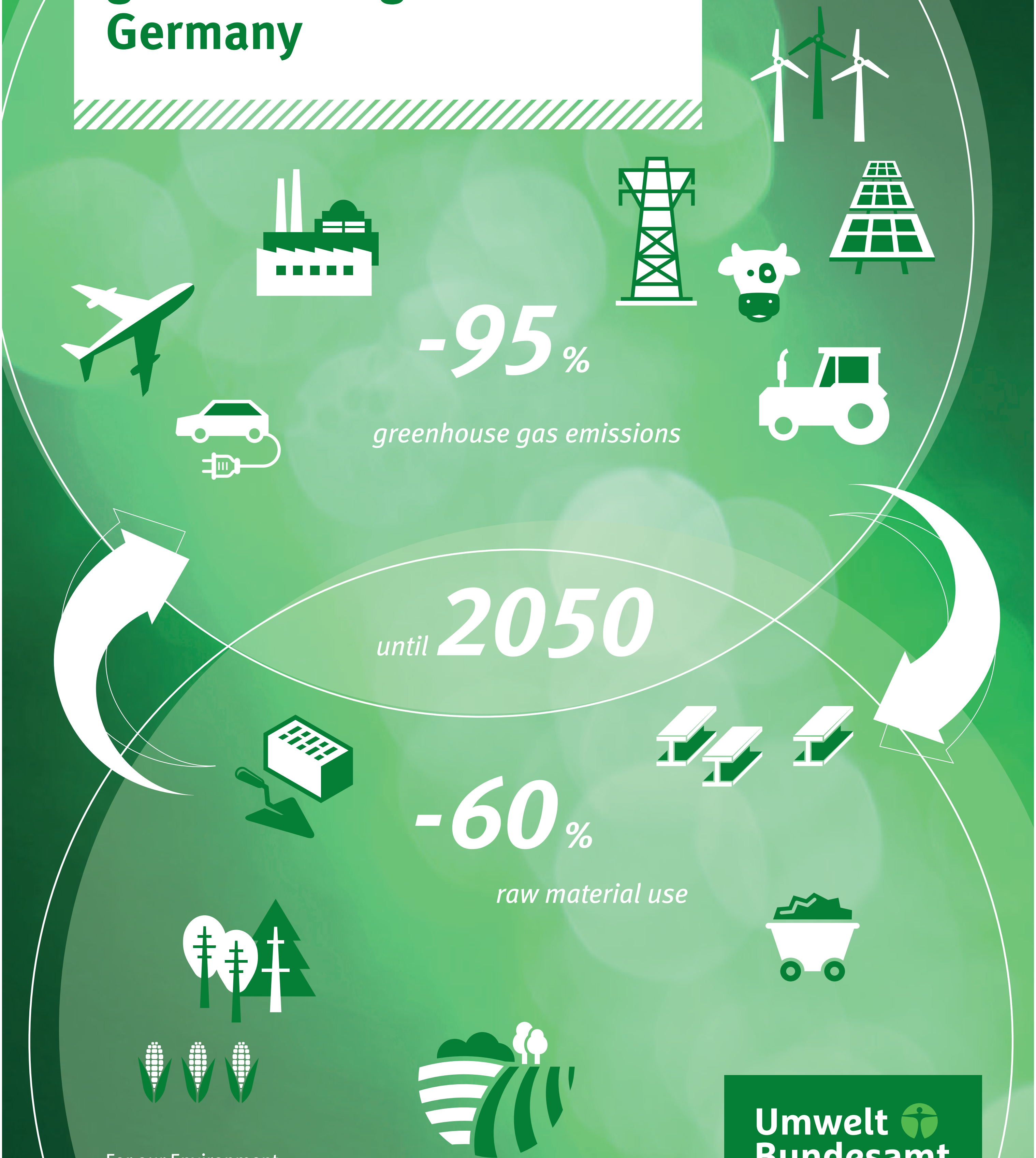
A resource efficient pathway towards a greenhouse gas neutral Germany



For our Environment

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A resource efficient pathway towards a greenhouse gas neutral Germany

The following scenario results are mainly based on analyses of the ongoing “Transformation process for a greenhouse gas neutral and resource efficient Germany” research project (Project number/FKZ: 3715 41 115 0). The project is being carried out by the Consortium ifeu – Institute for Energy and Environmental Research GmbH, IEE – Fraunhofer Institute for Energy Economics and Energy System Technology, CONSIDEO GmbH and Dr. Karl Schoer SSG.

System dynamics modelling was carried out by CONSIDEO GmbH within the “KliReX – Understanding and assessing the greenhouse gas mitigation potential of resource efficiency policy” project (Project number/FKZ: 3716 32 100 0).

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Elements of a future proof and sustainable Germany – greenhouse gas neutral and resource efficient

The economic growth made possible by the fossil energy based industrial revolution – and the associated use of resources [1] – with a constantly rising world population have meanwhile shown limitations to this type of economic activity. The environment is increasingly threatened, beginning with the problem of man-made climate change, erosion of fertile soils and water pollution, loss of biodiversity, and the various harmful impacts of anthropogenic pollutants on humans and the environment. After many years of wasteful exploitation, some resources are approaching their end or will cause increasingly unacceptable environmental impacts over the coming decades. Moreover, wealth and education, life expectancy, and life opportunities that have been achieved are extremely unequally distributed between industrialised countries and the rest of the world and within individual countries themselves.

As early as the 1990s, a number of studies showed possible ways to achieve a sustainable and environmentally sound development (see "Sustainable Germany – towards a sustainable and environmentally sound development" (UBA 1998a) and "Future-proof Germany in a globalised world" (BUND & Misereor (Eds.) 1996a). The "basic requirement" of sustainable development is that environmental functions, i. e. the natural bases of life in their various roles are not further endangered for this and the next generations.

The use of natural resources has been growing steadily for years, global consumption of primary raw materials alone tripling over the past 40 years to almost 85 billion tonnes in 2015 (Ekins, et al. 2017b). In 2050, the population of the world, estimated to be up to 10 billion people, is expected to consume more than 140 billion tonnes of minerals, ores, fossil fuels and biomass if today's preferred consumption patterns continue (Fischer-Kowalski, et al. 2011a).

Despite a growing number of measures to reduce climate change, all anthropogenic greenhouse gas emissions continued to rise from 1970 to 2010, even with higher absolute increases between 2000 and 2010. In 2010 anthropogenic greenhouse gas emissions reached a value of 49 ± 4.5 Gt CO_2 equivalents (CO_2eq hereinafter) per year, i. e. around 30 % more than in 1990[2] (IPCC 2014h). The increased use of fossil fuels led to a 58 % increase in CO_2 emissions compared to 1990 (International Energy Agency 2016k)[3]. This is linked to the increase in global average temperature in 2016, which was the highest average temperature ever measured. The temperatures were on average 0.83 °C higher than in the comparative period of 1961–1990 and 1.1 °C higher than in the pre-industrial era (World Meteorological Organization (WMO) 2017n).

The growing demand for resources increasingly affects ecosystems and thus endangers the welfare of the world's population. Extraction, processing and treatment of raw materials and the manufacture of products require large amounts of fossil energy in some cases and thus affect the climate. In addition, extraction and processing of abiotic raw materials are often associated with contamination of drinking water resources, waterbodies, soil and breathing air in the extraction countries, resulting in health damage. Due to the high demand for water and land, there are often conflicts of use which frequently endanger the livelihood of the local population. Against the background of the limited availability of natural resources and the environmental impacts associated with their use, it is clear that this type of resource use in industrialised countries cannot be transferred elsewhere in the world. Thus, the urgent need arises for an equitable distribution of resources and access to them, both within today's generations (intragenerational justice) and between present and future generations (intergenerational justice).

Quick action is required to avoid coming to a point where we deprive ourselves of our own natural foundations. Sustainable development therefore requires a profound transformation of society and industry.

But which paths are those that lead to a sustainable and future-proof Germany in Europe? The development of complex and dynamic systems such as the anthroposphere is fairly difficult to describe. This is why so-called scenario studies have become a common tool. They allow us to analyse various possible "futures" and establish a set of solutions for sustainable development. This German

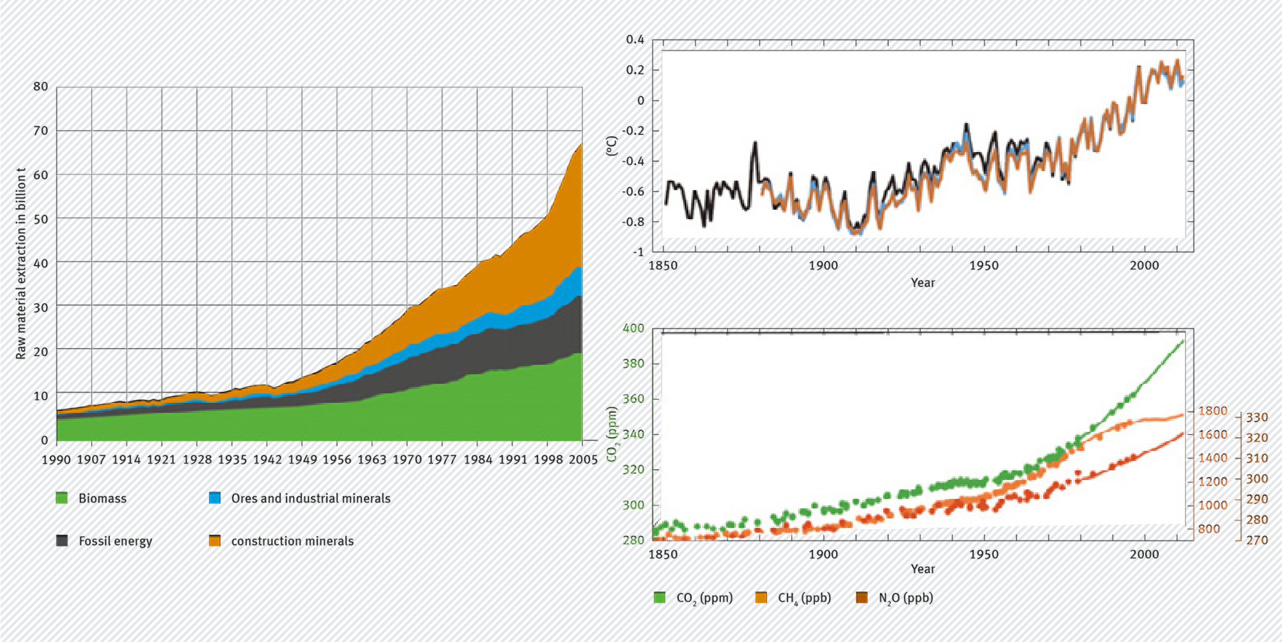
1 Abiotic and biotic primary raw materials (including energy carriers), area, water, soil, air, streaming resources such as geothermal energy, wind, tidal and solar energy and ecosystem services.

2 1990: about 38 Gt CO_2eq per year.

3 Up to 2014.

Figure 1.1

1900 – 2009 global raw material extraction (left), global average combined land and ocean surface temperature anomaly (top right), global average greenhouse gas concentration (bottom right)



Source: Krausmann, et al. 2009a (left); IPCC 2014h (right)

Environment Agency (UBA) report describes the initial results of such a scenario study that considers greenhouse gas neutrality and resource protection in a joint and integrated manner.

It is undisputed that climate change and its consequences, apart from resource conservation, is one of the greatest global challenges of our time and will continue to be over the long term. Therefore, ambitious and comprehensive climate protection measures are needed to limit global warming. Industrialised countries have a particular responsibility because their present prosperity is based to a considerable measure on global exploitation of natural resources, e.g. use of fossil fuels and the increasing global use of land. In addition to the necessary implementation of greenhouse gas reductions, the reduction of raw material consumption is a further paramount objective of the policy to maintain our natural basis of existence and act within planetary boundaries.

Germany's national and international obligations

In 2010, the Federal Republic of Germany also committed itself to a reduction of greenhouse gas emissions (GHG emissions) by 80 to 95 % against 1990 based on this historical responsibility and its economic performance. In the Paris Agreement, the Contracting Parties to the United Nations Framework Convention on Climate Change agreed in 2015 on a common approach to fight climate change with a view of keeping global warming well below 2 °C against the pre-industrial level, and make efforts to limit the temperature rise in 1.5 °C . Against this background the German Environment Agency believes that Germany– as a rich industrialised nation and one of the leading nations in climate protection – must specify its contribution to be in the upper range of the 2050 target corridor of 95 % reduction of greenhouse gas emissions against 1990 as adopted by the Federal Government.

In 2012 Germany implemented a strategy with the German resource efficiency programme (ProgRess) (BMUB 2012b) and continued it with ProgRess II in 2016 in order to increase resource efficiency across the entire value chain and achieve an absolute reduction in the use of resources. ProgRess will continue to steadily develop according to the Federal Government's decision.

Germany has also set specific targets at an early stage with regard to sustainable use of natural resources, in particular the use of raw materials and land use. In its Sustainable Development Strategy of 2002 (Bundesregierung 2002a), the Federal Government formulated the objective to decouple Germany's economic development from the use of natural resources and the related environmental impacts. In concrete terms, the Federal Government has decided to double abiotic raw material productivity[4] by 2020 compared to 1994 and reduce land-take by urbanisation and transport to 30 ha/day by 2020. In the new version of the 2016 Sustainability Strategy (Bundesregierung 2017o), these goals are also being updated and supplemented in the light of the United Nations' Sustainable Development Goals (SDG). Thus, land-take is to be limited to less than 30 ha/day by 2030. With regard to the use of raw materials, the trend for total raw material productivity[5] of 2000–2010 is to be continued until 2030, which corresponds to an annual increase of 1.3 percent. This objective is also being pursued as the main target in the current version of the German Resource Efficiency Programme (ProgRess II) (BMUB 2016l) and complemented by sectoral objectives.

An increase in resource efficiency is also increasingly being pursued in Europe by implementing appropriate policies (EEA 2016g). Sustainable use of natural resources and increasing resource efficiency are becoming more important internationally. This has been shown by the United Nations' 2030 Agenda objectives and, not least, the G7 decision of Elmau and Toyama (BMUB 2016h) and G20 decision of Hamburg (G20 Germany 2017 2017m).

Clear, politically acknowledged international goals, as seen in climate protection, do not exist for sustainable raw material and resource use today. In the 1990s, various authors suggested an increase in resource efficiency by a factor of 10 (Lehmann und Schmidt-Bleek 1993a, Schmidt-Bleek 1993b), the idea being a reduction of the per capita resource use by 90 %. More recently, a figure of 3 to 8 tonnes has been proposed (Bringezu 2015b, IRP 2014f, Fischer-Kowalski, et al. 2011a).

4 The "raw material productivity" indicator is the ratio of the gross domestic product (GDP) to the abiotic direct material input (DMI). DMI is the sum of the mass of domestic raw material extraction and the mass of imported goods. The indicator does not include the indirect raw material use due to imported finished products, nor does it map the shift of resource-intensive production processes etc. to foreign countries and unused extractions.

5 Compared to raw material productivity, the total raw material productivity also takes into account the indirect raw material use due to imported semi-finished and finished products. The gross domestic product is correspondingly supplemented by the monetary value of imports to harmonise with system limits.

Industry and society must be fundamentally transformed along sustainable development if we want to achieve the above objectives and at the same time enable the necessary adaptation to unavoidable impacts of climate change. Such a transformation towards greenhouse gas neutrality and resource conservation simultaneously affects all sectors of our society: mobility, agriculture and food system, industry, commerce, and building and housing also contribute to greenhouse gas emissions and resource depletion in addition to energy supply. Protection of natural resources and climate protection belong together and help exploit synergies between the two policy areas and mitigate counterproductive interactions.

Greenhouse gas neutral Germany in 2050

The UBA study "Germany in 2050 – A Greenhouse Gas-Neutral Country" (UBA 2014a)– having a pure focus on climate protection – indicated at the time that ambitious climate protection targets are technically achievable and feasible in the German industrial marketplace. The study considered all greenhouse gas emission sources according to international reporting and, in addition, included nationally caused greenhouse gas emissions from international aviation and maritime transport, plus emissions from land use, agriculture and forestry (LULUCF)[6]. UBA has shown in its study how a total greenhouse gas reduction of almost 95 % compared to 1990 or an annual per capita emission of 1 tonne CO_2eq can be achieved in the individual sectors and fields of application. The analysis is based on technologies already available and assumes specific, partly ambitious further developments and innovations within these technologies. Changes in lifestyle or altered consumption patterns in nutrition and mobility behaviour have also been assumed to a limited extent. However, the study's focus was deliberately on the use of technical solutions and did not include cost estimates, political enforcement options or issues of societal acceptance.

It has been shown that energy supply for all fields of application must be completely greenhouse gas neutral in 2050, since, according to our current knowledge, a complete reduction of greenhouse gas emissions is not possible in fields such as agriculture and in some industrial processes. This requires both an energy supply based completely on renewable

6 Land use, land use changes and forestry.

energy and the maximum possible exploitation of existing efficiency potential. In addition, the use of fossil fuels outside energy generation must be completely replaced by regenerative and electricity-based energy sources in all fields of application. The study also shows that energy needs expected for 2050 can be entirely met by renewable energy sources and that there is a large demand for direct use of renewable electricity across all fields of application. The combustible, fuel and raw material demand[7] in the fields of application will be satisfied by hydrogen production from electrolysis of water and subsequent catalytic synthesis of hydrogen and carbon dioxide to produce hydrocarbon compounds (e.g. methane or liquid fuels).

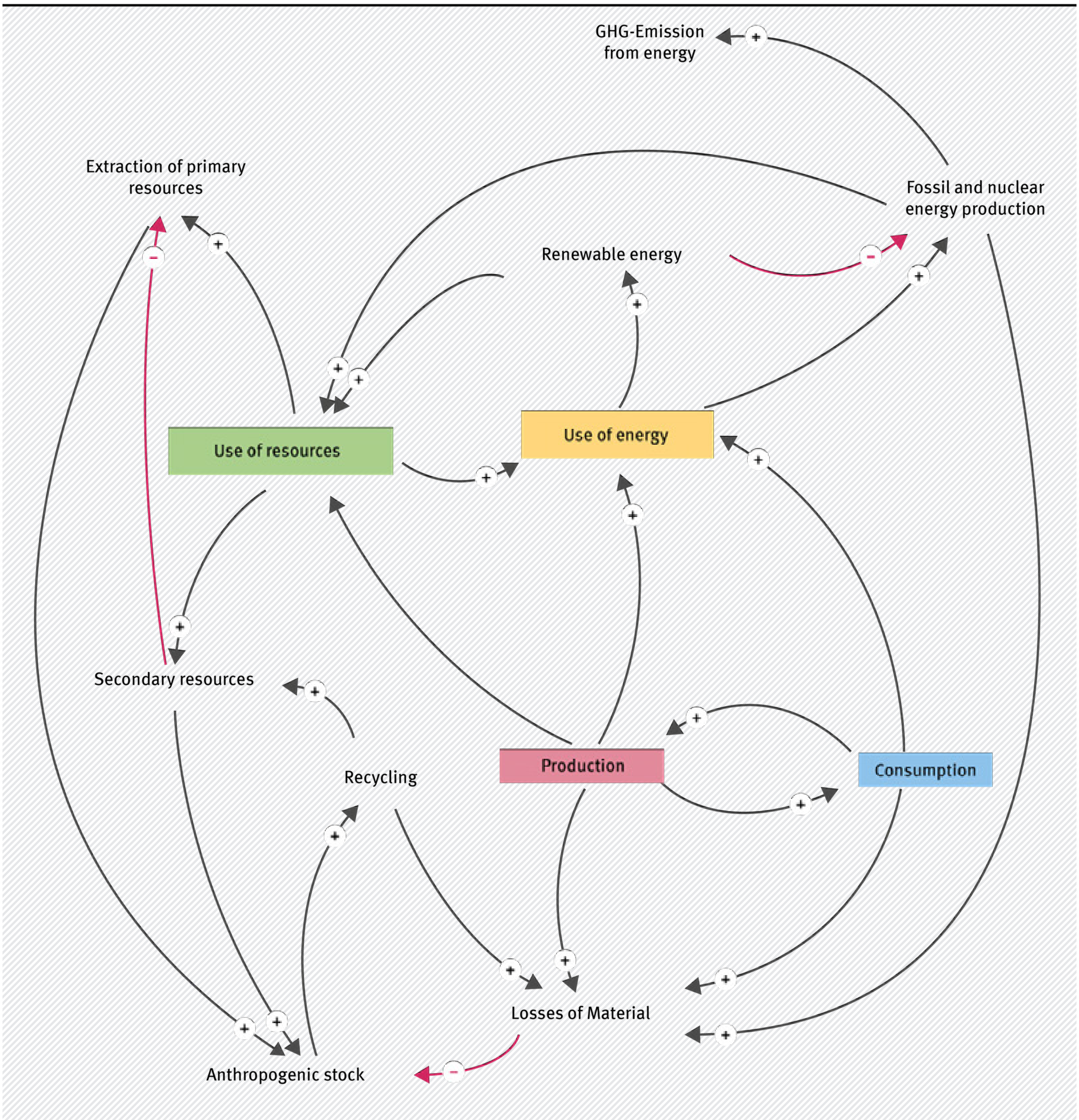
The largest part of greenhouse gas emissions is caused by energy provision and use, which means that the entire energy system must be restructured across all fields of application (electricity, heat, transport, industry) to meet the long-term climate protection targets. There will be a high demand for regenerative electricity generating installations (net electricity generation) and application techniques must be significantly changed. Depending on the technology involved, it will be necessary to restructure or even dismantle infrastructure. The construction of power generation installations will lead to a significant increase in the use of certain raw materials such as metals and building minerals. The other side of the coin is a decreasing resource use due to a decline in the use of fossil energy and its infrastructure. In addition, more and more raw material will be available in anthropogenic recycling stock, thus primary raw material extraction can be reduced over the long term.

Even if the demonstration of technical feasibility is an important step on the route to greenhouse gas neutrality, the transformation to a greenhouse gas-neutral society requires a much broader perspective. In particular, raw materials and resources needed for this transformation must be considered both in terms of their temporal development and of the interaction of various sectors and the interaction between the energy system and the resource system. The protection of natural resources and climate protection belong strongly together in an effort to systematically exploit synergies between the two policy fields.

7 Non-energy requirement for final energy carriers.

Figure 1.2

Systemic links between raw material use and climate protection



Source: own illustration

These two policy fields cannot be considered alone nationally since the impacts of climate change can be felt globally. Also, global trade interconnections and heterogenous resource distribution make a global analysis, the consideration of the various interplayand therefore a systemic embedding indispensable. Both national and international distributional and social issues are also important building blocks for concrete proposals for a gradual implementation of a greenhouse gas neutral and resource-efficient Germany using specific tools.

Systemic approach – routes towards a greenhouse gas neutral and resource efficient Germany in 2050

Mutual dependencies and feedbacks between resource conservation and climate protection require a systemic approach. Figure 1.2 shows in a very simplified form how energy use and raw material use are coupled. Production of goods and the corresponding consumption are the driving forces behind energy and raw material use. When energy is used in a non-sustainable form (fossil, nuclear), the results are extraction and consumption of raw materials accompanied by the negative environmental effects mentioned. Besides, the raw materials used are lost for further use. The use of raw materials for the construction of renewable energy systems shows a different picture. These raw materials remain in anthropogenic stock and a part of them can be channelled towards further use in the sense of a circular economy. In the long term, this also offers opportunities in terms of added value when recycling and production installations are placed within one industry and raw materials do not have to be imported.

This transformation process is being studied by several different UBA scenarios through an interdisciplinary process with external support by research projects. The results of the scenarios describe possible pathways into the future – a solution space. Key questions in this process are:

- What existing technologies are plausible to establish sustainable routes towards a greenhouse gas neutral, post-fossil and, if possible, a resource efficient Germany in 2050?
- What tools and measures do we need to implement this?
- How will the raw material demand in a greenhouse gas neutral Germany develop up to 2050?
- How do climate and resource protection interact?
- Do raw material saving and resource efficient approaches and options needed to achieve a greenhouse gas neutral industry actually exist?
- What contributions can and should industry and society make?
- Which problems (for example, raw material shortages) can already be foreseen today?

This study only presents the first of these scenarios. This "Germany – resource efficient and greenhouse gas neutral – Energy efficiency" (GreenEe) scenario focuses on an ambitious and energy efficient transformation route towards greenhouse gas neutrality in a resource efficient way, in line with the target scenario "Greenhouse Gas Neutral Germany in 2050". The ongoing work on additional scenarios will further specify the solution space and consider the impacts and interaction of the effort level during the transformation process towards greenhouse gas neutrality (GreenLate, GreenSupreme), the selection of installation technology with regard to material efficiency (GreenMe) and lifestyle (GreenLife) (see Table 1.1). Using system dynamics modelling approaches, in-depth analyses of single specific aspects of the energy system transformation (see chapter 3.2).

This second edition of the report contain a number of minor additions to the model and updated result figures. This includes figures showing resource use in the supporting years (2030 and 2040, see chapter 3.2) and methodical enhancements considering freight transport based on insights gained during the project. In addition, recalculations especially in the energy sector and on emissions in agriculture were undertaken.

Table 1.1

Overview of the planned scenarios, the scenario in this study is boxed in green

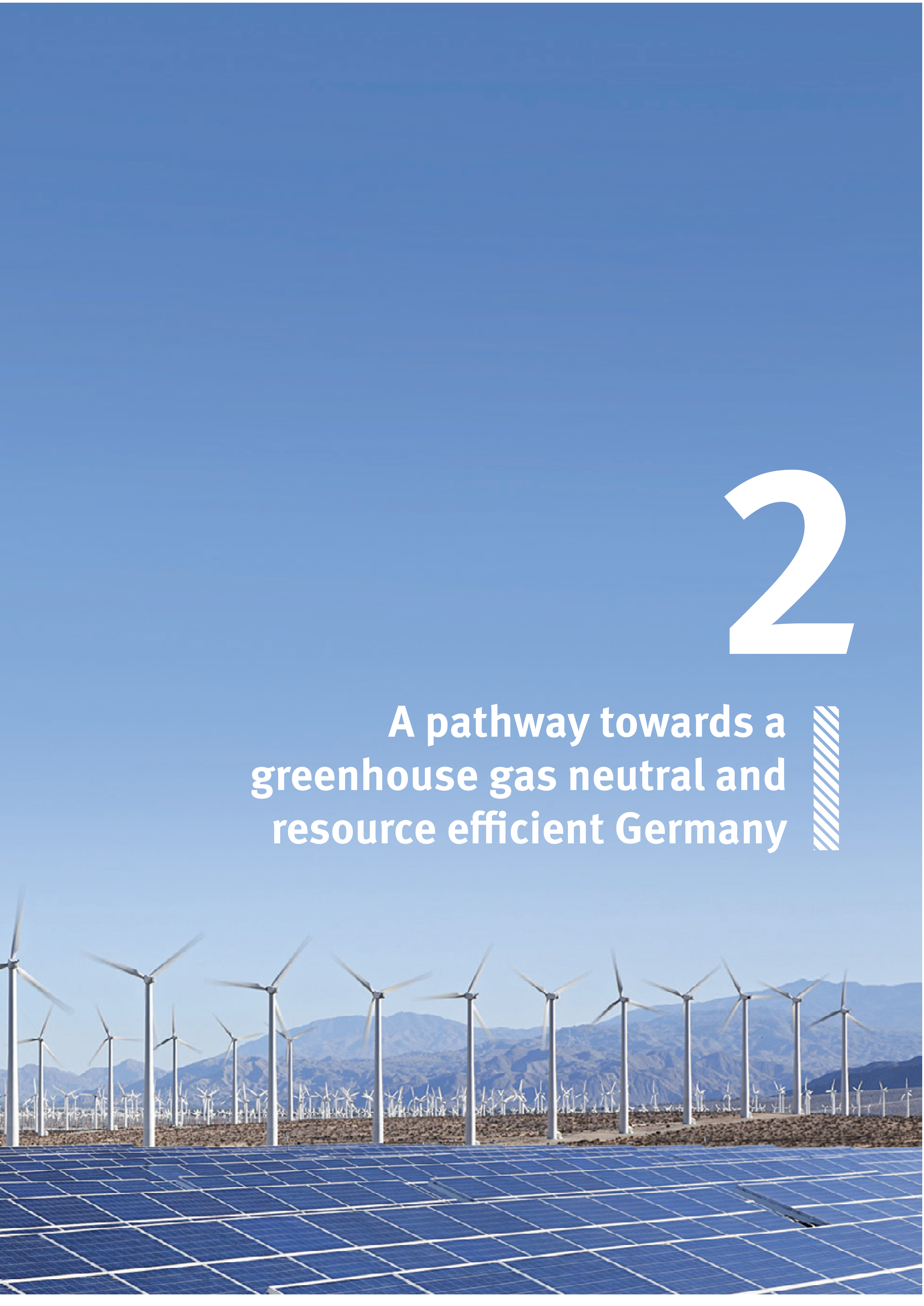
	GreenEe	GreenLate	GreenMe	GreenLife	Green-Supreme
Greenhouse gas reduction in 2050	Very high	Very high	Very high	Very high	Very high
Ambition level of climate protection efforts on the transformation pathway (2030 and 2040)	High	Medium	High	High	Very high
Final energy consumption	Low	High	Low	Very low	Very low
Raw material use	Medium	High	Low	Low	Low
Raw material efficiency	High	Medium	Very high	High	Very high
Changes in behaviour*	Medium	Medium	Medium	Very high	Very high

* For example, in the field of nutrition, mobility, consumption, etc.

Source: own illustration

2

A pathway towards a greenhouse gas neutral and resource efficient Germany



2.1 Basic scenario assumptions

Germany – a country with high population density and strong industrial power – is embedded in the European Union (EU) and the world. Today's structures can be assumed not to change fundamentally on the way towards a greenhouse gas neutral society. The basic assumption of the scenario presented is that Germany will remain a manufacturing industrial marketplace in 2050. Economic growth will be moderate at an average of 0.7 % and foreign trade will hardly change compared to today. However, establishing a greenhouse gas neutral and resource efficient society requires change and rethinking. This applies to all areas of daily life, especially to business activity in Germany.

Regardless of recent developments, the future figures of demographic development will be fairly constant. The presented GreenEe scenario[1] assumes that neither birth rates nor life expectancy will significantly change, and, assuming moderate immigration, the population will be nearly 72 million people in 2050 (Statistisches Bundesamt 2015a). According to the demographic trend, living space requirement will still be rising until 2030 and will then be reduced to the 2010 living space requirement. In 2050, no net land-take will take place. Land-take will be reduced to 20 ha/day by 2030, and will move towards net zero in the subsequent decades until 2050. In the GreenEe scenario, the extension of municipal infrastructure such as water supply, wastewater disposal and telecommunication infrastructure will be linked to population development and the development of new impervious surfaces.

A future proof and distinctive information and communication technology (ICT) will be an integral part of people's everyday life and all sectors of industry by 2050. A healthy and sustainably produced diet will also be part of a steady development towards a sustainable society. A transport transition comprising avoidance, changing and improvement of energy efficiency will materialise in both passenger and freight transport. Transport avoidance will be facilitated by intelligent logistics in freight transport and the 'city of short distances' in personal transport. Energy need for transport will decrease, inasmuch as engines and vehicles will be further optimised technically. Freight transport will be shifted from the road to more energy-efficient means of transport such as rail or ship and attractive offers for rail or public transport will make passenger transport more climate friendly. Transport infrastructure will only change moderately: the scenario assumes that neither new waterways nor new airports will be built. The infrastructure will be equipped with a special charging arrangement for electric vehicles and a network expansion for overhead-line hybrid lorries in accordance with sustainable energy supply for transport.

Changes and improvements in energy infrastructure, in particular electricity grids, will also take place and ensure a greenhouse gas neutral and resource efficient supply based entirely on renewable energy. The integration of flexible generating installations, electricity consumers and storage will provide a high degree of supply security in the supply dependent production of renewable energy such as wind and photovoltaics. This means that digital networking will issue corresponding price signals across all fields of application, i. e. industry and households, encouraging load management and thus temporally shifting electricity needs. Availability of raw materials and acceptance by the population through care for landscape and species protection will ensure an efficient handling of energy. Energy efficiency in buildings, industry and transport, enhancing sector coupling[2] and direct electricity use will go hand in hand with the expansion of renewable energy.

At the same time, resource transition takes place in the use of natural resources in Germany and in particular in the use of abiotic and biotic raw materials. The focus here is not on the products, but on services and needs such as mobility, housing, nutrition, communication, etc., which should be rendered as resource efficient as possible. The raw materials required for this will be largely circulated, whereby non renewable raw materials will be increasingly replaced by regrowing or renewable raw materials. Instead of natural deposits, anthropogenic deposits (material stocks of long lived goods, infrastructure, buildings and landfills) will be increasingly used; critical raw materials such as gallium, indium and

1 Germany – resource efficient and greenhouse gas neutral – Energy efficiency.

2 Sector coupling is understood to mean a stronger interlocking of electricity, heat, combustible, fuel and raw materials markets. Sector coupling enables direct or indirect use of regenerative electricity, greenhouse gas-neutral supply to all fields of application or complete substitution of fossil energy carriers and raw materials. Sector coupling increases flexibility in the power system and thus supports the integration of fluctuating renewable energy generation.

antimony increasingly substituted by less critical raw materials. Ecodesign has established itself as a fundamental principle in product design. Aspects such as extended life time, repairability, dismantlability, waste prevention, reusability and recyclability are taken into account and addressed in the sense of overall ecological product optimisation as early as during the design phase.

The scenario described mainly in technical terms in the following is a possible route to such a society. This description will especially take into account the interactions between various fields of industry and life. Altered consumption patterns are only assumed in mobility behaviour and nutrition.

2.2 Final energy demand

The cross-sectoral, secure energy supply is a central foundation for our current prosperity level and our economic performance. To a large extent, these are based on the use of fossil fuels and the excessive use of resources, which are the two main causes of today's environmental problems. The transformation of the energy supply towards an environmentally friendly, greenhouse gas-neutral society and economy is based on three central principles:

- Efficiency: exploiting energy and resource efficiency potentials across all sectors;
- Renewable energies: expanding renewable energies and their use in all fields of application, and especially in electricity generation;
- Sector coupling: direct or indirect use of regenerative electricity across all fields of application towards the complete substitution of fossil fuels and raw materials.

UBA's study "Germany in 2050 – A Greenhouse Gas-Neutral Country" (UBA 2014a) showed that sustainable and ambitious climate protection targets – essentially no CCS, use of crop-based bioenergy and basically no nuclear energy – can only be achieved through a total transfer to renewable energy since greenhouse gas emissions are unavoidable in sectors such as agriculture and industry.

Table 2.1

Overview of the final energy consumption of the GreenEe scenario in TWh (classify into energy carriers) a)

		Electricity b)	Gases	Coal	Other fossils	Other renewables c)	Fuels d)	Raw materials	Total
2015 g)	PH e)	132	235	7	182	81	0	0	637
	ITS f)	149	110	0	102	27	0	0	388
	Industry	228	247	119	90	32		269 h)	985
	Transport	12	2	0	0	30	683	0	727
	Total	521	594	126	374	170	683	269	2,737
2030	PH	143	250	0	57	84	0	0	534
	ITS	142	96	0	48	21	27	0	334
	Industry	164	218	132	52	7	0	282	855
	Transport	41	0	0	0	0	518	0	560
	Total	490	565	132	157	112	545	282	2,283
2040	PH	147	110	0	22	138	0	0	416
	ITS	138	41	0	32	40	23	0	273
	Industry	225	188	62	25	7	0	282	789
	Transport	94	0	0	0	0	312	0	406
	Total	605	339	62	78	185	334	282	1,885
2050	PH	135	0	0	0	173	0	0	308
	ITS	137	0	0	0	91	19	0	247
	Industry	281	169	0	0	16	0	288	754
	Transport	116	0	0	0	0	184	0	299
	Total	669	169	0	0	279	202	288	1,608

a) Figures rounded to whole numbers. b) Incl. electricity for hydrogen in industry (steel, chemestry). c) Environmental heat in particular. d) Including national demand for international transport (maritime transport and aviation). e) Private households. f) Unlike the scenario results, the historical fuel demands in ITS are not listed separately. g) (UBA 2016d). h) (BMWI 2017d).

Source: model calculation

Energy efficiency potentials that take into account raw material efficiency are a decisive factor for the renewable energy demand and thus also for the demands for raw material. It must also be taken into account that fossil fuels should not be substituted directly and identically by renewable energies. Rather, drawing on the example of the current energy system, the systematic efficiency and associated costs must be considered.

Sector coupling, meaning the direct or indirect use of regenerative electricity for heat (Power to Heat, PtH), combustible, fuel and raw material supply (Power to Gas, PtG and Power to Liquid, PtL) plays an important role in this context. This does not mean that today's energies should be substituted one-for-one, for example fossil gas by renewable gas. Rather, Power to X technologies (PtX) should be integrated in the transformation process according to their substitution potential (UBA 2016a). In practice, this means that electromobility should be used early on in transport, and Power to Heat, especially in conjunction with heat pumps in private households and CTS[3], because they already have a positive climate effect. PtX technologies are often associated with the conversion of process technologies and their integration into industry, particularly of Power to Heat, is also of great importance for climate protection. In order to limit the absolute need for renewable energies and thus also the demand for raw materials, changes to efficient PtX technologies are inevitable in the context of ambitious climate protection policy. Against this background, the transformation of the energy supply is directly linked to the transformation in the fields of application.

The GreenEe scenario assumes that efficiency measures will be implemented across all fields of application by 2030. At the same time, the integration of efficient Power to X technologies such as PtH (with heat pumps for space heat supply) and electromobility is already being carried out. Particularly when it comes to space heat supply, raising efficiency potentials can reduce the final energy consumption by about 25 % by 2030 compared to 2015. The decade between 2030 and 2040 will essentially witness the market penetration of PtX technologies in all fields of application, including transport. This period will also be marked by an increasingly important role of overhead catenary hybrid lorries and the conversion of process technologies in the industry, which will be completed by 2050. In contrast to UBA's study "Germany in 2050 – A Greenhouse Gas-Neutral Country" (UBA 2014a), the GreenEe scenario assumes that the period leading up to 2050 will bring a stronger penetration of electromobility into vehicle fleets including freight transport, and of PtH technologies in industry and in buildings that are difficult to renovate. It is also assumed that hydrogen, which will be needed in the steel industry and in some installations of the chemical industry, will be mainly generated on site (near the production site) through water electrolysis. In 2050, the final energy consumption for hydrogen (97 TWh) in Germany will require a power generation of almost 110 TWh (see Section 2.3).

The scenario in the present study also takes into account the non-energetic final energy consumption for hydrocarbons as a raw material for the chemical industry, which is assumed to be provided by means of the Power to Gas/Liquid process. At the same time, the scenario also accounts for the energy requirements due to the national demand for international transport (maritime transport and aviation).

The resulting trend of final energy consumption across all fields of application is shown in Table 2.1. The subsequent Sections 2.3 to 2.6 describe this transformation path in more detail.

2.3 Energy supply

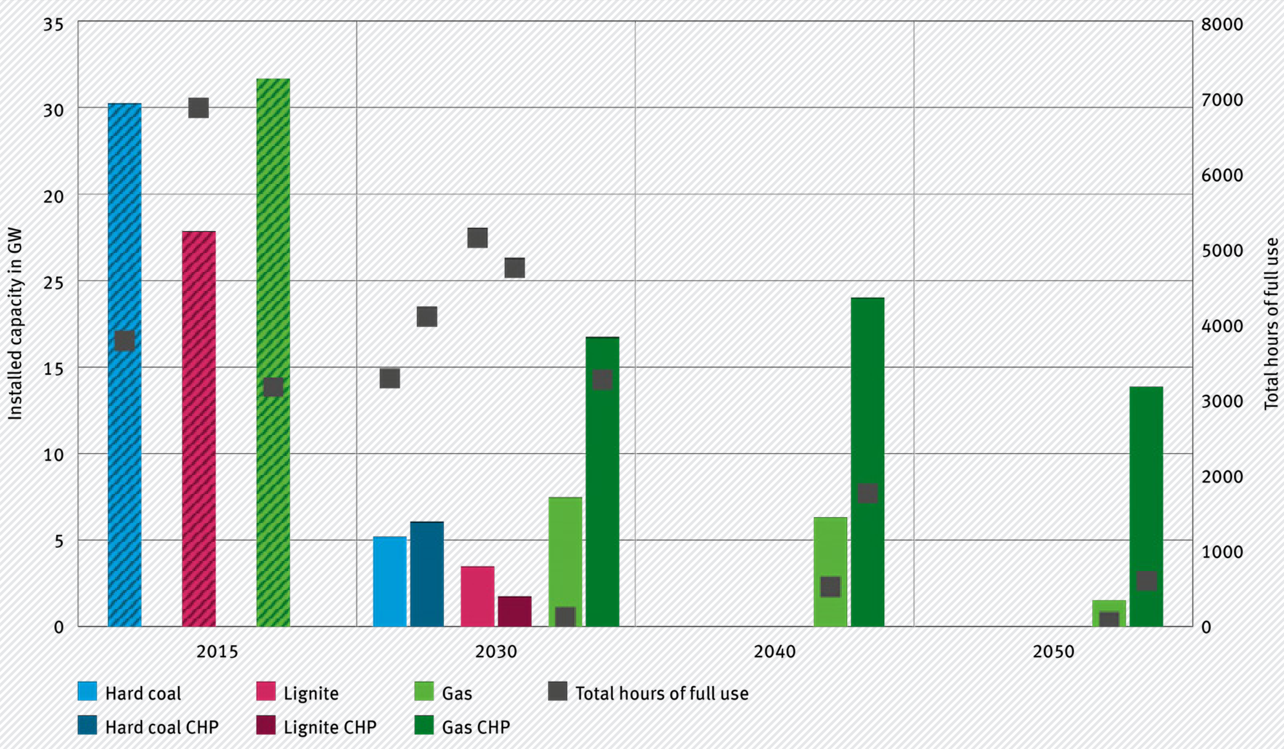
The secure and sustainable supply of energy listed in section 2.2 "Final energy demand" requires a very ambitious and continuous expansion of renewable energies, especially for electricity generation. In the case of national electricity supply, this is accompanied by a reduction in coal-based power production against the background of greenhouse gas reduction. In the GreenEe scenario, the proportion of electricity production based on coal in 2030 is just around 12.5 %. The assumption is that regulatory measures would deem all hard coal-fired power plants older than 40 years and all lignite-fired power plants older than 30 years to be out of operation. These older power plants have offset their previously high investment costs and can often achieve a high profit. The simultaneous reduction of lignite and hard coal use could potentially support an orderly structural change in the lignite regions. In addition to decommissioning, the necessarily high greenhouse gas reductions in the energy supply market lead to relatively few hours of full use, especially in the case of lignite power plants. Against this background, it would be necessary to increase the flexibility of coal-fired power plants compared to the current situation or to further reduce their capacity.

Regarding renewable energies, the focus lies on the expansion of wind and photovoltaic capacities. In 2050, onshore wind energy will contribute around 414 TWh and photovoltaic installations around 181 TWh – that is a total of just around 75 % of the electricity demand's overall coverage. Against the backdrop of the high long-term electricity demands, an early expansion of renewable energies is indispensable, particularly due to the increasing integration of sector coupling technologies with direct electricity use. The scenario predicts that the 2030 installed capacity in Germany will be about 90 GW each of onshore wind energy and photovoltaics. Offshore wind installations have a capacity of almost 16 GW, which contributes a good 70 TWh to the electricity supply. The current expansion corridors in

3 Commerce, trade and services

Figure 2.1

Trend of conventional power plant technologies and their utilisation[a) b) c)]



a) The 2015 data is not separated according to CHP and non-CHP and is therefore illustrated by shaded bars. The installed capacities are net capacities. The 2015 installed net capacity values stem from the Federal Network Agency's list of power plants (Bundesnetzagentur 2017e). The 2015 gross electricity generation values are calculated by AGEB (AGEB 2017f) and converted over the ratio of net to gross electricity generation from the 2017 projection report (Bundesregierung 2017g). The total hours of full use were calculated from the ratio of net electricity generation to installed net capacity.

b) The "Gas" combustible category groups all gaseous fossil and renewable fuels together.

c) The data on the total hours of full use represents average values.

Source: own illustration of model calculation

Germany must therefore be significantly increased for decarbonisation in the fields of application through sector coupling. Target-oriented expansion corridors should consider the holistic restructuring of energy supply and application, the dismantling and steadily increasing development level of renewable energy installations. This would assure stakeholders of planning security and future-proof perspectives.

Based on the GreenEe scenario and using onshore wind energy as an example, the annual (gross) addition of approximately 3.7 GW in 2015 should be increased by approximately 115 MW/a. The 2030 addition would thus amount to gross 5.5 GW/a. Between 2020 and 2030, the net addition would be an average of approximately 3 GW/a. In light of the recently adopted political direction that legally dictates capping the gross addition at 2.8 GW/a (or 2.9 GW/a in 2019 and 2020) through the Renewable Energy Act, it becomes clear that this implies a considerable "catch-up" is needed to achieve the climate protection level envisaged in the scenario.

In the absence of a timely adaptation of expansion corridors that meet the requirements of sector coupling, a substantial increase of the 2020–2030 expansion is needed. In concrete terms, these would have to rise from 2.9 to a gross 8 GW/a in order to reach the 2030 results of the GreenEe scenario. Extreme developments (e.g. 8 GW/a) will also result in subsequent expansion peaks due to the replacement of dismantled installations at the end of their service life. An early continuity and an increase in expansion corridors reduce the corresponding adjustment issues and consolidate the replacement of dismantled capacities. This means that all stakeholders can plan and operate sustainably in spite of the necessarily high climate protection ambitions. The current expansion corridors of renewable energies require an increase even against the backdrop of less ambitious climate protection requirements, due solely to dismantling installations that have reached the end of their service life – a desirable outcome if only for industrial policy reasons.

In the case of hydropower, it is assumed that the technical and ecological potential is largely exhausted, but it is estimated that the energy yield can be increased to 27 TWh/a by 2030 through the modernisation and expansion of existing installations.

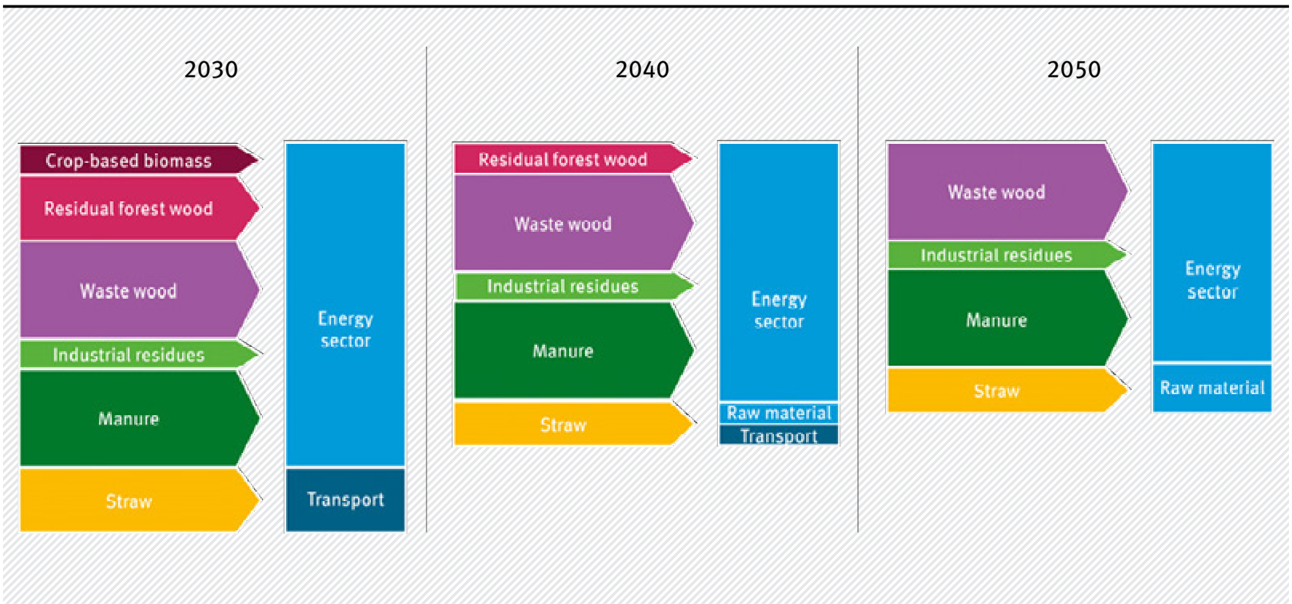
Crop-based bioenergy is not regarded as sustainable in the long term because of competition for cultivation areas and the negative effects on water, soil, biodiversity and nature conservation. On the other hand, fermentable biomass from residual waste streams such as manure, will contribute to the energy supply in the long term. Taking into account the assumptions made in the Agriculture sector (see Section 2.7) regarding the methods for keeping farm animals, there is a 2050 biogas for gas and electricity supply around 10 TWh. Waste wood in the form of biogenic residue is used as fuel at the end of its cascading use. The use of forest wood for fuel will fall to zero by 2050. According to the assumptions made in the Forestry sector (see Section 2.7) it is estimated that this material flow will be used in the form of wood for the sake of resource conservation or will remain in the forest to ensure nutrient sustainability.

Straw is also generally suited as a material resource, especially in the Construction sector (insulation, dry building material). However, issues of fire safety render this material use controversial. The scenario therefore assumes that straw is entirely used for ethanol production since this energy carrier can be used in several areas. It is assumed that by 2030, straw will be used in transport and will thus contribute to fulfilling the quota of minimum shares of renewable energies, which are expected to be stipulated by the updated RED (Renewable Energy Directive). The following decade assumes a steadily increasing use of straw in the chemical industry, which means that 2050 will witness a contribution towards fulfilling the demand in the chemical industry alone.

In the course of the transformation process, biomass energy will be increasingly reduced to the amount of residual material generated in a sustainable economy. Due to the growing competition for fertile cultivation areas, the disproportionately high area usage for crop-based bioenergy compared with other renewable energy sources and the problematic socioeconomic connection with food prices on the world market (UBA 2014a, UBA 2013a), the cultivation of biomass for fuel will be successively reduced in accordance with the service life of currently operating installations. Energy-efficient utilisation will be achieved in the long term by using sewage gas, waste wood and manure.

Figure 2.2

Qualitative representation of the energetic use of biogenic residues*



* It is assumed that in 2050, straw will be used as a raw material in the chemical industry.

Source: own illustration

Figure 2.3 shows the trend in electricity generation capacities and the resulting amount of electricity. It is clear that in order to satisfy the final energy consumption for electricity and gas (for hydrogen in industry, see section 2.2.), national electricity generation in Germany will steadily increase. It must be also noted that the direct use of electricity, where technically feasible, is necessary from an overall system perspective. This is the only way to limit the demand for renewable energy installations and the associated raw material demands.

Taking into account the potential for greater flexibility in the demand for electricity from electromobility, heat supply and electrolysis for hydrogen production in industry, the scenario signals conventional power plant capacities (gas turbines and CCGT plants) to be around 15 GW in 2050, in addition to pumped storage (10 GW) and short- term storage (batteries) of almost 1 GW.

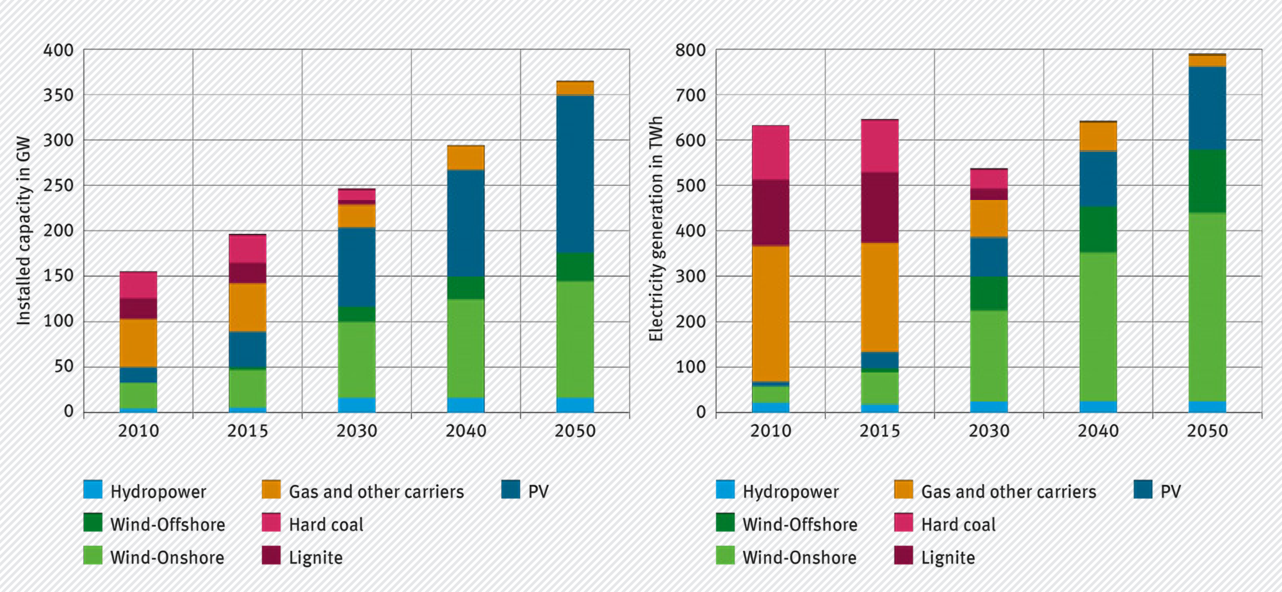
At an early stage, the share of renewable energies in the electricity supply must be very high in order to ensure a high degree of substitution and thus greenhouse gas mitigation effects of the PtX technologies. This will already have amounted to around 75 % by 2030. On the other hand, the integration of renewable energies in the supply of combustibles, fuels and raw materials proceeds much slower, as shown in Table 2.2.

Imports

Progress in the international community is also of great importance for a complete supply based on greenhouse gas-neutral energies in Germany. UBA's study "Germany in 2050 – A Greenhouse Gas-Neutral Country" (UBA 2014a) did not regard Germany as an "island" with self-sustained energy supply. On the contrary, in light of the international commitment to climate protection which materialised in the Paris Agreement, it must be assumed that an ambitious climate protection policy is also being implemented globally and that energy markets for renewable energy carriers are being developed. The 2015 import dependency was around 70 % (AGEB 2017h). Imports are almost exclusively of fossil origin, with current demands for mineral oil, natural gas and hard coal being almost entirely imported. These structures will not change fundamentally even in a regenerative energy system. Against the background of the economic viability of German marketplaces in

Figure 2.3

Trend in electricity generation capacities (left) and electricity generation (right)*



* The historical values of the left graph are taken from (BMWI 2017i, UBA 2017j). Source: own illustration of model calculation

Table 2.2

Share of renewable energy in the types of energy carriers in the GreenEe scenario

	Electricity	Combustibles and fuels	Raw materials*
2030	75 %	8 %	4 %
2040	92 %	17 %	45 %
2050	100 %	100 %	100 %

* Non-energy demand. Source: model calculation

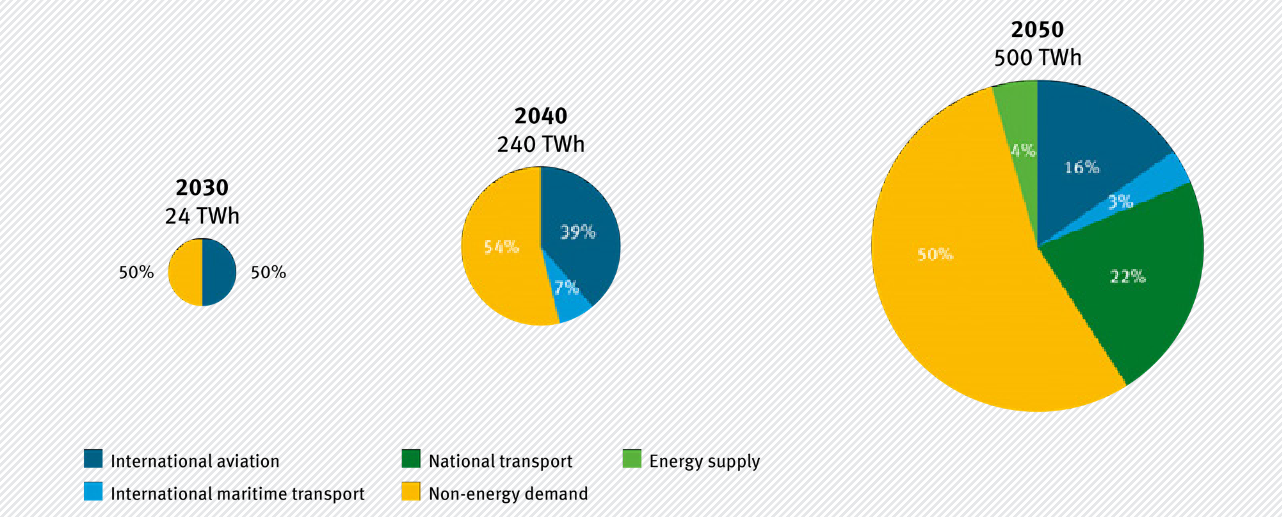
the international context, it is still assumed that a large part of combustibles, fuels and raw materials (i.e. liquid and gaseous regenerative final energy carriers) are imported. Specifically, it is assumed that significant proportion of transport (especially national passenger and freight transport, international aviation and maritime transport) and the raw material demand in chemical industry based on imports. In 2050, there will be an import dependency of about 50 % regarding net electricity generation[4].

Currently, petroleum-based products from the chemical industry are particularly important. Their energetic use at the end of a cascading usage and against the background of increased recycling rates could also only partially occur after 2050. It is therefore recommended to shift the chemical industry's long-term greenhouse gas emissions-relevant production rapidly to greenhouse gas-neutral raw materials. The GreenEe scenario therefore assumes that renewable electricity-based energy carriers will be used for non-energy demands of the chemical industry by 2030. There is also an urgent need for action in aviation, where the International Civil Aviation Organization (ICAO) has set itself the goal of making aviation's growth greenhouse-gas neutral by 2020. In addition to a global market-based measure (GMBM), the ICAO is currently using crop-based biofuels as a key strategy to achieve a greenhouse gas-neutral growth. UBA rejects this approach for climate and environmental policy reasons so that fuels from regenerative PtL plants are already being used at an early stage in this field of application (UBA 2016a). The GreenEe scenario therefore assumes that half of the chemical industry and aviation's demand will be fulfilled by regenerative products in 2030. Decarbonisation in the transport sector will be achieved by increasing electromobility and the shift of the remaining fuel demands to regenerative imported energy carriers will only occur in the decade after 2040.

4 Corresponds approximately to current primary energy.

Figure 2.4

Import distribution in the GreenEe scenario

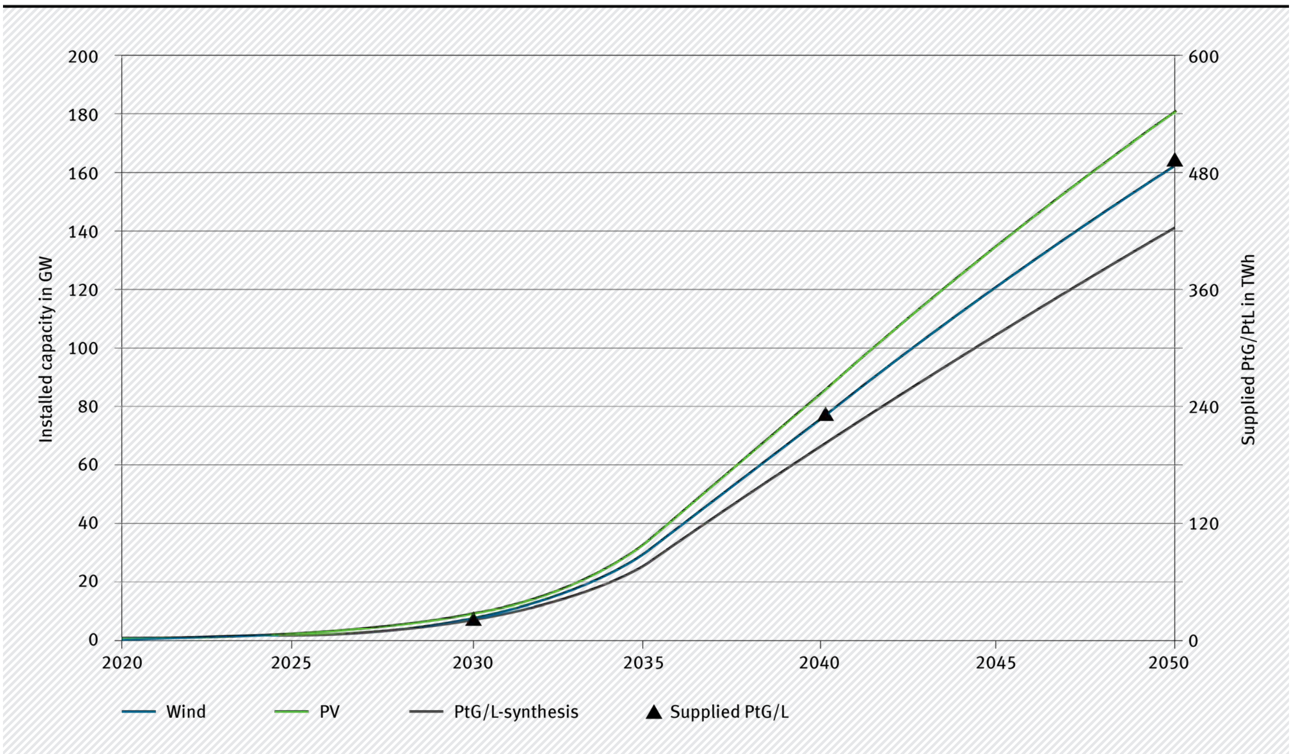


Source: own illustration of model calculation

Taking into account the illustrated long-term demands, it becomes clear that PtL installations will be required on cost-effective renewable energy sites as early as 2030. Against the backdrop of the currently low number of concrete international projects or installations, it is assumed that even a timely expansion of capacities can no longer be implemented by the 2050 target. It is therefore assumed that in particular the decade after 2030 will witness a considerable expansion of international renewable electricity generating installations with subsequent use in PtG and PtL installations. The necessary expansion pathways are shown in Figure 2.5.

Figure 2.5

Import supply in the GreenEe scenario*



* Example location in South Morocco and only showing onshore wind and photovoltaics for simplification.

Source: own illustration of model calculation

2.4 Buildings

A large share of the final energy is currently consumed for heating and hot water. Consistent energy savings could significantly reduce this high consumption – this includes the renovation of building stock as a key element. This makes it easier to restructure the heat supply towards being greenhouse gas-neutral and based on regenerative energies.

A potential transformation towards a greenhouse gas-neutral Germany can take the following path. In principle, an ambitious climate protection policy needs a heat supply that is emission-free and as efficient as possible. This excludes many technologies from the outset. For example, condensing boilers are out of the question, because producing methane from renewable energy is (according to current knowledge) very inefficient. Preferred solutions thus are electric heat pumps in individual houses and heating networks. The GreenEe scenario assumes that the sale of all heat generators will double by 2030 compared to the current level and will subsequently slightly decrease. Further key points are:

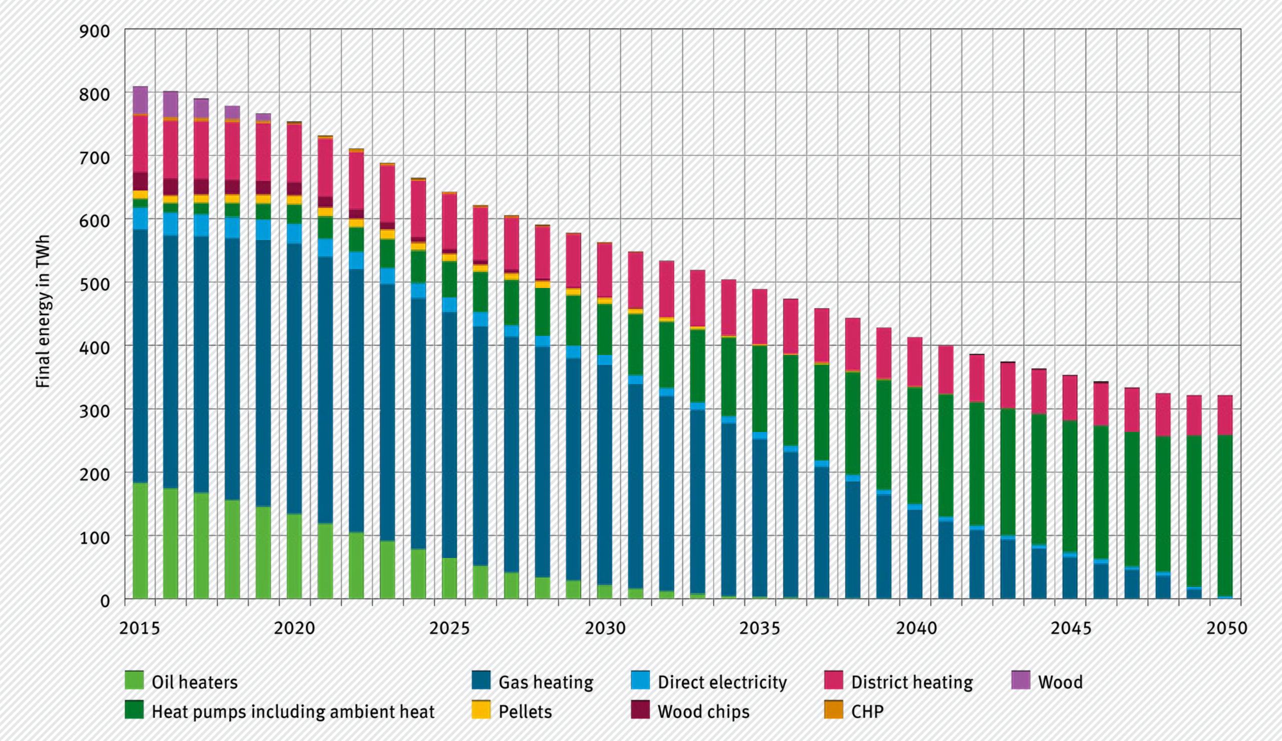
- from 2020: No new construction of oil heaters
- from 2030: No new construction of decentralised heaters with biogenic fuels
- from 2040: No new construction of gas heaters

Future installation technology needs to focus on the availability of electricity from renewable sources. In order to meet this flexibility, the scenario assumes an electricity consumption shift potential of around six hours for internal space heating using heat pumps and around two hours for air conditioning. Residential buildings can be kept cool with passive measures and therefore do not receive any air-conditioning in this scenario.

The per capita living space in the scenario increases slightly up to 2030 and remains almost constant thereafter until 2050 at 49 m² per person. The 2050 living space is thus a total of 3.5 billion m². The net floor space in non-residential buildings rises slightly from 2.3 to 2.5 billion m². In terms of raw materials, the GreenEe scenario's building construction sector is based on the "Sustainability and Recycling" scenario in the sensitivity study on the circular economy potential in building construction (Deilmann,

Figure 2.6

Trend of the final energy consumption for internal space heating and hot water for the entire building stock according to the type of heating technology in the GreenEe scenario



Source: own illustration of model calculation

Table 2.3

2050 useful energy and final energy consumption (including ambient heat) in residential and non-residential buildings

TWh/a	Useful energy			Final energy		
	Internal space heating	Hot water	TOTAL	Internal space heating	Hot water	**TOTAL**
Residential buildings	120.6	40.1	160.7	142.3	81.4	**224**
Non-residential buildings	62.3	8.7	71	71.5	27.5	**99**
- CTS	58.3	5.7	64	65.4	19.4	**84.8**
- Industry	4	3	7	6.1	8.1	**14.2**

Source: model calculation

Gruhler und Krauß 2014c), which was adapted to the assumptions made regarding residential space development and energy renovation[5].

The scenario widely assumes very high renovation standards at the passive house level. The energy renovation rate rises from 2.2 % in 2020 to 3 % by 2050, meaning an average rate of 2.6 % over the period up to 2050. The average room temperature is assumed to be 20.5 °C .

5 The intention is to consider the design of building energy renovation, optimised from a raw material perspective, in one of the remaining scenarios.

These climate protection measures could help lower the final energy consumption for internal space heating and hot water by about 60 percent by 2050 (Figure 2.6). In the case of buildings that are difficult to renovate, the final energy consumption can be decreased through insulation, but not as much as in the average. The high insulation standards of other buildings would offset this shortcoming (UBA 2016i). Heat pumps and conducted heat completely replace oil and gas boilers in the heating supply, even in difficult-to-renovate buildings. Heat pumps provide 75 percent of the heating, district heating and CHP heat pump systems just under 23 percent.

Around two-thirds of the useful energy and final energy demand come from residential buildings, 20 % and 30 % of which are for hot water supply. For non-residential buildings, the proportion of hot water is lower (Table 2.3).

The high energy standards mean that in 2050, most of the energy demand stems from buildings with an internal space heating demand of less than 50 kWh/m² (93 percent of residential buildings, 96 percent of non-residential buildings). Only individual buildings (under 1 percent) have a heating demand of over 120 kWh/m² e.g. heritage-protected buildings. In 2050, the average final energy consumption for internal space heating and hot water is 52 kWh/m² for residential buildings and 34 kWh/m² for non-residential buildings.

The scenario establishes that the key output for buildings is to achieve the described renovation rates and standards to an acceptable extent. Both rates and standards are still far from these figures. The rapid implementation of high renovation standards is desirable from a raw material perspective as well, since the temporarily increased raw material demand for insulation materials can be offset by the saving in raw materials used to energy supply, initially fossil energy carriers and subsequently raw materials for the construction of renewable energy installations (Ritthoff, et al. 2015d). In addition, the market share of heating technology must shift away from gas and oil boilers towards electric heat pumps and district heating. Added to this is the fact that changes only occur slowly in the building stock. Targeting standards and framework conditions, but above all, sufficient capacities in both professional and personnel terms must be achieved quickly.

2.5 Transport

The key in establishing a greenhouse gas-neutral and resource-efficient transport relies on a transport transition that avoids trips and reduces distances, shifts towards less environmentally-harmful transport modes and improves energy efficiency as well as on an energy transition in transport – meaning the complete renunciation of fossil energy carriers. A transport transition lowers energy consumption and thus the demand for renewable energies in transport, thus actually enabling an energy transition. The two transitions must therefore go hand in hand.

The GreenEe scenario outlines important starting points, namely the current forecasts of future transport developments compiled within the framework of the Federal Transport Infrastructure Plan (Forecast of transport interconnectivity 2030 (BMVI 2014b)), as well as results of UBA's study "Climate Change Mitigation in Transport until 2050" (UBA 2016b)[6]. Specific action fields are:

- measures to avoid and shift transport towards climate neutrality and energy efficiency and to provide more efficient transport management, including the development of the necessary transport infrastructure (UBA 2016b, UBA 2017a);
- incentives to increase energy efficiency (for example, CO_2 passenger car fleet target figures) for all modes of transport (UBA 2016b, UBA 2016c, UBA 2017a).

UBA's study "Climate Change Mitigation in Transport until 2050" (UBA 2016b, UBA 2017a) provides a detailed description of the individual measures and the resulting effects on mileage and transport performance. These include, for example, the development of a sustainable transport infrastructure, the abolition of environmentally harmful subsidies or the further development of distance-based road tolls. The transport performance in road freight transport was adapted by modelling it endogenously in comparison to (UBA 2016b), to take account of modified production volumes in Germany as well as lower imports and exports.

Depending on implementation depth, the measures of the *transport transition* can reduce the final energy consumption and the greenhouse gas emissions from

6 Summary in English on pages 37–56 in the cited publication.

transport by 40–70 % by 2050 compared to 1990. Regarding the demand for raw materials, environmental impacts and costs, such a reduction of energy consumption is essential for decarbonising transport – a stepping stone for the supply of sustainable energy in a greenhouse gas-neutral Germany.

However, a transport transition is not sufficient to achieve greenhouse gas neutrality in transport. As a further measure, transport must be completely converted to greenhouse gas-neutral energy carriers by means of an *energy transition in transport*. This includes:

- replacing internal combustion engines by electric drives where technically feasible;
- substituting fossil fuels step by step with greenhouse gas-neutral fuels.

The electrification of means of transport takes precedence due to the higher energy and cost efficiency compared to the use of greenhouse gas-neutral fuels in internal combustion engines (UBA 2016c). It is therefore reasonable to achieve corresponding efficiency potentials through electrification before the more complex conversion to regenerative fuels (essentially to PtL) takes place to cover the remaining demand.[7, 8] Against the background of long-term greenhouse gas-neutral liquid fuel demands, this transformation must take place simultaneously with the electrification of means of transport. However, there are many areas of transport that cannot be electrified in the future (or only partially), such as international maritime transport and aviation (UBA 2014a). In these transport modes, greenhouse gas-neutral fuels play a key role on the path towards the decarbonisation of transport.

Due to its high share in the national final energy consumption and the high substitution effect of fossil energy carriers, the electrification of road transport will play an important complementary role in the transport transition measures already over the period up to 2030 in the transformation towards greenhouse gas-neutral transport. Regarding passenger cars and light commercial vehicles (LCV), the GreenEe scenario therefore proposes

- to increase both pure electric vehicles and externally rechargeable hybrid electric vehicles (plug-in hybrids) by 2030, thus increasing the number of electric vehicles in Germany to about 8 million and clearly exceeding the German Government's target of 6 million electric vehicles;
- to increase the number of electric vehicle new registrations by 2040 to such an extent that market penetration will largely be completed.

A correspondingly rapid market penetration by electromobility in passenger cars and LCVs will require a quota for electric vehicles and demanding energy efficiency targets in addition to the EU CO_2 fleet values for newly registered vehicles. This should occur in parallel to the large-scale construction of the charging infrastructure for electric vehicles.

Electrification will also take place in road freight transport by heavy goods vehicles (HGV) by 2050. However, this is limited by the additional battery weight in purely electric vehicles and the resulting reduced freight volume. This is why electric lorries (purely electric or externally rechargeable hybrid electric vehicles) can only be used for local and regional transport and overhead line hybrid lorries with pantograph and diesel engines will carry out long-distance transport. For overhead line hybrid lorries, the scenario assumes

- the overhead line infrastructure must be erected as soon as possible along the heavily used motorway sections to ensure a sufficiently dense network as a prerequisite for the market introduction of overhead line hybrid lorries;
- the share of overhead line hybrid lorries will increase in new registrations for heavy solo lorries (20–28 t gross vehicle weight/GVW), road trains and articulated lorries (up to 40 t GVW) between 2030 and 2040 (fast market penetration).

For example, from 2040 onwards, new road trains and articulated lorries will only be registered as electric vehicles – externally rechargeable hybrids or

7 For specific energy consumption (except maritime transport), the scenario assumes the identical premise as the study (UBA 2016b) To determine the final energy consumption in international maritime transport, values for the specific final energy consumption are either directly used from EcoTransIT 2018 (www.ecotransit.org) (IVE mbH 2018a) or converted to specific final energy consumption (per tonne-kilometres) by using average container payloads (bulk material and three types of containers). These values are attributed to the divisions for the classification of the type of goods from NST 2007.

8 Renewable liquid fuels can be produced from either electricity-based PtL and biomass-based processes, or processes that require very high temperature inputs, but no electricity. An example is the so-called Sun-to-Liquid process, researched in the EU Horizon 2020 project.

overhead line hybrids. However, both types of drive can only be partially electric and are still dependent on liquid, post-fossil fuels for the remaining portion of the mileage. The present scenario envisages using PtL for this purpose.

Regarding the demand for raw materials, electric vehicles are currently at a disadvantage compared to vehicles with an internal combustion engine. For example, an average compact car with an electric motor currently has a roughly 75 % higher primary raw material input[9]. This is mainly due to the high demand for raw materials in battery production, alike the demand for metal raw materials for electric components production, and currently also the fossil-dependent electricity supply (UBA 2016m). The latter will be significantly reduced by the (global) transformation towards renewable energies. Regarding vehicle batteries, the GreenEe scenario assumes an increase in capacity and energy density as well as a change in technology, which leads to significant raw material savings. It has been assumed that by 2030, all passenger cars and LCVs will use the Li-Ion cell types nickel-cobalt-aluminium, nickel-manganese-cobalt and lithium-iron-phosphate (each with a graphite anode) in equal proportions. Until 2030, lorries will only use lithium-iron-phosphate batteries for their lower costs. In 2050 however, all road vehicles will only use lithium-sulphur batteries. In addition to the choice of type and energy density of the battery, the weight of the vehicle body is also relevant for raw material considerations. The GreenEe scenario assumes that lightweight construction in new passenger cars will lead to a weight reduction of around 10 % by 2030 and 20 % by 2050. This will be made possible by the use of aluminium, high-strength steels and general downsizing[10]. In the case of commercial vehicles, lightweight construction is assumed to enable a tare weight reduction by 6 % for newly registered solo lorries and 10 % for road trains, articulated lorries and LCVs.[11]

Establishing greenhouse gas-neutral rail transport is comparatively easy since this is already largely operated electrically today. International aviation and maritime transport produces a large part of the final energy consumption in transport. This is a result of the constant high level of transport performance in international maritime transport.[12] According to the current assessment of technology development, these modes cannot be electrified by 2050. Therefore, the successful transition to greenhouse gas-neutral transport relies on a step-by-step replacement of fossil fuels by synthetic, greenhouse gas-neutral fuels (essentially PtL). This process must be completed by 2050.

9 Measured as cumulated raw material use, which sums up all (including biotic) materials used throughout the life of a product according to their raw material mass (e.g. for metallic raw materials this is the weight of ore).

10 The effects of using other lightweight construction materials such as carbon fibre reinforced plastics (CFRP), other lightweight construction options and other raw material saving measures will be considered in one of the remaining scenarios.

11 Regarding other vehicle components, particularly electric components, analogous assumptions are made for the development of material savings, shares of secondary raw materials and raw material efficiency as for development in the industry.

12 The transport performance is calculated from the division specific amount of handled goods and the distance between the port of departure or destination. From this performance 50 percent are attributed to Germany. By additionally using the import and export volumes for each division from URMOD these values are projected until 2050. Together with the division specific energy consumption per tonne-kilometre the German part of the final energy demand in international maritime transport is calculated. The advantage of this approach is that in comparison to (UBA 2016c) the results from URMOD-calculations may be considered.

The final energy consumption from transport is the product of the transport performance (measured in passenger- or tonne-kilometres) and the specific energy consumption. Between 2010 and 2050, freight transport is expected to witness a strong increase in transport performance, while passenger transport will only undergo minor changes. Measures for transport avoidance, shift and improvement are implemented in both transport performance and specific final energy consumption (UBA 2017a). The assumptions made by UBA's study "Climate Change Mitigation in Transport until 2050" (UBA 2016b) are adopted for the specific energy consumption – except in maritime transport.

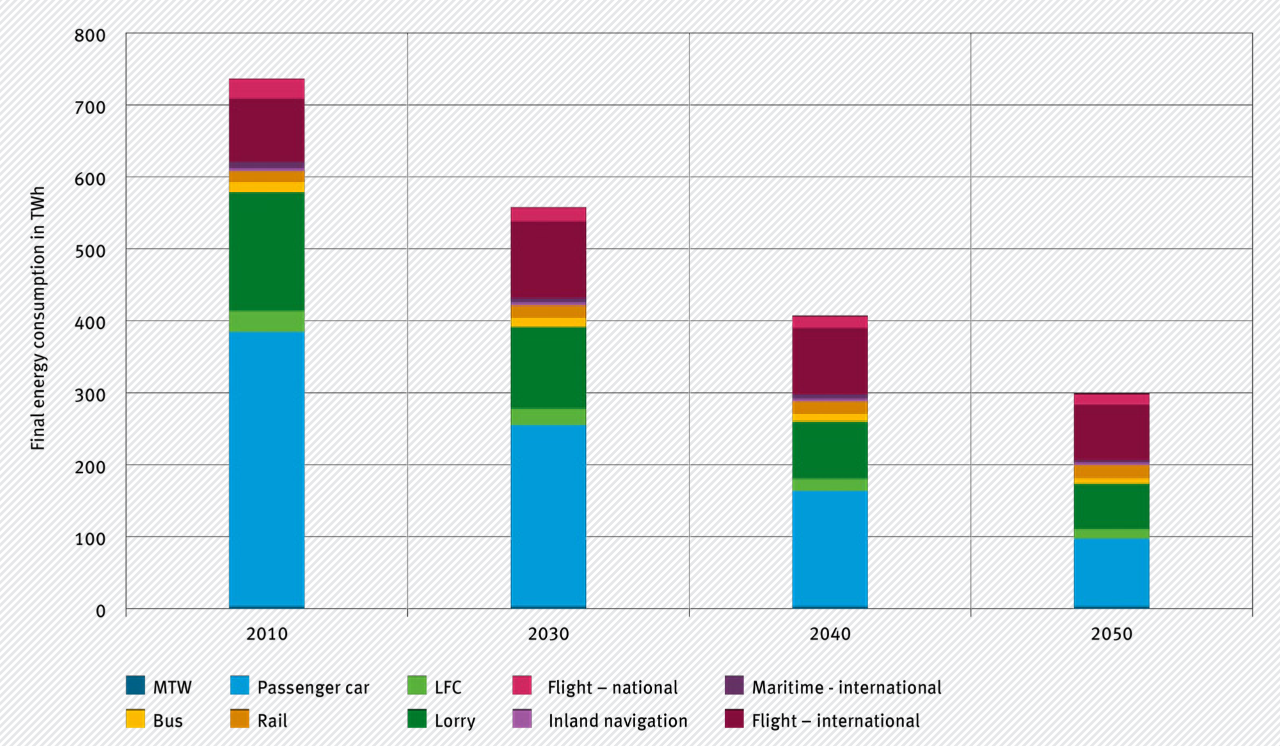
The final energy consumption resulting from the scenario is presented by means of transport (shown in Figure 2.7) and final energy carriers (shown in Figure 2.8). Despite the increasing transport performance of some means of transport, freight and passenger transport will experience a significant decrease of approximately 32 % by 2030 and approximately 70 % by 2050 compared to 2010. This is largely due to increased electrification. Accordingly, the share of electricity consumed in the national final energy consumption for transport in 2050 will be significantly greater than that of fuels. In addition to electricity, mainly greenhouse gas-neutral liquid fuels (PtL) will be used as final energy carriers (UBA 2016c).

The final energy consumption of fuels of international transport in 2050 is approximate as the national total demand of fuels for road, rail and inland waterways. This underlines the increasing importance of international aviation and maritime transport in climate protection and highlights the challenges. The energy transition in transport must therefore also address this area. In the described scenario, this requires the provision of large quantities of greenhouse gas-neutral PtL produced from renewable electricity[13].

13 The aim of the study is the resource-efficient minimisation of greenhouse gas emissions as a result of the need for climate protection. Aviation in particular causes considerable climate-damaging impacts that are not attributable to greenhouse gas emissions (UBA 2012a). Eco-efficient flight trajectories have considerable potential to enable more climate-friendly flying.

Figure 2.7

Final energy consumption for transport in the GreenEe scenario by means of transport*

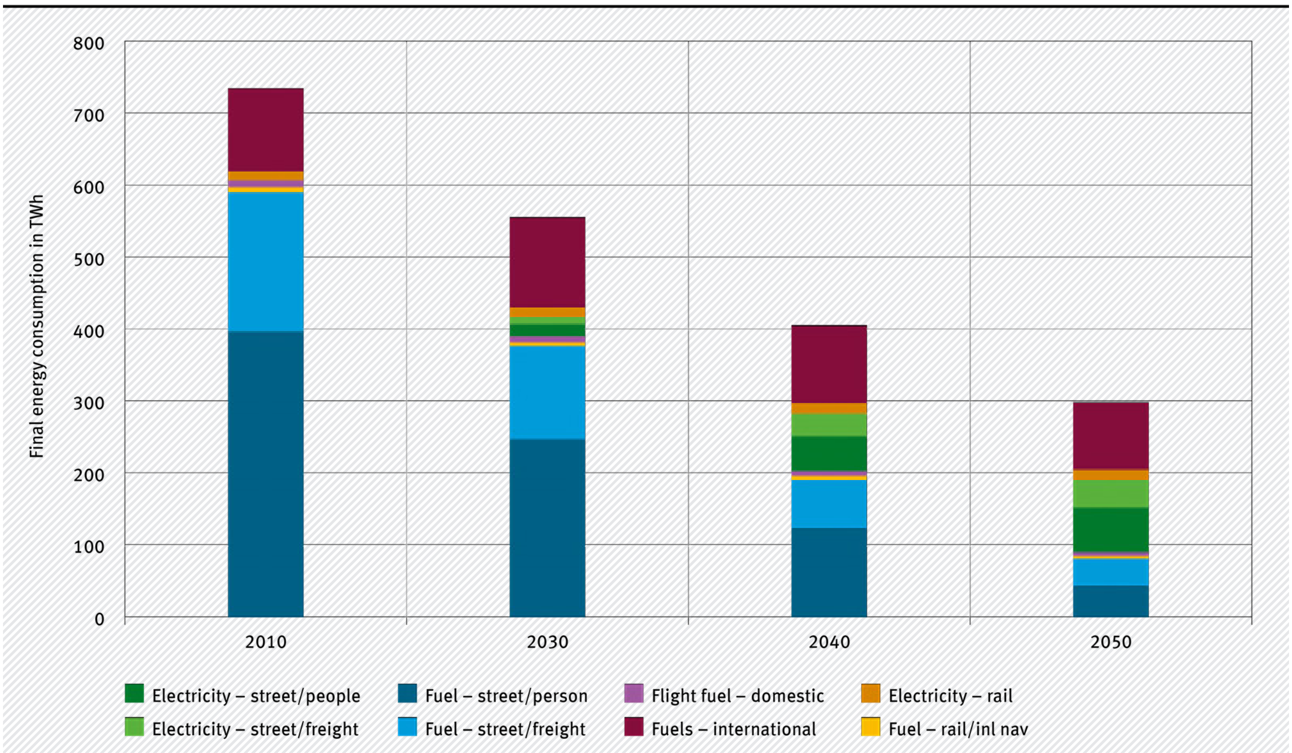


* The "LCV" category comprises light commercial vehicles and category "MTW" the motorized two-wheelers.

Source: own illustration of model calculation

Figure 2.8

Final energy consumption for transport in the GreenEe scenario by means of transport and energy carriers*



* The "Fuel – rail/inl nav" category covers all fuels for rail transport and inland waterways.

Source: own illustration of model calculation

2.6 Industry

Industry and commerce (excluding the facilities for public electricity and heat generation) are one of the main causes of greenhouse gas emissions in Germany. The direct greenhouse gas emissions from industry and commerce[14] have decreased by 34 % between 1990 and 2010, but at 187 million tonnes of CO_2eq their share of total greenhouse gas emissions in Germany in 2010 remained at roughly 20 %. The main cause of direct greenhouse gas emissions from industry and commerce is the use of fossil fuels to provide energy (process heat, steam, mechanical work). In some industrial processes, process-related greenhouse gas emissions arise from the use of carbon-containing raw materials (e.g. limestone), from the non-energy use of carbon-containing energy carriers (e.g. as a reducing agent), or from the process-related release of greenhouse gases other than CO_2 (e.g. from the use of solvents and fluorinated gases). These "process-related" emissions account for about a third of total greenhouse gas emissions from industry and commerce. Furthermore, industry and commerce are indirectly responsible for a significant share of greenhouse gas emissions from the energy sector due to their high final energy consumption (FEC), especially in the form of electricity.

The various causes of greenhouse gas emissions, i. e. direct energy-related greenhouse gas emissions and direct process-related greenhouse gas emissions, each require specific measures to approach the goal of greenhouse gas neutrality also in the industrial sector. A particular challenge is the process-related greenhouse gas emissions because they can only be mitigated, if at all, by fundamental procedural changes or by substitution of raw materials.

Industrial fossil combustibles are the main source of direct greenhouse gas emissions in the industrial sector and are primarily used for heat generation, in particular the production of industrial process heat (temperatures from below 100° C to over 1500° C). The energy-related greenhouse gas emissions cannot be sufficiently reduced by efficiency improvements alone. For this purpose, a technical conversion of process heat generation to CO_2-free or CO_2-neutral technologies is necessary. In concrete terms, it is therefore assumed that a large part of the process heat generation will be switched to Power to heat processes by 2050. Only where electricity cannot be used directly as an energy carrier for process-related reasons are renewable fuels used, which are obtained by means of Power to gas (PtG) or Power to liquid (PtL).

The use of biogenic combustibles for industrial processes, in the form of crop-based biomass, is not considered for industrial use for reasons of sustainability, as is the case in the energy industry. Biogenic residues, on the other hand, can also contribute to the energy supply of the industry. For example, process-related biogenic residues are still found in the paper and pulp industry and it is reasonable to use them for direct energy production on site.

For the reduction of energy-related greenhouse gas emissions it is imperative that the integration of PtX techniques in the industry in the transformation process simultaneously lead to the conversion of the energy supply to renewable energies. Only in this way can relevant greenhouse gas reductions in the production of process heat be achieved in industry. As a result, great effort is being made in the scenario to further improve energy and material efficiency in the industry such as with consistent use of waste heat.

The following describes how these fundamentally presented greenhouse gas mitigation measures were provided in the GreenEe scenario for the various industries.

With regard to the **steel industry** it is assumed that the use of scrap and electricity-based electric steel production in arc furnaces can be increased by about 100 % (to about 27 million tonnes of crude steel per year) by 2050. The remaining demand for crude steel (18 million tonnes) must continue to be covered by the reduction of iron ore. However, this is no longer to be done with the aid of the coke-based blast furnace process because its high CO_2 emissions can hardly be reduced in the process. Instead, primary steel production shall be carried out in gas-based direct reduction systems and subsequent melting in the electric arc furnace in 2050. Such direct reduction systems already exist, especially in countries where natural gas is cheap, which is then converted in a first process step into the chemically effective reducing

14 Own calculation according to NIR (German National Inventory Report) based on CO_2 equivalents for source groups CRF 1.A.2. ("Manufacturing industries and construction") and 2. ("Industrial processes and product use").

agents hydrogen and CO. It would therefore make sense to operate these plants directly with hydrogen instead of converting these in an energy-intensive process to methane and then to split them back into hydrogen and CO. The greenhouse gas emissions hitherto associated with steel production can thus be almost completely avoided. In the scenario it is assumed that there will be no comprehensive supply network for hydrogen; accordingly, the hydrogen supply is provided close to the steelworks by electrolysis based on renewable electricity and water. As a result, the demand for the steel industry for fossil combustibles will be completely eliminated by 2050, but the annual energy consumptions of the steel industry will rise significantly to around 47 TWh/a for electricity and 66 TWh/a for renewable hydrogen[15]. Since blast furnaces are usually continuously operated for up to 20 years before they are upgraded for the next “campaign” (“relining”), it is assumed that the conversion of the installation park is to begin by 2030 at the latest so that it can be completed in an economically feasible manner by 2050.

For the **non-ferrous metal industry**, in spite of a long-term increase in production, it is assumed that energy-related greenhouse gas emissions will fall to zero by 2050 and the electricity demand will decrease by about one third to 10 TWh/a through efficiency improvements and the conversion of installations to PtG combustibles or electricity and through an increase in the proportion of secondary production (from 56 % to 90 %). The process-related greenhouse gas emissions from anode burn-off and the so-called anode effects in the primary aluminium industry will be reduced to zero by 2050 by switching to inert anodes.

For the **foundry industry** it is assumed that the share of energy-intensive non-ferrous metal foundries in total production will increase to about 25 % by 2050, given a slightly decreasing overall production volume. Significant improvements in energy efficiency and an extensive conversion to electricity-driven melting furnaces will be able to completely eliminate direct CO_2 emissions by 2050, while at the same time readily reducing demand for electricity to 6.5 TWh. Process-related greenhouse gas emissions from the use of coal as a carburising agent can also be avoided by substitution with PtG/PtL-based carbon carriers.

15 Nearly 75 TWh of electricity is required to supply hydrogen.

The **chemical industry** contributes to greenhouse gas emissions, not only because of its energy consumption and process-related emissions, but also by fossil carbon-based products because a large part of this carbon is consumed after the utilisation phase of the product by being converted into CO_2 by burning or biodegradation and emitted in the waste sector. Regarding the energy demand of the chemical industry, it is assumed that this will be reduced by 55 % by 2050, especially by switching to more energy-efficient processes. The present demand for fossil combustibles (natural gas, petroleum products, coal) is assumed to be completely replaced by hydrogen or PtG/PtL combustibles by 2050. The non-energy consumption of the chemical industry on carbon-containing raw materials is to be met completely by hydrocarbons generated by PtG/PtL by 2050. For the long-term reductions in the waste sector for energy recovery, an early substitution of the carbon-containing starting materials of some products will be necessary in view of the longevity of these products and high recycling rates. Therefore, the scenario assumes that 12 TWh of the non-energy consumption of the chemical industry for long-life products will be covered by PtG/PtL hydrocarbons as early as 2030, see Chapter 2.3.

For the **cement industry** it is assumed that cement clinker will be replaced by novel binding agents at 50 % of the current production volume. These new processes will only produce 1/3 of the process-related CO_2 emissions compared to the existing clinker process and a 50 % lower energy consumption is expected. For the conventional method, on the other hand, only a reduction of the thermal energy consumption by 10 % and the electrical energy consumption by 30 % is assumed. With regard to the firing of rotary kilns, it is assumed that these will be converted firstly from coal and the substitute combustibles used up to now to natural gas, and then completely to methane (from Power to gas) produced by renewable sources by 2050. If by 2050 waste is still available for co-incineration, which can only be exploited thermally, the demand for renewable methane would be correspondingly reduced. In contrast to (UBA 2014a) the scenario does no longer assume a decrease in the clinker factor because the hitherto most significant clinker exchangers of granulated blast furnace slag and fly ash will no longer be available after the conversion of the steel industry (see above) and the energy industry. If this cannot be absorbed by other substitutes, the clinker factor will rise from the current value of 0.77 to about 0.9 by 2050, i.e. approximately 4.6 million tonnes more clinker will be required by 2050 than described in (UBA 2014a), and the final energy consumption and the process-related emissions of the cement industry will decrease less sharply.

In the scenario, the assumed process changes to other industrial sectors will lead to a 30 % reduction in demand for quicklime, which will result in a correspondingly lower energy consumption and correspondingly low process-related emissions from the **lime industry**. Here too, the combustible demand will be completely covered by PtG/PtL fuels by 2050.

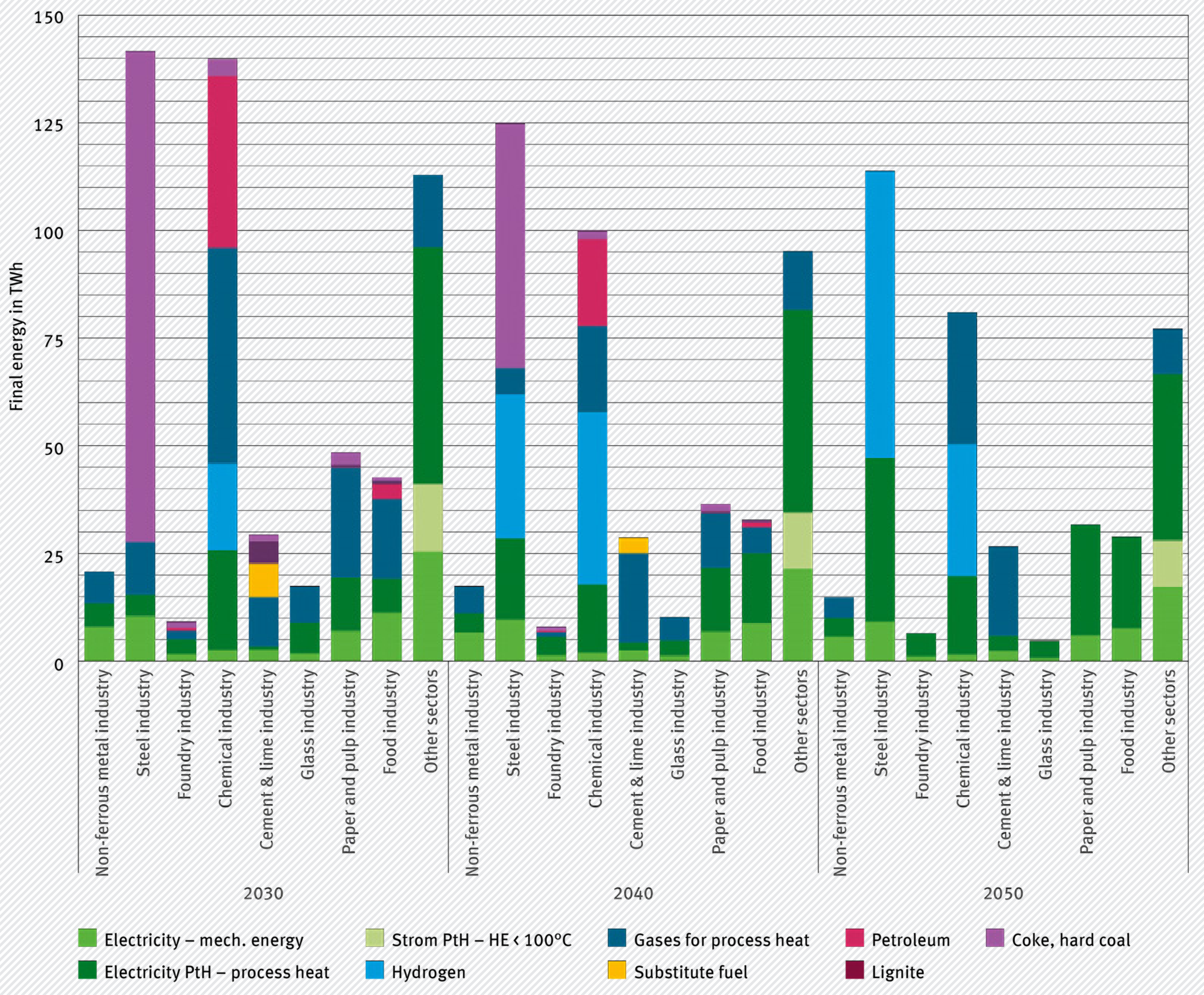
The share of **fluorinated greenhouse gases** (FGG)[16] in total greenhouse gas emissions has so far only been barely 2 %, but with a slightly rising trend. Within the framework of the scenario it is assumed that the FGG can already be substituted by other substances by 2030 that have no or significantly lower greenhouse gas potential in almost all fields of application. The total greenhouse gas emissions from the production and application of FGG will already fall by 87 % by 2030, and will drop to about 9 % of the CO_2eq of 2010 by 2050.

The **use of solvents and other chemical products** in industry, crafts and private households contributes to the greenhouse effect through direct emissions of

16 Partially fluorinated hydrocarbons – pFHCs, fully fluorinated hydrocarbons – fFHCs and sulphur hexafluoride – SF6.

Figure 2.9

Final energy consumption by industrial sectors in the GreenEe scenario*



* In the "gases for process heat" category, both fossil and renewable gases other than hydrogen are recorded as final energy.

Source: own illustration of model calculation

nitrous oxide (N_2O) and photochemical processes in the atmosphere through the formation of secondary greenhouse gases (ozone) or greenhouse aerosols. The scenario assumes that these emissions will be reduced by more than 50 % to about 800,000 tonnes of CO_2eq by substance substitutions and more efficient (more economical) use of the products in all fields of application by 2050.

The above-described development of the individual sectors and the assumptions for other sectors are reflected in Figure 2.9. The final energy consumption for all energy applications, including the demands for space heating, hot water, information and communication technology, air conditioning and lighting, across all energy carriers, will decrease continuously by 35 % to 466 TWh/a from 2010 to 2050. It should be noted that, in addition to the conversion of the industrial processes from fossil combustibles to direct use of renewable electricity, the conversion to renewable combustibles using PtG/PtL will create additional demand for renewable power generation installations. In the GreenEe scenario it is assumed that by providing hydrogen for industrial applications, there will be an additional electricity demand for water electrolysis of around 110 TWh/a.

The energy-related greenhouse gas emissions will drop to zero by 2050 by converting the energy supply. Process-related emissions will continue to decrease by about 68 % by 2030 and by 74 % by 2040 compared to 1990 levels. In 2050 process-related emissions will only be about 16.2 million tonnes of CO_2eq, which corresponds to a reduction of about 83 % from 1990. The main issuers of the remaining process-related emissions will be the cement, lime and glass industries.

2.7 Agriculture & LULUCF

The second largest greenhouse gas emission source in Germany after the energy sector is agriculture. Above all, emissions from the use of agricultural soils[17] and fermentation in the digestion of ruminants are high and have changed only slightly over the past ten years. Other significant emissions are caused by the storage of manure and fermentation residues, lime fertilisation and the application of urea.

Greenhouse gas reductions in the agricultural sector can only be achieved to a certain extent through technical measures. In addition, in order to achieve the necessary reduction of at least 50 % by 2050, modified production systems and, above all, a reduction in animal stocks are necessary. In order to avoid carbon leakage to other countries, the consumption of animal products, e.g. meat, must be reduced to a degree that corresponds to a healthy diet[18].

Emission trend in the GreenEe scenario (Table 2.4) thus results from assumptions regarding technical, structural and societal changes and is essentially based on the UBA study (UBA 2014a)[19]. Against the backdrop of changing methods in national reporting, however, simplifications were made in the derivation of the transformation path to the illustrated target scenario “ÖKO-20 %”[20].

Until 2030, livestock will only be able to be reduced to a limited extent. Thereafter, a steady decline in livestock will occur, also based on changed dietary habits, until 2050.[21] From the decrease of livestock, emissions will be reduced from the digestion of ruminants as well as from the reduced amount of resulting manure. Contributing to the reduction of emissions from manure management, from 2030 all fermentation residue storage will be covered and by 2050 all recordable manure will be fermented in biogas plants. Due to agricultural land use competition and adverse environmental impacts (see UBA 2013), energy crops will no longer be used

17 Direct and indirect emissions from agricultural soils result e.g. from the application of mineral and commercial fertilisers (including fermentation residues).

18 According to the recommendations of the German Society for Nutrition.

19 The explanations are based on the expert opinion of the Thünen Institute for the German Environment Agency (Osterburg, Kätsch und Wolff 2013b).

20 An expansion of organic farming to 20 % of the agricultural area is assumed by 2050.

21 By 2050 no suckler cows, bulls and heifers, sheep minus 50 %; in conventional farming in addition dairy herd minus 38 %, pig stock minus 11 % (UBA 2014a)

Table 2.4

Overview of emission trend in agriculture (CO_2eq)*

Agriculture	1990	By 2030	By 2040	By 2050
Soils	28,763,506	19,255,749	16,766,533	14,661,374
Digestion	34,664,197	23,227,069	16,689,037	10,151,005
Manure management	13,158,304	6,728,865	3,568,089	1,606,268
Liming	2,704,013	1,618,818	1,559,409	1,500,000
Urea application	479,601	528,061	498,388	468,715
Other (fermentation residues from NaWaRo biogas)	393	181,711	0	0
Total	79,770,014	51,540,274	39,081,457	28,387,362
Change from 1990		**-35 %**	**-51 %**	**-64 %**

* The data for 1990 and 2010 are taken from the 2016 national emissions reporting,

Source: model calculation

in the GreenEe scenario in biogas plants from 2030, so that the resulting emissions will decline rapidly.

In spite of a slight increase in the urea application and associated CO_2 emissions[22], a reduced use of mineral fertilizer and an increased nitrogen efficiency will reduce the total nitrogen surplus to a maximum of 50 kg N per hectare by 2030, which will primarily reduce direct and indirect N_2O emissions. A further greenhouse gas reduction is due to reduced fertilizer production[23].

It is assumed that lime will continue to be used on agricultural land as well as in the forestry sector to stabilise the soil pH and maintain soil fertility. Liming will generate emissions of about 1.5 million tonnes CO_2 annually.

Overall, agricultural greenhouse gas emissions in the scenario will be reduced by more than half compared to 1990. While a reduction of 35 % will be achieved by 2030, it will already be around 50 % in 2040.

Agricultural land-use changes, such as the dewatering of moorlands or the break-up of grassland, result in additional emissions that are not attributed to agriculture, but to land use, land-use change and forestry (LULUCF) according to climate reporting. In the LULUCF category, all anthropogenic emissions and land-related greenhouse gas sinks are handled – in addition to arable land, also forest, grassland, wetlands, settlements and other land.

The current emission trend is characterised by a continually decreasing net carbon storage in the forest as well as by high emissions from the organic soils of arable land and grassland. Because of the forest's high carbon sink of around -58 million tonnes of CO_2eq in 2010, LULUCF is still a net carbon sink (UBA 2016e).

However, without further measures it is to be expected that the net carbon storage in the forest will be considerably reduced (or even so much carbon will be released that the forest becomes an emission source) (Bundesregierung 2017g) and the emissions of the other land-use activities will remain similarly high. The most effective climate protection measures are therefore those that restore peaty soils and further enrich forest biomass.

About 5 percent of agricultural land in Germany is located on drained moorland (UBA 2016e). As an effective climate protection measure, it is assumed that 5 percent of this area will be restored annually from 2020, with the aim of using only around 180,000 hectares of former moorland areas and infrastructure in 2050. This reduces greenhouse gas emissions from 2040 to 4 million tonnes. The resulting significant restrictions on agricultural

22 The CO_2 emissions from the urea application have not yet been taken into account in the UBA study (UBA 2014a).

23 The resulting emissions are attributed to the chemical industry.

production are taken into account by a decrease in the number of livestock.

In order to restore and preserve moors, peat products will be gradually replaced by alternative substrates by 2050, and peat extraction will thus be discontinued.

In order to minimise further stress on agricultural and forestry land, residential and transport land-take will decrease gradually to 20 hectares per day in 2030 and will fall to 0 hectares per day by 2050. The areas already converted to organic soils will continue to emit 2.5 million tonnes of CO_2eq in 2050.

The assumptions for maintaining the forest as a net carbon sink are essentially based on the current "nature conservation scenario" of the model for forest development and wood resources (WEHAM)[24]. Correspondingly, the cultivation cycles in broadleaved stands are lengthened and the unused forest area is increased from 4.2 %[25] to 6.9 %. At the same time, forests that do not correspond to a natural potential vegetation (predominantly conifers) will be actively converted, which leads to a more intensive use of the forest.

These measures assume that overall wood supply will be reduced, as a result of which the wood products storage decreases. However, owing to the prohibition of certain wood preservatives outdoors, it is assumed that some wood utilised outdoors (e.g. masts, railway sleepers, etc.) will be substituted by other materials. Furthermore, the direct use of wood to produce energy will be greatly reduced by increased cascade utilisation. The use of residual forest wood to produce energy will be reduced to zero by 2050. As a result, reduced wood supply will be countered by a reduced demand for wood[26].

Table 2.5 shows the trends of LULUCF emissions in tonnes of CO_2eq up to 2050. The total without forest is presented separately in order to emphasise the reduction of emissions without carbon sinks as well as the base emissions. Overall, the emissions can be reduced by more than 85 % compared to 1990, while at the same time the forest can be conserved as a relevant carbon sink.

In addition to their respective contribution to climate protection, the measures described in the fields of agriculture and LULUCF also contribute significantly to resource conservation. It is worthy to note here in particular the reduced demand for agricultural production with regard to area, nutrients, water and biomass (e.g. by reducing the feed requirements and terminating the use of crop-based biomass for energy production) and, on the other, the positive effects of reduced nutrient surpluses in the water, air and soil as well as biodiversity.

24 Average values according to (Rüter, Stürmer und Dunger 2017c).

25 Formally protected and other unused forestry land.

26 The sharp decrease in the energy use of wood and its effect on wood demand could only be considered qualitatively in this study. No clear statement can be made as to whether a reduced wood supply can be completely compensated for, or whether this may affect the import-export ratio.

Table 2.5

Overview of emission trend in the field of LULUCF (CO_2eq)

LULUCF	1990	2010	By 2030	By 2040	By 2050
Arable and grassland (rewetting moorlands)	39,054,000	38,088,420	15,235,638	4,000,000	4,000,000
Peat extraction	4,127,590	4,074,000	1,018,500	0	0
Settlement areas	1,885,560	3,267,200	3,011,333	2,840,889	2,500,000
Total without forest	43,099,923	45,429,833	19,265,335	6,840,978	6,500,000
Change from 1990		**5.4 %**	**-55.3 %**	**-84.1 %**	**-84.9 %**
Forest*	-73,220,000	-57,995,483	-32,000,000	-30,000,000	-35,000,000

* In contrast to the first edition from 2017, the information on the development of emissions in the area of wood products (HWP) is not given. While the values for forest, following the assumptions for forest management and development according to the WEHAM nature conservation scenario, (Rüter, Stürmer and Dunger 2017c) are taken, in the GreenEe scenario the wood products are used differently compared to (Rüter, Stürmer and Dunger 2017c). In the GreenEe scenario, emissions are expected to tend to be lower than in (Rüter, Stürmer and Dunger 2017c).

Source: model calculation

2.8 Waste & wastewater

Various measures have already made a significant contribution to climate protection and resource conservation in the waste sector. Since the early 1990s, landfilling biodegradable waste in Germany has been greatly reduced by separate collection of recyclable waste components and the expansion of residual waste treatment capacities. Furthermore, landfill gas has been collected and treated. Since 2005, the disposal of biodegradable waste has no longer been permitted, thus the waste deposited after this time virtually does not contribute to landfill gas generation[27].

If possible, landfill gas is used to produce energy. However, the full amount of gas cannot be collected for technical reasons. The declining trend of methane emissions from landfills will continue and decrease further as biological degradation of organic matter in the landfill body progresses. However, several decades of active mitigation measures will be needed until methane production will fully peter out. Landfill mining and aerobic stabilisation processes (landfill aeration) will accelerate the decline in landfill methane emissions.

About 5 million tonnes of residual municipal waste was treated in Germany in mechanical-biological treatment plants (MBT) in 2010. It is expected that this treatment volume will remain constant until 2050. A trend towards the conversion of MBA to mechanical-biological stabilisation systems (MBS) can already be recognised. Due to the particular MBS process, the amount of waste gas and the creation of methane and nitrous oxide are significantly lower than from conventional mechanical-biological processes. In the scenario, a continuous transition is assumed starting from 2020 so that MBS plants will be operated exclusively by 2050 and accordingly the greenhouse gas emissions from the MBA sector will decrease continuously until 2050.

The share of fossil greenhouse gas emissions from waste flows to produce energy will be almost completely removed by 2050. Against the background of increasing recycling rates, the interaction with the production of these long-lived substance components in the industrial sectors and thus the early provision of sufficient greenhouse gas-neutral raw materials must be taken into account for the transformation path (see Chapter 2.3).

About 13 million tonnes of biowaste were treated and recycled in Germany in 2010. About two-thirds of this was composted and one third treated in biowaste fermentation plants. During treatment, methane and nitrous oxide emissions are particularly produced. The current compulsory separate collection of biowastes will continue in the scenario and, at the same time, it is expected that the proportion of biowaste fermentation will increase from 2020 while the proportion of composting will decrease.

27 Landfill gas, which can contain 50–60 % of methane, is produced during biodegradation of organic matter in landfills under the exclusion of air.

Table 2.6

Greenhouse gas development in the waste and wastewater sector (CO_2eq)

	By 2010	By 2030	By 2040	By 2050
Landfill		3,083,333	1,483,333	700,000
MBT		136,300	123,167	96,900
Composting/ fermentation		779,974	708,736	566,260
Cesspits		70,208	60,847	42,125
Wastewater treatment plants		1,975,248	1,815,987	1,497,465
Total	13,677,254	6,045,064	4,192,070	2,902,750
Change from 1990	**-62.3 %**	**-84 %**	**-89 %**	**-92 %**

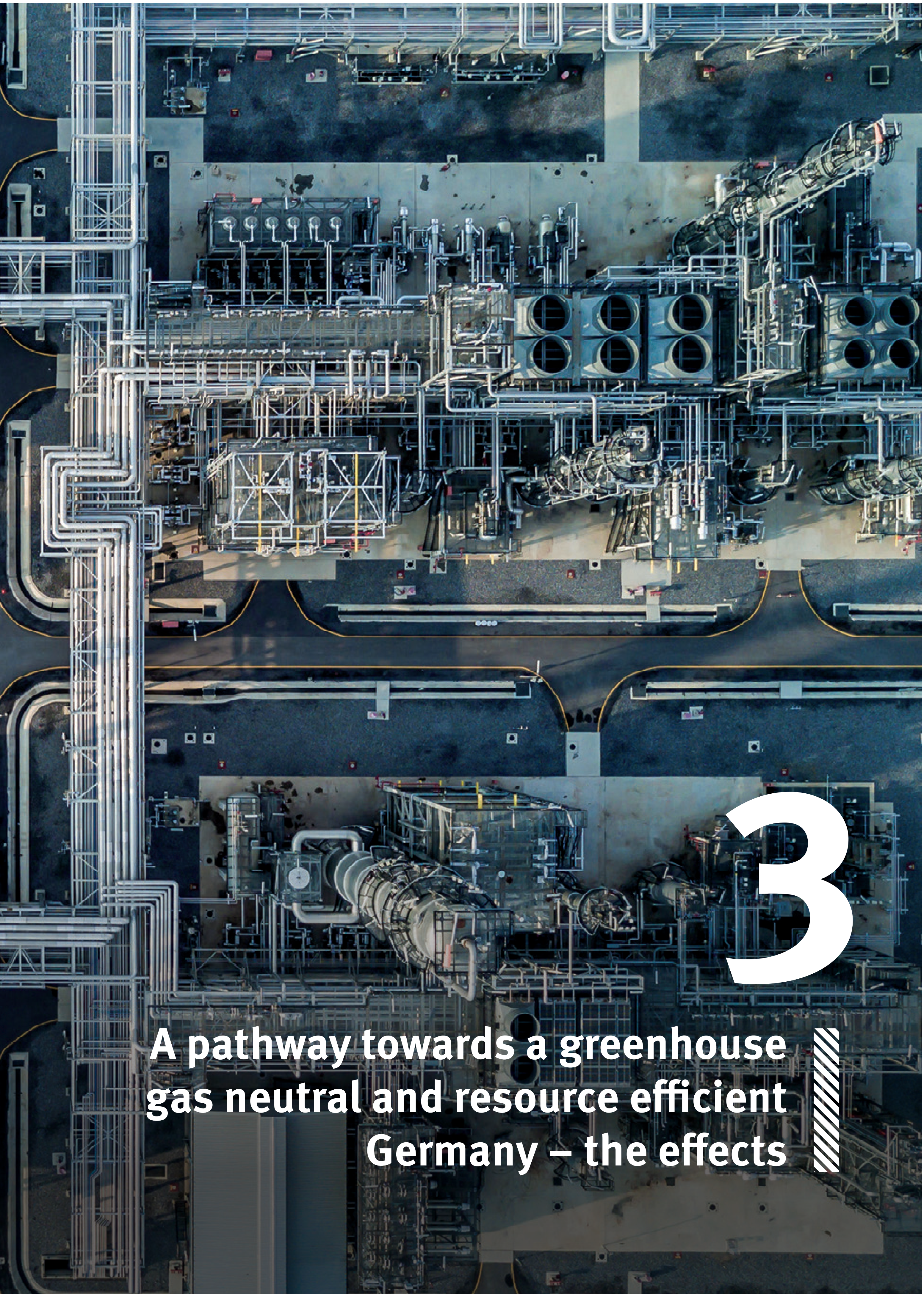
Source: model calculation

A progressive development and gradual adjustment of the installation stock to the state of the art will ensure continuous reduction of greenhouse gas emissions by 2050. Important measures include the reduction of methane production through active aeration of decomposing processes and better collection of biogas and leak prevention. Nitrous oxide production can in particular be reduced by targeted separation of ammonia in the collected exhaust air.

Wastewater disposal in Germany is very advanced today and meets the European requirements of the Municipal Wastewater Directive regarding connection rate and cleaning procedures without exception. In addition, continuous improvement of wastewater disposal, increase of connection rate to the public wastewater infrastructure and the expected decrease in population in rural areas will further reduce the number of cesspits by 2050, thereby contributing to emission reduction.

In wastewater treatment plants, the wastewater resource is used to generate energy through combustion of sewage gas in the company's cogeneration plants. The generated electricity is currently consumed predominantly in-house and covers between 30 % and 70 % of their electricity demand, which is necessary for the treatment of wastewater. The heat demand of the plants (digesters, operating rooms) is generally completely covered. Furthermore, increased gas production can be achieved through more efficient technologies, process optimisation and additional equipment that use anaerobic techniques (Haberkern, et al. 2008a). In addition to local heat concepts and flexible electricity generation, flexibility options also include the upgrading and feeding of sewage gas into the gas network and the associated substitution of fossil resources. Wastewater disposal companies can therefore use two systems to make a reasonable contribution to reducing greenhouse gases. On the one hand, net electricity consumption can be reduced by increased gas production and reduced energy consumption, on the other hand, making wastewater treatment more flexible can help conserve resources and save greenhouse gases. The GreenEe scenario assumes that half of the gas will be fed into the grid and the other half used locally in combined heat and power plants.

The emissions that are hard to influence include those that result from wastewater treatment. These correlate with the dietary habits of the population and the associated agriculture and livestock. As a result of alterations in these two areas, there will still be changes that cannot yet be foreseen and may further reduce the emissions from wastewater treatment plants.



3

A pathway towards a greenhouse gas neutral and resource efficient Germany – the effects

3.1 Effect on greenhouse gas emissions

Climate change and its consequences can already be seen today (UBA 2017k). Rapid and ambitious climate protection actions are needed to limit global warming. As early as 2010, the German Federal Government declared Germany's necessary contribution to the long-term target of reducing greenhouse gases by at least 80 to 95 % compared to 1990. In 2015, the Contracting States to the UNFCCC agreed in the Paris Agreement on a common goal to keep global warming well below 2 °C above pre-industrial levels and making efforts to limit the temperature rise to 1.5 °C . Against this background, the Federal Government has also decided the Climate Action Plan 2050 with sectoral targets for 2030 and a 55 % reduction across all emission source groups by 2030 compared to 1990.

From UBA's point of view a rapid and ambitious climate protection policy should be implemented in order to be able to manage the consequences of climate change for humans and the environment, with the goal of a 95 % greenhouse gas reduction by 2050. Scientific investigations show that limiting the temperature increase can be achieved with a higher probability if early and ambitious mitigations are implemented. If climate policy implementation is delayed, costs and dependency on risky technologies such as nuclear energy or CO_2 capture and storage (CCS) will increase, which UBA believes are not parts of a sustainable energy system (Clarke, et al. 2014e).

Against this background, as already stated in the UBA study "Germany in 2050 – A Greenhouse Gas-Neutral Country" (UBA 2014a), the presented GreenEe scenario specified a greenhouse gas reduction of 95 % by 2050 compared to 1990. The transformation pathway towards this will be implemented over the remaining decades through continuous ambitious climate protection measures and accompanying research and development. Accordingly, a 60 % greenhouse gas reduction will be achieved across all sectors by 2030 and 80 % by 2040 compared to 1990.

The reduction in energy-related greenhouse gas emissions must make a disproportionate contribution to climate protection, especially by 2030, and in the decade up to 2040. Changes in the power plant estate will also make a significant contribution. In addition to the pure substitution of fossil energy supply, the expansion of renewable energies must also meet the technology requirements of sector coupling such as PtH with heat pumps and electromobility. Against this background, a substantial increase in the expansion corridors of renewable energies is necessary by 2030. Increasing energy efficiency and enhancing potential savings across all energy applications in industry and transport, and especially in space heat supply, shall also significantly contribute to greenhouse gas savings in the energy sector by 2030. Coal-based energy supply shall be entirely abolished in the subsequent decade to be followed by a fully renewable energy supply by 2050 (see Section 2.3).

The significant reductions in other energy-related applications such as energy sector, buildings and industry may offset lower greenhouse gas reductions in transport by 2030. In this scenario, the transport sector (excluding international maritime transport and aviation) will lag behind the Federal Government's sectoral targets laid down in the Climate Action Plan (BMUB 2016f) with a reduction of around 30 % by 2030 compared to 1990 (see Table 3.1). Energy-related emission reductions without transport by 2030 will be above the Federal Government's targets in the Climate Action Plan. These greenhouse gases will be reduced by about 66 % by 2030 and by about 85 % by 2040 compared to 1990. Agriculture can also make a significant reduction by 2030 and a 35 % reduction compared to 1990 will slightly exceed the sectoral target of the Climate Action Plan.

In contrast to the Climate Action Plan, greenhouse gas emissions in the LULUCF area will also be considered. By 2030, greenhouse gas emissions will be reduced by 57 % compared to 1990. In the decade up to 2040, the approaches described in Section 2.7 of this emissions source group will make a disproportionate contribution to reducing greenhouse gases in addition to the energy sector (another 27 % compared to 1990).

Table 3.1

Greenhouse gas reduction according to the GreenEe scenario[a)] by 2030 compared to the Federal Government's targets

Climate Action Plan					GreenEe scenario		
	2030 emission target		Reduction against 1990			2030 emissions	Reduction against 1990[b)]
	From	To					
	Million t CO_2eq		%			Million t CO_2eq	%
Energy sector	175	183	62 %	61 %	**Energy (without transport) and industry**	330	66 %
Industry	140	143	51 %	49 %			
Buildings	70	72	67 %	66 %			
Transport	95	98	42 %	40 %	**Transport**	109	34 %
Agriculture	58	61	34 %	31 %	**Agriculture**	51	35 %
Others	5	5	87 %	87 %	**Waste**	6	83 %
Overall total	**543**	**562**	**56 %**	**55 %**		**496**	**60 %**

a) Data without LULUCF and international aviation and maritime transport.
b) The National Inventory Report 2016 v6 is the basis of the 1990 figures as opposed to the Climate Action Plan.

Source: BMUB 2016f and model calculation

Emissions from international aviation and maritime transport that are also taken into account will be increasing by 2030 due to the growing volume of transport and the still low proportion of greenhouse gas-neutral fuels. By 2050, fossil fuels will be completely substituted with renewable energy carriers.

The scenario predicts that the lower end of the Federal Government's target corridor for 2050, i. e. an 80 % reduction in greenhouse gases compared to 1990 will already be reached by 2040. The energy sector will produce the largest share of greenhouse gas emissions (around 70 %) and the transport sector will account for about 23 % of energy-related emissions. This can be attributed to the assumption in the GreenEe scenario that renewable fuels (PtL) will only be available late in the transformation process for this field of application and the ambitious market integration of electromobility cannot offset the emissions due to fossil fuel use (see Section 2.3). In the decade after 2040, the remaining fuel demand will be partially covered by fossil fuels until they are completely substituted by 2050. The relevance of emissions that are very difficult to avoid in agriculture will also become clear.

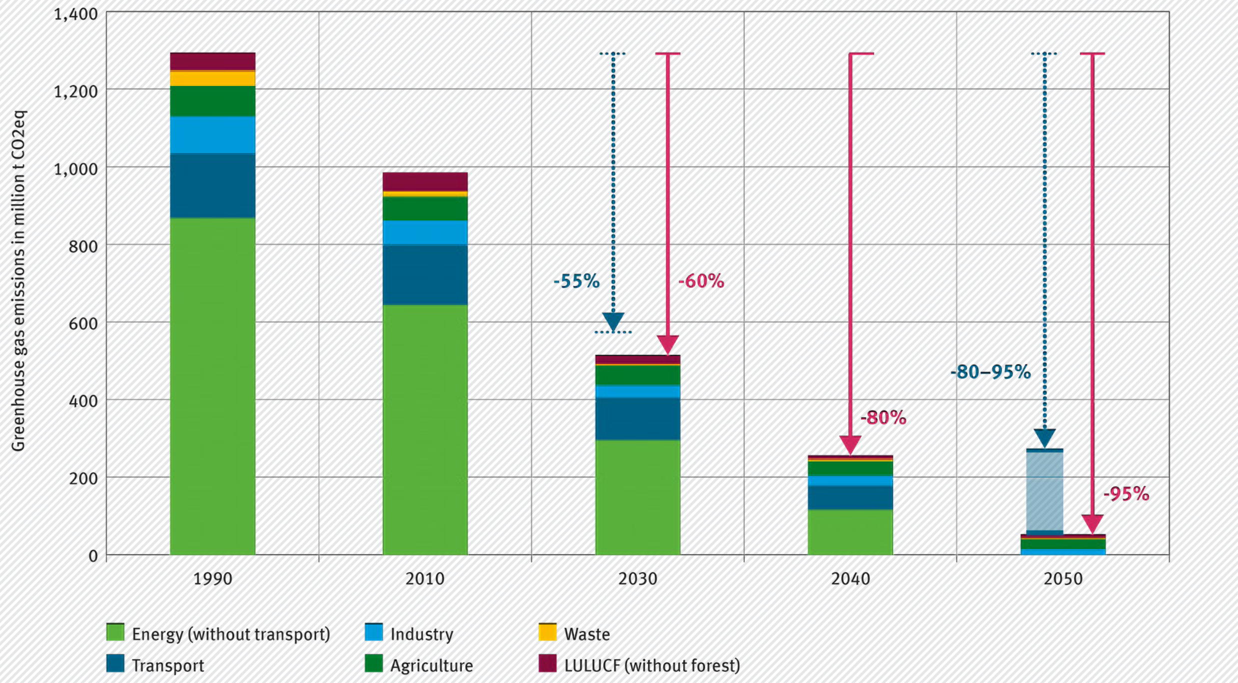
Energy-related emissions will almost completely be avoided when the energy supply is fully converted to renewable combustibles for electricity generation, fuels (including demands by international aviation and maritime transport) and raw materials by 2050. By 2050, the complete transition to new process technologies will also be performed so that emissions in the industrial sector will be reduced to just those which are inevitable: around 35 %[1] of total emissions at the destination. The largest remaining source of emissions will be agriculture accounting for nearly 55%[2] of total greenhouse gas emissions in 2050.

1 Without consideration of LULUCF.

2 Without consideration of LULUCF.

Figure 3.1

Greenhouse gas emissions across all emission source groups[a] according to the GreenEe scenario compared to the Federal Government's[b] targets



a) Without international aviation and maritime transport
b) The Federal Government's targets do not include the emission source group LULUCF.

Source: own illustration of model calculation

3.2 Effect on resource use

Consequences of the transformation to GHGNG on Germany's raw material demand

The effects of the transformation towards a greenhouse gas neutral Germany on raw material consumption are manifold and far-reaching and not limited to Germany alone. Because of the German industry's foreign trade interconnections and the import of a variety of consumer goods, Germany receives a significant quantity of its raw materials from abroad, which greatly exceeds the amount of raw materials extracted in Germany. In accordance with the polluter pays principle, these raw materials are also allocated to Germany's raw material demand. This is done by adding the actual raw material demands needed for their production to the imports and exports (calculation in raw material equivalents). This provides information on Raw Material Input (RMI) and, taking into account exports, Raw Material Consumption (RMC), measured in units of mass.

Germany's raw material consumption totalled 1,374 million tonnes in the 2010 reference year and was dominated by non-metallic minerals and fossil energy carriers. It is therefore an obvious conclusion to reduce both raw material demand and greenhouse gas emissions at the same time by reducing the use of fossil energy carriers. Many approaches to reduce raw material input also lead to energy savings, and an increased use of secondary raw materials or optimisation of processing operations towards waste avoidance.

On the other hand, as illustrated in the scenario presented, transformation to greenhouse gas neutrality requires the energy system to be greatly restructured, significant changes must be made in application technologies by increasing the use of PtX techniques and infrastructure must be rebuilt. This, in turn, includes a fluctuating increase in raw material demand for the construction of new infrastructure, especially metals and construction minerals that are then bound in the anthropogenic stock (Hertwich, et al. 2016n). In addition, rebuilding reduces the demand for fossil energy carriers while raw materials from the anthropogenic stock will be available for recycling because of the dismantling of infrastructure. This will also be illustrated by the systemic consideration of a potential global transformation to be presented in the following section.

In addition to mineral raw materials (for foundations, buildings, glass) and steel (for wind turbines and power pylons), the essential raw materials needed in renewable energy systems include non-ferrous metals such as copper and aluminium (for wind turbines, photovoltaic systems, batteries, power lines, coils) and technology metals such as neodymium and dysprosium (magnets for generators). These raw materials will then be available to the economic cycle over the long term so that future use of primary raw materials can be significantly reduced. A temporary additional demand for other raw materials that are bound in the anthropogenic stock opposes the saving in fossil raw materials. To what extent and in which composition the anthropogenic stock is built up and to what extent primary raw materials can be saved depends to a large extent on the choice of technologies (Hertwich, et al. 2016n) (Figure 3.2)[3].

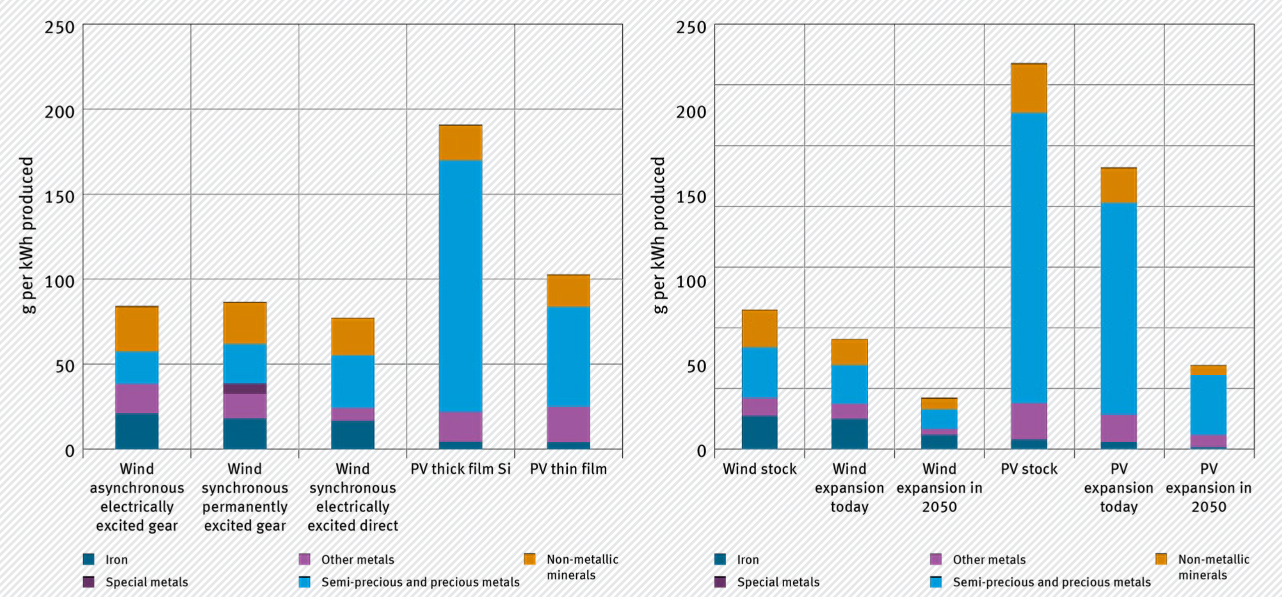
For example, renewable energy installations added today have significantly lower raw material demands than existing installations. Resource efficiency potential, in particular for iron and precious and semi-precious metals, has been increased through further development and substitution in recent years. An extrapolation of further developments beyond today's best available technology suggests that raw material demand in relation to installed lifetime performance[4] can be expected to decrease by about 60 % for onshore wind and about 80 % for photovoltaic (Wiesen, et al. 2017l).

3 For example, the demand of rare earth metals and semi-precious metals varies significantly depending on the generator type of wind turbines (Wiesen, et al. 2017l).

4 As technology develops, it is expected that both service life and efficiency and performance of installations will increase.

Figure 3.2

Selected raw material use for some power generation installation according to the current state (left)[a] and in development (right)[b] based on (Wiesen, et al. 2017l)



a) Distinctions between onshore wind turbines are made according to the respective generator type. They are (a) asynchronous generator (rotor "rushes" ahead of magnetic field) with a high-ratio gear and electrically excited (example: GAMESA G90), (b) synchronous generator (rotor rotates synchronously with the magnetic field), which is permanently energised and uses a gearbox (system example: VESTAS V112) and (c) electrically excited synchronous generator with a direct drive (system example: ENERCON E-82). In photovoltaic systems, a distinction is made between thick-film and thin-film cell techniques. Thick-film cells use a system with polycrystalline silicon absorbers, while thin-film cells apply a copper-indium-gallium-diselenide absorber. Both systems are modelled as on-roof installations (Wiesen, et al. 2017l).

b) To illustrate the changed raw material demands during the assumed technical development, one installation of type each was represented. Wind energy onshore is represented here by a system with an electrically excited synchronous generator with direct drive, since this installation type dominates the current market in Germany. The technical development is mapped with the variation of the parameters rated power, full load hours, rotor diameter and hub height. For photovoltaics, the modelling is based on a thick-film cell system with an absorber made of polycrystalline silicon rated at 3 kW_p. There is a variation in terms of service life, film thickness, efficiency and full load hours (Wiesen, et al. 2017l).

Source: own illustration based on Wiesen, et al. 2017l

Thus, ambitious measures must be developed and implemented for enhancing resource efficiency and cycle management in order to shape the transformation towards a greenhouse gas-neutral Germany as resource efficient and resource saving as possible.

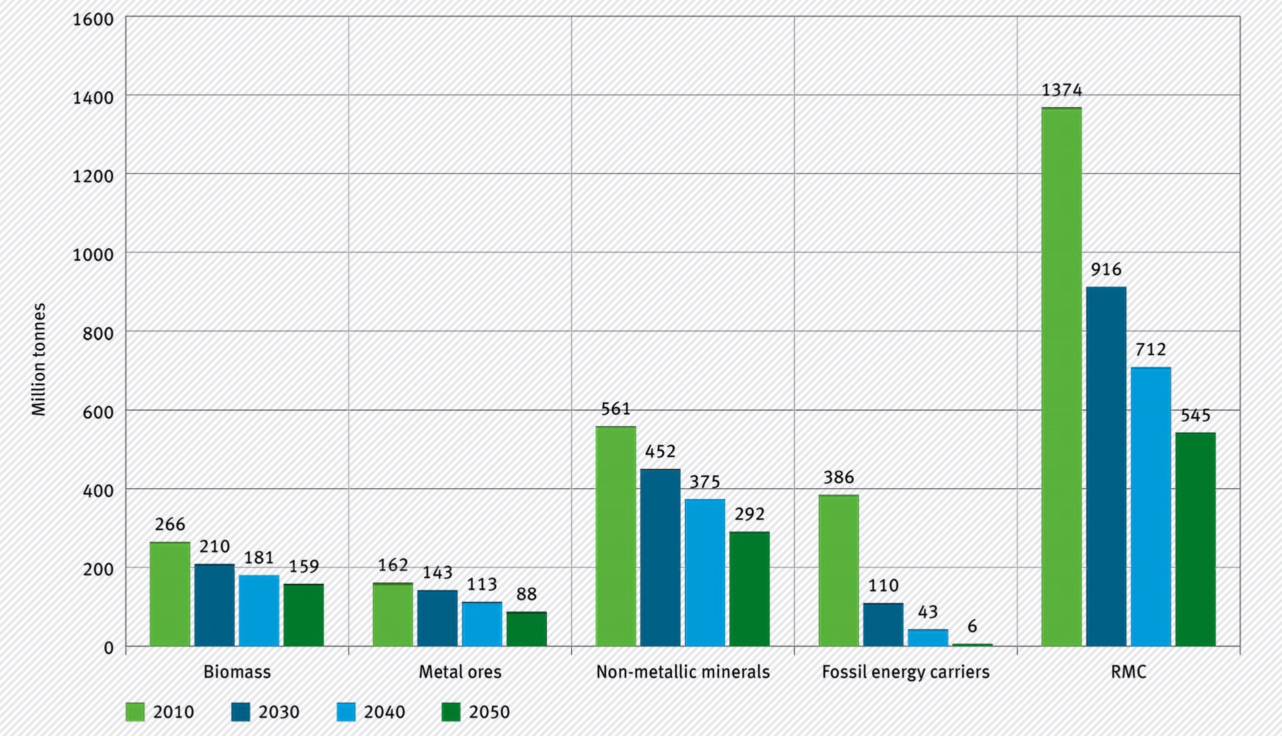
Due to the German Resource Efficiency Programme's ambitious development (BMUB 2012b) envisaged by the Federal Government and taking into account general technical progress, at least over recent years, the trend of 1.1 % increase per year in resource efficiency can be upheld until 2050. In addition, based on an extensive literature study, further specific and differentiated efficiency potentials and potentials for the use of secondary raw materials and material substitutions, which also contributes to the reduction of primary raw material extraction, have been identified – for example in the metal processing industry, chemical industry or the construction sector.

Increasing resource efficiency is also sought in Europe through the implementation of appropriate policies and objectives (EEA 2016g). It can be assumed that this will continue in an ambitious manner, since the importance of the sustainable use of natural resources and the increase in resource efficiency are becoming more important internationally. Thus, the United Nations Agenda 2030, the decisions of the G7 of Elmau, Toyama and Bologna (BMUB 2016h) and the decision of the Hamburg G20 (G20 Germany 2017 2017m) explicitly address the increase of resource efficiency. It can therefore be expected that European and non-European countries will make significant progress in terms of technological development and resource efficiency. Thus, the GreenEe scenario assumes that the 2050 technical development state will be comparable across Europe. Internationally, the gap will decrease significantly, meaning that the global technological development state in 2050 will correspond to that of Germany in 2040.

Overall, the GreenEe scenario indicates that for the expected primary raw material consumption by 2050, it is possible to transition towards a greenhouse gas-

Figure 3.3

Raw material consumption (RMC) by type of raw materials in the GreenEe scenario, calculation in raw material equivalents (RME)



Source: own illustration of model calculation

neutral Germany through resource efficiency.[5] The raw materials consumption (RMC) will drop by roughly 60 % from 1,374 million tonnes in 2010 to 545 million tonnes in 2050, whereas the decrease is nearly constant with a reduction of -33 % in 2030 and -48 % in 2040 (Figure 3.3). The decline per person is slightly lower at 54 %, reaching 7.6 tons per capita in 2050, due to the expected population development (Figure 3.4).

As expected, the consumption of fossil fuels will decline the most in terms of percentage, from 386 million tonnes in 2010 to 6 million tonnes in 2050 (around -98 %), with the highest lowering between 2010 and 2030 (-71 %). The remaining quantities of fossil energy carriers can be attributed to the production of imported goods outside of Europe, since the scenario assumes an incomplete conversion of the energy system and production technologies to renewable energy sources or raw materials. In Germany, the decline in the use of fossil energy carriers by 2030 will mainly be due to a decline in coal-fired electricity generation. In addition, there will be an increased decline in the use of oil and gas from 2030 onwards, as electricity-based technologies for heat supply and in the mobility sector will become more widespread.

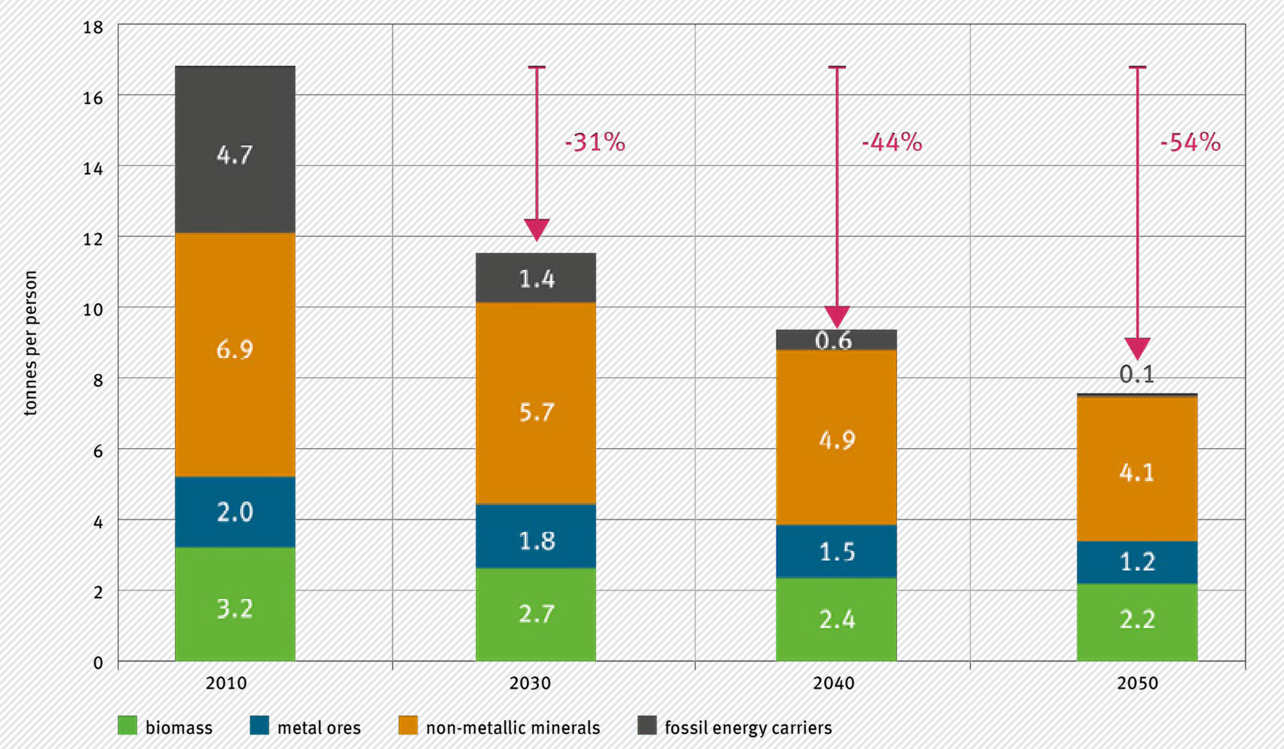
Another significant decline will occur in the use of non-metallic minerals, which will decline nearly constantly by a half from 561 million tonnes in 2010 to 292 million tonnes in 2050 (-48 %). Dominant factors are

- the significant reduction in the use of building minerals due to the reduced construction activity underlying the GreenEe scenario (such as no net additional soil sealing that impacts civil engineering activities, mostly low expansion of the supply infrastructure, no hydropower expansion, no major new infrastructure projects such as airports or similar),
- increasing the recycled share of building materials, and
- using alternative building materials and alternative construction methods.

5 The presented figures differ slightly from those described in the first edition from October 2017 due to recalculations and minor methodological adjustments.

Figure 3.4

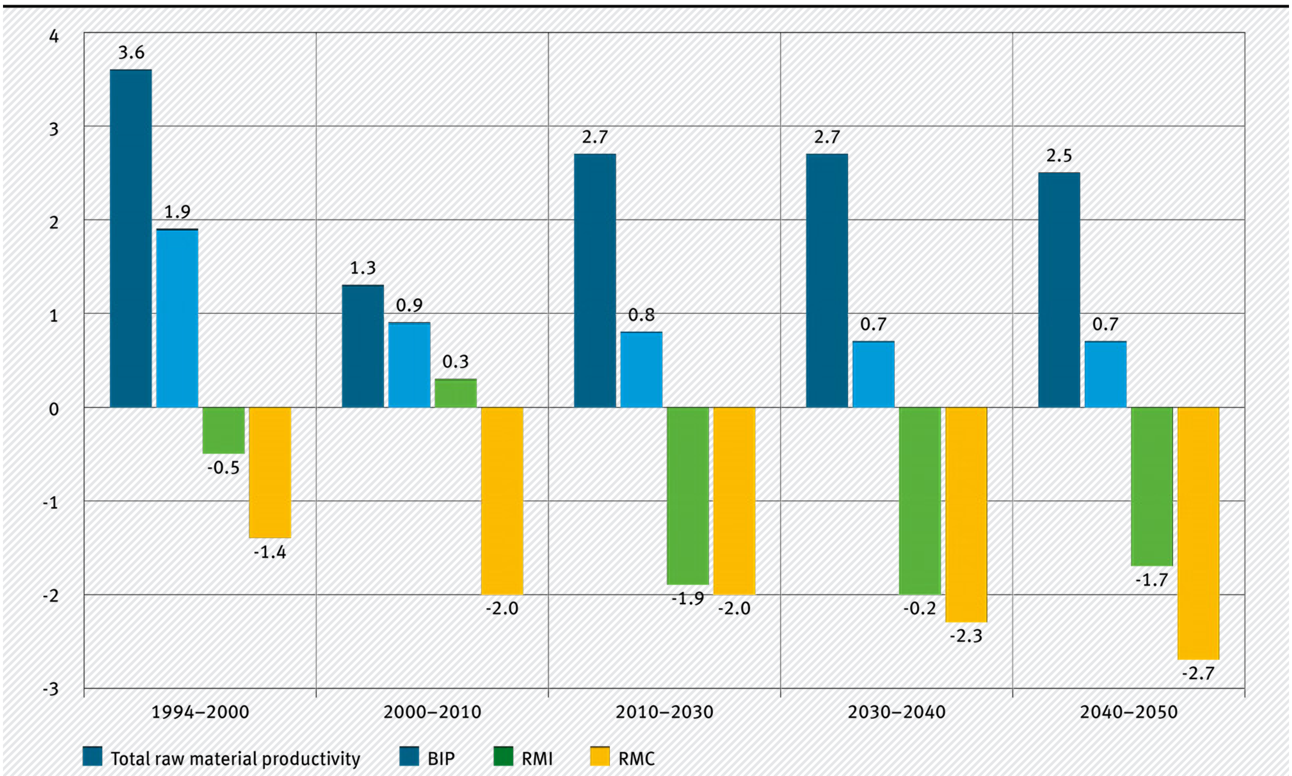
Raw material use per person (RMC/cap), absolute and percentage change, in the GreenEe-Scenario



Source: own illustration of model calculation

Figure 3.5

Components of total raw material productivity and 1994 – 2050 raw material consumption, annual average change in %*



* URMOD for 2010, 2030, 2040 und 2050; linked with 2000 and 2010 key figures of the UGR-RME model and the UGR 1994 – 2015 timeline of the UGR Material Flow Accounting (EW-MFA). Linear interpolation between supporting years.

Source: own illustration of model calculation

The use of non-metallic minerals, particularly building minerals (the mass-dominant raw material category of raw material consumption) in 2050 accounts for more than 53 % of total raw material use (around 41 % in 2010).The scenario assumes changes in dietary habits, particularly a reduced meat consumption, which dominates the reduction in biomass use from 266 million tonnes in 2010 to 159 million tonnes in 2050 (reduction of 40%). The decline in animal feed alone is estimated at 52 million tonnes (including feed used abroad for meat production) and thus accounts for 49 % of the reduction. Foregoing the use of crop-based bioenergy also leads to a relevant reduction in biomass utilisation.

The decline in the use of metal ores is speeding up over the considered time period, with a reduction of -11 % until 2030 to -30 % in 2040 and -46 % in 2050 compared to 2010. In total, the use of metal ores decreases from 162 million tons in 2010 to 88 million tons in 2050. Despite the identified and assumed efficiency potentials and the significantly increased use of secondary raw materials in the metal processing industry and in mechanical engineering two different developments lead to a slower reduction in the use of metal ores, especially in the first two decades observed. On one hand, the future development of the energy infrastructure requires a considerable amount of metallic raw materials. The further mechanisation of industry and society in the fields of information and communication technology[6] and medicine for example, also increases the demand for technology and precious metals. On the other hand, efficiency and conservation potentials can essentially be achieved in the use of mass metals (for example iron, copper, lead and aluminium). The use of these metals will decrease by 75 % in 2050 compared to 2010. By contrast, the use of technology and precious metals will decrease by only 29 %, with the largest decline being in metals for steel refining.

Overall, the GreenEe scenario's resource policy parameter trend shows that ambitious climate and resource protection should benefit from each other and should thus be jointly discussed in politics and implemented. At 7.6 tonnes/person (Figure 3.4), the GreenEe scenario in 2050 reaches the sustainable raw material use corridor of 5 to 8 tonnes/capita/year as discussed in the literature (Bringezu 2015b, IRP 2014f, Fischer-Kowalski, et al. 2011a). Also, an annual average reduction of raw material input (RMI) of 1.8 % with simultaneously increasing economic growth can clearly achieve a complete decoupling of economic development and raw material use (Figure 3–5). An annual average increase of 2.6 % would set the trend of total raw material productivity[7] above the target of, for example, ProgRess II (BMUB 2016l) and the new edition of the German Sustainability Strategy (Bundesregierung 2017o), which stipulate a trend update for 2000–2010.

Systemic perspective on a global transformation

Scenarios for the expansion of renewable energies in Germany should also be reflected against the background of international development. A system dynamic simulation model[8] considers not only the issue of the available sum of raw materials, but also the temporal progressions, the maximum required mining capacities and production capacities for the respective renewable energy technologies. The simulation model balances the raw material use[9] and the greenhouse gas emissions caused by the energy supply over time. It is not about providing exact calculations and forecasts, but demonstrating the system behaviour of the greenhouse gas neutral energy system outlined above. The orders of magnitude of the changes and the curve shapes play a key role in gaining qualitative insights.

The illustrated energy system is greatly simplified by onshore wind power, offshore wind power, photovoltaic and PtG/PtL technologies and the corresponding necessary cabling. Calculations are based on reference installations from (Wuppertal Institut 2014g, Wiesen, et al. 2017l). Accordingly, the influence of different installation technologies or a technology mix is not mapped below. This is part of ongoing work within the framework of UBA's interdisciplinary process. Depending on the demand and pattern of the expansion scenario, installation capacities will be expanded over time and, after the corresponding service life, will reduce again in current simulation runs. According to the inventory of the

6 The scenario assumes a rise of ICT devices in households in line with general economic growth, meaning that the overall future device supply will increase. On the other hand, the scenario assumes that raw material conservation through increased efficiency and an increasing demand for ICT will offset the additional raw material use in industry and services.

7 Total raw material productivity is calculated from the GDP and the monetary value of imports/RMI.

8 GEE(R) model: Global Renewable Energy and Raw Materials, Project number: FKZ 3716321000.

9 Iron, non-ferrous base metals, semi-precious metals, rare-earth metals, precious metals, industrial minerals, building minerals, fossil raw materials.

Table 3.2

Overview of the three future scenarios

	WEO NP scenario	WEO 100% RE scenario	WEO GreenEe scenario
Final energy consumption	high	high	low
Renewable energies share in energy supply	low	maximum	maximum
Use of fossil and nuclear energy	yes	no	no
Sector coupling – direct electricity consumption*	moderate	medium	very high
Sector coupling – indirect PtG/PtL	none	very high	high

* This includes Power to Heat and electromobility.

Source: own illustration

respective installation type, raw materials are bound in the anthropogenic stock and a recycling rate is assumed according to the current state of the art. The construction of renewable energy installations will use mainly primary raw materials[10] until a balance between expansion and dismantling is established and the demand for primary raw materials can be reduced to a required minimum through recycling[11]. Depending on the installed capacity of renewable energy installations, fossil raw materials will be substituted, first for the direct use of electricity and then to temporally offset for the provision of PtG/PtL energy carriers for the substitution of combustibles, fuels and non-energy demands of carbon carriers as described in Section 2.3 of the GreenEe scenario.

Different future scenarios are compared to show the systemic effects. The comparison is based on the World Energy Outlook's (WEO) (International Energy Agency 2015c) New Policies scenario, which only accepts a very modest expansion of renewable energies. The scenario makes assumptions about the energy demand trend in the respective sectors and energy carriers for different regions of the world. It compares the following three considerations[12]:

The "WEO NP scenario" shows the trend of the final energy demand of the WEO's New Policies scenario. However, UBA believes that this does not represent a sustainable development because fossil and nuclear fuels and biomass are still being used on a larger scale.

Therefore, a second – hypothetical – demonstration scenario (WEO 100 %RE scenario) assumes that a complete substitution will take place through renewable energies. Unlike in the WEO NP scenario, in addition to fossil energy, nuclear energy and biomass[13] in a simplified form will be substituted with other renewable energies in identical final energy form – in the sense of sustainability. Thus, current technologies continue to be used (internal combustion engine, fuel based space and process heat supply, etc.), but their energy demands will be exclusively covered by renewable energies.

The third global future development (WEO GreenEe scenario) is based on the GreenEe scenario for Germany described above with high efficiency demands and a high degree of direct electricity use.

10 Depending on availability (through the circular economy), secondary raw materials are also used on a pro rata basis.

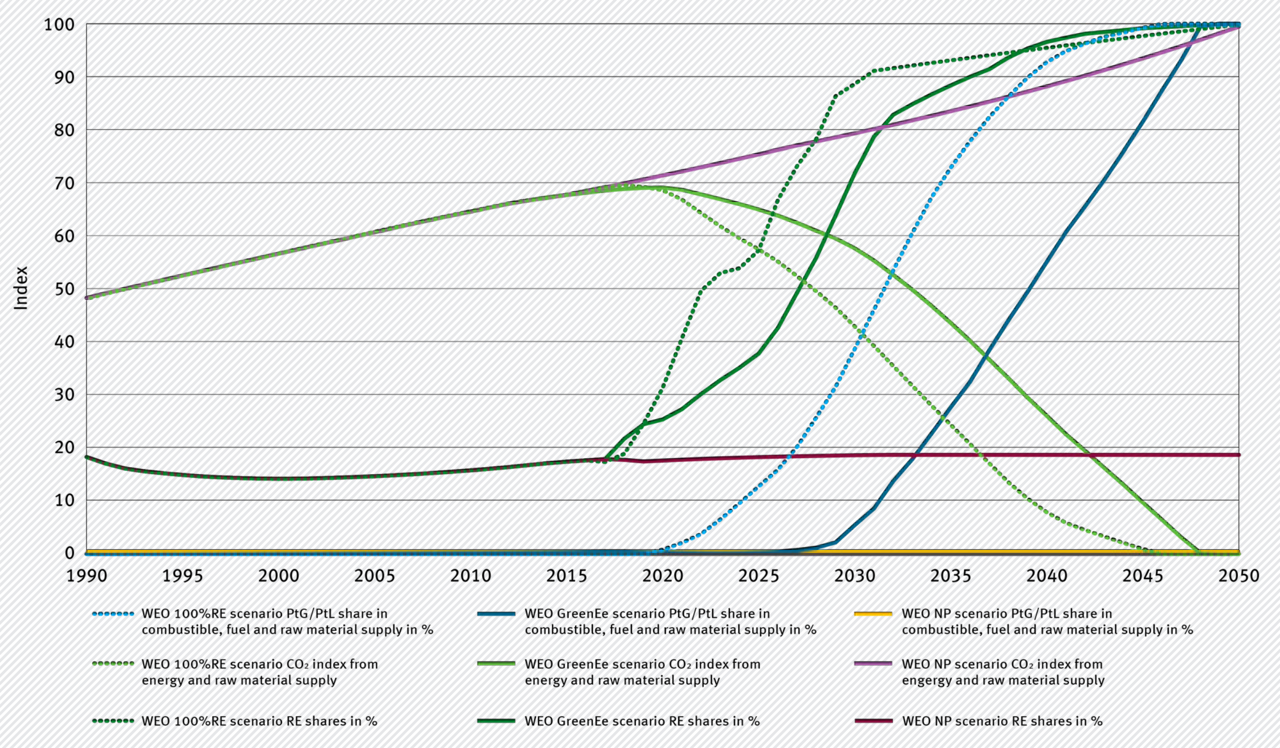
11 Simplified assumption of an average 70 % recycling rate over all raw materials. 100 % recycling is thermodynamically not possible and perhaps ecologically only conditionally advantageous. The recycling rate and capacity will be considered in further Green scenarios in more detail.

12 For comparability, the non-energy demand that is not part of the WEO considerations is extrapolated based on the GreenEe scenario and the WEO's economic trend and assumed identically in all three future scenarios.

13 The German Environment Agency believes that due to the growing competition for fertile cultivation areas, the disproportionately high area intensity of energy production from biomass compared with other renewable energy sources and the problematic socioeconomic connection with food prices on the global market, the cultivation of biomass for fuel will be successively reduced in accordance with the service life of currently operating installations (UBA 2014a, UBA 2013a).

Figure 3.6

Overview of system dynamic modelling*



*Curves for the CO_2 index and EE share and PtG/PtL share of combustible, fuel and raw material supply are annual mean values and have been smoothened. Seasonal fluctuations occur due to the fluctuating generation of renewable energies. Alternating generation is offset by fossil energy and stored in a renewable energy system. The corresponding model oscillation of the CO_2 index and EE share and PtG/PtL share of combustible, fuel and raw material supply until a complete renewable energy system in 2050 was smoothened for better illustration.

Source: own illustration of simulation results

Figure 3.6 provides an overview of the three simulations. Both the WEO 100 %RE scenario and the WEO GreenEe scenario show a total reduction of the depicted energy-related greenhouse gas emissions by 2050 (light green dotted and solid curve), which is achieved by the complete switch to renewable energies (dark green dotted and solid curve). However, the WEO 100 %RE scenario shows a significantly higher demand for electricity generation capacities in 2050 due to the higher electricity demand for PtG/PtL installations to provide more combustibles and fuels than in the WEO GreenEe scenario. In order to map an almost continuous expansion of renewable energies, the WEO 100 %RE scenario requires a stronger annual expansion and thus a faster increasing share of renewable energies by 2040 than the WEO GreenEe scenario. Both the WEO 100 %RE scenario and the WEO GreenEe scenario show that a fully renewable energy system without CO_2 emissions can only be achieved by 2050. Due to the moderate use of renewable energies and continued intensive use of fossil fuels in the WEO NP scenario (burgundy curve), greenhouse gas emissions will increase massively and continuously until 2050 (purple curve). It also becomes clear that the WEO 100 %RE scenario and the WEO GreenEe scenario present a complete substitution of the combustible, fuel and raw material supply with PtG/PtL. However, the WEO NP scenario shows no substitution of these fossil energy carriers (yellow curve).

The different future scenarios also show differences in the raw material use. This is due to the consumption of fossil energy carriers and the stipulation of raw materials in the anthropogenic stock. The raw materials bound in the anthropogenic stock can be reused after the relevant period of use (circular economy). The more raw materials from the anthropogenic stock that can be reused, the fewer primary raw materials need to be added to the system.

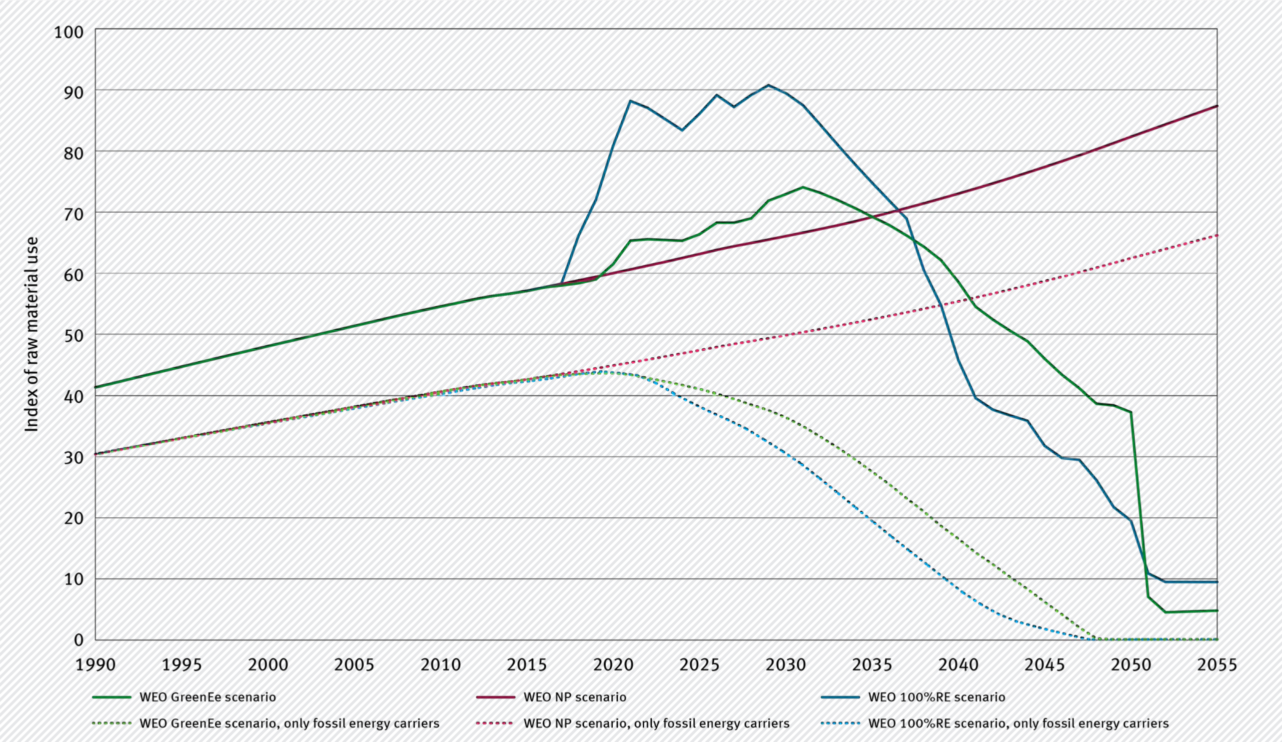
The following Figure 3.7 shows the raw material consumption of the energy supply systems for the three future scenarios. The raw material share which flows into the construction of a renewable energy system and the fossil raw material fraction are presented here. Similar to the greenhouse gas emissions shown in Figure 3.6, the use of fossil raw materials WEO 100 %RE scenario and WEO GreenEe scenario drops to zero by 2050. As illustrated in Figure 3.6, showing the early expansion of renewable energies in the WEO-100 %RE scenario, this (blue dotted) curve drops earlier than in the WEO GreenEe scenario (green dotted curve). It becomes clear that retaining fossil energy carriers, as in the WEO NP scenario, entails a higher and permanently increasing demand for raw material consumption which is not sustainable. Over time it becomes clear that by switching entirely to a renewable energy supply, the primary raw material extraction in the energy supply system can be significantly reduced by almost a factor of 5 compared to 2010. The main reason for this is the high number of renewable energy installations which provide enough raw materials to recycle at the end of the life cycle of the installations.

Likewise, when comparing the WEO 100 %RE scenario to the WEO GreenEe scenario, it becomes clear that a "one-to-one" conversion and retaining today's techniques results in a significantly higher raw material use in the transformation path, furthermore this remains above the level of an efficiently designed energy supply, as in the WEO GreenEe scenario. This implies that the conversion of fields of application to the direct use of electricity by means of Power to heat and electromobility – away from the fuel-based energy supply – should take place everywhere that it is technically feasible. The use of regenerative energy carriers made of PtG and PtL techniques must be reduced to a minimum. This is the only way to achieve a long term sustainable and efficient energy system including efficient use of energy and raw materials.

From this it can be inferred that the cumulative raw material cost increases steadily in a fossil energy system (WEO NP scenario). In the course of a changeover to a complete renewable energy supply and a high recycling rate, the cumulative raw material cost increase slows significantly over the course of time as the share of renewable energies increases. After reaching a complete renewable energy system, the cumulative raw material demand

Figure 3.7

Comparative qualitative illustration of raw material consumption of the system dynamics



Source: own illustration of simulation results increases only marginally relative to the fossil energy system, as the primary raw material requirement can be reduced to a minimum by recycling. In the WEO GreenEe scenario with an efficient energy system, the cumulated raw material demand is about 10 % below the level of the WEO 100 %RE scenario.

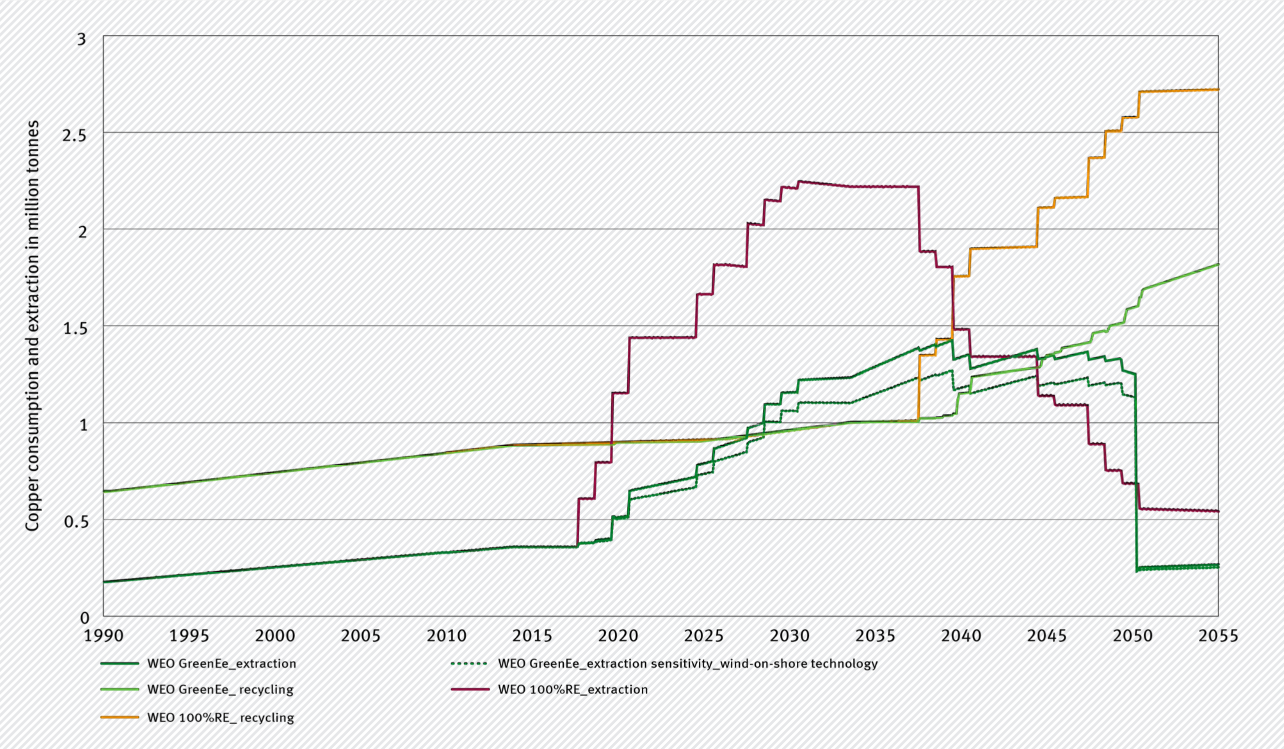
In addition, when converting the energy supply, the demand for individual raw materials in the transformation path is also of great interest. For example, copper is one of the most important metals for a renewable energy system. In the GreenEe scenario (Chapter 2) the raw material demand is not further optimised. In order to identify the typical systemic patterns, in the case of the global dynamic simulations, it was decided to only look at one type of wind turbine, acknowledging that the mix of different generators would hightly affect the amount and composition of needed raw materials (see also Figure 3.2). The model uses an Enercon E-82 for onshore windturbines. The choice of the type of wind turbines will affect significantly the copper demand, depending on the type of the generator.[14]

In the model, the demand for copper is determined by the progress of conversion of the energy supply system to renewable energies of wind onshore, offshore and photovoltaics, as well as the integration of PtG/PtL techniques and power line extension. In addition, a constant demand for mirroring other usage (e.g., ICT, cable, etc.) is considered. The findings of the systemic analysis are shown in Figure 3.8. It can be seen that an early expansion of renewable energies leads to an early and steep increase in copper consumption (burgundy curve) if the overall demand for production capacities is high and nevertheless a steady expansion is required, as assumed in the WEO100 %RE scenario. Whereas increasing efficiency potential and ensuring efficient

14 Framework assumptions of the reference installation: nominal power 2.3 MW; full load hours 1,715 h/a; 82m rotor diameter; 108m hub height; material and raw material requirement in g/kWh: total raw material requirement 102.31, of which iron 22.69, non-ferrous base metals 11.5, semi-precious metals 31.23, precious metals 0.02, building minerals 21.85 based on (Wiesen, et al. 2017l).

Figure 3.8

Copper use in a renewable energy system*



* Furthermore, other demands e.g. electromobility are not included in this example

Source: own illustration of simulation results

sector coupling – and if the expansion of PtG/PtL final energy carriers is only intensified later as in the WEO GreenEe scenario – the copper peak will occur correspondingly later and somewhat flatter (dark green curve). In both scenarios, a plateau is exceeded followed by a reduction in copper consumption (based on primary material) due to recycling. Depending on the different amounts of installed renewable technologies, the recycling levels are different (orange and light green curve), respectively. Both curves show the time lag associated with the time raw materials are bound in the anthropogenic stock. The high demand for copper could lead to global economic policy implications for construction and mining capacities.

New raw material reserves could also be exploited that are from today's perspective not economically viable. This also implies that if the expansion of renewable energies is increased later towards the targeted 2050, a rapid decrease in the demand for copper will occur immediately after that (green curve). Against this backdrop, it is obvious that a steady expansion of renewable energy also increases planning safety and sustainable prospects for those involved in the extraction of raw materials. The equilibrium of construction and dismantling can also be achieved earlier and more evenly, compared to an abrupt decline in the demand for raw materials and resources. For the model simulations the assumptions made for copper deposits corresponded to (Sverdrup und Ragnarsdóttir 2014j). In line with that, we can conclude that the availability copper is not a limiting factor from a physical point of view for the conversion of the energy system. However, "low grade" raw material[15] deposits are increasingly being exploited in the transformation path alongside "high grade". The potential concomitant economic implications indicate that the subsequent construction and replacement of installations will probably lead to an increase in raw material costs.

15 In the model, three groups of ore grades are used in the deposits for simplicity. Thus, the effort (energy, investment) can be estimated later because the lower the ore content, the more complex and energy- and cost-intensive is the extraction. High grade includes the metal concentrations of 10–400 kg/tonne, low grade of 2–10 kg/tonne of ore and ultra low grade 2–0.4 kg/tonne (Sverdrup und Ragnarsdóttir 2014j).

As already shown in Figure 3.2, the choice of a renewable energy system can significantly influence raw material use. Against this background, Figure 3.8 shows a sensitivity for a wind turbine onshore with a significantly lower copper demand (green dotted curve). It is clear that an increase with a subsequent plateau in the construction of a renewable energy system will be the same. Nevertheless the peak of the curve is 10 % lower in this sensitivity analysis, demonstrating that the choice of the respective technology strongly influences the raw material demand.

For the raw material policy, systemic considerations show that the conversion of energy supply to renewable energy systems with low raw material demand, as early and progressively as possible, helps to conserve raw materials. It also shows that lower maximum raw material capacities per month are needed, that planning security will be given to stakeholders and that adjustment frictions will be reduced, so that the conversion of the energy supply is likely to be cheaper.

4

Conclusion and need for action to implement the transformation process

The present scenario "GreenEe" shows that it is possible to transform Germany to both greenhouse gas neutral and resource efficient. One side of the balance is greenhouse gas and raw material saving due to exit from fossil energy carriers and the other is the increased raw material use for the construction of the renewable energy system. In the GreenEe scenario it is possible to reduce the GHG emissions in 2050 by 95 % compared to 1990 and the raw material consumption (RMC) from 1,370 million tonnes by almost 60 % compared to 2010. However, in the case of individual raw materials (e.g. copper), a markedly increased global demand must be expected, and this demand can increase drastically over certain periods.

The scenario demonstrates that related ambitious climate and resource efficiency policies helps to achieve both goals. Considering both policy field in a systemic way, should be further discussed and implemented in future politics.

Within this scenario however, clearly not all questions and possibilities for a transformation towards a sustainable Germany were dealt with exhaustively. Some of these questions will be examined in other "Green" scenarios and presented at the end of 2019. The results of five scenarios will then specify the solution space via the various transformation paths, showing how a greenhouse gas-neutral and resource-efficient Germany can be achieved by 2050 and beyond. For this purpose, key parameters such as energy efficiency across all fields of application, levels of effort in implementing climate protection measures in the transformation pathway, raw material used by the techniques, and lifestyle changes will be considered to demonstrate a variety of plausible options. The results of the first scenario "GreenEe" presented in this publication should therefore be understood as an initial input for discussion on how climate and resource protection are connected and should be addressed politically and systemically.

On the basis of this first scenario, to implement the transformation process the following recommendations arise for action and research:

Common international advancement

Climate and resource protection challenges are not locally or nationally limited. Rather, they place global demands on the world community and should be jointly advanced. In parallel to its own activities, Germany should work internationally and in Europe to ensure that other states also aim for greenhouse gas neutrality by 2050 (UBA 2016j). Common advancement entails entering into long-term sustainable cooperation with other states. In particular, research, development and dissemination of knowledge about renewable energy technologies and resource conservation must be consistently extended.

According to the scenario results for renewable PtG/PtL imports, there is already an identified need for 2030 that requires an early expansion of renewable energy installations abroad. It cannot of course be assumed that installations for the generation of renewable energies abroad are built and used exclusively for German demand. This expansion must also ensure that local and regional stakeholders benefit significantly and as equal partners. There is also a development opportunity for regions with a high potential of renewable energies.

As an industrial state, Germany has played a major role in climate change and global resource use. The resulting prosperity, as well as the technological know-how, carry an obligation for a particular commitment to an integrated and systemic climate and resource protection policy.

Ambitious goals

In order to limit climate change and global warming, ambitious and comprehensive targets and measures for climate protection and resource conservation are needed. UBA therefore considers it necessary for the Federal Government to set ambitious compulsory targets for climate protection in 2050, the reduction of greenhouse gases by 95 % in comparison to 1990, and in the conservation of resources – a substantial reductions in resource consumption. In international discussion, a target corridor of 3 to 8 tonnes per capita and year is proposed [1]. The transformation pathway should be

1 See: (Lehmann und Schmidt-Bleek 1993a, Schmidt-Bleek 1993b); (Bringezu 2015b, IRP 2014f, Fischer-Kowalski, et al. 2011a), and the decision of the G7 of Elmau und Toyama (BMUB 2016h) and the G20 of Hamburg (G20 Germany 2017 2017m).

carefully designed to ensure the security of long-term planning, investment and decision-making for all social and economic stakeholders.

Within the transformation pathway, the greenhouse gas mitigation target of 55 %, as set out in the climate protection plan and the energy concept of the Federal Government up to 2030, will be regarded as a minimum contribution for Germany's continuous development towards a sustainable society, which cannot be allowed to fall short. A 95 % reduction by 2050 requires more ambitious reduction targets for 2030 and 2040.

In order to reduce the global use of raw materials to a sustainable level, industrialised countries such as Germany must significantly reduce their raw material use. In 2002, Germany was one of the first countries to set a concrete target for increasing raw material productivity and further developed it with the German Resource Efficiency Program (ProgRess). This must now also be ambitiously implemented for the period beyond 2030. In addition, it is necessary to significantly reduce the raw material demand and to set appropriate ambitious targets.

Exit from fossil energies

The renouncement of fossil energies is indispensable both from a climate protection and a resource conservation perspective. Retaining fossil energy carriers leads to a permanent increase in greenhouse gases in the atmosphere and an increase in raw material consumption. None of these can be continued indefinitely.

The largest greenhouse gas mitigation effects can still be achieved today in the power supply sector through the expansion of renewable energies. For national energy industry, this means that coal-fired power plants must be shut down as part of an orderly and rapid structural change. The reduction of lignite use must be linked to an orderly structural change in the German lignite regions. The structural change should cushion social hardships by opening up regional alternatives.

Renewable energy expansion corridors

Wind on- and offshore as well as photovoltaics are the main pillars of a renewable energy supply in Germany. The current expansion corridors do not meet the sectoral requirements needed for necessary

climate and resource protection, nor do they even suffice to reduce any foreseeable dismantling in the medium term. The essential greenhouse gas mitigation effects through the integration of sector coupling [2] techniques such as electromobility and Power to heat, can only be ensured if the expansion of renewable energies is significantly greater than the expansion targets previously laid down in the EEG.

Also from an industrial policy perspective and for planning clarity, a clear and permanent increase in the expansion corridors is necessary which takes into account steady expansion and also possible adjustment frictions due to the dismantling or the repowering of installations. It is only in this way that the provision of raw materials directly linked to the construction of this infrastructure can be secured and that planning security and future viability can also be ensured in these economic areas. In the case of a delayed and time-consuming expansion of renewable energies by 2050, in order to achieve the greenhouse gas reduction target, high to very high raw material demands with correspondingly significant economic policy implications for the extraction of raw materials would probably occur.

And lastly, only through a steady expansion of renewable energies can an orderly reconstruction or dismantling of the fossil-based system take place.

Energy efficiency and energy efficient sector coupling
Efficient sector coupling, i. e. the substitution of fossil energy carriers by direct or indirect use of electricity over all fields of application, is a central pillar of climate protection and resource protection in addition to the expansion of renewable energies and the exploitation of existing energy efficiency potentials. Retaining today's techniques such as internal combustion engines, and a "one-to-one" substitution of fossil energy carriers by renewable energy carriers (PtG/PtL) would lead to significantly higher electricity demands and raw material use.

The integration of sector coupling techniques and the corresponding reconstruction of the associated infrastructure should take place in the transformation

2 Sector coupling refers to the stronger integration of the electricity, heat, fuel, power and raw materials markets. Sector coupling enables the direct or indirect use of renewable electricity to supply all fields of application in a greenhouse gas-neutral manner or to completely substitute fossil energy carriers and raw materials. Sector coupling increases flexibility in the electricity system, thus supporting the integration of fluctuating renewable electricity generation.

pathway according to their substitution potential. The restructuring of the energy supply must therefore go hand in hand with restructuring in the fields of application. This means that PtX techniques such as electromobility and Power to heat, especially in connection to heat pumps, should be used at an early stage as they already have a positive effect on the climate. In industry too, the integration of PtX techniques, and in particular Power to heat, which are often associated with the conversion of process technologies, is of great importance for climate protection and should be advanced through corresponding research and development projects.

In order to limit the necessary total electricity demand and thus the renewable energy installations as well as their raw material use, energy saving and efficiency potentials should be consistently developed across all energy applications and wherever possible, the fields of application should be switched to direct electricity use. The use of regenerative energy carriers from PtG and PtL techniques must be reduced to a minimum to meet the requirements of energy efficiency and resource conservation.

Similarly, in the course of the transformation process, hydrocarbons from PtG/PtL processes must also be used at an early stage where they are necessary in the context of long-term greenhouse gas reduction targets. In real terms, this involves the use of long-lasting products in the relevant production processes of the chemical industry, from which energy can only be recovered at the end of a cascade use after 2050. There is also an urgent need for action for the early use of PtL energy carriers in aviation. Only in this way can the goal of the ICAO (International Civil Aviation Organisation) for greenhouse gas-neutral growth from 2020 onwards be guaranteed alongside global market-based measures, not through the use of biofuels from crop-based biomass.

Healthy eating

Greenhouse gas reductions in the agricultural sector can only be achieved to a certain extent through technical measures. In order to achieve the necessary reduction of at least 50 % by 2050, additional changes in production systems and above all a reduction in animal stocks are necessary. In order to avoid carbon leakage to other countries, the consumption of animal products, i. e. of meat, must be reduced to a level that corresponds to a healthy diet (for example, according to the recommendations of the German Society for Nutrition).

In relation to the nutritional system, this implies that animal husbandry for meat and milk production, as well as the entire transport, processing and disposal system, have to be adapted accordingly. Balanced, seasonal, regional and little pre-processed food can make an important contribution to both climate protection and resource conservation.

Exploiting raw material efficiency

Full exploitation of known resource efficiency potentials enables a clear and accelerated reduction in raw material use. More recently, with the adoption of the German Resource Efficiency Programme (ProgRess) in 2012 and its first update in 2016, research on resource-saving and resource-efficient production technologies and products has shown a wide range of potentials, and policy has steadily improved the necessary conditions for their implementation. Activities must be pursued ambitiously and also used to promote innovation in order to enable further efficiency improvements. At the same time, regulations and economic incentives must be increasingly taken into account, in particular to extend the service life, increase the use of secondary raw materials and to promote material substitution. As in the field of nutrition, future non-technical measures (such as change in consumption, "sharing economy") can contribute to this.

Technology choice determines raw material demand

The choice of relevant installation technology has a decisive influence on the raw materials required. Thus necessary raw material uses have to be taken into account, in particular in the transformation of the energy system, the necessary conversion to electromobility, the energetic renovation and the restructuring of the industrial process technologies. As has been shown, it is also necessary to find the right balance between climate protection and resource conservation with regard to the rate of expansion in order to minimise any raw material demand peaks and to develop the necessary techniques and infrastructure for the production of secondary raw materials. This is even more important in the case of a common international advancement to greenhouse gas neutrality, which is felt to be necessary. It is also essential to implement resource-efficient technical and planning solutions for resource-friendly urban and infrastructure development, in order to further reduce the demand especially for building minerals.

Continuation of this interdisciplinary research and research needs

This study makes an initial contribution to the discussion about combining climate and resource protection towards a greenhouse gas-neutral and resource-efficient Germany. This work and research will be continued within the framework of the interdisciplinary UBA project.

From our point of view, the following aspects should be taken into account:

- A combined assessment of climate and resource protection is necessary to meet the challenges of energy, resource and traffic transition. However, these are complex systems that require careful investigation of instruments and measures if there is a desire to prevent unwanted side effects.
- For work beyond the current scenario, other and further techniques and system constellations must be considered. Further investigations must be carried out on how and in what order or speed the combined development and conversion of the energy systems and fields of application can be organised and the techniques necessary for this implementation developed.
- It is necessary to focus on raw material demands and the possibilities for their reduction with regard the techniques, processes and products necessary for the transformation. Therefore, to continue this interdisciplinary study, UBA will vary the selection of relevant techniques in a further scenario ("GreenMe") and design further key areas on the basis of their raw material efficiency. It should also be taken into account how previously known advantages and disadvantages of technical measures for the reduction of greenhouse gas emissions and energy demands [3], which mainly result from the use of fossil energy carriers, are developing in a future renewable energy system.

3 The increased raw material demand for electric vehicles can also be attributed to the (fossil) energy demand in production. In contrast, the positive effects of building insulation can also be attributed to the raw material savings resulting from the reduced use of fossil energy carriers.

- Social aspects, including distribution issues and sustainable development perspectives, must be considered from the outset in the development of specific instruments in order to avoid creating undesirable problems.

- Ultimately, it is important to highlight the economic and social implications of both the acceptance and the necessary changes in the production and consumption patterns of such a profound transformation both nationally and internationally.

The work on the other scenarios of the interdisciplinary UBA project presented here is intended to contribute to the answer to the questions outlined above. In addition, UBA will continue to deal intensively with the Nexus Climate and Resource Conservation in the coming years, supported by further research projects and jointly with external partners. Questions of the necessary instrumentation of the transformation will have a particular focus.

Finally, it should be noted that this initial contribution has already demonstrated how climate and resource protection can work hand in hand on the pathway towards a greenhouse gas neutral and resource-efficient Germany. It is an impetus for the necessary systemic and integrated policy making in Nexus Climate and Resource Conservation.

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