhebung von Netznutzungsentgelten für den Speicherstrombezug von Pumpspeicherwerken (Investigation of the impacts on the electricity industry and energy policy of charging system usage fees for the purchase of electricity from pumped storage plants). Study commissioned by Vattenfall Europe Transmission, Berlin; and Öko-Institut, Prognos, Ziesing, H.-J. (2009): Modell Deutschland — Klimaschutz bis 2050: Vom Ziel her denken (Model Germany — climate protection to 2050: target-based thinking). Study commissioned by WWF, Berlin.

17 German Energy Agency (2008): Untersuchung der elektrizitätswirtschaftlichen und energiepolitischen Auswirkungen der Erhebung von Netznutzungsentgelten für den Speicherstrombezug von Pumpspeicherwerken (Investigation of the impacts on the electricity industry and energy policy of charging system usage fees for the purchase of electricity from pumped storage plants). Study commissioned by Vattenfall Europe Transmission, Berlin.

18 Federal Environment Agency's power plant database (October 2012), Dessau-Roßlau.

19 Office of Technology Assessment at the German Bundestag (TAB) (2012): Renewable energy sources to secure the base load in electricity supply, TAB report no. 147, Berlin, April 2012

20 Specht, M.; Baumgart, F.; Feigl, B.; Frick, V.; Stürmer, B.; Zuberbühler, U.; Sterner, M.; Waldstein, G. (2010): Speicherung von Bioenergie und erneuerbarem Strom im Erdgasnetz (Storage of bioenergy and renewables in the natural gas grid), Renewable Energy Research Association (FVEE) annual conference 2009, Berlin.

21 AGEB (2012): Evaluation Tables on the Energy Balance for the Federal Republic of Germany 1990 to 2011, s.l.

22 Federal Environment Agency, national trend tables for German reporting on atmospheric emissions since 1990, http://www.umweltbundesamt.de/emissionen/publikationen.htm; 7 November 2012.

23 Federal Environment Agency (2012): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 — National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, Dessau-Roßlau

24 Federal Environment Agency (2012): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 — National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, Dessau-Roßlau

25 BMU (German Federal Environment Ministry) (2011): Erneuerbare Energien — Innovationen für eine nachhaltige Energiezukunft (Renewables — innovations for a sustainable energy future), s.l.

26 BMU (German Federal Environment Ministry) (2011): Erneuerbare Energien — Innovationen für eine nachhaltige Energiezukunft (Renewables — innovations for a sustainable energy future), s. l.

27 Federal Environment Agency (2012): Globale Landflächen und Biomasse nachhaltig und ressourcenschonend nutzen (Using global land areas and biomass sustainably while protecting resources), Dessau-Roßlau

28 IPCC (2011): IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN), Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C., Edenhofer, O. (eds), Cambridge University Press, Cambridge and New York, 2011.

29 BMU (German Federal Environment Ministry) (2011): Erneuerbare Energien — Innovationen für eine nachhaltige Energiezukunft (Renewables — innovations for a sustainable energy future), s.l.

30 BMU (German Federal Environment Ministry) (2011): Erneuerbare Energien — Innovationen für eine nachhaltige Energiezukunft (Renewables — innovations for a sustainable energy future), s.l.

31 Hagelüken, C.; Meskers, C.E.M. (2010): Complex lifecycles of precious and special metals. In: Graedel, T.; van der Voet, E. (eds.): Linkages of Sustainability. Strüngmann Forum Report, vol. 4. Cambridge, MA: MIT Press; and Graedel, T. E. (2011): On the Future Availability of the Energy Metals. In: Clarke, D. R.; Fratzl, P., (eds.): Annual Review of Materials Research. Vol. 41, p. 323-335.

32 Erdmann, L.; Graedel, T. (2011): The Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses. In: Environmental Science & Technology 45(18), p. 7620–7630.

33 Moss, R.L.; Tzimas, E.; Kara, H.; Willis, P.; Kooroshy, J. (2011): Critical metals in strategic energy technologies — Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. European Union, Joint Research Centre (JRC), Luxembourg.

34 See U.S. Department of Energy (ed.) (2012): SunShot Vision Study. Washington.

35 Deutsches Zentrum für Luft- und Raumfahrt, Institut für Energie- und Umweltforschung & Wuppertal Institut für Klima, Umwelt und Energie (2004): Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland (Ecologically optimized extension of renewable energy utilization in Germany). Research project commissioned by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; Stuttgart, Heidelberg, Wuppertal.

36 Paschen, H.; Oertel, D. & Grünwald, R. (2003): Möglichkeiten geothermischer Stromerzeugung in Deutschland — Sachstandsbericht (Possibilities for geothermal electricity generation in Germany), TAB report no. 84, Office of Technology at the German Bundestag (TAB), Berlin.

37 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

38 Frick, S., Kaltschmitt, M. (2009): Ökologische Aspekte einer geothermischen Stromerzeugung — Analyse und Bewertung der Umwelteffekte im Lebensweg (Ecological aspects of geothermal electricity generation — Analysis and assessment of the life cycle environmental effects), Erdöl, Erdgas, Kohle, 125, issue 1, 37-42.

39 Sullivan, J.L., Clark, C.E., Han, J.W. and Wang, M.Q. (2010): Life Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems, Argonne National Laboratory, Argonne/ESD/10–5, August 2010.

40 Deutsches Zentrum für Luft- und Raumfahrt, Institut für Energie- und Umweltforschung & Wuppertal Institut für Klima, Umwelt und Energie (2004): Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland (Ecologically optimized extension of renewable energy utilization in Germany). Research project commissioned by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; Stuttgart, Heidelberg, Wuppertal.

41 Deutsches Zentrum für Luft- und Raumfahrt, Institut für Energie- und Umweltforschung & Wuppertal Institut für Klima, Umwelt und Energie (2004): Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland (Ecologically optimized extension of renewable energy utilization in Germany). Research project commissioned by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; Stuttgart, Heidelberg, Wuppertal.

42 Erdmann, L.; Feil, M.; Behrendt, S. (2011): Kritische Rohstoffe für Deutschland (Critical raw materials for Germany). Kreditanstalt für Wiederaufbau (KfW, ed.), Frankfurt a.M.; and Elsner, H. (2011): Kritische Versorgungslage mit schweren Seltenen Erden — Entwicklung 'Grüner Technologien' gefährdet? (Critical supply situation of heavy rare earth metals — Development of 'green technologies' at risk?) In: Commodity Top News, No. 36, Deutsche Rohstoffagentur (DERA), part of the German Federal Institute for Geosciences and Natural Resources, Hanover.

43 See Hatch, G.P. (2011): Critical Rare Earths: Global Supply & Demand Projections and the Leading Contenders for New Sources of Supply. Technology Metals Research (TMR), Carpentersville.

44 Wagner, H.J.; Baack, C.; Eickelkamp, T.; Epe, A.; Lohmann, J.; Troy, S. (2011): Life cycle assessment of the offshore wind farm Alpha Ventus. Energy, 36(5), p. 2459–2464.

45 Federal Environment Agency (2013): Potenzial der Windenergie an Land (Onshore wind energy potential), Dessau-Roßlau

46 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

47 Office of Technology Assessment at the German Bundestag (TAB) (2012): Renewable energy sources to secure the base load in electricity supply, TAB report no. 147, Berlin, April 2012

48 DVGW (2011): Mit Gas-Innovationen in die Zukunft (Gas innovations for the future), s. l.

49 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

50 BMU (German Federal Environment Ministry) (2012): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global (Long-term scenarios and strategies for the expansion of renewables in Germany, taking account of European and global developments), s.l.

51 Valentin, F. and von Bredow, H. (2011):Power-to-Gas: Rechtlicher Rahmen für Wasserstoff und synthetisches Gas aus erneuerbaren Energien (Power-to-gas: Legal framework for hydrogen and synthetic gas from renewable energy sources), Energiewirtschaftliche Tagesfragen 61 (2011), issue 12, p. 99–105.

52 Elliger, T. (1212): Elektrolyse im Fokus — Technologien zur Wasserstofferzeugung im Vergleich (Focus on electrolysis — A comparison of technologies for producing hydrogen), presentation on 13 March 2012 at Windgas — ETP Energy Innovation Days, Berlin.

53 DBI Gas- und Umwelttechnik GmbH and Fraunhofer IWES: First interim report on the project 'Klimaschutz und regenerativ erzeugte chemische Energieträger — Infrastruktur und Systemanpassung zur Versorgung mit regenerativen chemischen Energieträgern aus in- und ausländischen regenerativen Energien' (Climate protection and renewably sourced chemical energy vectors — Infrastructure and system adaptations for supplying chemical energy vectors from domestic and foreign renewables), project 3712 46 100, — publication with final report expected 2014.

54 Smolinka, T., Günther, M., Garche, J. (2011): Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien (Status and development potential of electrolysis of water for producing hydrogen from renewable energy sources). Final report of 22 December 2010, revised version 05 July 2011.

55 DBI Gas- und Umwelttechnik GmbH and Fraunhofer IWES: First interim report on the project 'Klimaschutz und regenerativ erzeugte chemische Energieträger — Infrastruktur und Systemanpassung zur Versorgung mit regenerativen chemischen Energieträgern aus in- und ausländischen regenerativen Energien' (Climate protection and renewably sourced chemical energy vectors — Infrastructure and system adaptations for supplying chemical energy vectors from domestic and foreign renewables), project 3712 46 100, — publication with final report expected 2014.

56 Kersten, M. (2012): Research Services of the German Bundestag: Power to Gas, 16 May 2012, s. l.

57 Sterner, M. (2009): Bioenergy and renewable methane in integrated 100% renewable energy system, dissertation, University of Kassel, Specht et al (2010).

58 Kersten, M. (2012): Research Services of the German Bundestag: Power to Gas. No. 10/12 of 16 May 2012, updated version of 11 December 2012.

59 Müller-Syring, G., Henel, M., Rasmusson, H., Mlaker, H., Köppel, W., Höcher, T., Sterner, M., Trost, T. (2011): Power to Gas: Untersuchungen im Rahmen der DVGW-Innovationsoffensive zur Energiespeicherung (Research conducted as part of the DVGW innovation campaign for energy storage), bbr - Fachmagazin für Brunnen und Leitungsbau, 10/2011, p. 14-21.

60 Valentin, F. and von Bredow, H. (2011):Power-to-Gas: Rechtlicher Rahmen für Wasserstoff und synthetisches Gas aus erneuerbaren Energien (Power-to-gas: Legal framework for hydrogen and synthetic gas from renewable energy sources), Energiewirtschaftliche Tagesfragen 61 (2011), issue 12, p. 99–105.

61 Müller-Syring, G. et al (2011): Power to Gas — Entwicklung von Anlagenkonzepten im Rahmen der DVGW-Innovationsoffensive (Power-to-gas — Development of facility concepts as part of the DVGW innovation campaign), gwf-Gas, November 2011, p. 770–779.

62 Müller-Syring, G. et al (2011): Power to Gas — Entwicklung von Anlagenkonzepten im Rahmen der DVGW-Innovationsoffensive (Power-to-gas — Development of facility concepts as part of the DVGW innovation campaign), gwf-Gas, November 2011, p. 770–779.

63 Müller-Syring, G., Henel, M., Rasmusson, H., Mlaker, H., Köppel, W., Höcher, T., Sterner, M., Trost, T. (2011): Power to Gas: Untersuchungen im Rahmen der DVGW-Innovationsoffensive zur Energiespeicherung (Research conducted as part of the DVGW innovation campaign for energy storage), bbr - Fachmagazin für Brunnen und Leitungsbau, 10/2011, p. 14-21.

64 DVGW (2011): Mit Gas-Innovationen in die Zukunft (Gas innovations for the future), s. l.

65 Müller-Syring, G., Henel, M., Rasmusson, H., Mlaker, H., Köppel, W., Höcher, T., Sterner, M., Trost, T. (2011): Power to Gas: Untersuchungen im Rahmen der DVGW-Innovationsoffensive zur Energiespeicherung (Research conducted as part of the DVGW innovation campaign for energy storage), bbr - Fachmagazin für Brunnen und Leitungsbau, 10/2011, p. 14-21.

66 Müller-Syring, G., Henel, M., Rasmusson, H., Mlaker, H., Köppel, W., Höcher, T., Sterner, M., Trost, T. (2011): Power to Gas: Untersuchungen im Rahmen der DVGW-Innovationsoffensive zur Energiespeicherung (Research conducted as part of the DVGW innovation campaign for energy storage), bbr - Fachmagazin für Brunnen und Leitungsbau, 10/2011, p. 14-21.

67 Müller-Syring, G., Henel, M., Rasmusson, H., Mlaker, H., Köppel, W., Höcher, T., Sterner, M., Trost, T. (2011): Power to Gas: Untersuchungen im Rahmen der DVGW-Innovationsoffensive zur Energiespeicherung (Research conducted as part of the DVGW innovation campaign for energy storage), bbr - Fachmagazin für Brunnen und Leitungsbau, 10/2011, p. 14-21.

68 Müller-Syring, G., Henel, M., Rasmusson, H., Mlaker, H., Köppel, W., Höcher, T., Sterner, M., Trost, T. (2011): Power to Gas: Untersuchungen im Rahmen der DVGW-Innovationsoffensive zur Energiespeicherung (Research conducted as part of the DVGW innovation campaign for energy storage), bbr - Fachmagazin für Brunnen und Leitungsbau, 10/2011, p. 14-21.

69 DVGW (2011): Mit Gas-Innovationen in die Zukunft (Gas innovations for the future), s. l.

70 Burmeister, F. (2012): Potenziale der Einspeisung von Wasserstoff ins Erdgasnetz — eine saisonale Betrachtung (The potential for blending hydrogen into the natural gas network — a seasonal view), energie|wasser-praxis 06/2012, p. 52–57.

71 ERDÖL ERDGAS KOHLE (2012): Untertage-Gasspeicherung in Deutschland (Underground gas storage in Germany), Erdöl Erdgas Kohle 128 (2012), issue 11, p. 411–423.

72 ERDÖL ERDGAS KOHLE (2012): Untertage-Gasspeicherung in Deutschland (Underground gas storage in Germany), Erdöl Erdgas Kohle 128 (2012), issue 11, p. 411–423.

73 Crotogino, F. (2011): Wasserstoffspeicherung in Kavernen: Wind-Wasserstoff-Systeme — wie geht's weiter? (Hydrogen storage in caverns: The future of wind hydrogen systems), conference proceedings of the Pro H2 Technologie Forum 2011, 12 October 2011, Solvay GmbH, Hannover; and Crotogino, F.; Hamelmann, R. (2007): Conference proceedings of the 14th Symposium on Use of Renewable Energy Sources and Hydrogen Technology, Stralsund, 8–10 November 2007, Fachhochschule Stralsund, p. 11–17.

74 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

75 InSpEE joint project: Informationssystem Salzstrukturen: Planungsgrundlagen, Auswahlkriterien und Potentialabschätzung für die Errichtung von Salzkavernen zur Speicherung von Erneuerbaren Energien (Salt structures information system: Planning criteria, selection criteria and potential assessment for the construction of salt caverns for the storage of renewables). Teilprojekt Bewertungskriterien und Potentialabschätzung (Sub-project: Evaluation criteria and potential assessment), (FKZ 03ESP323A, BMWi IIIC2 / PT-J ERG6), s. l.

76 The American Physical Society (2011): Direct air capture of CO_2 with chemicals, USA.

77 The American Physical Society (2011): Direct air capture of CO_2 with chemicals, USA.

78 Federal Environment Agency (2006): Verfahren zur CO_2-Abscheidung und -Speicherung (Processes for CO_2 capture and storage), Climate Change series, research report 203 41 110 UBA-FB 000938, Dessau.

79 Federal Environment Agency (2006): Verfahren zur CO_2-Abscheidung und -Speicherung (Processes for CO_2 capture and storage), Climate Change series, research report 203 41 110 UBA-FB 000938, Dessau.

80 Federal Environment Agency (2006): Verfahren zur CO_2-Abscheidung und -Speicherung (Processes for CO_2 capture and storage), Climate Change series, research report 203 41 110 UBA-FB 000938, Dessau.

81 Federal Environment Agency (2006): Verfahren zur CO_2-Abscheidung und -Speicherung (Processes for CO_2 capture and storage), Climate Change series, research report 203 41 110 UBA-FB 000938, Dessau.

82 German Energy Agency (2012): Integration erneuerbaren Stroms in das Erdgasnetz (Integrating renewable electricity into the natural gas network), Strategieplattform Power to Gas, Thesenpapier Technik und Technologieentwicklung http://www.powertogas.info/thesen.html; downloaded 11 December 2012.

83 Fraunhofer Institute for Solar Energy Systems, Smolinka, T. et al (2011): Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien (Status and development potential of electrolysis of water for producing hydrogen from renewable energy sources), short version of final report of 5 July 2011, s. l.

84 DBI Gas- und Umwelttechnik GmbH, Henel, M. (2012): Ergebnisse des DVGW-Projektes Energiespeicherkonzepte (Results of the DVGW project on energy storage concepts) (G1-07-10), DBI Fachforum Energiespeicher-Hybridnetze, presentation, 12 September 2012, Berlin.

85 Purr, K. (2012): Die Rolle von regenerativ erzeugten chemischen Energieträgern in einem auf erneuerbaren Energien basierenden Energiesystem (The role of renewably sourced chemical energy vectors in an energy system based on renewables), presentation at the Leuphana Energieforum on 17 September 2012, Lüneburg.

86 https://www.entsoe.eu/resources/ntc-values/ntc-matrix/, downloaded 11 December 2012.

87 50Hertz Transmission GmbH; Amprion GmbH; TenneT TSO GmbH; TransnetBW GmbH (2012): Netzentwicklungsplan Strom 2012 (Power grid development plan 2012) — 2nd revised draft by transmission network operators, s.l.

88 BMU (German Federal Environment Ministry) (2012): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global (Long-term scenarios and strategies for the expansion of renewables in Germany, taking account of European and global developments), s.l.

89 BMU (German Federal Environment Ministry) (2012): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global (Long-term scenarios and strategies for the expansion of renewables in Germany, taking account of European and global developments), s.l.

90 Prognos AG, EWI, GWS (2010): Energieszenarien für ein Energiekonzept der Bundesregierung (Energy scenarios for a national German energy concept), study commissioned by the German Federal Ministry for Economic Affairs and Energy (BMWi), Basel, Cologne, Osnabrück.

91 BMU (German Federal Environment Ministry) (2012): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global (Long-term scenarios and strategies for the expansion of renewables in Germany, taking account of European and global developments), s.l.

92 Prognos AG, EWI, GWS (2010): Energieszenarien für ein Energiekonzept der Bundesregierung (Energy scenarios for a national German energy concept), study commissioned by the German Federal Ministry for Economic Affairs and Energy (BMWi), Basel, Cologne, Osnabrück.

93 German Energy Agency (2012): Integration der erneuerbaren Energien in den deutschen/europäischen Strommarkt (Integrating renewables into the German/European electricity market), Berlin.

94 https://www.entsoe.eu/resources/data-portal/country-packages/, downloaded 13 December 2012.

95 German Energy Agency (2012): Integration der erneuerbaren Energien in den deutschen/europäischen Strommarkt (Integrating renewables into the German/European electricity market), Berlin.

96 http://eurogas.org/, downloaded 19 November 2012.

97 TOTAL (2011): Liquefied natural gas — A booming Industry, Courbevoie, France. s.l.

98 Vallentin, R. (2011): Energieeffizienter Städtebau mit Passivhäusern — Begründung belastbarer Klimaschutzstandards im Wohnungsbau (Energy-efficient town planning with passive housing — Justifying robust climate protection standards in house building), Dissertation, Munich.

99 WWF (2009): Modell Deutschland — Klimaschutz bis 2050: Vom Ziel her denken (Model Germany — Climate protection to 2050: target-based thinking), Berlin.

100 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

101 WWF (2009): Modell Deutschland — Klimaschutz bis 2050: Vom Ziel her denken (Model Germany — Climate protection to 2050: target-based thinking), Berlin.

102 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

103 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen (Energy target 2050: 100% renewable electricity supply), Dessau-Roßlau.

104 BMU (German Federal Environment Ministry) (2012): Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global (Long-term scenarios and strategies for the expansion of renewables in Germany, taking account of European and global developments), s.l.

105 NIR: National Inventory Report

106 NIR: National Inventory Report

107 Öko-Institut (Institute for Applied Ecology) (2013): Treibhausgasneutraler Verkehr 2050: Ein Szenario zur zunehmenden Elektrifizierung und dem Einsatz stromerzeugter Kraftstoffe im Verkehr, (Carbon-neutral transport 2050 – A scenario for increasing electrification and the use of electricity-based fuels in transport), Berlin

108 BMVBS (German Federal Ministry of Transport, Building and Urban Development) (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012); p. 53/101; Hamburg / BMVBS (2007): Verkehr in Zahlen 2007/2008 (Transport Figures 2007/2008), p. 54.

109 Umweltbundesamt (2005): Determinanten der Verkehrsentstehung (Determining factors in traffic growth); UBA-Texte 26/2005, Dessau.

110 OECD (2003): Organisation for Economic Co-Operation and Development: Project on Decoupling Transport Impacts and Economic Growth - Analysis of the Links between Transport and Economic Growth; Document ENV/EOPC/T (2003)4/Final, Paris.

111 BMVBS (German Federal Ministry of Transport, Building and Urban Development) (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012); p. 216pp; Hamburg. / Statistisches Amt der DDR (1991) (Statistical yearbook of the GDR (1991)): Statistisches Jahrbuch 1990 der Deutschen Demokratischen Republik (Statistical yearbook of the German Democratic Republic 1990); p. 249, Berlin.

112 BMVBS (German Federal Ministry of Transport, Building and Urban Development) (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012), p. 241, Hamburg

113 BMVBS (German Federal Ministry of Transport, Building and Urban Development) (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012); p. 240pp; Hamburg / Statistisches Amt der DDR (1991) (Statistical yearbook of the GDR (1991)): Statistisches Jahrbuch 1990 der Deutschen Demokratischen Republik (Statistical yearbook of the German Democratic Republic 1990); p. 248, Berlin.

114 TREMOD (Transport Emissions Model) 5.32 (2012) / BMVBS (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012); p. 218pp, Hamburg

115 BMVBS (German Federal Ministry of Transport, Building and Urban Development) (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012); p. 250pp/263, Hamburg

116 TREMOD (Transport Emissions Model) / after 1990: BMVBS (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012); p. 240pp, Hamburg

117 TREMOD (Transport Emissions Model) 5.32 (2012) / BMVBS (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012), p. 219, Hamburg

118 TREMOD (Transport Emissions Model) 5.32 (2012) / BMVBS (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012); p. 244pp, Hamburg

119 TREMOD (Transport Emissions Model) 5.32 (2012) / BMVBS (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012), Hamburg

120 TREMOD (Transport Emissions Model) 5.32 (2012) / BMVBS (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012), Hamburg

121 TREMOD (Transport Emissions Model) 5.32 (2012) / BMVBS (2011): Verkehr in Zahlen 2011/2012 (Transport Figures 2011/2012), Hamburg

122 Öko-Institut (Institute for Applied Ecology) (2013): Treibhausgasneutraler Verkehr 2050: Ein Szenario zur zunehmenden Elektrifizierung und dem Einsatz stromerzeugter Kraftstoffe im Verkehr, (Carbon-neutral transport 2050 – A scenario for increasing electrification and the use of electricity-based fuels in transport), Berlin

123 ITP/BVU (2007): Prognose der deutschlandweiten Verkehrsverflechtungen 2025 (Forecast of nationwide transport relations in Germany 2025), München/Freiburg.

124 Umbrella (2011): Umbrella-Arbeitsgruppe Ressourcenverfügbarkeit im Rahmen der BMU-geförderten Projekte LithoRec und LiBRi: Ressourcenverfügbarkeit von sekundären Rohstoffen - Potentialanalyse für Lithium und Kobalt - Abschlussbericht, Oktober 2011. http://www.pt-elektromobilitaet.de/projekte/batterierecycling/abschlussberichte-recycling/bericht-ressourcenverfuegbarkeit-projektuebergreifend.pdf.

125 Umbrella (2011): Umbrella-Arbeitsgruppe Ressourcenverfügbarkeit im Rahmen der BMU-geförderten Projekte LithoRec und LiBRi: Ressourcenverfügbarkeit von sekundären Rohstoffen - Potentialanalyse für Lithium und Kobalt - Abschlussbericht, Oktober 2011. http://www.pt-elektromobilitaet.de/projekte/batterierecycling/abschlussberichte-recycling/bericht-ressourcenverfuegbarkeit-projektuebergreifend.pdf.

126 Bundesanstalt für Straßenwesen (BASt) (2010): Tempolimit auf Autobahnen 2008 (Speed limits on autobahns 2008), Bergisch Gladbach.

127 TRL (Transport Research Laboratory) (2009): Emission factors 2009 (report 3) – exhaust emission factors for road vehicles in the UK, Wokingham.

128 European Commission (2011): White Paper – Roadmap to a Single European Transport Area: Towards a competitive and resource-efficient transport system, Brussels.

129 Umweltbundesamt (2010): Sachstandsbericht – CO_2-Emissionsminderung im Verkehr in Deutschland (Status report – CO_2 Emissions Reduction in the Transport Sector in Germany) (UBA-Texte 05/2010), Dessau-Roßlau.

130 DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V.) (German Aerospace Centre) et al. (2010): Mobilität in Deutschland (MID 2008) (Mobility in Germany), s.l.

131 Umweltbundesamt (2010): Sachstandsbericht – CO_2-Emissionsminderung im Verkehr in Deutschland (Status report – CO_2 Emissions Reduction in the Transport Sector in Germany) (UBA-Texte 05/2010), Dessau-Roßlau.

132 Finanzwissenschaftliches Forschungsinstitut an der Universität zu Köln (Institute for Public Economics University of Cologne) (FiFo) (2011): Steuerliche Behandlung von Firmenwagen in Deutschland (Taxation of company cars in Germany), Cologne.

133 Pache, E. (2005): Möglichkeiten der Einführung einer Kerosinsteuer auf innerdeutschen Flügen (The possibilities of introducing a kerosene tax on domestic flights in Germany) (UBA-Texte 12/2005); Berlin.

134 Umweltbundesamt (2009): Politikszenarien V (UBA-Reihe „climate change“ 16/2009), (Policy scenarios V – UBA 'climate change' series 16/2009), Dessau-Roßlau.

135 Statistisches Bundesamt (destatis) (Federal Statistical Office) (2012): Fachserie 8 Reihe 5 – Seeschifffahrt (Shipping), Wiesbaden.

136 Hacker, F. et al. (2011): Marktpotenziale und CO_2-Bilanz von Elektromobilität – Arbeitspakete 2 bis 5 des Forschungsvorhabens OPTUM: Optimierung der Umweltentlastungspotenziale von Elektrofahrzeugen (The market potentials and CO_2 balance of electromobility – Parts 2 to 5 of the OPTUM Project: Optimising the environmental benefit of electric vehicles), Berlin.

137 Kloess, M. et al. (2011): Potenziale effizienter Nutzfahrzeugantriebe für einen nachhaltigen Straßengüterverkehr bis 2050 (Potential of efficient commercial vehicle drives for sustainable road freight by 2050); Vienna.

138 National Research Council (NRC) (2008): Review of the 21st Century Truck Partnership; Washington.

139 Hill N. et al. (2010): SULTAN – Development of an Illustrative Scenarios Tool for Assessing Potential Impacts of Measures on EU Transport GHG. Report for 'EU Transport GHG: Routes to 2050?' project (Commissioned by the Directorate-General for Climate Action (DG CLIMA) of the European Commission), London

140 International Maritime Organization (IMO) (2009): Second IMO GHG Study 2009, London.

141 Nitsch, J. (2003): Potenziale der Wasserstoffwirtschaft – Externe Expertise für das WBGU-Hauptgutachten 2003 "Welt im Wandel: Energiewende zur Nachhaltigkeit" (The potential of the hydrogen economy External expertise for the German Advisory Council on Global Change (WBGU) Flagship Report 2003 'World in transition: Towards sustainable energy systems'), Berlin/Heidelberg.

142 Sachverständigenrat für Umweltfragen (SRU) (The German Advisory Council on the Environment) (2012): Umweltgutachten 2012 – Verantwortung in einer begrenzten Welt (Environmental Report 2012 – Responsibility in a finite world), Berlin.

143 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau.

144 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau.

145 AGEB (2009): Arbeitsgemeinschaft Energiebilanzen (Energy Balances Work Group): Energiebilanzen der Bundesrepublik Deutschland 1990-2007 und Auswertungstabellen (Energy balances for the Federal Republic of Germany 1990-

2007 and evaluation tables 1990-2008). Last updated September 2009 DIW Berlin, EEFA, Köln. October 28th 2009 (http://www.agenergiebilanzen.de).

146 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau.

147 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau.

148 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau.

149 Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 - National Inventory Report for the German Greenhouse Gas Inventory 1990 - 2011, Federal Environmental Agency, Climate Change Nr. 08/2012, 2012, Federal Environmental Agency.

150 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau.

151 VCI: Zukunftsfähige Energieversorgung: Daten und Fakten, (Future-proof energy supply - data and facts), as of 23/11/2011.

152 Statistisches Bundesamt (Federal Statistical Office): Produzierendes Gewerbe: Eisen und Stahl (Manufacturing sector, iron and steel) (Fachserie 4 Reihe 8.1). – data are no longer collected by the Federal Statistical Office since 2010, but continue to be recorded by the Wirtschaftsvereinigung Stahl (German Steel Federation) and made available to the Federal Environment Agency for emissions reporting.

153 Umweltbundesamt (2011): Reporting pursuant to the United Nations Framework Convention on Climate Change and the Kyoto Protocol in 2011. Climate Change, Nr. 11/2011). Umweltbundesamt, Dessau, 2011.

154 Umweltbundesamt (2011): Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011 (Development of specific carbon dioxide emissions in the German electricity mix in 1990-2010 and first estimates for 2011). Umweltbundesamt, Dessau-Roßlau.

155 Stahlinstitut VDEh/Wirtschaftsvereinigung Stahl (German Steel Federation) im Stahl-Zentrum (2010): Leitbild Nachhaltigkeit Stahl : Indikatoren für eine nachhaltige Entwicklung (sustainability concept for steel - indicators for a sustainable development) (November 2010). Stahlinstitut VDEh, Düsseldorf.

156 Wirtschaftsvereinigung Stahl (German Steel Federation) Schrottbilanz für die BR Deutschland (Scrap balance of the Federal Republic of Germany) – http://www.stahl-online.de/Deutsch/Linke_Navigation/Stahl_in_Zahlen/_Dokumente/Schrottbilanz_Deutschland_2009.pdf, last accessed on 13/08/2012.

157 Klöpfer, E., Bach, F.- W., Evertz, T., Otto, M.; Redenius, A. (2012): Ressourceneffizienz bei der Herstellung von dichtereduzierten Stählen mit dem Bandgießverfahren (resource efficiency in the production of reduced-density steel in strip casting). In: Chemie Ingenieur Technik (2012) Nr. 10.
– see also: Dahlmann, P., Endemann, G., Kerkhoff, H.J., Lüngen, H.B. : Wege zur Effizienzsteigerung in der Stahlindus-

trie (2010) (strategies to increase efficiency in the steel industry): Faktensammlung (collected facts) (updated: September 2010). Stahlinstitut VDEh, Düsseldorf.

158 Feralpi (2011): Investition in Umweltschutz und Klimavorsorge (investment in environmental and climate protection). In: stahl und eisen, Nr. 6/7, p. 42.

159 Hirsch, A.; van der Stel, J.; Sert, D. (2012): ULCOS top gas recycling blast furnace. In: stahl und eisen, No. 4, p. 32–40. – see also http://www.ulcos.org/en/research/blast_furnace.php (last visited 13/08/12).

160 Born, C.; Granderath, R. (2010): Recovery of waste heat from the waste gas of electric arc furnaces. In: stahl und eisen, No. 12, p. 45–50.

161 Umweltbundesamt (2012); Emissionsfaktoren zur Eisen- und Stahlindustrie für die Emissionsberichterstattung. (Emission factors for the iron and steel industry for emissions reporting) Dessau-Roßlau.

162 Dorndorf, M., Abel, M. ; Hein, M. ; Huber, H. (2011): Zukunftskonzept für effiziente Elektrostahlerzeugung. (Concept for the future of electric furnace steel production). In:_Stahl und Eisen (2011) No. 7, p. 136-144.

163 European Commission, Joint Research Centre, Institute for Prospective Technological Studies, European IPPC Bureau: Best Available Techniques (BAT) Reference Document for Iron and Steel Production : Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control).

164 http://www.ulcos.org/de/research/electrolysis.php, last accessed on 13/08/12.

165 https://www1.eere.energy.gov/industry/steel/pdfs/moe_steelmaking.pdf or http://sadoway.mit.edu/research/molten-oxide-electrolysis, last accessed on 13/08/12.

166 http://www.metalleproklima.de/bestpractice/kupfer-in-windkraftanlagen, last accessed on 31/07/2012.

167 WirtschaftsVereinigung Metalle, Geschäftsbericht PERSPEKTIVEN 2011/2012, (business report, s.l.)

168 WirtschaftsVereinigung Metalle, Metallstatistik 2009, (metal statistics 2009, s.l.).

169 WirtschaftsVereinigung Metalle, Metallstatistik 2008, (metal statistics 2008, s.l.).

170 WirtschaftsVereinigung Metalle, Metallstatistik 2008, (metal statistics 2008, s.l.).

171 Federal Environment Agency (2009): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2009 (Series Climate Change, Nr. 02/2009). Umweltbundesamt, Dessau, 2009.

172 WirtschaftsVereinigung Metalle, Geschäftsbericht PERSPEKTIVEN 2011/2012, (business report, s.l.)

173 VDI Richtlinie 2286 (2008): Emissionsminderung Aluminiumschmelzanlagen, 2008 .(VDI Guideline 2286 (2008), Emission control - Electrolytic aluminium reduction process)

174 Aurubis (2012): Umweltreport 2011 (environmental report 2011), s.l..

175 VDI Richtlinie VDI 2102-2, Emissionsminderung Kupfer- und Kupferlegierungsschmelzanlagen, (Emission control - Copper and copper alloy melting plants) 2012.

176 Aurubis (2012): Umweltreport 2011 (environmental report 2011), s.l..

177 Aurubis (2012): Umweltreport 2011 (environmental report 2011), s.l..

178 VDI Guideline 2597, Emissionsminderung Anlagen zur Herstellung von Blei und Bleilegierungen (Emission control - Plants for the production of lead and lead alloys), 2004.

179 Firmeninformation Xstrata Zinc GmbH (2010)

180 Befesa Zink Freiberg GmbH (2011), Umwelterklärung (environmental statement), s.l..

181 Stephan Kohler(2010): Erfolgsfaktor Energieeffizienz (Success factor energy efficiency), World of Metallurgy – ERZMETALL 63 No. 5.

182 Aurubis (2012): Umweltreport 2011 (environmental report 2011), s.l..

183 Hiebel, M., Pflaum, H. (2009): Recycling für den Klimaschutz, Müll und Abfall (recycling to protect the climate and reduce waste) 41, No.1, S.4-7.

184 UNEP International Resource Panel (2011): Recycling Rates of Metals- a Status Report, no publication location

185 WirtschaftsVereinigung Metalle, Metallstatistik 2008, (metal statistics 2008, s.l.).

186 IEA Technology Perspectives 2010 Scenarios & Strategies to 2050, IEA 2010

187 http://www.rusal.ru/en/development/innovations/inert_anode.aspx, last accessed on 09/10/2013.

188 The European Foundry Association (CAEF) (2011): The European Foundry Industry 2010, s.l.

189 Bundesverband der Deutschen Gießerei-Industrie (German foundries association, BDG), website information, last accessed in July 2012.

190 BDG-Strukturdaten und Gussproduktion 2010, Bundesverband der Deutschen Gießerei-Industrie (German foundries association, BDG), 2012.

191 The European Foundry Association (CAEF) (2011): The European Foundry Industry 2010, s.l.

192 The European Foundry Association (CAEF) (2011): The European Foundry Industry 2010, s.l.

193 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008)(Database for the assessment of energy efficiency measures 2008), Climate Change 07/2012, Dessau-Roßlau

194 Foundrybench - Foundry Energy Efficiency Benchmarking (2011): Improving the energy efficiency of foundries in Europe (Final Report), EU-Project, IEE/07/585/SI2.500402.

195 Foundrybench - Foundry Energy Efficiency Benchmarking (2011): Improving the energy efficiency of foundries in Europe (Final Report), EU Project, IEE/07/585/SI2.500402.

196 Institut für Gießereitechnik gGmbH (IfG), Bundesverband der Deutschen Gießerei-Industrie (published by the German foundries association, BDG), (2009) Energieeffizienter Gießereibetrieb (Energy-efficient operation of foundries) (Version 1.0), s.l.

197 Bayerisches Landesamt für Umweltschutz (Bavarian Environment Agency) (2005): Effiziente Energieverwendung in der Industrie – Teilprojekt „Metallschmelzbetriebe", Effiziente Energienutzung in Nicht-Eisen-Metall-Schmelzbetrieben (Efficient use of energy in industry - project section: Efficient energy use in non-ferrous metal-melting plants), Augsburg.

198 Junker, O. (Simmerath) (2008): Einsatz von Induktionsöfen zum Schmelzen und Gießen von Kupferwerkstoffen (Use of induction furnaces for melting and casting copper material), s.l.

199 Bayerisches Landesamt für Umweltschutz (Bavarian Environment Agency) (2005): Effiziente Energieverwendung in der Industrie – Teilprojekt „Metallschmelzbetriebe", Effiziente Energienutzung in Nicht-Eisen-Metall-Schmelzbetrieben (Efficient use of energy in industry - project section: Efficient energy use in non-ferrous metal-melting plants), Augsburg.

200 Junker, O. (Simmerath) (2005):Sicheres und energiesparendes Schmelzen im Mittelfrequenztiegelofen: Schmelzen und Warmhalten von Gusseisenwerkstoffen (Safe and energy-saving ways of melting iron casting material and keeping it hot), s.l.

201 Institut für Gießereitechnik gGmbH (IfG), Bundesverband der Deutschen Gießerei-Industrie (published by the German foundries association, BDG), (2009) Energieeffizienter Gießereibetrieb (Energy-efficient operation of foundries) (Version 1.0), s.l.

202 Institut für Gießereitechnik gGmbH (IfG), Bundesverband der Deutschen Gießerei-Industrie (published by the German foundries association, BDG), (2009) Energieeffizienter Gießereibetrieb (Energy-efficient operation of foundries) (Version 1.0), s.l.

203 Dodik-Pelja, S., Adams, A., (2006): Kostenreduktion mit Lean Manufacturing durch direktes Gießen (Reducing costs through lean manufacturing and direct casting), GIESSEREI -PRAXIS (12): 377-384, s.l.

204 Enzenbach, T. (2009): Abwärmenutzung bei Kupolofen-Schmelzanlagen mit dem Einsatz von Thermalöl als Wärmeträger (Waste heat utilisation in cupola furnaces with thermal oil as heat vector), Giesserei 96 (10):68-7.

205 Foundrybench - Foundry Energy Efficiency Benchmarking (2011): Improving the energy efficiency of foundries in Europe (Final Report), EU Project, IEE/07/585/SI2.500402.

206 Energieeffizienter Gießereibetrieb (Energy-efficient operation of foundries) (Version 1.0), Institut für Gießereitechnik gGmbH (Institute for foundry technology, IfG), Bundesverband der Deutschen Gießerei-Industrie (published by the German foundries association, BDG), 2009

207 Bettinger, Kenzler (2009): Abwärmenutzung bei einem Kupolofen (Waste heat recovery in a cupola furnace), Georg Fischer Singen, Abschlussbericht (final report) (Umweltinnovationsprogramm (environmental innovation scheme)).

208 Enzenbach, T. (2009): Abwärmenutzung bei Kupolofen-Schmelzanlagen mit dem Einsatz von Thermalöl als Wärmeträger (Waste heat utilisation in cupola furnaces with thermal oil as heat vector), Giesserei 96 (10):68-7.

209 Energieeffizienter Gießereibetrieb (Energy-efficient operation of foundries) (Version 1.0), Institut für Gießereitechnik gGmbH (Institute for foundry technology, IfG), Bundesverband der Deutschen Gießerei-Industrie (published by the German foundries association, BDG), 2009

210 Bundesverband der Deutschen Gießerei-Industrie (German foundries association, BDG), website information, last accessed in July 2012.

211 Magnetische Blockerwärmung: Stimmt das Potenzial für eine kommende Standardlösung? (Magnetic billet heating - could this have the potential for a standard solution?), Elektrowärme International (2):123-126, 2010.

212 The European Foundry Association (CAEF) (2011): The European Foundry Industry 2010, s.l.

213 VCI: Press release of February 29th 2012.

214 VCI: Responsible Care 2009.

215 VCI: Brochure ‘Chemieprodukte schützen das Klima‘ (Chemical products protect the climate).

216 VCI (2011) Factbook 01, Die Energie[r]evolution, Daten und Fakten (The energy (r)evolution, data and facts) III.

217 Fachagentur Nachwachsende Rohstoffe (Renewable raw materials (FNR)), Last updated 2008.

218 VCI: Rohstoffbasis der chemischen Industrie: Daten und Fakten, (Raw materials base of the chemical industry – data and facts), as of 23.11.2011.

219 VCI Factbook

220 VCI: Zukunftsfähige Energieversorgung: Daten und Fakten, (Future-proof energy supply – data and facts), as of 23.11.2011.

221 VCI: Chemiewirtschaft in Zahlen (The chemical industry in numbers, Ausgabe (edition) 2011.

222 VCI: Zukunftsfähige Energieversorgung: Daten und Fakten, (Future-proof energy supply – data and facts), as of 23.11.2011.

223 Umweltbundesamt (2012): Nationaler Inventarbericht zum Deutschen Treibhausgasinventar (National inventory report on the German greenhouse gas inventory) 1990–2010.

224 Zement-Taschenbuch 2008, (Cement yearbook 2008), issued by Verein Deutscher Zementwerke e.V. (German cement industry association) 51st edition, Verlag Bau+Technik GmbH, Düsseldorf.

225 Zement-Taschenbuch 2008, (Cement yearbook 2008), issued by Verein Deutscher Zementwerke e.V. (German cement industry association) 51st edition, Verlag Bau+Technik GmbH, Düsseldorf.

226 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

227 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

228 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

229 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

230 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

231 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

232 Umweltbundesamt (2011): Reporting pursuant to the United Nations Framework Convention on Climate Change and the Kyoto Protocol in 2011 (Climate Change Series No.11/2011). Dessau-Roßlau

233 http://de.statista.com/statistik/daten/studie/153695/umfrage/produktion-von-zement-nach-laendern/, last accessed on 30.10.2012.

234 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

235 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

236 European Cement Research Academy GmbH (ECRA) (2009): Development of State of the Art-Techniques in Cement Manufacturing: Trying to look ahead. CSI/ECRA-Technology Papers, Düsseldorf/Genoa.

237 Achternbosch, Bräutigam (2000): Herstellung von Zementklinker- Verfahrensbeschreibung und Analysen zum Einsatz von Sekundärbrennstoffen, (The production of cement clinker – process description and analyses of the use of secondary fuels) FZKA 6508.

238 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

239 BREF (2010): Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries (http://www.bvt.umweltbundesamt.de/archiv-e/bvt_zement-kalk-magnesiumoxidindustrie_vv.pdf).

240 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

241 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

242 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

243 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

244 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

245 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

246 Verein Deutscher Zementwerke e.V. (VDZ) (2010): Umweltdaten der deutschen Zementindustrie (Environmental data of the German cement industry) 2010, Düsseldorf.

247 Ruppert, J., Scheuer, W., Schäfer, S. (2009): Bereitstellung einer qualitätsgesicherten Datengrundlage für die Emissionsberichterstattung zur Umsetzung von internationalen Luftreinhalte- und Klimaschutzvereinbarungen für ausgewählte Industriebranchen - Teilvorhaben 03: (Quality-assured data for emissions reporting for the implementation of international agreements on clean air and climate protection for selected industry sectors – part 03: Cement Industry, Düsseldorf.

248 Umweltbundesamt (2011): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2011 (Series Climate Change, Nr. 11/2011). Dessau-Roßlau.

249 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

250 Umweltbundesamt (2011): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2011 (Series Climate Change, Nr. 11/2011). Dessau-Roßlau.

251 Umweltbundesamt (2012): Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011 (Development of specific carbon dioxide emissions in the German electricity mix in 1990–2010 and first estimates for 2011), Dessau-Roßlau.

252 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

253 Umweltbundesamt (2011): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2011 (Series Climate Change, Nr. 11/2011). Dessau-Roßlau.

254 BREF (2010): Reference Document on Best Available Techniques in the Cement, Lime and Magnesium Oxide Manufacturing Industries (http://www.bvt.umweltbundesamt.de/archiv-e/bvt_zement-kalk-magnesiumoxidindustrie_vv.pdf).

255 Vereinigung der Österreichischen Zementindustrie (VÖZ) (Austrian Cement Industry Association) (issued) (2010): Energieeffizienz in der österreichischen Zementindustrie, (Energy efficiency in the Austrian cement industry), Vienna.

256 European Cement Research Academy GmbH (ECRA) (2009): Development of State of the Art-Techniques in Cement Manufacturing: Trying to look ahead. CSI/ECRA-Technology Papers, Düsseldorf/Genoa.

257 Vereinigung der Österreichischen Zementindustrie (VÖZ) (Austrian Cement Industry Association) (issued) (2010): Energieeffizienz in der österreichischen Zementindustrie, (Energy efficiency in the Austrian cement industry), Vienna.

258 Bayerisches Landesamt für Umweltschutz (Bavarian Environment Agency) (2011): Niedertemperaturverstromung mittels ORC-Anlage im Werk Lengfurt der Heidelberger Zement AG – Auswertung der Messergebnisse aus vier Messkampagnen zur Bewertung der Anlageneffizienz, (Low-temperature conversion into power in the ORC plant in Heidelberger Zement's Lengfurt cement works – evaluation of four sets of measuring data to assess the efficiency of the plant) s.l.

259 Ahrens, R. H. (2012): Zementwerk will Stromkosten um 30 % senken (Cement works want to lower electricity costs by 30%), VDI-Nachrichten, 43/2012, 26 October 2012, Düsseldorf.

260 Harder, J. (2011): Trends in power generation from waste heat in cement plants, ZKG International, No. 5-2011.

261 Vereinigung der Österreichischen Zementindustrie (VÖZ) (Austrian Cement Industry Association) (issued) (2010): Energieeffizienz in der österreichischen Zementindustrie, (Energy efficiency in the Austrian cement industry), Vienna.

262 Vereinigung der Österreichischen Zementindustrie (VÖZ) (Austrian Cement Industry Association) (issued) (2010): Energieeffizienz in der österreichischen Zementindustrie, (Energy efficiency in the Austrian cement industry), Vienna.

263 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

264 OECD/IEA and the World Business Council for Sustainable Development (WBCSD) (2009): Cement technology Roadmap 2009 – Carbon emissions reductions up to 2050, s.l.

265 www.celitement.de, last accessed on 26.9.2012.

266 www.novacem.com, last accessed on 26.9.2012.

267 www.zeobond.com, last accessed on 26.9.2012.

268 WWF (2009): Modell Deutschland – Klimaschutz bis 2050: Vom Ziel her denken (Model Germany – climate protection to 2050: target-based thinking), Berlin.

269 OECD/IEA and the World Business Council for Sustainable Development (WBCSD) (2009): Cement technology Roadmap 2009 – Carbon emissions reductions up to 2050, s.l.

270 Federal Association of the German Glass Industry (BV Glas), 2010 annual report.

271 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI).

272 Umweltbundesamt (2012): Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011 (Development of specific carbon dioxide emissions in the German electricity mix in 1990-2010 and first estimates for 2011), Dessau-Roßlau.

273 Umweltbundesamt (2012): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 – National Inventory Report for the German Greenhouse Gas Inventory 1990-2010, Climate Change 08/2012, Dessau-Roßlau.

274 Fleischmann, B. (2010): Die Entwicklung des Energieverbrauchs in der deutschen Glasindustrie (Energy consumption trends in the German glass industry). In: 2012 training course – Energieverbrauch und Energierückgewinnung in der Glasindustrie (Energy consumption and energy recovery in the glass industry), Hüttentechnische Vereinigung der Deutschen Glasindustrie, s.l.

275 Van Limpt, Beerkens, Energy efficiency in glass production. (2010): 2012 training course – Energieverbrauch und Energierückgewinnung in der Glasindustrie (Energy consumption and energy recovery in the glass industry), Hüttentechnische Vereinigung der Deutschen Glasindustrie.

276 VDI, Emissionsminderung – Glashütten (Emission control – Glassworks), VDI 2578, VDI/DIN Manual Air Pollution Prevention, Volume 3, 1999.

277 Nölle, G. (1997): Technik der Glasherstellung (Glass manufacturing techniques), Deutscher Verlag für Grundstoffindustrie, Stuttgart.

278 Research Center for Energy Economics (FfE) (1999): Ermittlung von Energiekennzahlen für Anlagen, Herstellungsverfahren und Erzeugnisse (Calculating energy indicators for plants, production processes and products), s.l.

279 www.kalk.de/10.html, last accessed 26.9.2012.

280 www.kalk.de/10.html, last accessed 26.9.2012.

281 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI), pp 157-167.

282 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI), pp 157-167.

283 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI), pp 157-167.

284 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI), pp 157-167.

285 Umweltbundesamt (2011): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2011 – National Inventory Report for the German Greenhouse Gas Inventory 1990-2009, Dessau-Roßlau.

286 Umweltbundesamt (2012): Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix 1990-2010 und erste Schätzungen 2011 (Development of specific carbon dioxide emissions in the German electricity mix in 1990-2010 and first estimates for 2011), Dessau-Roßlau.

287 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report). Report on the research project of the Federal Ministry of Economics and Technology, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Federal Ministry of Finance and the Federation of German Industries (BDI), pp 157-167.

288 www.kalk.de/21.html, last accessed 26.9.2012.

289 VDP (2012): Papier 2012 Ein Leistungsbericht (Paper 2012 – performance report), German Pulp and Paper Association (VDP), s.l.

290 VDP: Papier 2012 Ein Leistungsbericht (Paper 2012 – performance report), German Pulp and Paper Association (VDP), 2012, personal information from VDP

291 National Inventory Report for the German Greenhouse Gas Inventory 1990-2010, NIR 2011, p. 327, CRF 2 D 1 and Appendix 3 Chapter 19.2.41.

292 EfA: Die neuen Erfolgsfaktoren der Papierindustrie (The new success factors of the paper industry), Effizienz Agentur NRW.

293 CEPI (2011): unfold the future, The Forest Fibre Industry, 2050 Roadmap to a low-carbon bio-economy.

294 Statistisches Bundesamt (Federal Statistical Office) (2011): Statistisches Jahrbuch 2011 (Statistical Yearbook 2011), Chapter 14.6.

295 BVE (2012): Federation of German Food and Drink Industries, Die Ernährungsindustrie in Zahlen 2012 (Food and drink industry facts & figures 2012); www.bve-online.de/themen/branche-und-markt/daten-und-fakten/deutsche-ernaehrungsind2012, last accessed on 22.10.2012.

296 Statistisches Bundesamt (Federal Statistical Office) (2011): Statistisches Jahrbuch 2011 (Statistical Yearbook 2011), Chapter 14.6.

297 Statistisches Bundesamt (Federal Statistical Office) (2012): GENESIS-Online table 42111-0101, last accessed 22.10.2012.

298 BVE (2012): Federation of German Food and Drink Industries, Die Ernährungsindustrie in Zahlen 2012 (Food and drink industry facts & figures 2012); www.bve-online.de/themen/branche-und-markt/daten-und-fakten/deutsche-ernaehrungsind2012, last accessed on 22.10.2012.

299 Federal Ministry of Food, Agriculture and Consumer Protection (2012): Statistisches Jahrbuch 2012 (Statistical Yearbook 2012), Chapter D Section VI No. 280, Berlin/Bonn, http://berichte.bmelv-statistik.de/SJT-4050700-0000.pdf

300 Association of the German Dairy Industry (MIV) (2012): Beilage zum Geschäftsbericht 2011/2012 Zahlen – Daten – Fakten (Annex to 2011/2012 Annual Report, Facts & Figures), Berlin, www.milchindustrie.de/fileadmin/Dokumente/Verband/ZahlenDatenFakten_2011_2012_Homepage.pdf

301 Fachverband der Stärke-Industrie e.V. (Association of the German Starch Industry) (2009): Zahlen und Fakten zur Stärke-Industrie (Starch industry facts & figures) — 2009, Berlin, www.staerkeverband.de/downloads/FSI_zahlen2008.pdf

302 Fachverband der Stärke-Industrie e.V. (Association of the German Starch Industry) (2012): Zahlen und Fakten zur Stärke-Industrie (Starch industry facts & figures) — 2012, Berlin, www.staerkeverband.de/downloads/FSI_zahlen2012.pdf

303 Statistisches Bundesamt (Federal Statistical Office) (various years): Fachserie 4, Reihe 3.1, selected/relevant reporting nos.

304 Statistisches Bundesamt (Federal Statistical Office) (various years): Fachserie 4, Reihe 3.1, selected/relevant reporting nos.

305 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report), Essen, link: www.rwi-essen.de/media/content/pages/publikationen/rwi-projektberichte/PB_CO_2-Monitoring-2010.pdf, last accessed on 22.10.2012

306 Deutscher Brauer Bund e.V. (German Brewers Federation) (2011): Bierausstoß 1960-2011 (Beer production 1960-2011), Berlin, link: www.brauer-bund.de/download/Archiv/PDF/statistiken/Bierausst o%C3%9F%201960%20-%20 2011.pdf

307 Reference Document on Best Available Techniques in the Food, Drink and Milk Industries, 2006; http://eippcb.jrc.es/reference/BREF/fdm_bref_0806.pdf.

308 AG Energiebilanzen e.V. (2008, 2012): Energy balances for 1990, 1995, 2000, 2005, link: www.ag-energiebilanzen.de/viewpage.php?idpage=63, Berlin/Cologne.

309 Umweltbundesamt (2012): Datenbasis zur Bewertung von Energieeffizienzmaßnahmen 2008 (Auswertung für das Jahr 2008), (Database for the evaluation of energy efficiency measures 2008, evaluation for 2008) Climate Change 07/2012, Dessau-Roßlau, www.uba.de/uba-info-medien/4267.html. ISSN 1862-4359.

310 Umweltbundesamt (2012): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 National Inventory Report for the German Greenhouse Gas Inventory 1990-2010, Dessau-Roßlau

311 Bayerisches Landesamt für Umwelt (Bavarian Environment Agency) (2001): Minderung öko- und klimaschädigender Abgase aus industriellen Anlagen durch rationelle Energienutzung — Fleischverarbeitender Betrieb (Mitigation of climate and environment-damaging emissions from industrial plants through rational energy usage — meat processing, January 2001; www.lfu.bayern.de/energie/co2_minderung/doc/fleischverarbeitung.pdf.

312 Bayerisches Landesamt für Umwelt (Bavarian Environment Agency) (2000): Minderung öko- und klimaschädigender Abgase aus industriellen Anlagen durch rationelle Energienutzung — Fleischverarbeitender Betrieb (Mitigation of climate and environment-damaging emissions from industrial plants through rational energy usage — milk processing, December 2000; www.lfu.bayern.de/energie/co2_minderung/doc/endbericht_molkerei.pdf.

313 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report), Essen, link: www.rwi-essen.de/media/content/pages/publikationen/rwi-projektberichte/PB_CO_2-Monitoring-2010.pdf, last accessed on 22.10.2012

314 NIR: National Inventory Report for the German Greenhouse Gas Inventory 1990-2010; www.uba.de/uba-info-medien/4292.html.

315 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report), Essen, www.rwi-essen.de/media/content/pages/publikationen/rwi-projektberichte/PB_CO_2-Monitoring-2010.pdf, last accessed on 22.10.2012

316 Fachverband der Stärke-Industrie e.V. (Association of the German Starch Industry) (2012): Zahlen und Fakten zur Stärke-Industrie (Starch industry facts & figures) — 2012, page 66, Berlin, www.staerkeverband.de/downloads/FSI_zahlen2012.pdf

317 Fachverband der Stärke-Industrie e.V. (Association of the German Starch Industry) (2012): Zahlen und Fakten zur Stärke-Industrie (Starch industry facts & figures) — 2012, Table 2.4, Berlin, link: www.staerkeverband.de/downloads/FSI_zahlen2012.pdf

318 Fachverband der Stärke-Industrie e.V. (Association of the German Starch Industry) (2012): Zahlen und Fakten zur Stärke-Industrie (Starch industry facts & figures) — 2012, Section 2.7, Berlin, link: www.staerkeverband.de/downloads/FSI_zahlen2012.pdf

319 Handelsblatt dated 18.09.2012, Stratmann, Klaus: Topic – Energieeffizienz (Energy efficiency); supplement.

320 Textile+Fashion Confederation: Economic Outlook for 2005 to 2011, link: www.textil-mode.de/deutsch/Themen/Konjunktur-Statistik/K291.htm.

321 Deutsche Bank Research (2011): Textil-/Bekleidungsindustrie: Innovationen und Internationalisierung als Erfolgsfaktoren (Textile & clothing industry: Innovation and internationalisation as success factors), Aktuelle Themen 519, 6 July 2011.

322 Industrievereinigung Chemiefaser e.V.: www.ivc-ev.de/live/index.php?page_id=188.

323 Stegmaier et al (2006): Energieverbrauch in der Textilveredlung: Verbrauchszahlen und neue Entwicklungen zum effizienten Einsatz (Energy consumption in textile finishing: Consumption data and new developments in energy efficiency), Presentation to the Annual Conference of the Textile Research Board, Dresden, 14-15 November 2006.

324 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report), September 2011 report, s.l.

325 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report), September 2011 report, s.l.

326 RWI (2011): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft – Monitoringbericht 2010 (Climate protection commitment of German Industry – 2010 monitoring report), September 2011 report, s.l.

327 Umweltbundesamt (2011): Avoiding fluorinated greenhouse gases – Prospects for phasing out. Climate Change 08/2011. Dessau-Roßlau.

328 Umweltbundesamt (2011): Avoiding fluorinated greenhouse gases – Prospects for phasing out. Climate Change 08/2011. Dessau-Roßlau.

329 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau.

330 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau.

331 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau.

332 Umweltbundesamt (2011): Avoiding fluorinated greenhouse gases – Prospects for phasing out. Climate Change 08/2011. Dessau-Roßlau.

333 Gschrey, B., Schwarz, W. (2011): Projektionen zu den Emissionen von HFKW, FKW und SF_6 für Deutschland bis zum Jahr 2050 (Projections of HFC, PFC and SF_6 emissions for Germany up to 2050). Umweltbundesamt, Climate Change 21/2011. Dessau-Roßlau.

334 Gschrey, B., Schwarz, W. (2011): Projektionen zu den Emissionen von HFKW, FKW und SF_6 für Deutschland bis zum Jahr 2050 (Projections of HFC, PFC and SF_6 emissions for Germany up to 2050). Umweltbundesamt, Climate Change 21/2011. Dessau-Roßlau.

335 Gschrey, B., Schwarz, W. (2011): Projektionen zu den Emissionen von HFKW, FKW und SF_6 für Deutschland bis zum Jahr 2050 (Projections of HFC, PFC and SF_6 emissions for Germany up to 2050). Umweltbundesamt, Climate Change 21/2011. Dessau-Roßlau.

336 Gschrey, B., Schwarz, W. (2011): Projektionen zu den Emissionen von HFKW, FKW und SF_6 für Deutschland bis zum Jahr 2050 (Projections of HFC, PFC and SF_6 emissions for Germany up to 2050). Umweltbundesamt, Climate Change 21/2011. Dessau-Roßlau.

337 Gschrey, B., Schwarz, W. (2011): Projektionen zu den Emissionen von HFKW, FKW und SF_6 für Deutschland bis zum Jahr 2050 (Projections of HFC, PFC and SF_6 emissions for Germany up to 2050). Umweltbundesamt, Climate Change 21/2011. Dessau-Roßlau.

338 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau. 1990-2010 data from 2012 NIR/CRF tables.

339 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau. 1990-2010 data from 2012 NIR/CRF tables.

340 Fachagentur Nachwachsende Rohstoffe e. V. FNR (2011): Nachwachsende Rohstoffe — Spitzentechnologie ohne Ende (Renewable resources — limitless leading-edge technology), Gülzow.

341 Fachagentur Nachwachsende Rohstoffe e. V. FNR (2012): Basisdaten Bioenergie Deutschland (Base bioenergy data for Germany), Gülzow.

342 Nationale Akademie der Wissenschaften Leopoldina (2012): Bioenergie — Möglichkeiten und Grenzen (Bioenergy — opportunities and limits), Halle (Saale).

343 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau. 1990-2010 data from 2012 NIR/CRF tables.

344 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012.

345 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau. 1990-2010 data from 2012 NIR/CRF tables.

346 Umweltbundesamt (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990-2010. Climate Change 08/2012. Dessau-Roßlau.

347 1990-2010 data from 2012 CRF tables, 2050 data estimated by UBA.

348 BMU (German Federal Environment Ministry) (2011): Kreislaufwirtschaft. Abfall nutzen — Ressourcen schonen (Life cycle management. Using waste — saving resources), Berlin.

349 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990 — 2010, p. 571, Dessau-Roßlau.

350 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990 — 2010, p. 571 et seq., Dessau-Roßlau.

351 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, p. 571, Dessau-Roßlau.

352 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990 — 2010, p. 573, Dessau-Roßlau.

353 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, p. 575 et seq., Dessau-Roßlau.

354 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, p. 575 et seq., Dessau-Roßlau.

355 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, p. 592., Dessau-Roßlau.

356 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, p. 595., Dessau-Roßlau.

357 Federal Statistical Office (2012): Umwelt. Öffentliche Wasserversorgung und Abwasserentsorgung nach Ländern. Anschlussgrad und Wasserabgabe 2010 (Environment. Public water supply and wastewater disposal by region. Connection rate and water delivery 2010), Wiesbaden.

358 Federal Environment Agency (2011): Reporting pursuant to the United Nations Framework Convention on Climate Change and the Kyoto Protocol in 2011. National Inventory Report for the German Greenhouse Gas Inventory 1990–2009, Dessau-Roßlau.

359 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, p. 585 et seq., Dessau-Roßlau.

360 Dehoust, G. (2012): Presentation on 8 November 2012 at the Berliner Abfallrechtstage (Waste Management Law Conference), excerpts from the environmental research planning project 'Substantive implementation of Article 29 of Directive 2008/98/EC — Scientific-technical foundation for a national waste prevention programme' (Project No. FKZ 3710 32 310). Commissioned by the Federal Environment Agency; not yet published.

361 IZM (2012): EuP Preparatory Studies 'Imaging Equipment', 2007; JRC: Integration of resource efficiency and waste management criteria in European product policies.

362 Öko-Institut (Institute for Applied Ecology), Forschungszentrum Jülich, Systems Analysis and Technology Evaluation (IEK-STE), DIW Berlin, Fraunhofer Institute for Systems and Innovation Research (FhG-ISI), Hans-Joachim Ziesing, 2009, Politikszenarien für den Klimaschutz V — auf dem Weg zum Strukturwandel. Treibhausgas-Emissionsszenarien bis zum Jahr 2030 (Policy scenarios for climate protection V — towards structural change. Greenhouse gas emission scenarios to 2030), UBA Climate Change 16/2009, Berlin; Karlsruhe; Jülich: UBA, 2009. Adapted in: prognos; Öko-Institut, 2009, Modell Deutschland — Klimaschutz bis 2050: Vom Ziel her denken (Model Germany — Climate protection to 2050: target-based thinking), Basel; Berlin: WWF, 2009, p. 154.

363 Max Rubner-Institut, Federal Research Institute of Nutrition and Food (2008): Nationale Verzehrsstudie II, Ergebnisbericht, Teil 2 (National Nutrition Survey II, report, part 2), Karlsruhe.

364 Federal Environment Agency (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, p. 571 et seq., Dessau-Roßlau.

365 Osterburg, B., Kätsch, S., Wolff, A. B2013): Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

366 Federal Environmental Agency (2010): Daten zur Umwelt, Ausgabe 2011 (Data on the Environment 2011), Umwelt und Landwirtschaft, Dessau-Roßlau.

367 Federal Environmental Agency (2010): Daten zur Umwelt, Ausgabe 2011 (Data on the Environment 2011), Umwelt und Landwirtschaft, Dessau-Roßlau.

368 FAO (2012): Animal Production and Health division. Greenhouse gas emissions from the dairy sector. A life cycle assessment, http://www.fao.org/docrep/012/k7930e/k7930e00.pdf, Abruf 18.09.2012.

369 Meyer, R., Sauter, A. (2002): TA-Projekt Entwicklungstendenzen von Nahrungsmittelangebot und -nachfrage und ihre Folgen Basisanalysen, Arbeitsbericht Nr. 81, (TA Project: Basic analysis of food supply and demand trends and their consequences, Working Report No. 81, Office of Technology Assessment at the German Bundestag (TAB)), s.l.

370 BMELV (2011): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland 2011 (Statistical Yearbook for Food, Agriculture and Forestry 2011), Wirtschaftsverlag NW GmbH, Bremerhaven.

371 BMELV (2011): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland 2011 (Statistical Yearbook for Food, Agriculture and Forestry 2011), Wirtschaftsverlag NW GmbH, Bremerhaven.

372 Strohm, K. (2010): Stoffstromanalyse des deutschen Biokraftsektors für das Jahr 2007, Arbeitsberichte aus der vTI-Agrarökonomie 09/2010, Braunschweig (Thünen Institute Agricultural Economics Report: “Material flow analysis of the German biofuel sector for the year 2007”).

373 BMWi und BMU (Federal Ministry for Economic Affairs and Energy and Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety) (2010): Energiekonzept für eine umweltschonende, zuverlässige und bezahlbare Energieversorgung, Berlin (Energy Concept for an Environmentally Sound, Reliable and Affordable Energy Supply).

374 Strohm, K. (2010): Stoffstromanalyse des deutschen Biokraftsektors für das Jahr 2007, Arbeitsberichte aus der vTI-Agrarökonomie 09/2010, Braunschweig (Thünen Institute Agricultural Economics Report: “Material flow analysis of the German biofuel sector for the year 2007”).

375 Strohm, K. (2010): Stoffstromanalyse des deutschen Biokraftsektors für das Jahr 2007, Arbeitsberichte aus der vTI-Agrarökonomie 09/2010, Braunschweig (Thünen Institute Agricultural Economics Report: ‚Material flow analysis of the German biofuel sector for the year 2007").

376 Thünen Institute (2013): Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig.

377 Strohm, K. (2010): Stoffstromanalyse des deutschen Biokraftsektors für das Jahr 2007, Arbeitsberichte aus der vTI-Agrarökonomie 09/2010, Braunschweig (Thünen Institute Agricultural Economics Report: "Material flow analysis of the German biofuel sector for the year 2007").

378 Peters, D., Holst, N., Herrmann, B., Lulies, S., Stolte, H. (2010): Nachwachsende Rohstoffe in der Industrie. Stoffliche Nutzung von Agrar- und Holzrohstoffen in Deutschland (Renewable raw materials in industry. Use of agricultural and forestry products for the production of raw materials in Germany), FNR, Rostock.

379 Peters, D., Holst, N., Herrmann, B., Lulies, S., Stolte, H. (2010): Nachwachsende Rohstoffe in der Industrie. Stoffliche Nutzung von Agrar- und Holzrohstoffen in Deutschland (Renewable raw materials in industry. Use of agricultural and forestry products for the production of raw materials in Germany), FNR, Rostock.

380 Federal Environmental Agency (2012): Globale Landflächen und Biomasse nachhaltig und ressourcenschonend nutzen (Sustainable use of Global Land and Biomass Resources), Dessau-Roßlau

381 BMELV (2011, 2010, 2009 and other earlier years): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland 2011 (Statistical Yearbook for Food, Agriculture and Forestry 2011), Wirtschaftsverlag NW GmbH, Bremerhaven.

382 BMELV (2010): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland (Statistical Yearbook for Food, Agriculture and Forestry), Wirtschaftsverlag NW GmbH, Bremerhaven.

383 BMELV (2010): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland (Statistical Yearbook for Food, Agriculture and Forestry), Wirtschaftsverlag NW GmbH, Bremerhaven.

384 Peters, D., Holst, N., Herrmann, B., Lulies, S., Stolte, H. (2010): Nachwachsende Rohstoffe in der Industrie. Stoffliche Nutzung von Agrar- und Holzrohstoffen in Deutschland (Renewable raw materials in industry. Use of agricultural and forestry products for the production of raw materials in Germany), FNR, Rostock.

385 Strohm, K. (2010): Stoffstromanalyse des deutschen Biokraftsektors für das Jahr 2007, Arbeitsberichte aus der vTI-Agrarökonomie 09/2010, Braunschweig (Thünen Institute Agricultural Economics Report: "Material flow analysis of the German biofuel sector for the year 2007").

386 Federal Environment Agency (2012): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 - National Inventory Report for the German Greenhouse Gas Inventory 1990, Dessau-Roßlau.

387 EEA (European Environment Agency) (2012): GHG Inventory 2012 Submission, Period 1990 to 2010, Germany, Reported 2012-01-13, http://cdr.eionet.europa.eu/de/eu/ghgmm/envtw7blw/index_html?page=1.

388 Haenel, HD., Rösemann, C., Dämmgen, U., Poddey, E., Freibauer, A., Döhler, H., Eurich-Menden, B., Wulf, S., Dieterle, M., Osterburg, B. (2012): Berechnung von gas- und partikelförmigen Emissionen aus der deutschen Landwirtschaft 1990 - 2010 - Report zu Methoden und Daten (RMD) Berichterstattung 2012 (Calculations of gaseous and particulate emissions from German agriculture 1990 - 2010), Landbauforschung Special Edition 356, s.l.

389 Federal Environment Agency (2011): Nationale TrendTablen für die deutsche Berichterstattung atmosphärischer Emissionen 1990 - 2010 (Endstand 14.12.2011) (National trend tables for German reporting of atmospheric emissions), available to download at: http://www.umweltbundesamt.de/emissionen/archiv/2012/2011_12_14_EM_Entwicklung_in_D_TrendTable_THG_v1.2.0.zip

390 Federal Environment Agency (2012): InventarTablen in Common Reporting Format (CRF), CRF 2012 XLS in ZIP, Fassung zur EU-Submission (GHG inventories in common reporting format for submission to the EU), available to download at: http://cdr.eionet.europa.eu/de/eu/ghgmm/envtw7blw/index_html?page=1

391 Haenel, HD., Rösemann, C., Dämmgen, U., Poddey, E., Freibauer, A., Döhler, H., Eurich-Menden, B., Wulf, S., Dieterle, M., Osterburg, B. (2012): Berechnung von gas- und partikelförmigen Emissionen aus der deutschen Landwirtschaft 1990 - 2010 - Report zu Methoden und Daten (RMD) Berichterstattung 2012 (Calculations of gaseous and particulate emissions from German agriculture 1990 - 2010), Landbauforschung Special Edition 356, s.l.

392 Osterburg, B., Kätsch, S., Wolff, A.(2013): Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig, according to data fromError! Bookmark not defined.

393 Federal Environmental Agency (2011): Nationale TrendTablen für die deutsche Berichterstattung atmosphärischer Emissionen 1990 - 2010 (Endstand 14.12.2011) (National trend tables for German reporting of atmospheric emissions), available to download at: http://www.umweltbundesamt.de/emissionen/archiv/2012/2011_12_14_EM_Entwicklung_in_D_TrendTable_THG_v1.2.0.zip

394 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Edition 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

395 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Edition 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

396 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

397 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

398 IPCC (Intergovernmental Panel on Climate Change) (1996): Greenhouse Gas Inventories, Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 3, module 4: agriculture, s.l.

399 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

400 Thiering, J., Bahrs, E. (2011): Biogasproduktion in Deutschland – Sollte die energetische Nutzung von Wirtschaftsdünger explizit gefördert werden? (Biogas Production in Germany – Should the Energetic Use of Manure be Explicitly Promoted?), GJAE 60 (2011), Number 4.

401 Thiering, J., Bahrs, E. (2011): Biogasproduktion in Deutschland – Sollte die energetische Nutzung von Wirtschaftsdünger explizit gefördert werden? (Biogas Production in Germany – Should the Energetic Use of Manure be Explicitly Promoted?), GJAE 60 (2011), Number 4.

402 Thiering, J., Bahrs, E. (2011): Biogasproduktion in Deutschland – Sollte die energetische Nutzung von Wirtschaftsdünger explizit gefördert werden? (Biogas Production in Germany – Should the Energetic Use of Manure be Explicitly Promoted?), GJAE 60 (2011), Number 4.

403 Thiering, J., Bahrs, E. (2011): Biogasproduktion in Deutschland – Sollte die energetische Nutzung von Wirtschaftsdünger explizit gefördert werden? (Biogas Production in Germany – Should the Energetic Use of Manure be Explicitly Promoted?), GJAE 60 (2011), Number 4.

404 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

405 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

406 Osterburg, B., Nieberg, H., Rüther, S., Isermeyer, F., Haenel, HD., Hahne, J., Krentler, JG., Paulsen, AM., Schuchardt, F., Schweinle, J., Weiland, P. (2009): Erfassung, Bewertung und Minderung von Treibhausgasemissionen des deutschen Agrar- und Ernährungssektors, Arbeitsberichte aus der vTI-Agrarökonomie, 03/2009 Braunschweig/Hamburg/Trenthorst (Thünen Institute Agricultural Economics Report: Monitoring, assessing and mitigating greenhouse gas emissions from the German food and agricultural industry).

407 Federal Environment Agency (2012): Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2012 - National Inventory Report for the German Greenhouse Gas Inventory 1990, Dessau-Roßlau.

408 Zehetmeier, M., Baudracco, J., Hoffmann, H., Heißenhuber, A.(2012): Does increasing milk yield per cow reduce greenhouse gas emissions? A system approach Animal Vol. 6 1, pp. 154-166.

409 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

410 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

411 Hülsbergen, KJ., Feil, B., Biermann, S., Rathke, GW., Kalk, WD., Diepenbrock, W. (2001): A method of energy balancing in crop production and its application in a long-term fertilizer trial, Agriculture, Ecosystems and Environment 86 (3), pp. 303-321.

412 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

413 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

414 Kassow, A., Blank, B., Paulsen, HM., Aulrich, K., Rahmann, G. (2009): Studies on greenhouse gas emissions in organic and conventional dairy farms, Ressortforschung für den Ökologischen Landbau, s.l...

415 Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., El-Hage Scialabba, N., Niggli, U. (2012): Enhanced top soil carbon stocks under organic farming. PNAS Early Edition. Link: http://www.pnas.org/content/early/2012/10/10/1209429109.

416 Rahmann, G., Aulrich, K., Barth, K., Böhm, H., Koopmann, R., Oppermann, R., Paulsen, HMM., Weißmann, F. (2008): Die Klimarelevanz des ökologischen Landbaus – Stand des Wissens, Landbauforschung - vTI Agriculture and Forestry Research 1/2 (58), p. 71-89 (The impact of organic farming on climate change – state of knowledge, agricultural research).

417 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

418 Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., El-Hage Scialabba, N., Niggli, U. (2012): Enhanced top soil carbon stocks under organic farming. PNAS Early Edition. Link: http://www.pnas.org/content/early/2012/10/10/1209429109.

419 Sanders, J., Offermann, F., Nieberg, H. (2012): Wirtschaftlichkeit des ökologischen Landbaus in Deutschland unter veränderten agrarpolitischen Rahmenbedingungen (The economic development of organic farms in Germany and impact of changed agricultural policy framework conditions), Landbauforschung- vTI Agriculture and Forestry Research, Special Issue 364, Braunschweig.

420 Schaak, D., Barbian, T., Gerber, A., Jansen, M., Zander, K., Roehl, R. (2011): Zahlen, Daten, Fakten: Die Bio-Branche 2011 (Figures, data, facts: The organic sector 2011), BÖLW, Berlin.

421 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor, Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l. (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector).

422 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und

Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

423 BMELV (2010): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland (Statistical Yearbook for Food, Agriculture and Forestry), Wirtschaftsverlag NW GmbH, Bremerhaven.

424 FAO (2011): Global Food Losses and Food Waste. Extent, Causes and Prevention, Link:http://www.fao.org/docrep/014/mb060e/mb060e00.pdf, Abruf 27.08.2012.

425 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

426 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

427 Monier, V., Mudgal, S., Escalon, V., O`Connor, C., Gibon, T., Anderson, G., Montoux, H., Reisinger, H., Dolley, P., Ogilvie, S., Morton, G. (2010): Preparatory Study On Food Waste Across EU 27 - Final report. European Commission (DG ENV) Directorate C-Industry, Technical Report 2010-054.

428 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

429 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart). Und andere.

430 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

431 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

432 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

433 Teitscheid, P., Göbel, C., Ritter, G., Blumenthal, A., Friedrich, S., Frick, T., Grotstollen, L., Möllenbeck, C., Rottstegge, L., Pfeiffer, C., Baumkötter, D., Wetter, C., Uekötter, B., Burdick, B., Langen, N., Lettenmeier, M., Rohn, H. (2012): Verringerung von Lebensmittelabfällen – Identifikation von Ursachen und Handlungsoptionen in Nordrhein-Westfalen, Münster. (Reducing food waste – identifying causes and recommendations for action in North Rhine Westphalia, Münster.)

434 Federal Environment Agency (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen, Dessau-Roßlau. (Energy target 2050:100% electricity from renewable sources)

435 Hafner, G., Barabosz, J., Schneider, F., Lebersorger, S., Scherhaufer, S., Schuller, H., Leverenz, D. (2012): Ermittlung der weggeworfenen Lebensmittelmengen und Vorschläge zur Verminderung der Wegwerfrate bei Lebensmitteln in Deutschland, Institut für Siedlungswasserbau, Wassergüte- und Abfallwirtschaft der Universität Stuttgart (ISWA) und Institut für Abfallwirtschaft der Universität für Bodenkultur Wien (BOKU), gefördert durch das BMELV, Stuttgart (Determination of discarded food and proposals for a minimization of food wastage in Germany, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA) and Institute of Waste Management (BOKU) University of Natural Resources and Life Science Vienna, funded by the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection), Stuttgart).

436 Grünberg, J., Nieberg, H., Schmidt, T. (2010): Treibhausgasbilanzierung von Lebensmitteln (Carbon Footprints): Überblick und kritische Reflektion, Landbauforschung – vTI Agriculture and Forestry Research 2 2010 (60), pp. 53-72.

437 Max Rubner Institut (2008): Nationale Verzehrsstudie II Ergebnisbericht, Teil 2, Link: http://www.bmelv.de/SharedDocs/Downloads/Ernaehrung/NVS_Ergebnis berichtTeil2.pdf?__blob=publicationFile, Abruf 27.08.2012.(German national food consumption survey)

438 Leonhäuser, IU. (2003): Ernährungsverhalten: Genuss und Reue – wie entwickelt sich unser Verhältnis zum Fleischverzehr? (Indulgence and remorse – how are our attitudes to eating meat changing?) In: Isermeyer, F. (Ed.): Fleisch 2025: Vortrags- und Diskussionstagung am 18. März 2003 im Forum der FAL, gemeinsam veranstaltet von der Bundesforschungsanstalt für Landwirtschaft (FAL) und der Gesellschaft der Freunde der FAL. Landbauforschung Völkenrode Sonderheft 262 (p. 1-11).

439 BMELV (2010): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland (Statistical Yearbook for Food, Agriculture and Forestry), Wirtschaftsverlag NW GmbH, Bremerhaven.

440 Max Rubner Institut (2008): Nationale Verzehrsstudie II Ergebnisbericht, Teil 2, Link: http://www.bmelv.de/SharedDocs/Downloads/Ernaehrung/NVS_Ergebnis berichtTeil2.pdf?__blob=publicationFile, Abruf 27.08.2012.(German national food consumption survey)

441 German Nutrition Society (2004): DGE nutrition circle – quantitative dietary guidelines. DGEInfo 05/2004 – Beratungspraxis. Link: http://www.dge.de/modules.php?name=News&file=article&sid=415 , Abruf 17.09.2012.

442 VEBU - German Vegetarian Alliance (2012): Vegetarische Ernährungspyramide. (wiss. Konzeption von Leitzmann C und Keller M 2010. Vegetarische Ernährung. 2. Auflage 2010), Link: http://vebu.de/gesundheit/lebensmittel/686-vegetarische-ernaehrungspyramide, Abruf 17.09.2012.

443 FAO (2006): Livestock's long shadow. Environmental issues and options, Rome, Italy.

444 Meyer, R., Sauter, A. (2002): TA-Projekt Entwicklungstendenzen von Nahrungsmittelangebot und -nachfrage und ihre Folgen Basisanalysen, Arbeitsbericht Nr. 81, Office of Technology Assessment at the German Bundestag (TAB).

445 Goodland, R., Anhang, J. (2009): Livestock and Climate Change- What if the key actors in climate change are… cows, pigs and chickens?, World Watch, November/December 2009, o.O.

446 Goodland, R., Anhang, J. (2009): Livestock and Climate Change- What if the key actors in climate change are… cows, pigs and chickens?, World Watch, November/December 2009, o.O.

447 Grünberg, J., Nieberg, H., Schmidt, T. (2010): Treibhausgasbilanzierung von Lebensmitteln (Carbon Footprints): Überblick und kritische Reflektion, Landbauforschung – vTI Agriculture and Forestry Research 2 2010 (60), pp. 53-72.

448 Grünberg, J., Nieberg, H., Schmidt, T. (2010): Treibhausgasbilanzierung von Lebensmitteln (Carbon Footprints): Überblick und kritische Reflektion, Landbauforschung – vTI Agriculture and Forestry Research 2 2010 (60), pp. 53-72.

449 Schmidt, TG., Osterburg, B. (2006): Aufbau des Berichtmoduls ‚Landwirtschaft und Umwelt' in den Umweltökonomischen Gesamtrechnungen (Design of the 'Agriculture and Environment' reporting model in the report on integrated environmental and economic accounting), Braunschweig: FAL, Arbeitsberichte des Bereichs Agrarökonomie 2005/06, Braunschweig.

450 Umweltbundesamt (2011): Nationale TrendTablen für die deutsche Berichterstattung atmosphärischer Emissionen. 1990 - 2010 (Endstand 14.12.2011). Im Internet unter: http://www.umweltbundesamt.de/emissionen/archiv/2012/2011_12_14_EM_Entwicklung_in_D_TrendTable_THG_v1.2.0.zip

451 IPCC (Intergovernmental Panel on Climate Change) (1996): Greenhouse Gas Inventories, Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 3, module 4: agriculture, s.l.

452 IPCC (Intergovernmental Panel on Climate Change) (2006): Greenhouse Gas Inventories. Revised 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use, s.l.

453 Alexandratos, N., Bruinsma, J. (2012): World agriculture towards 2030/2050. The 2012 Revision. Global Perspective Studies Team, ESA Working Paper No. 12-03, June 2012, Agricultural Development Economics Division, Food and Agriculture Organization of the United Nations.

454 Christensen, TR., Friborg, T. (editors) (2004): EU Peatlands: Current Carbon Stocks and Trace Gas Fluxes, Concerted Action CarboEurope-GHG.

455 Bundesregierung (2002): Perspektiven für Deutschland. Unsere Strategie für eine nachhaltige Entwicklung, s.l. (Perspectives for Germany. Our strategy for sustainable development)

456 Umweltbundesamt (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen, (Energy Target 2050 - 100% electricity from renewable sources) Dessau-Roßlau.

457 Offermann, F., Banse, M., Ehrmann, M., Gocht, A., Gömann, H., Haenel, H-D., Kleinhanß, W., Kreins, P., Ledebur, O. von, Osterburg, B., Pelikan, J., Rösemann, C., Salamon, P., Sanders, J. (2012): vTI-Baseline 2011-2021: agrarökonomische Projektionen für Deutschland (Agri-economic projections for Germany), Landbauforschung vTI agriculture and forestry research – Special issue 355.

458 AMI (Agricultural Market Information Company) (2012): Bio-Strukturdaten – Bodennutzung und Tierhaltung 2010, Marktwoche Ökolandbau 07.5-9. (Organic structural data – soil use and animal husbandry)

459 Schmidt, TG., Osterburg, B. (2009): Aufbau des Berichtsmoduls 'Landwirtschaft und Umwelt' in den umweltökonomischen Gesamtrechnungen: Projekt II: Ergänzungen und Anwendung der Ergebnisse aus Projekt I ; Endbericht [online]. (Design of the 'Agriculture and Environment' reporting model in the report on integrated environmental and economic accounting: Project II: Supplements and application of the results of Project I; Final report [online]) Link: http://www.destatis.de/jetspeed/portal/cms/Sites/destatis/Internet/DE/Content/Publikationen/Fachveroeffentlichungen/UmweltoekonomischeGesamtrechnungen/LandwirtschaftUmwelt,templateId=renderPrint.psml, Accessed 07.06.2010.

460 Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, AK., Nitsch, H., Nieberg, H., Sanders, J., Meyer zu Hartlage, O., Beckmann, E., Anspach, V. (2012): Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor (Study on the preparation of an efficient and well adapted climate protection policy for the agricultural sector), Landbauforschung – vTI Agriculture and Forestry Research, Special Issue 361, s.l.

461 Bundesregierung (2002): Perspektiven für Deutschland. Unsere Strategie für eine nachhaltige Entwicklung, s.l. (Perspectives for Germany. Our strategy for sustainable development)

462 Schnug, E., Haneklaus, S. (2002): Landwirtschaftliche Produktionstechnik und Infiltration von Böden – Beitrag des ökologischen Landbaus zum vorgebeugenden Hochwasserschutz (Agricultural production processes and soil infiltration – contribution of organic farming to preventative flood control), Landbauforschung Völkenrode 4 (52), S. 197-203.

463 Seufert, V., Ramankutty, N., Foley, JA. (2012): Comparing the yields of organic and conventional agriculture, Nature letter, Online publication.

464 AMI (Agricultural Market Information Company) (2012): Bio-Strukturdaten– Bodennutzung und Tierhaltung 2010, Marktwoche Ökolandbau 07.5-9. (Organic structural data - soil use and animal husbandry)

465 Thünen-Institut für Betriebswirtschaft (various volumes): Wirtschaftliche Lage ökologischer und konventioneller Vergleichsbetriebe für das Wirtschaftsjahr 2008/09, 2009/10 und 2010/11. (Economic performance of comparable organic and conventional farms for the financial years 2008/09, 2009/10 and 2010/11) Institut für Betriebswirtschaft des vTI auf Grundlage des Testbetriebsnetzes. Link:http://www.ti.bund.de/no_cache/de/startseite/institute/

bw/projekte/betriebswirtschaftliche-analysen-oekologischer-landbau/analyse-der-wirtschaftlichen-lage-oekologisch-wirtschaftender-betriebe.html

466 AMI (Agricultural Market Information Company) (2012): Bio-Strukturdaten– Bodennutzung und Tierhaltung 2010, Marktwoche Ökolandbau 07.5-9. (Organic structural data - soil use and animal husbandry)

467 Osterburg, B., Zander, K. (2004): Regionale Strukturen des ökologischen Landbaus in Deutschland. (Regional structures of organic farming in Germany) Arbeitsbericht des Bereichs Agrarökonomie, FAL Braunschweig, Braunschweig.

468 AMI (Agricultural Market Information Company) (2012): Bio-Betriebe und -Flächen in Deutschland 2011 nach Bundesländern. (Organic farms and land in Germany 2011 by federal state) http://www.ami-informiert.de/fileadmin/redaktion/bio_daten/strukturdaten/Strukturdaten_nach_Bundeslaendern_2011_PDF.pdf

469 AMI (Agricultural Market Information Company) (2012): Bio-Strukturdaten– Bodennutzung und Tierhaltung 2010, Marktwoche Ökolandbau 07.5-9. (Organic structural data - soil use and animal husbandry)

470 Osterburg, B., Zander, K. (2004): Regionale Strukturen des ökologischen Landbaus in Deutschland. (Regional structures of organic farming in Germany) Arbeitsbericht des Bereichs Agrarökonomie, FAL Braunschweig, Braunschweig.

471 Sanders, J., Offermann, F., Nieberg, H. (2012): Wirtschaftlichkeit des ökologischen Landbaus in Deutschland unter veränderten agrarpolitischen Rahmenbedingungen (The economic development of organic farms in Germany and impact of changed agricultural policy framework conditions), Landbauforschung- vTI Agriculture and Forestry Research, Special Issue 364, Braunschweig.

472 Schaak, D., Barbian, T., Gerber, A., Jansen, M., Zander, K., Roehl, R. (2011): Zahlen, Daten, Fakten: Die Bio-Branche 2011 (Figures, data, facts: The organic sector 2011), BÖLW, Berlin.

473 Schaak, D., Barbian, T., Gerber, A., Jansen, M., Zander, K., Roehl, R. (2011): Zahlen, Daten, Fakten: Die Bio-Branche 2011 (Figures, data, facts: The organic sector 2011), BÖLW, Berlin.

474 Statistisches Bundesamt (2012): Umwelt. Öffentliche Wasserversorgung und Abwasserentsorgung nach Ländern. (Public water supply and wastewater management by federal state) Anschlussgrad und Wasserabgabe 2010, Wiesbaden.
BMELV (2011, 2010, 2009 and earlier volumes): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland 2011 (Statistical Yearbook for Food, Agriculture and Forestry 2011), Wirtschaftsverlag NW GmbH, Bremerhaven. SJELF Tab. 342 and Schaak, D., Barbian, T., Gerber, A., Jansen, M., Zander, K., Roehl, R. (2011): Zahlen, Daten, Fakten: Die Bio-Branche 2011 (Figures, data, facts: The organic sector 2011), BÖLW, Berlin.

475 Schaak, D., Rampold, C., Willer, H., Rippin, M., von Koerber, H. (2011): Analyse der Entwicklung des ausländischen Angebots bei Bioprodukten mit Relevanz für den deutschen Biomarkt (Analysis of imports of organic products with relevance for the German organic market), Agrarmarkt Informations-GmbH, Forschungsinstitut für biologischen Landbau, AgroMilargo Research, fleXinfo, Bonn.

476 Schaak, D., Rampold, C., Willer, H., Rippin, M., von Koerber, H. (2011): Analyse der Entwicklung des ausländischen Angebots bei Bioprodukten mit Relevanz für den deutschen Biomarkt (Analysis of imports of organic products with relevance for the German organic market), Agrarmarkt Informations-GmbH, Forschungsinstitut für biologischen Landbau, AgroMilargo Research, fleXinfo, Bonn.

477 Schaak, D., Rampold, C., Willer, H., Rippin, M., von Koerber, H. (2011): Analyse der Entwicklung des ausländischen Angebots bei Bioprodukten mit Relevanz für den deutschen Biomarkt (Analysis of imports of organic products with

relevance for the German organic market), Agrarmarkt Informations-GmbH, Forschungsinstitut für biologischen Landbau, AgroMilargo Research, fleXinfo, Bonn.

478 Osterburg, B., Kätsch, S., Wolff, A. (2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

479 Osterburg, B., Kätsch, S., Wolff, A.(2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

480 Thünen Institute (2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

481 Osterburg, B., Kätsch, S., Wolff, A.(2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

482 Osterburg, B., Kätsch, S., Wolff, A.(2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig). Based on BMELV (Federal Ministry of Food, Agriculture and Consumer Protection) (2011 and earlier volumes): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland (German Statistical Yearbook for Food, Agriculture and Forestry), Wirtschaftsverlag NW GmbH, Bremerhaven., and Deutsche Gesellschaft für Ernährung (2004): DGE-Ernährungskreis – Lebensmittelmengen. (DGE Nutrition Plate - recommended allowances) DGEInfo 05/2004 – Beratungspraxis. Link: http://www.dge.de/modules.php?name=News&file=article&sid=415 , Abruf 17.09.2012. and other sources and assumptions (see Chapter ? and ?).

483 BMELV (2010): Statistisches Jahrbuch über Ernährung, Landwirtschaft und Forsten der Bundesrepublik Deutschland (Statistical Yearbook for Food, Agriculture and Forestry), Wirtschaftsverlag NW GmbH, Bremerhaven.

484 Osterburg, B., Kätsch, S., Wolff, A.(2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

485 Osterburg, B., Kätsch, S., Wolff, A.(2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

486 Osterburg, B., Kätsch, S., Wolff, A.(2013): Szenarioanalysen zur Minderung von Treibhausgasemissionen der deutschen Landwirtschaft im Jahr 2050 (Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

487 Umweltbundesamt (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen, (Energy Target 2050 - 100% electricity from renewable sources) Dessau-Roßlau.

488 Umweltbundesamt (2010): Energieziel 2050: 100% Strom aus erneuerbaren Quellen, (Energy Target 2050 - 100% electricity from renewable sources) Dessau-Roßlau.

489 Seemüller, M. (2001) "Ökologische bzw. konventionell-integrierte Landbewirtschaftung." (Integrated organic and conventional land management) ERNO 2 (2) 94-96.

490 Osterburg, B., Kätsch, S., Wolff, A. (2013): Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig).

491 Statistisches Bundesamt (2011): (German Federal Statistical Office 2011) Kumulierte Treibhausgas-Emissionen bzw. kumulierter Primärenergieverbrauch mit Vorleistungen aus dem In- und Ausland nach Gütergruppen. (Cumulative greenhouse gas emissions and primary energy consumption by product group, including domestic and foreign upstream services.) Rechenstand 2010

492 NIR (2012): National Inventory Report for the German Greenhouse Gas Inventory 1990–2010, Dessau-Roßlau. http://www.umweltbundesamt.de/emissionen/publikationen.htm

493 Intergovernmental Panel on Climate Change (IPCC): Guidelines for National Greenhouse Gas Inventories 1996/2006, Good Practice Guidance 2003 http://www.ipcc-nggip.iges.or.jp/public/2006gl/

494 Common Reporting Format CRF (2012); Tables for climate reporting in accordance with the UNFCCC 1990–2010, Dessau-Roßlau.

495 Common Reporting Format CRF (2012): Tables for climate reporting in accordance with the UNFCCC 1990–2010, Sheets 5-5 F, Dessau-Roßlau.

496 Krug, J., Olschofsky, K., Dunger, K., Riedel, T. (2011): Hintergründe zur Reduktion der Senkenleistung aus Waldbewirtschaftung seit 1990 (Background to the reduction in sink effect from forest management since 1990). vTI-Arbeitsbericht 2011/04. http://literatur.vti.bund.de/digbib_extern/bitv/dn049786.pdf

497 Rüter, S. (2011): Projection of Net Emissions from Harvested Wood Products in European Countries - For the period 2013-2020. Hamburg: vTI, Arbeitsbericht aus dem Institut für Holztechnologie und Holzbiologie Report No. 2001/01.

498 Rüter, S. (2011): Projection of Net Emissions from Harvested Wood Products in European Countries - For the period 2013-2020. Hamburg: vTI, Arbeitsbericht aus dem Institut für Holztechnologie und Holzbiologie Report No. 2001/01. 2001/01.

499 European Agricultural Fund for Rural Development (EAFRD) http://wayback.archive.org/web/20051223113612/http://www.mcpfe.org/resolutions/helsinki/resolution_h1.pdf

500 Rüter, S. (2011): Welchen Beitrag leisten Holzprodukte zur CO_2-Bilanz? (How do wood products contribute to the CO_2 balance?) AFZ-Der Wald 2011/15. http://www.holzundklima.de/docs/2011-08_Rueter_AFZ-2011-15_15-18.pdf

501 Intergovernmental Panel on Climate Change (IPCC): Guidelines for National Greenhouse Gas Inventories 1996/2006, Good Practice Guidance 2003 http://www.ipcc-nggip.iges.or.jp/public/2006gl/

502 Paul, C., Weber, M., Mosandl, R. (2009): Kohlenstoffbindung junger Aufforstungsflächen (Carbon capture in young areas of afforestation), Karl Gayer Institut & Technische Universität München, Lehrstuhl für Waldbau (unpublished), Munich.

503 Rüter, S. (2011): Welchen Beitrag leisten Holzprodukte zur CO_2-Bilanz? (How do wood products contribute to the CO_2 balance?) AFZ-Der Wald 2011/15. http://www.holzundklima.de/docs/2011-08_Rueter_AFZ-2011-15_15-18.pdf

504 Rüter, S. (2011): Welchen Beitrag leisten Holzprodukte zur CO_2-Bilanz? (How do wood products contribute to the CO_2 balance?) AFZ-Der Wald 2011/15. http://www.holzundklima.de/docs/2011-08_Rueter_AFZ-2011-15_15-18.pdf

505 Paul, C.; Weber, M.; Mosandl, R. (2009): Kohlenstoffbindung junger Aufforstungsflächen (Carbon capture in young areas of afforestation), Karl Gayer Institut & Technische Universität München, Lehrstuhl für Waldbau (unpublished), Munich.

506 Rüter, S.; Rock, J.; Köthke, M.; Dieter, M. (2011): Wie viel Holznutzung ist gut fürs Klima? (How much use of wood is good for the climate?) AFZ-Der Wald 2011/15.

507 Federal Environmental Agency (2012): Schwerpunkte 2012 (What Matters 2012) Federal Environmental Agency, p. 34–57, Dessau-Roßlau.

508 Federal Environmental Agency (2012): Glossar zum Ressourcenschutz. (Resource conservation glossary.) Federal Environmental Agency, Dessau-Roßlau.

509 Raschka, A.; Carus, M. (2012): Stoffliche Nutzung von Biomasse — Basisdaten für Deutschland, Europa und die Welt (Use of biomass for the production of raw materials — basic data for Germany, Europe and the world). Nova-Institut GmbH, Hürth.

510 Albrecht, S.; Rüter, S.; Welling, J.; Knauf, M.; Mantau, U.; Braune, A.; Baitz, M.; Weimar, H.; Sörgel, S.; Kreissig, J.; Deimling, J.; Hellwig, S. (2008): ÖkoPot - Ökologische Potenziale durch Holznutzung gezielt fördern. (Targeted support for increasing environmental potential.) Final report on BMBF project FKZ 0330545, Stuttgart.

511 Rhomberg, H. (2012): The Natural Change in Urban Architecture. Speech given on 12.11.2012 to the European Resource Forum 2012. http://www.resourcesforum.eu/images/ppt/1_02_Rhomberg.pdf

512 Rüter, S. (2011): Welchen Beitrag leisten Holzprodukte zur CO_2-Bilanz? (How do wood products contribute to the CO_2 balance?) AFZ-Der Wald 2011/15.

513 Rüter, S. (2011): Welchen Beitrag leisten Holzprodukte zur CO_2-Bilanz? (How do wood products contribute to the CO_2 balance?) AFZ-Der Wald 2011/15.

514 Thünen Institute (2011): The German Reference Level for Forest Management, background paper, information for the Federal Ministry of Food, Agriculture and Consumer Protection (BMELV), Eberswalde and Hamburg.

515 Krug. J., Köhl, M., Riedel, T., Bormann, K., Rüter, S., Elsasser, P. (2009): Options for accounting carbon sequestration in German forests; Carbon Balance and Management, Volume 4/2009.

516 Rüter, S., Rock, J., Köthke, M., Dieter, M. (2011): Wie viel Holznutzung ist gut fürs Klima? (How much wood use is good for the climate?) AFZ-Der Wald 2011/15.

517 Thünen Institute (2013): Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig.

518 Thünen Institute (2013): Scenario analyses on the reduction of greenhouse gas emissions from German agriculture in 2050, Thünen Report, Expert opinion commissioned by the German Federal Environment Agency, Braunschweig.