Resource-Efficient Pathways towards Greenhouse-Gas-Neutrality – RESCUE

Summary Report

For our Environment

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Summary Report

The results of the scenario modeling shown in this report are based to a large extent on the research project “Transformationsprozess zum treibhausgasneutralen und ressourcenschonenden Deutschland” (engl. “Transformation process to a greenhouse-gas neutral and resource -efficient Germany”) (FKZ: 3715 41 115 0) carried out by a research consortium consisting of:

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Inhalt

Executive Summary

Global greenhouse gas (GHG) emissions continue to rise despite the implementation of various climate protection measures. In 2017, fossil GHG-emissions were with 37 Gigatons (Gt) about 63 % above 1990 levels (EK, 2019b). Furthermore, global materials extraction has accelerated in the last decades to more than 90 Gt in 2017 (a fifteen-fold increase compared to 1900, UNEP, 2019b). Already today, an estimated four out of nine planetary boundaries have been surpassed (i.e., climate change, altered biogeochemical cycles (phosphorus and nitrogen), land-system change, and biosphere integrity, Rockström et al., 2009; Steffen et al., 2015). Urgent action is needed to ensure that humanity preserves the life-giving functions of our natural environment. In order to face these challenges, a fundamental transformation across all societal groups and economic sectors is required.

Against this background and given the known interdependencies between climate protection and sustainable resource management, the RESCUE-study ("Resource-efficient Pathways towards Greenhouse-Gas-Neutrality") presented in this report analyzes six scenarios that describe possible transformation pathways towards a GHG-neutral and resource-efficient Germany in 2050. The scenarios focus on different levels of ambition towards achieving GHG-neutrality (GreenLate – slow transition, GreenSupreme – fast transition), enhanced material efficiency (GreenMe), and a wider implementation of sustainable life-styles (GreenLife).

In all Green-scenarios, the overall GHG mitigation target for 2030 of the German Climate Action Plan is reached, in particular due to the significant progress in the energy sector (however, not all individual sector targets are met). All Green-scenarios have in common that a transformation towards 100 % renewable energy (electricity, fuels, and feedstocks) takes place until 2050. By 2050, GHG-reductions of 95 % in GreenLate and 97 % in GreenSupreme are achieved which considers the GHG-emissions that are also accounted for in the climate targets of the German Federal Government. Through sustainable agriculture and forestry management (i.e., natural sinks), GreenLife and GreenSupreme achieve net zero emissions and even GreenLate comes close to this goal. The Green scenarios thus show that no carbon capture and storage (CCS) is required for GHG-neutrality in Germany. In order to develop along the lines of the Paris Agreement, national GHG-emissions should be reduced by at least 70 % by 2030 compared with 1990 levels as outlined in GreenSupreme.

The largest reductions in raw materials consumption (RMC) is associated with the phase-out of fossil energy carriers. Overall, in GreenLate the RMC can be reduced by 56 % compared to 2010. In GreenSupreme a reduction of RMC of up to 70 % is possible through a combination of measures targeting energy efficiency, recycling, material substitution, the use of innovative materials (e.g., textile-reinforced concrete), and sustainable lifestyles. However, the demand for certain raw materials that are central for the transformation towards a GHG-neutral and resource-efficient society are likely to increase (e.g., metals).

In conclusion, the results of the RESCUE study highlight that ambitious efforts both at national and international level, as well as enhanced international cooperation similar to the story line of the GreenSupreme scenario, are necessary in order to limit global warming to 1.5 °C above pre-industrial levels, and to achieve a globally equitable use of raw materials. Given current trends, this may appear to be a daunting task. Nevertheless, the study also shows that achieving GHG-neutrality and a sustainable level of raw materials use are still possible. However, for making this vision a reality, action must be taken now and every contribution (both from a production and consumption standpoint) must be seriously considered and utilized.

1 Introduction

Background

Natural resources such as raw materials (biomass, metals, non-metallic minerals, fossil fuels), water, land, and ecosystems provide the backbone of modern society. Their use enables the provisioning of feed and food as well as drinking water, housing and infrastructure, transportation, communication, and an almost infinite array of products and services. And their constantly increasing use has serious consequences. Already today, an estimated four out of nine planetary boundaries have been surpassed, irreversibly changing the functioning of major Earth system processes (such as climate change, altered biogeochemical cycles (phosphorus and nitrogen), land-system change, and biosphere integrity, Rockström et al., 2009; Steffen et al., 2015). Over the last few decades, a combination of changes in land and ocean uses, overexploitation and pollution, climate change, and invasive alien species have led to catastrophic declines in biodiversity as more than 1 million animal and plant species are now threatened with extinction (IPBES, 2019). Raw materials are particularly relevant here because their extraction and processing alone results in more than half of global greenhouse gas (GHG) emissions and over 90 % of global biodiversity loss and water stress (UNEP, 2019a). On the other hand, they play a central role in renewable energy technologies, sustainable building materials and infrastructure, modern communication systems, and low-carbon mobility (Mancini et al., 2019).

Global materials extraction has accelerated in the last decades from around 6 Gt (billion tonnes) in 1900 to more than 90 Gt in 2017 (UNEP, 2019b). Current scenario work by UNEP and the OECD estimates that this could further double to around 160 to 180 Gt by mid-century (Hatfield-Dodds et al., 2017; OECD, 2019; UNEP, 2019b). The sustainable use of raw materials is therefore fundamental to achieving the environmental and socio-economic targets set out in the United Nations' Agenda 2030.

Despite an increasing number of measures to mitigate climate change, global GHG-emissions have nevertheless increased from 27 to 49 Gt CO_2-equivalents (CO_{2eq}) between 1970 and 2010 (IPCC, 2014). Emissions from the burning of fossil fuels and from industrial processes contributed 78 % to total GHGs during this time period. As a result, the global average temperature has increased by 0.85 °C between 1880 and 2012 (IPCC, 2014). In 2018, the global mean temperature was found at approximately 0.79 °C above average temperatures during the 20th century and 1 °C above pre-industrial levels (UBA, 2017c). The UNFCCC's[1] Paris Agreement was adopted in 2015 with the aim to keep the increase in global average temperature to well below 2 °C above pre-industrial levels; and to limit the increase to 1.5 °C (UNFCCC, 2015). However, current policies presently in place around the world are insufficient and projected to result in about 3.3 °C warming above pre-industrial levels (Climate Action Tracker, 2019).

Policy framework and situation in Germany

The material wealth and economic prosperity of industrialized countries such as Germany is based to a large extent on the continued use of fossil energy carriers and other raw materials which are often sourced through global supply chains. Various policy frameworks and initiatives already exist to reduce resource consumption and slow climate change in Germany and the European Union (EU).

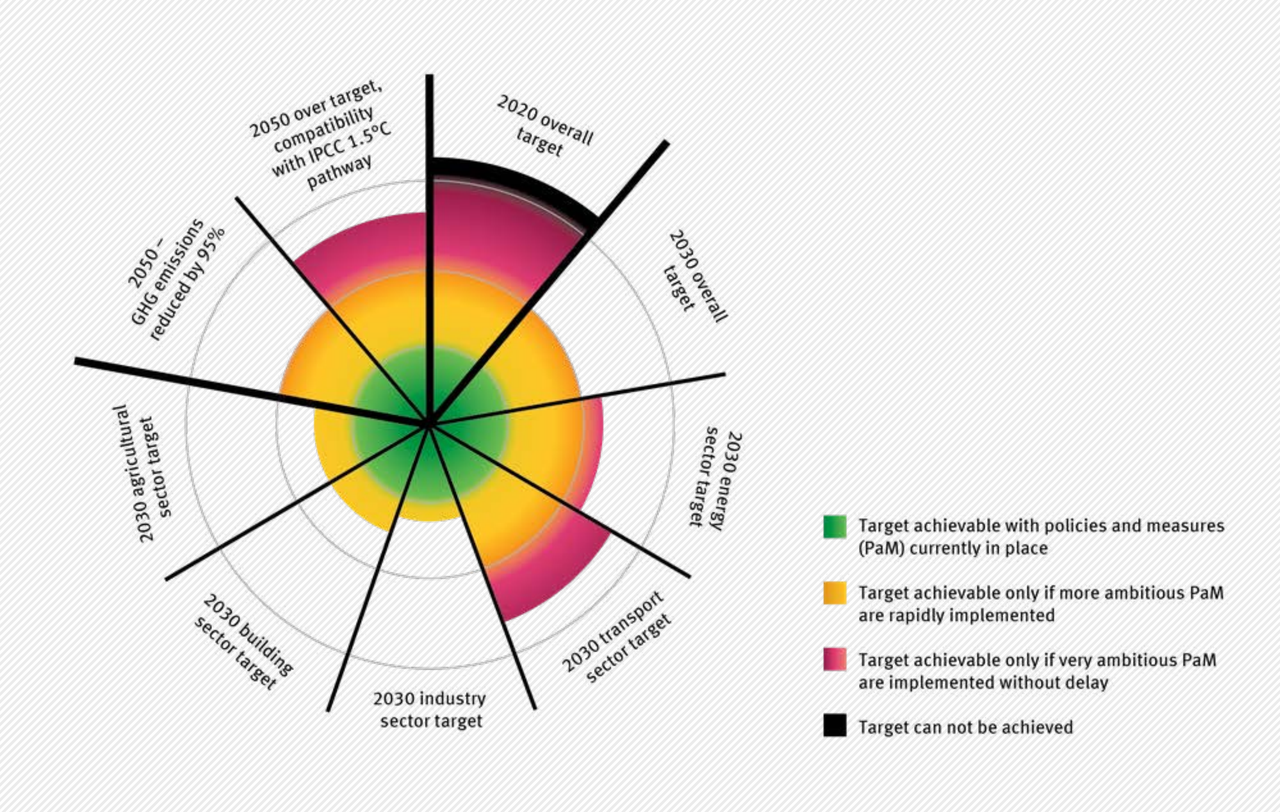
At the EU level, the **European Commission (EC)** published the 6th EU Environment Action Programme in 2012 which aims, amongst others, at decoupling environmental impacts from economic growth and refers specifically to climate protection as well as sustainable resource use (EP & Rat der Europäischen Union, 2002). The "Europe 2020 strategy" and its related flagship initiatives outline the EC's vision of promoting a resource efficient EU and supporting the shift towards a GHG-neutral economy (EK, 2010). Currently, the EC circular economy strategy (comprising, e.g., an action plan and monitoring framework) serves as the basis for resource efficiency policy at EU-level (EK, 2019a). The energy roadmap puts forth possible routes to decarbonize the energy system by 2050 (EK, 2011) and in November 2018 a strategic long-term vision for a climate-neutral economy by 2050 was published (EK, 2018). These policies also fundamentally shape climate and resource policy in Germany.

With regard to **climate protection targets**, the German government has committed to GHG-emissions reductions of -80 to -95 % until 2050 in comparison to 1990 levels (BMWi, 2010). In

1 United Nations Framework Convention on Climate Change (UNFCCC).

Figure 1

Qualitative assessment of the likelihood to reach the GHG-emissions reductions as specified in the German Climate Action Plan 2050



Note: The "Eckpunkte für das Klimaschutzprogramm 2030" (Bundesregierung, 2019) presented by the Federal Government in September 2019 specifies "greenhouse gas neutrality" by 2050 as a new environmental action target for Germany. Additionally, measures to meet the 2030 targets are described. However, at the time of finalizing this report, the exact details of the underlying policy measures are not yet known and could therefore not be considered in the figure.

Source: Umweltbundesamt

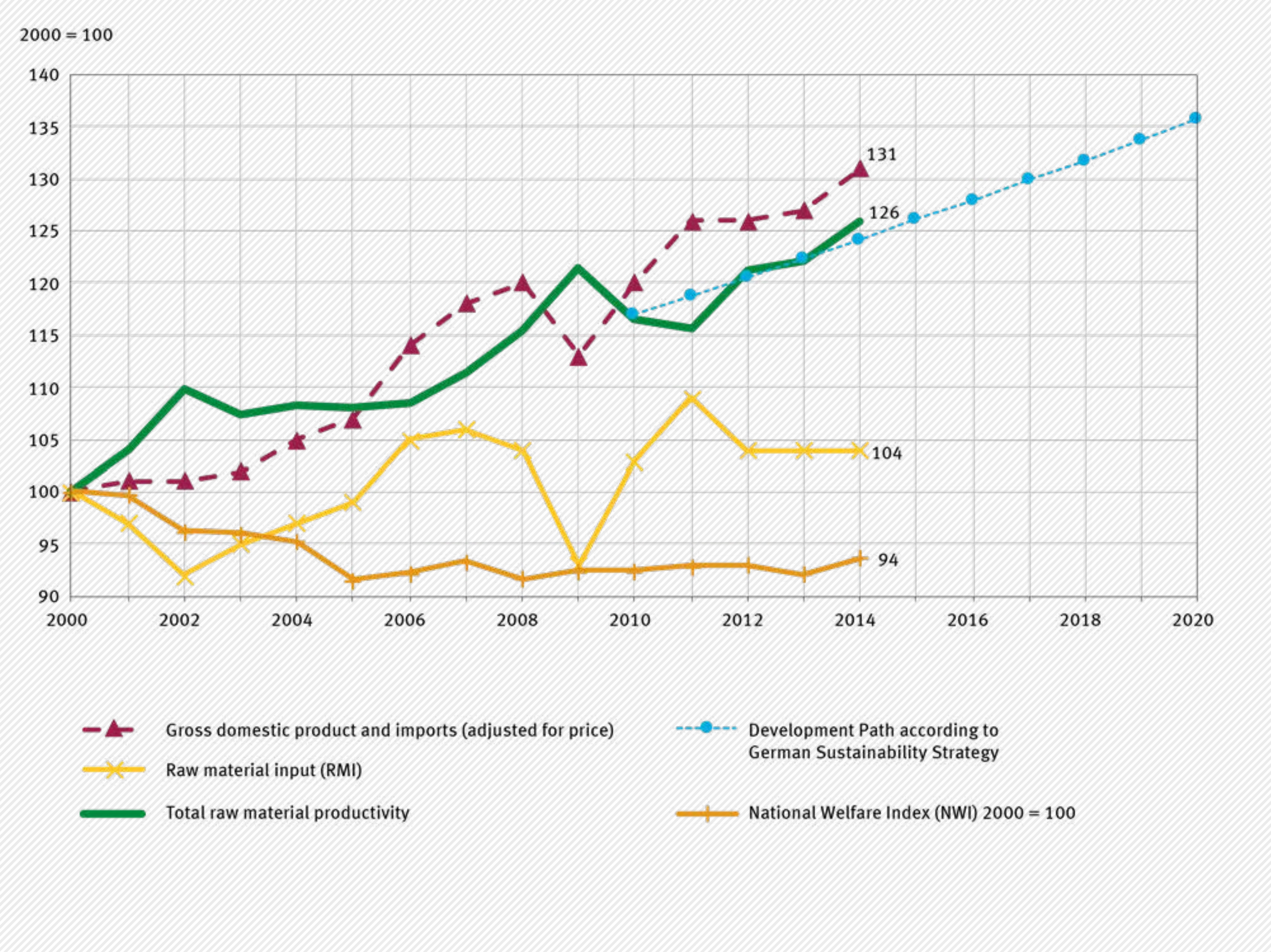
particular, the Climate Protection Plan 2050 defines the milestone target of a GHG emission reduction of at least 55 % by 2030 compared to 1990 and the necessary reduction contributions of the individual sectors to achieve this target (BMU, 2016). The German government has set "greenhouse gas neutrality" as a new environmental action target for Germany by 2050 with the "Eckpunkte für das Klimaschutzprogramm 2030" (Bundesregierung, 2019) presented in September 2019.

Looking at current trends, territorial GHG-emissions were reduced from 1,251 million tonnes (MT) in 1990 to 907 MT in 2017 (reduction of 28 %). First estimates indicate that in 2018 GHG-emissions equaled 866 MT which translates into a further decrease in territorial GHG-emissions of 4.5 % compared with the previous year. The largest GHG-reductions since 1990 took place in the chemicals industry (-80 %) and in waste and waste water (-73 %) (UBA, 2019a). Only the transport sector showed an increase compared with 1990 level (around 2 %). However, despite the overall emissions reductions in most sectors in recent years, reaching the climate targets of the Climate Action Plan 2050 requires substantial additional efforts and seems increasingly challenging for a number of sectors and targets initially proposed (Figure 1).

With regard to **sustainable resource use**, Germany already proposed in its 2002 Sustainable Development Strategy to decouple the use of natural resources from economic growth (Bundesregierung, 2002). Building on this, the German Resource Efficiency Programme (ProgRess), adopted in 2012, specifies targets, guiding principles, and approaches to the conservation of natural resources (BMU, 2012). Among others, its objective are: (1) to decouple economic growth as far as possible from resource consumption and reduce the associated environmental burdens, and (2) to make the German economy more future-proof and competitive, thus promoting stable employment and social cohesion

Figure 2

Total raw material productivity, economic growth, and national welfare index* during the period 2000 to 2014



* While GDP provides a measure of the performance of an economy, it does not measure larger social welfare. Hence, the national welfare index (NWI) (UBA, 2019d) is shown as a complementary measure. In contrast to GDP, the NWI decreased between 2000 and 2005 and has since then been close to the value it already reached in 1992, but started to increase slightly from 2013 on.

Source: Umweltbundesamt based on data from UBA, 2018, 2019d

(BMU, 2019c). With the first update in 2016 (BMUB, 2016), ProgRess is also increasingly focusing on the interactions with other environmental policies, in particular climate protection.

The lead indicator of German resource politics is the "Total Raw Materials Productivity"[2] which compares the value of all goods submitted for final use (in EUR, price adjusted) relative to the mass of the raw materials used domestically and abroad for their production (in tonnes) (Figure 2). The denominator of the indicator accounts for both abiotic and biotic material uses.

2 Total raw material productivity = (GDP + imports)/RMI, with GDP: Gross Domestic Product and RMI: Raw Material Input. In the indicator, imports are taken into account not only by weight of imported goods but with the associated total primary raw material inputs (Raw Material Equivalents = RME).

Total raw material productivity in Germany increased by 26 % between 2000 and 2014, mainly due to the significant growth in gross domestic product (GDP) and import values. However, the use of primary materials increased by 4 % over the same time period and amounted to 2.64 billion tonnes (Gigatons = Gt) in 2014. In 2014, around 1.3 Gt of this was used for consumption and investment in Germany, and a further 1.34 Gt of raw material equivalents were exported. In addition to the approximately 1.1 Gt of raw materials extracted in Germany in 2014, an additional 1.54 Gt of raw material equivalents in the form of semi-finished and finished goods and raw materials were imported. Germany`s target is to continue the observed annual growth of 1.5 % per year from 2000 to 2010 further until 2030. The increase is with 1.9 % currently beyond this target.

Basic idea and outlook to this project

The transformation towards a sustainable and future-oriented society that acts within the planetary boundaries is associated to the use of natural resources. The RESCUE study presented in this report explores different transformation pathways for Germany towards a raw material efficient and GHG-neutral society considering all economic sectors.

RESCUE builds upon the German Environment Agency`s study “Germany in 2050 – A greenhouse gas neutral country” (UBA, 2014) which showed that it is technically feasible to reduce national GHG-emissions by 95 % until 2050 compared to 1990. The rapid phase-out of fossil fuels via the widespread use of renewable energy across all sectors of the economy is key for this transformation. By switching completely to renewable energies and exploiting efficiency potentials, it is possible to reduce territorial GHG-emissions from energy supply and use (electricity, heat, transport)[3] to zero. A central building block is sector coupling with direct electricity use (e.g. power to heat, electro-mobility) or indirect use via power to gas (PtG) and power to liquid (PtL) for the provisioning of GHG-neutral fuels for transport, raw materials for the chemical industry, and GHG-enutral fuels for process heat in industry. However, for certain sectors such as agriculture and LULUCF (Land use, land-use change, and forestry), and parts of industry, GHG reductions are limited, so that base emissions remain. However, raw materials use was not considered in previous studies.

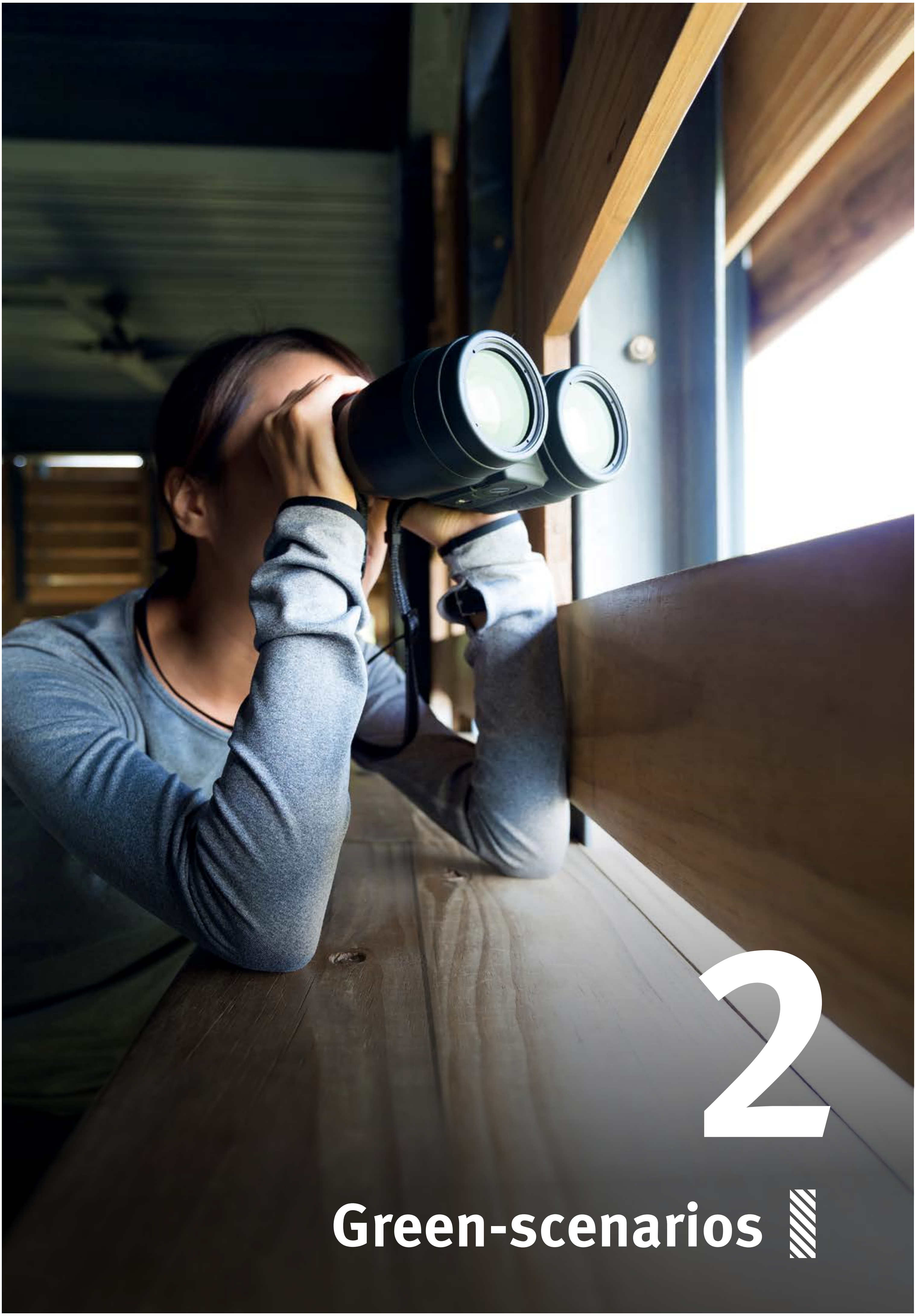
In the RESCUE project, ambitious climate protection and materials management are now being considered together across all economic sectors. This is done with six scenarios which show possible development paths for Germany until 2050. These include changes, e.g., to energy efficiency, material efficiency and product lifetimes, lifestyle changes, and economic growth. The aim is to (1) quantify the demand for raw materials (i.e., fossil fuels, metals, non-metallic minerals and biomass) associated with a GHG-neutral Germany until 2050, (2) capture the effects of individual measures and assumptions on raw material consumption and GHG-emissions, and (3) highlight possible synergies and obstacles between materials management and climate protection. Land use changes related to new settlements and transport infrastructure in Germany are partly considered. However, further aspects such as the availability of raw materials or other environmental impacts are only qualitatively discussed and present the basis for future studies.

Methods

In RESCUE[4], a combination of five models is used together with various sector-specific data to carry out quantitative assessments of GHG emissions and raw materials requirements in six scenarios between 2010 and 2050. Modeling of the transport sector is based on the Transport Emission Model (TREMOD) which analyzes the GHG emissions and energy uses of all means of passenger and freight transportation on a yearly basis (ifeu, 2019b; UBA, 2019c). The energy consumption for space heating and hot water in buildings under the changing scenarios assumptions is based on the Building Model (GEMOD) (ifeu, 2019a). Modeling of the agricultural sector is based on the Agriculture and LULUCF model (ALMOD, UBA, 2020a). The cross-sectoral build-up and optimization of the energy supply is based on the SCOPE model, which complies with the climate targets and ensures supply security and permanent coverage of demands in all applications and sectors (Fraunhofer IEE, 2016). We note that only a cost-based optimization of the energy sector is carried out in SCOPE and other societal and environmental costs are not included in the assessment. The economy-wide use of raw materials including the upstream raw material requirements and GHG-emissions (material and carbon footprints) are derived using the environmental and economic raw materials model (URMOD, ifeu, 2019c). Further information on the methodology and detailed results are provided in (UBA, 2020a, 2020b, 2020c, 2020d, 2020e).

3 The study only considered greenhouse gas emissions in Germany according to the annual National Inventory Report (NIR). Emissions from imported goods (carbon footprint) as well as emissions from exported goods are not considered.

4 The results presented are based largely on the UBA research project “Transformationsprozess zum treibhausgasneutralen und ressourcenschonenden Deutschland” (Forschungskennzahl 3715411150).



2

Green-scenarios

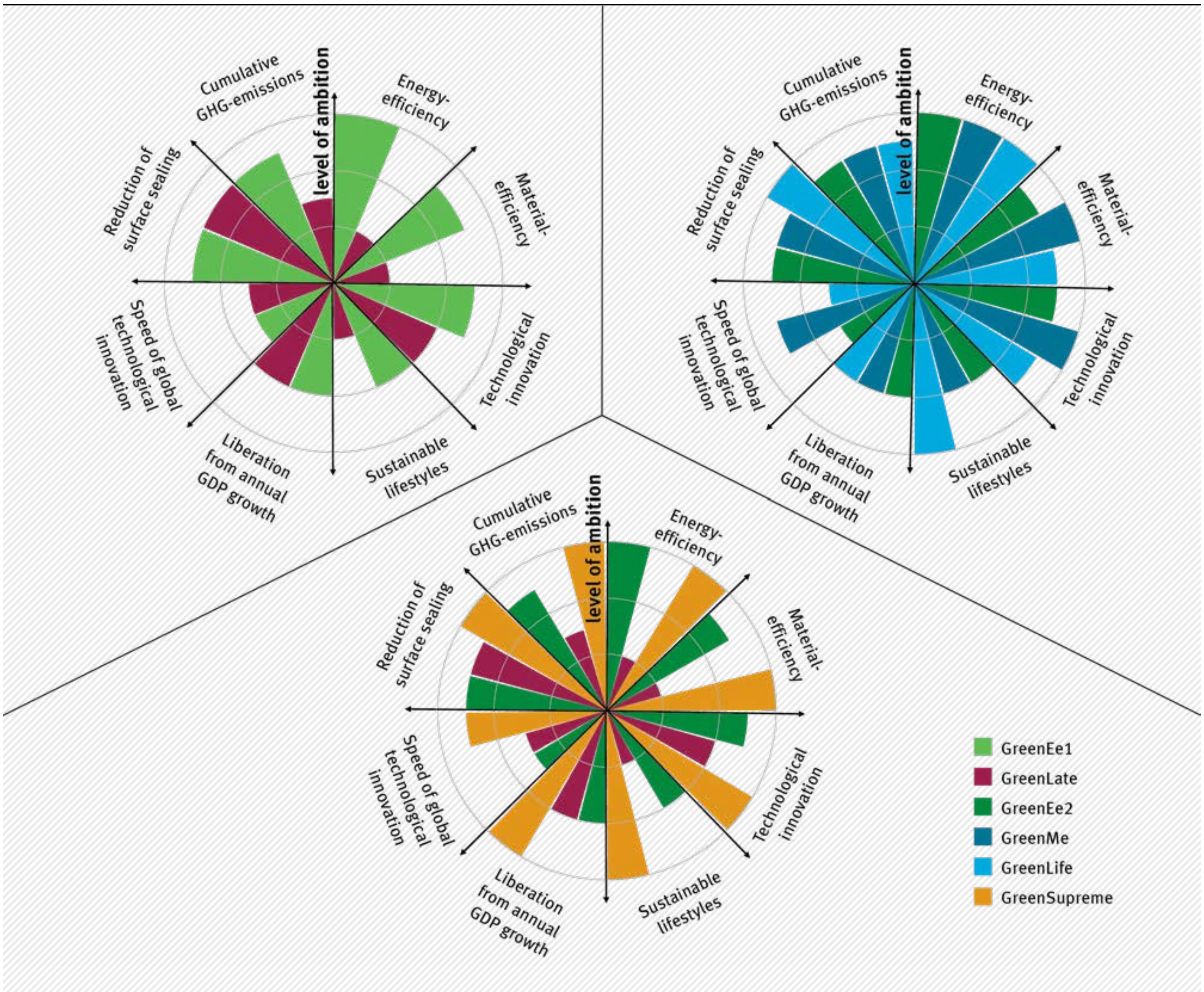
Against the background of the interdependencies and complexities of climate protection and natural resource conservation, six scenarios were developed and analyzed to map possible transformation pathways and solution spaces to maneuver toward a GHG-neutral and resource-efficient Germany. The results of the Green-scenarios describe possible pathways into the future and the associated GHG emissions (territorial perspective) and raw materials consumption (biomass, fossil fuels, metals, and non-metallic minerals) (consumption perspective including upstream raw materials requirements).

In all Green-scenarios, Germany continues to be a country with a high population density and strong industrial power, and is embedded in the European Union (EU) and the world. Today´s economic structures are assumed not to change fundamentally until 2050. Innovative information- and telecommunication technologies and digitalization are an integral part of society and in all economic sectors. The necessary infrastructures are planned and implemented in a timely manner to enable the transformation until 2050.

A common understanding by all societal groups exists that climate protection, decarbonization, energy savings, and resource conservation are necessary key characteristics going forward. Furthermore, all scenarios represent target scenarios that meet the GHG reduction targets of -55 % in 2030 and -95 % in 2050 compared to 1990 levels (BMU, 2016). However, the individual development paths to achieve these targets differ by scenario.

Figure 3

Comparison of the different parameters of the six GREEN-scenarios in RESCUE



Source: Umweltbundesamt

Among the key parameters of all Green-scenarios is the demographic development in Germany. All scenarios follow option V1 of the German Statistical Office according to which the population changes from currently 83 million people to about 72 million people in 2050 (Statistisches Bundesamt, 2015). A gradual reduction in infrastructure projects and building activities is assumed which avoids new additional soil sealing by 2050.

In all scenarios, the energy system is gradually retrofitted and based entirely on renewable energy by 2050 in which sector coupling[5], i.e., the direct or indirect use of renewable electricity for heat (power-to-heat (PtH), fuels (power-to-gas/liquids (PtG and PtL), and chemicals (power-to-chemicals (PtC)), allows the complete substitution of fossil fuels. Improvements in energy efficiency in all sectors (e.g., transport, industry, and buildings) combined with sector coupling and direct electricity use goes hand in hand with the expansion of renewable energy. Nuclear power and carbon capture and storage (CCS) technologies are not considered as they are prone to yet non-manageable environmental risks (UBA, 2015a) and, therefore, do not represent sustainable future strategies for Germany.

These overarching framework conditions and targets allow a comparison of the GHG-emissions and raw materials consumption associated with implementing the six scenario story lines. The effect of varying individual scenario parameters (see below) can be examined. The Green-scenarios presented in this study aim specifically at highlighting the potentials and interdependencies of differing levels of ambition towards GHG-neutrality (Green, Late, GreenSupreme), increased material efficiency (GreenMe), and the widespread implementation of more sustainable life-styles (GreenLife). Figure 3 provides an overview of the most important scenario parameters and how they differ by scenario. A short description of each individual Green-scenario is given below. Additional information are available in the detailed RESCUE fullreport (UBA, 2019e).

5 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.

GreenEe1 and Ee2

The two GreenEe scenarios stand for “Germany – resource efficient and greenhouse gas neutral – Energy efficiency” and focus on the implementation of energy efficiency measures across all sectors. In the scenario, it is assumed that a common understanding of the importance of climate protection/decarbonization, energy savings, and resource conservation exists among German citizens and this attitude increases over time, and is reflected in the political framework conditions. Other countries in the world follow Germany´s developments but at a slower pace (~10-year time delay) which means that the global development of renewable energy markets is possible and carbon leakage[6] is avoided. While in the GreenEe1 scenario, the domestic production capacities and therefore exports are continuously increasing, in GreenEe2 a more balanced trade situation is assumed, i.e., imports and exports converge and domestic production capacities decrease. Nevertheless, higher quality products and innovation continue in moderate economic growth in both scenarios at an average of 0.7 %.

Energy supply in 2050 is completely based on renewables and, where technically feasible, sector coupling enables the use of electricity across all fields of application. Energy efficiency improvements reduce the overall demand for energy in all sectors (e.g., transport, industry, and building and housing). If possible, renewable electricity is directly used. By 2050, for example, the industry has switched mostly to electricity-based process heat. In particular, the rapid decarbonization of the electricity sector proceeds quickly so that the integration of sector coupling technologies and a restructuring of the various sectors can take place simultaneously. Digitalization supports the optimization of energy supply and demand systems in order to reduce back-up capacities. Similar to today´s situation, energy imports to Germany consists mostly of fuels. By 2050, all fuel imports are fully based on renewables (i.e., PtX facilities built-up abroad). Only applications for which no direct electricity use is possible (e.g., fuels for aviation, heavy-duty vehicles, and certain industrial applications) use fuels produced via PtX routes.

6 When countries transfer the production of goods to countries with more relaxed emission limits.

In industry, the restructuring towards energy-efficient process technologies based on renewables is complemented by a reduction in process-based emissions to the currently known technically possible level. The transition of the transport sector comprises an increasing share of electric vehicles for personal mobility and public transportation until 2050. Transport avoidance is facilitated by intelligent logistics in freight transport and the 'city of short distances' in personal transport. In addition to technical measures, healthier eating habits of the population lead to reduced livestock in Germany. The development towards mixed forests is continued over time thus preserving the forest as a net carbon sink. Biodiversity protection is increasingly integrated into forest management, supported by the expansion of protected land areas for natural forest developments. Increasing use of secondary raw materials and material substitution in particular in the metals industry, chemical industry, and building sector fosters materials efficiency. Following the demographic trends, per capita living space requirement rise until 2030 and total living space is subsequently reduced to the 2010 level. Land-take for transport and settlements is reduced to 20 ha/day by 2030 and moves towards net zero in the subsequent decades until 2050.

GreenLate

In the GreenLate scenario ("Germany – resource efficient and greenhouse gas neutral – Late transition"), GHG emissions are cut by 95 % as well. Germany remains an export-oriented and strong industrial power with a modern and efficient society. However, the transitions process sets in at a later point in time compared to GreenEe, thus highlighting the challenges of late actions. Consequently, GHG emissions have to be reduced more radically and within a shorter period of time. This requires enormous structural changes and investments, especially towards the end of the first half of the century. As a result, improvements in energy- and materials-efficiency are lower than in the other scenarios. This trend is also visible at the international stage (with a ~10-year delay).

In 2050, energy supply is based completely on renewable sources. However, the energy demand is higher than in the other Green-scenarios as conventional technologies with lower efficiencies are still widely in use due to the late transition. Until 2050, efficient and power-based technologies for sector coupling can only be implemented for applications with short renewal cycles, or in areas for which high investment incentives exist. For example, the transition towards electric mobility for private transport is implemented late. This means that by 2050 a large number of conventional technologies are still in operation, e.g., in transport, space heating, and process heat supply. Similarly, measures targeting traffic reduction and relocation are implemented in the last years prior to 2050. The trend towards healthier diets only starts around 2025 and results in a higher share of livestock usage compared to the other scenarios.

GreenMe

The GreenMe scenario ("Germany – resource efficient and greenhouse gas neutral – Material efficiency") focuses on technical options to increase materials efficiency (i.e., the ratio between a certain benefit or result and the (raw) materials use required for this). Globally, it is assumed that other countries follow this trend at the same speed of technological development (no delay compared to the other Green-scenarios). Carbon leakage is thus avoided. Germany continues to be embedded in international trade in which imports and exports are balanced (similar to the GreenEe2 scenario).

The restructuring of the energy system and of sectors such as transport, industry, and building and housing develops in analogy to the GreenEe2 scenario. However, technologies with a smaller material footprint (measured by RMC) are favored. For example, for photovoltaic (PV) systems an increasing number of roof-top thin-film PV modules are installed, which have a smaller material footprint and land requirements than conventional ground-based PV systems. Similarly, foundations, elevations, and wind towers are designed with durability in mind, so that their service life can be significantly increased. A variety of additional material efficiency measures are implemented. These include, e.g., the light weighting of vehicles, use of alternative materials such as textile-reinforced concrete for construction, widespread use of wooden buildings, or the use of biotic materials as insulating materials in construction. Assumptions with regard to agriculture and healthy diets follow the two GreenEe scenarios.

GreenLife

The GreenLife-scenario ("Germany – resource efficient and greenhouse gas neutral – lifestyle changes") analyzes how changes of lifestyle and behavior, in addition to technical measures, influence GHG emissions and raw material consumption. Current trends as well as smaller niche developments for a more environmentally friendly behavior are scaled up to build this scenario.

The demand for durable and repairable products results in innovation in the production- and service sectors. The willingness of each individual to switch to sustainable lifestyles leads to a reduction in the demand for large living space and the retrofitting of larger homes into sub-units. Shared housing options are widely accepted and implemented. The share of multi-family homes in the building inventory increases. As a result, the demand for per-capita living space decreases and land-take is already reduced to 10 ha/day by 2030 and moves towards net zero until 2050. Resource-efficient construction is widely implemented and the share of wooden buildings increases.

With regards to mobility, domestic flights are becoming less attractive and by 2050 only ground transportation takes place within Germany (for both private and business trips). Holiday flights to international destinations are increasingly replaced by domestic trips and as a result flight traffic in 2050 is only slightly above 2010 levels.

Increasing urbanization results in the use of fewer cars. Instead, a mix of public transport, walking and biking, and ridesharing is used. Electro-mobility and electrified public transport outside of urban centers is widely implemented by 2050. As a result, the use of private vehicles in urban areas is negligible by 2050.

Increased awareness of environmental and health issues is an important factor for moving towards more sustainable diets. Food waste is avoided as far as possible and regional and seasonal foods are processed. Animal products are consumed much faster than in the other Green-scenarios, so that livestock in Germany decreases faster and more strongly.

The technical measures, such as the transformation of the energy system or the integration of new efficient technologies in industry, mobility and buildings, are the same as in GreenEe1 and GreenEe2.

GreenSupreme

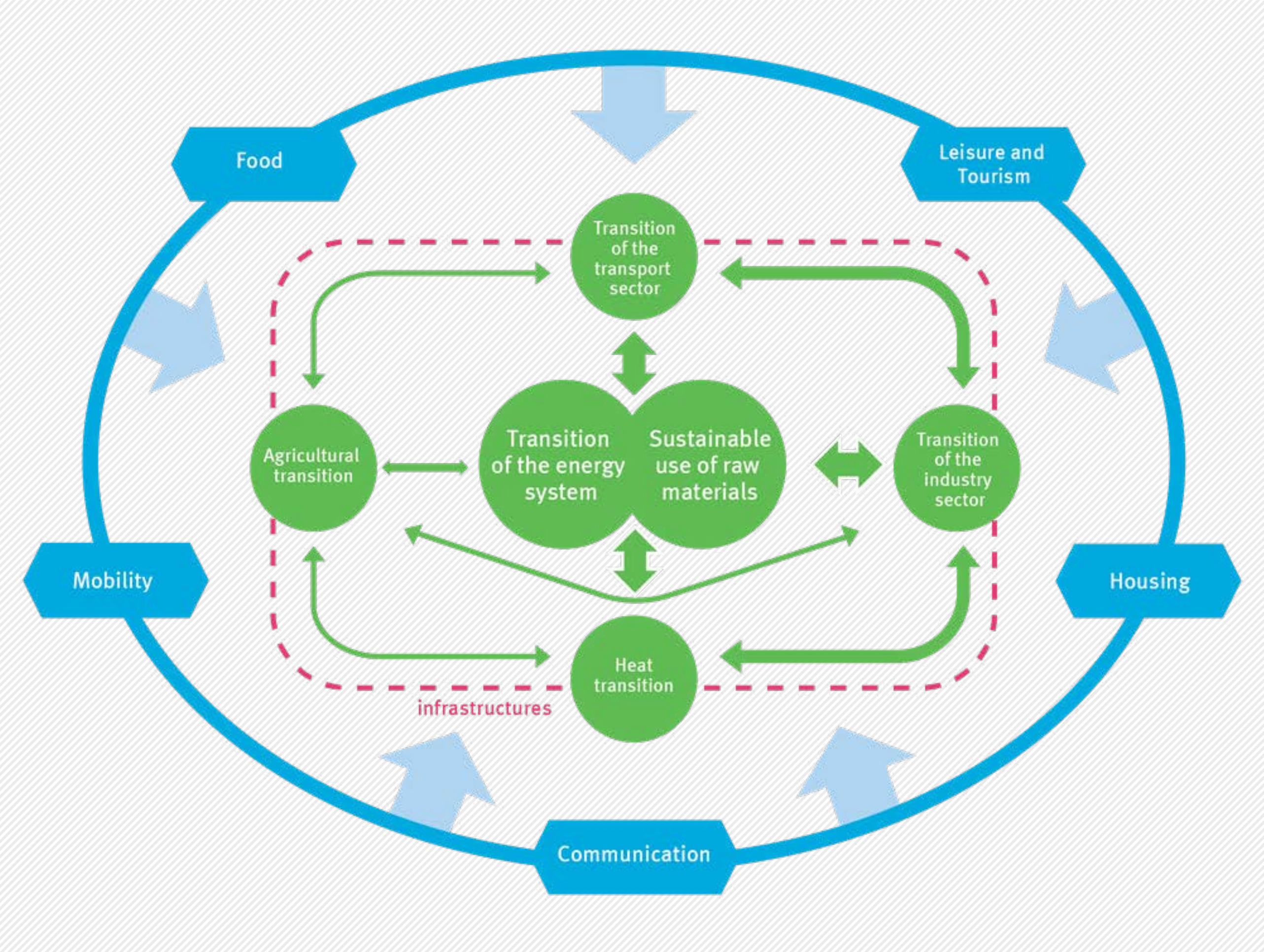
In GreenSupreme ("Germany – resource efficient and greenhouse gas neutral – Minimizing future GHG emissions and raw material consumption"), the most effective measures from the previous Green-scenarios are combined in order to further reduce GHG emissions and raw material consumption up to 2050. In a nutshell, this includes a combination of measures from GreenMe on material efficiency together with assumptions from GreenLife on sustainable and healthy lifestyles. In contrast to the other scenarios, which assume an average annual GDP growth of around 0.7 %, in GreenSupreme the annual GDP growth is assumed to be zero after 2030.

3 Action fields

Systemic change across all sectors and societal groups is necessary to enable the transition to a GHG-neutral and resource-efficient society. Various interdependencies exist between the supply of energy and raw materials and the demand for these via production, infrastructure needs, and individual consumption patterns (Figure 4). These interdependencies differ in their magnitude as shown by the width of the arrows in the figure. The needs and consumption patterns initiated by activities such as leisure and tourism, housing, communication, mobility, and food (blue hexagons) trigger a demand for products and services. Providing these demands requires energy and resources (e.g., raw materials, land area, and water) and results in associated environmental (e.g., GHG-emissions) as well as social impacts (e.g., corruption, violent conflicts, etc.). Transforming the energy supply ("Energiewende") and underlying materials system ("Rohstoffwende") (green circles at the center) towards increased sustainability is directly linked to the transformation of individual sectors (small green circles) and the other way around. This highlights that the transformation of the economy has to take place with both climate and resource protection in mind. The speed at which such a transformation of the energy and materials system is implemented has to consider possible peaks in raw materials demands and cumulative GHG-emissions along the transformation path and set incentives to ensure the long-term effectiveness of political measures and the readiness of necessary infrastructures and technologies. The following chapters describe the individual sectors/ application areas required for a transformation to a resource-efficient and GHG-neutral society.

Figure 4

Schematic illustration of the interactions between different transformation pathways for by GHG source categories



Source: Umweltbundesamt

3.1 Energy system

Energy generation in Germany is based mainly on fossil fuels. In 2018, 84 % of all GHG-emissions in Germany were caused in the energy sector. As a result, the restructuring of the energy system plays a key role in the mitigation of climate change. As a certain amount of GHG-emissions from agriculture and the industrial sector will remain, based on the mitigation options known today, it will be necessary to avoid energy-related GHG-emissions completely. This can be achieved if:

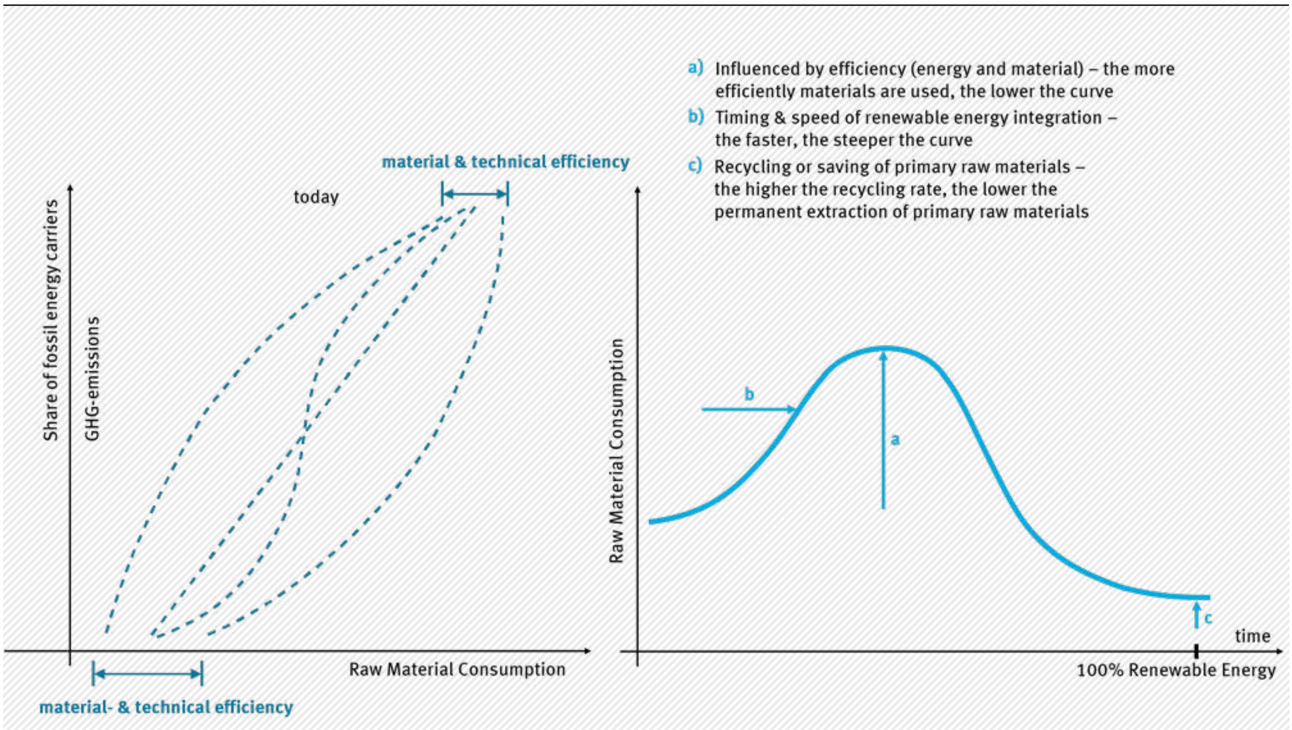
- energy and natural resources are used more efficiently across all sectors and energy demand is reduced,
- energy generation is switched to renewable energy carriers,
- sector coupling technologies are integrated in a way to increase energy efficiency, and
- energy infrastructure is adjusted to the requirements of the new energy system.

The German Environment Agency already illustrated in an earlier study (UBA, 2010, 2014, 2019b) that this kind of energy transition ("Energiewende") does neither require the use of carbon capture and storage (CCS) technologies or nuclear energy, nor the cultivation of biomass for energy generation.

When fossil energy carriers are completely substituted by renewable energy, energy-related GHG-emissions can be reduced to zero. At the same time, fossil energy carriers which currently make up about 30 % of primary raw materials consumption, can be reduced thereby lowering materials use (see Figure 5, on the left). Due to growth effects, functional losses, downcycling, and dissipative uses of materials, primary raw materials use cannot be completely avoided (Cullen, 2017; Mayer et al., 2019). The amount of primary raw materials required is influenced by factors such as, e.g., the energy and materials efficiency during production, the durability and repairability during the use phase, and the level of collection and recycling at end-of-life which can serve as an input into the economy. However, constructing an energy system based on renewables

Figure 5

Qualitative presentation of changes in greenhouse gas emissions and raw material consumption from energy supply (left) and qualitative presentation of raw material consumption as a function of the restructuring of the energy system to renewable energies (right)



Source: Umweltbundesamt

Table 1

Characteristics of the energy sector in the different scenarios

	GreenEe1/ GreenEe2	GreenLate	GreenMe	GreenLife	GreenSupreme
Phasing out coal power plants	before 2040				until 2030
Total phase out of coal as a fuel	until 2050				until 2040
Speed for increasing the share of renewable energy	fast				very fast
Energy efficiency potential realized	very high	intermediate	very high	very high	very high
Energy demand reduced by adjusted consumer behavior (behavioral change)	high	medium	high	very high	very high
Material efficiency of technologies applied	high	medium	very high	high	very high

will temporarily increase the demand for primary raw material, especially for metals. The faster the share of renewable energies in the system will grow, the faster these raw materials will be consumed, as illustrated in Figure 5 on the right side, where a more speedy development of renewable energy installations resulting in a steeper increase of raw material use.

Energy efficiency, i.e., the energy demand across all sectors and material efficiency, i.e., the choice of technologies applied determine the amount (top point of the curve) of primary raw materials used. In the end, also in a renewable system a certain amount of primary raw materials will be consumed, as it is not possible from a technical perspective to fully recycle all materials used. The overall consumption of primary raw materials, however, is influenced by the level of recycled materials that serve as an input to the economy (see Figure 5, right side).

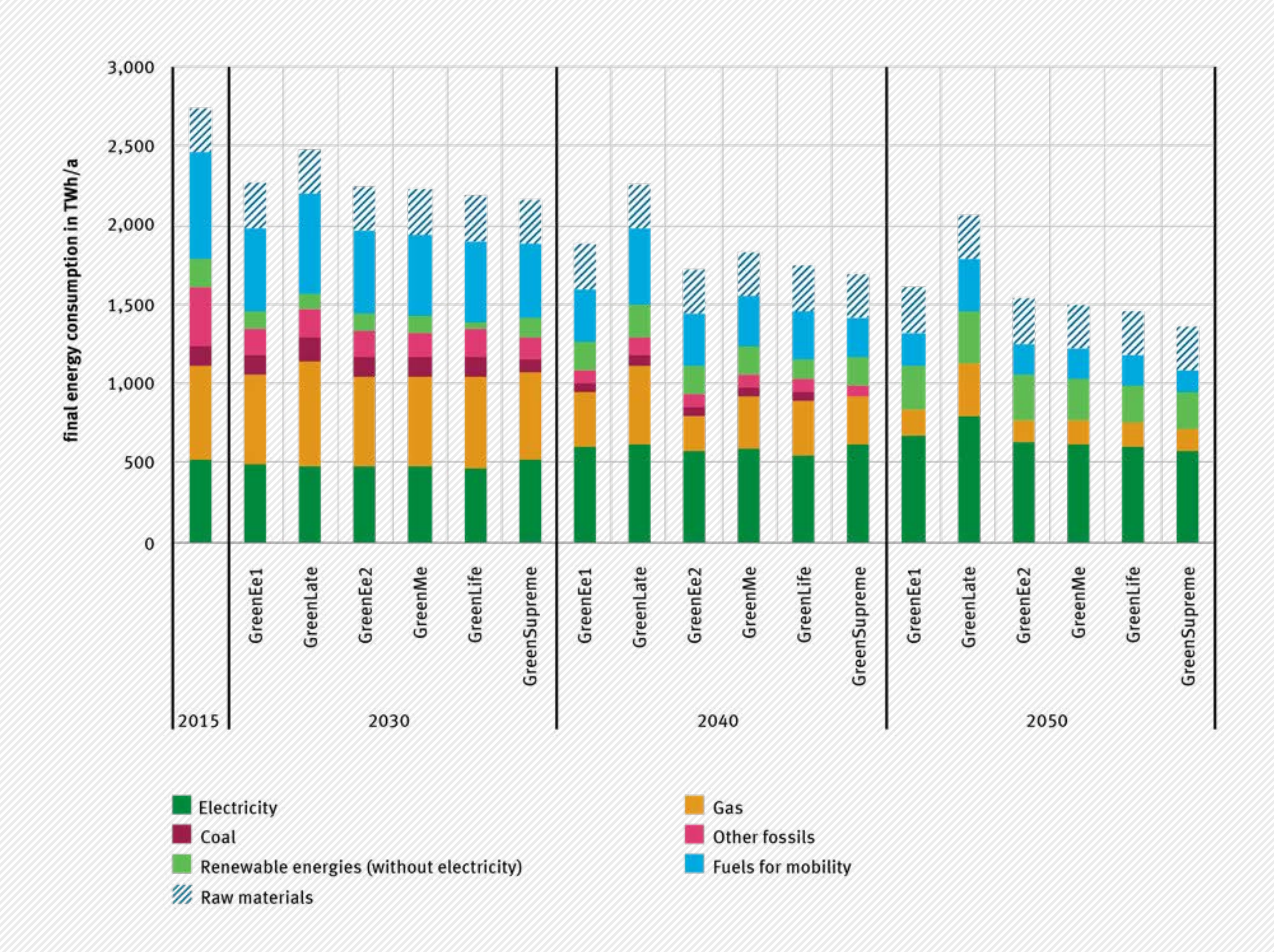
The Green-Scenarios have been constructed to reflect these influencing factors in an adequate way, illustrating a variety of potential solutions and the consequences related to different transitions pathways in the energy system. Table 1 provides an overview on the main characteristics of the energy system in each of the scenarios.

3.1.1 Final energy demand

The resulting energy demand in the different scenarios is summarized in Figure 6. It becomes evident that current energy demand is reduced by 50 per cent until 2050 in the GreenSupreme scenario, while this reduction equals only 25 per cent in the GreenLate scenario. Consequences of increasing direct electricity use by sector coupling techniques (PtX) are also visible in all Green-scenarios. In total, integration of power-to-heat (PtH) (across all sectors), electromobility and power-to-gas (PtG) and hydrogen-powered appliances cause a higher electricity demand, despite the power saving potential being realized at the same time. The way in which these power-to-X techniques are integrated into the energy system varies between the Green-scenarios. As a general rule, initially those sector coupling techniques will be applied that display a high GHG mitigation potential in order to advance GHG abatement (UBA, 2016b). GreenSupreme is a particularly ambitious scenario also in this respect as it assumes substitution of all fossil energy carriers by direct use of electricity produced from renewable energy by 2050. Already in 2040, coal ceases to be used both as an energy carrier and as a raw material (e.g., for steel production). In contrast, the development and application of low-carbon techniques lags behind in all sectors in the GreenLate scenario, particularly in the industrial sector and in heavy duty vehicle transport. The transition process is late but on the right track, so conventional

Figure 6

Trend in final energy consumption according to energy sources in the Green-scenarios



Notice: The energy sources electricity, fuels and gases as well as the non-energy demand are increasingly based on renewable energies. By 2050, all renewable energy requirements have been met.

Source: own figure based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

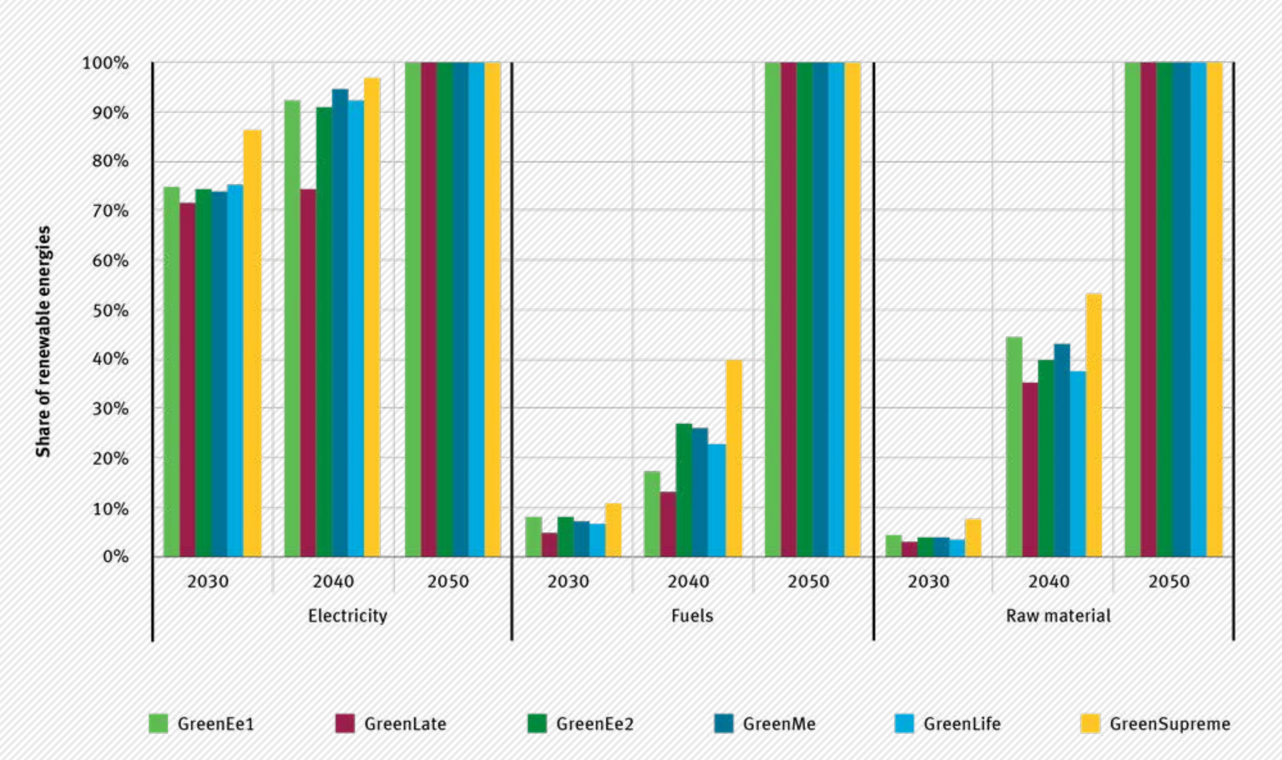
energy appliances are still in use by 2050, running on gaseous or liquid energy carriers on the basis of renewable energy. This way, GreenLate gives an impression on the consequences of less electrification in the different sectors.

Private households are able to use energy in a more efficient manner by energetically reconstructing and modernizing buildings, and by installing heat pumps or district heating systems. This way, energy demand can be significantly reduced by 2050. In GreenLate, energy demand is 33 per cent lower compared to the year 2015 and in GreenSupreme and GreenLife it is up to 59 per cent below 2015 values (UBA, 2019e). Throughout all Green-scenarios, coal is not used any more as an energy carrier in private households from 2030 onwards. In the manufacturing, trade, and services sector energy efficiency measures may reduce final energy demand by 19 per cent in GreenLate and by up to 40 per cent in GreenSupreme, compared to 2015. Except for the GreenLate scenario, gaseous energy carriers will not be used any longer by 2050 as the direct use of electricity is both more efficient and consequently less expensive compared to consuming methane produced in power-to-gas installations (UBA, 2019e). In the industry sector, the GreenLate scenario also displays the lowest reductions in final energy demand. In 2050, still about 900 TWh final energy[7] will be needed which is only 9 per cent below industries' final energy demand in the year 2015. In GreenSupreme, by contrast, a more ambitious approach to increase both energy and material efficiency, as well as a liberation from annual GDP growth, result in 33 per cent less final energy demand, with a remaining demand of

7 Including the non-energy demand for raw materials of 282 TWh.

Figure 7

Trends in the share of renewable energies in the energy supply for the various Green-scenarios



Notice: Fuels including international transports

Source: own figure based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

600 TWh[8] in 2050. The transport sector, in all Green-scenarios, is increasingly relying on electricity to the extent that electrically-driven technologies are available. In GreenLate, efficient sector coupling and, thus, the use of electricity as a fuel in transport and for heat generation happens at a later point in time, resulting in an untapped energy efficiency potential up to the year 2050 when compared to the other scenarios. Accordingly, GreenLate has the highest final energy demand among all Green-scenarios, namely 410 TWh in 2050. The share of liquid energy carriers is still at 72 per cent. In GreenSupreme, by comparison, a faster integration of electric mobility and a change in transport requirements result in a final energy demand of only 190 TWh, of which 45 per cent are made up by electricity.

With regard to GHG mitigation, all the Green-scenarios quickly substitute electricity from fossil fuels by electricity generated from renewable sources. Already by the year 2030 the share of electricity from renewables is above 70 per cent in all Green scenarios (Figure 7). GreenSupreme achieves a share of renewable electricity of more than 80 per cent in 2030. By 2040, in all scenarios except GreenLate the share of renewable electricity in gross electricity demand is higher than 90 per cent.

Already by the year 2030, all the scenarios require the import of hydrocarbons to be used as energy carriers in international air transport and in the chemical industry. However, raw materials as well as fuels for heating and transport are largely based on fossil materials up to the year 2040. Also in this regard, the high ambitions in the GreenSupreme scenario become obvious. By 2040 coal will be phased out both as an energy carrier and as a raw material. At the same time, renewable fuels produced by power-to-gas and -liquid will be used for national demand in transport early on, resulting in a 40 per cent share of renewable energy for fuels. The share of renewables in raw material consumption amounts to more than 50 per cent (UBA, 2019e).

8 Including the non-energy demand for raw materials of 282 TWh.

As a trend, the share of renewable raw materials grows faster than the share of renewable fuels for transport and heating. This is because raw materials used in the chemical industry become products that, in a circular economy, will be recycled multiple times before they are finally burned and used for energy generation. Accordingly, greenhouse gas emissions from raw materials are released into the atmosphere with some delay, while fuels are burned immediately nearly. Hence, a switch to renewable fuels shows immediately in the greenhouse gas inventory. In all Green-scenarios the switch to renewable energy will only be completed by 2050.

3.1.2 Electricity Supply

The substitution of fossil energy carriers by renewables and the resulting adjustment needs in the power generation system are at the core of climate and resource efficiency policies. In 2017, electricity generation from fossil fuels caused about 32 per cent of all GHG-emissions in Germany. The gradual phase-out of coal-fired power plants results in lower GHG-emissions and less resource consumption in the short to medium term. A carefully planned and systematic phase-out of coal-fired power plants is a prerequisite for a predictable and reliable structural change in lignite mining regions and has to be accompanied by concrete expansion plans for renewable energy. The shut-down of coal-fired power plants assumed here is comparable to the recommendations given to the German Federal Government by the Commission for Growth, Structural Change, and Employment (BMU, 2019a) shown in Figure 8.[9] With a steady and linear continuation of the shutdowns, the deadlines for coal-fired power generation in the Green-scenarios (except for GreenSupreme) are also within the scope of the Commission's recommendations. The GHG-emission reductions required in the scenarios until 2030 cause not only the shutdown of a number of coal-fired power plants. On top of that, the model reduces the number of full load hours for the remaining coal-fired power stations, so that for reasons of cost-efficiency a further reduction of capacity might occur. Full load hours of hard-coal fired power plants are on a similar scale like today. In total, the share of coal power generation (hard coal and lignite) in total gross electricity generation goes back from currently 34.4 per cent (BMWi, 2019) to a maximum of 14 per cent (74 TWh) in the year 2030. In GreenSupreme, already by the year 2030 no more electricity is generated from coal. Such a high level of ambition is required in order to abate GHG-emissions quickly to stay below the 1.5 °C level and to contribute to international efforts to curb global warming.

In contrast to coal-fired power stations, gas-fired power plants[10] will be needed for a longer time period to ensure a secure power supply. The modelling results in the Green-scenarios give a varied pictures, as no exogenous assumptions were made with regard to gas-fired power plants. With a less efficient pathway compared to the other scenarios, and a lower GHG-mitigation rate by 2040 in the energy sector, an expansion of gas-fired combined heat and power (CHP) installation can be expected in the GreenLate scenario, with a higher demand for gas turbines in the meantime. In 2050, the installed capacity of gas-fired power plants exceeds the one of today. Between 2030 and 2050, the scenarios GreenEe1, GreenEe2, GreenMe, and GreenLife show a significant reduction of gas-fired power plants, while between 2030 and 2040 an expansion of currently existing gas-fired CHP installations still occurs. By 2050, however, total capacity is below 5 GW and thereby lower than the capacity currently installed. In all Green-scenarios, full load hours of gas turbines are limited to a few hours, and gas fired CHP installations run on a significantly lower amount of full load hours, compared to today (UBA, 2019e).

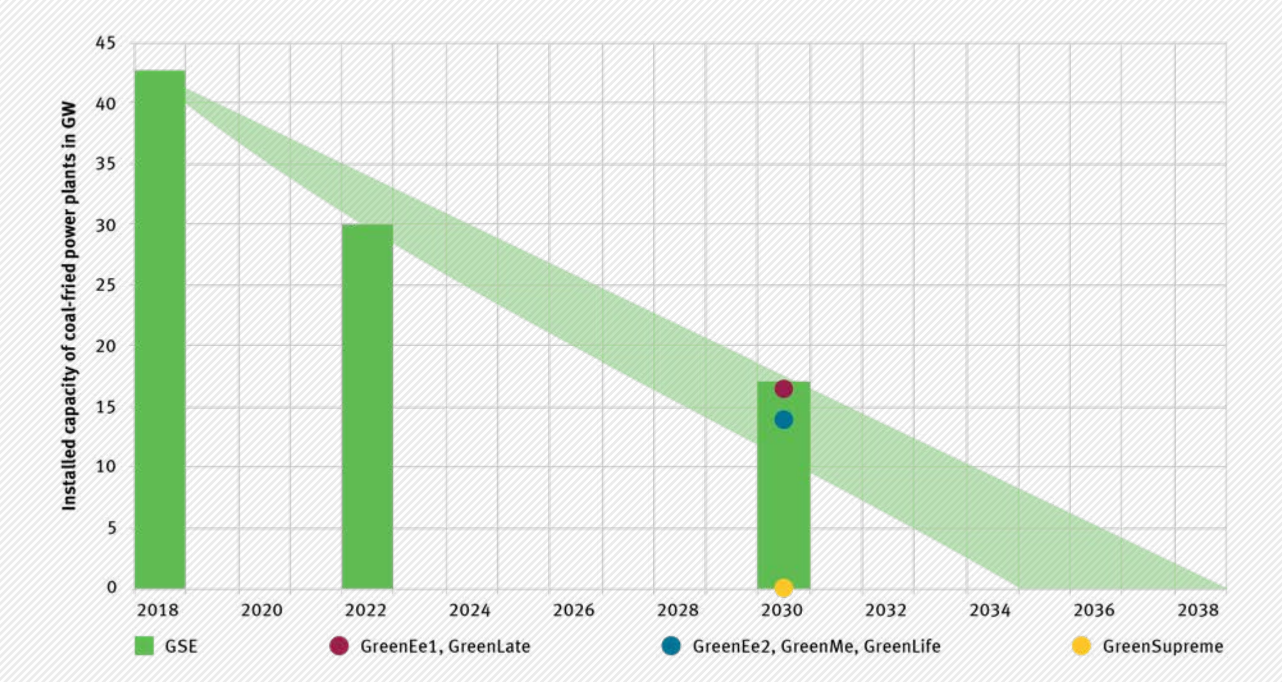
The expansion of renewable energy for electricity generation is influenced not only by the phase-out of fossil-fuel fired power plants and the envisaged reduction rate of GHGs, but also by the development of electricity demand. The latter is influenced by efficiency measures implemented as well as by the integration of sector coupling techniques. Another important factor includes the dismantling or repowering of existing renewable energy installations depending on their lifetimes. Wind power ashore and

9 All Green-scenarios assume that by 2030 only lignite power plants which have been in operation for less than 30 years will still be in use. The capacity of such plants amounts to almost 5.2 GW in total. In the GreenEe1 and the GreenLate scenarios, hard coal-fired power plants are shut down after 40 years in operation until the year 2030 which reduces the generation capacity to about 11 GW by 2030. The remaining Green-scenarios (i.e., GreenEe2, GreenMe, and GreenLife) assume identical years of operation for lignite and for hard coal-fired power plants. Consequently, the capacity of hard coal-fired power plants in these scenarios is 9 GW in 2030.

10 Gas-fired power plants are being increasingly based on renewable gases (via PtG) after 2040, see Chapter 5.2.3.1 in (UBA, 2019e).

Figure 8

Coal-fired power plants in the Green-scenarios compared to the recommendations of the Commission on Growth, Structural Change and Employment



Notice: GSE – Commission on Growth, Structural Change and Employment

Source: own figure based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

photovoltaics are the most important techniques. By 2030, generation capacity for wind power ashore grows to 82 GW in the GreenEe2-, GreenMe-, and GreenLife-scenarios, to almost 84 GW in GreenEe1, and to 88 GW in GreenLate. In GreenSupreme, up to 103 GW are required (Figure 9). Until 2050, generation capacity further increases to about 128 GW for all scenarios (except GreenLate where with 150 GW an even more ambitious expansion of renewable energy installations is necessary). By 2050, between 52 to 54 per cent of all electricity generation are based on wind energy ashore and in the GreenSupreme scenario this share equals even 57 per cent. The generation capacity of photovoltaics is doubled compared to currently installed capacity. The modelling results highlight that between 81 GW (GreenLate and GreenMe) and 104 GW (GreenSupreme) of photovoltaic will be installed by the year 2030. The installed PV-capacity is further increased to 131 GW in Supreme and up to 218 GW in GreenLate. Pathways with less electrifcation[11] such as GreenLate, are associated with a significantly higher expansion of renewable power plants (Figure 9).

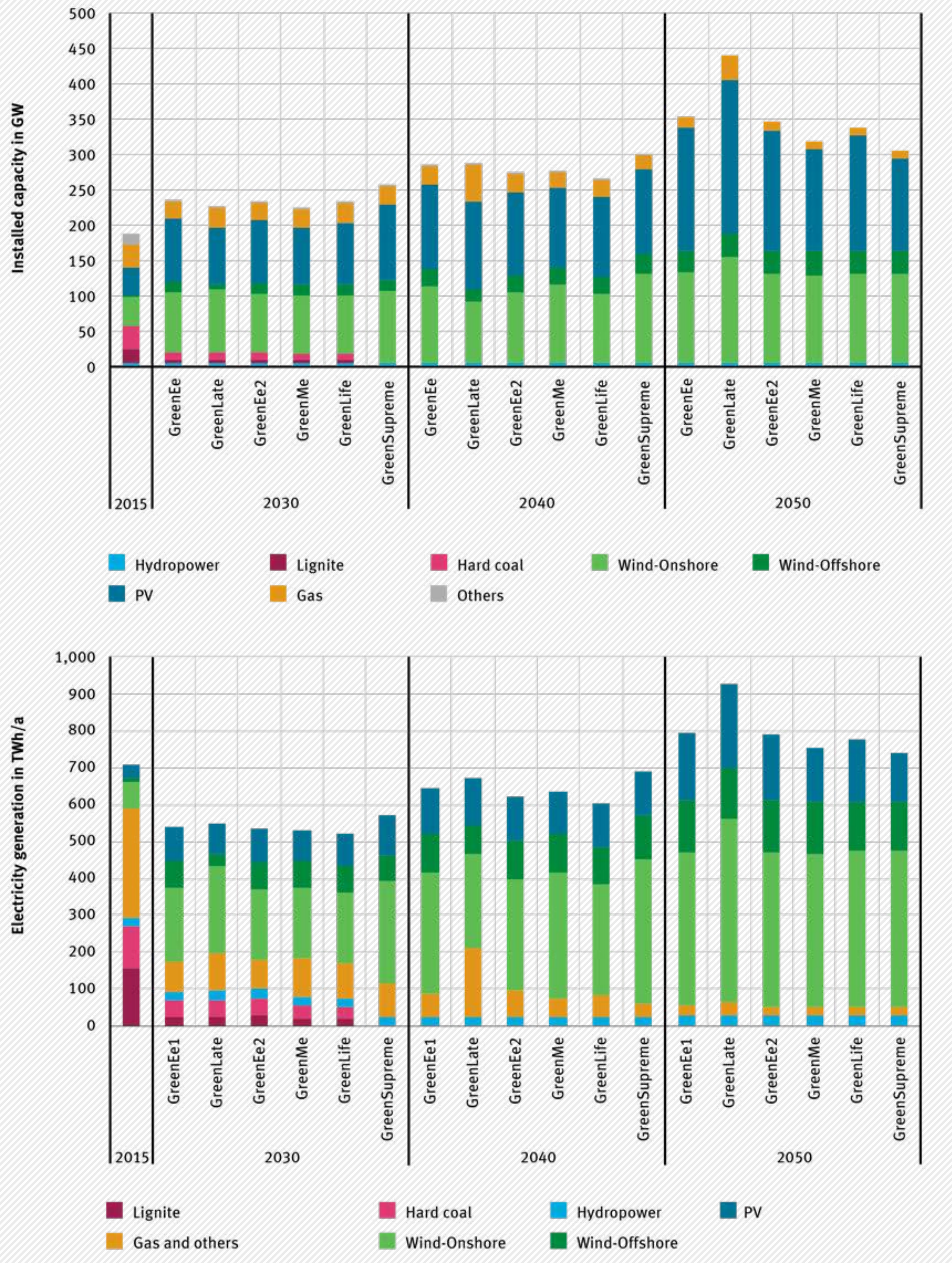
11 Less direct use of electricity through power to heat, electric mobility, etc..

The third pillar of renewable electricity supply is offshore wind power and the Green-scenarios reflect the expansion rate determined by the Renewable Energy Act until 2030. Accordingly, in all Green scenarios 15.6 GW offshore wind power are installed until 2030, with the exception of GreenLate where expansion is assumed to be behind schedule so that only 7.5 GW will be installed by 2030. The expansion rates continue in GreenEe1, GreenEe2, GreenMe, and GreenLife, so that by 2040 almost 24 GW, and by 2050 about 32 GW of offshore wind power capacity will be installed. In contrast, GreenLate catches up with the delay completely in the decade before 2050. GreenSupreme speeds up the expansion of wind power offshore and achieves an installed capacity of more than 27 GW already by 2040. Hence in 2050 about 18 per cent of all electricity generation is based on wind power offshore, while in GreenLate, due to the higher total electricity demand, this share is only at 15 %.

With an installed capacity of 5.2 GW in all Green-scenarios, hydropower contributes 24 TWh/a to the electricity supply as early as 2030. In all Green-scenarios, electricity generated from deeper geothermal energy increases tenfold, However, with not more than 1.5 TWh/a, this represents a negligible contribution.

Figure 9

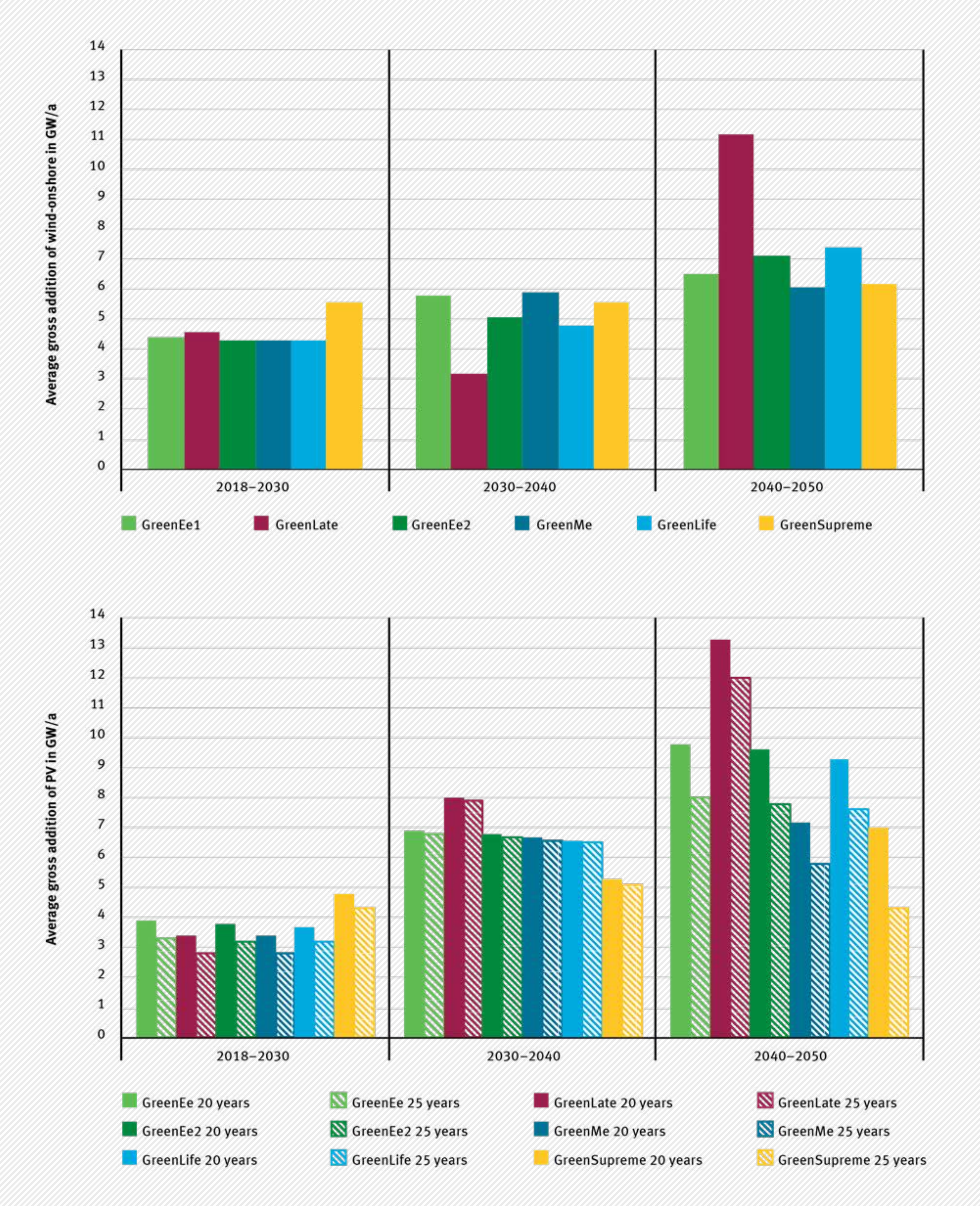
Trends in electricity generation in the Green-scenarios: installed capacity (top) and electricity generation (bottom)



Source: own figure based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

Figure 10

Average gross addition of wind (top) and photovoltaics (PV) (bottom) in the Green-scenarios



Note: Wind energy on land is assumed to have a life-time of 20 years.

Source: own figure based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

In 2018, biomass which contributed 43.3 TWh of electricity, 132 TWh of heat, and 31.6 TWh of fuel to the energy supply and is largely based on crop biomass (requiring 2.2 million hectares of arable land for their production). This is associated with competition for land (also as potential carbon sinks) and negative impacts on water, soil, biodiversity, and nature conservation (UBA, 2013). In all green scenarios it is assumed that the energetic use of crop biomass ends by about 2030. In addition, the energetic use of residual forest wood is also assumed to decline in all Green scenarios and is completely avoided until 2050 due to environmental and nature conservation advantages when leaving residual wood in the forests. This strengthens the natural carbon sink and benefits biodiversity. By 2050, bioenergy from residues will contribute between 4.7 and 5.6 TWh of electricity, just under 34 TWh of process heat, and 20.6 TWh of biogas and ethanol to the energy supply.

The change of the power supply is shown in Figure 9. It becomes evident, that wind energy ashore has to be expanded on average by at least 4 GW each year and photovoltaics by 3.5 GW[12], starting without delay. This expansion rate can be considered the absolute minimum, as energy efficiency measures assumed in the Green-scenarios are on the more ambitious side. In case energy efficiency on the demand side is not realized to a sufficient extent, a more extensive and rapid expansion of renewable energy will be required in order to still achieve the aspired GHG-mitigation targets. If the international commitment made in the Paris Agreement is taken seriously, this would require to install at least 5.5 GW wind energy ashore each year and 4.8 GW photovoltaic (Figure 10).

To ensure a smooth and steady transition, permanent adjustments to the expansion rate are required. Sudden changes in the policy framework should be avoided. Expansion requirements should be reassessed depending on latest developments (e.g., of the electricity demand) and should be adjusted early on if required. The extension of the operating life also has an influence. The replacement of expiring renewable capacities plays an increasing role in the necessary expansion paths. Longer operating times have a positive effect on the expansion paths.

However, the challenges are particularly great for the necessary expansion of onshore wind energy. The maximum possible potential of newly installable plants on the areas designated under planning law by 2030 amounts to 55.4 GW, if the currently installed plants are dismantled by approx. 20 GW by 2030 and the EEG subsidy expires after 20 years (UBA, 2019i). Nevertheless, due to considerable uncertainties, the potential that can be realized will probably be considerably lower[13]. Furthermore, the deconstruction and repowering of current plants must be taken into account. With the expiry of EEG support for all plants commissioned up to and including 2000, considerable decommissioning is expected from 2021[14]. Approximately half of the plants (and the capacity) are located outside the areas currently determined under planning law and can therefore generally not be repowered (UBA, 2019i) from the point of view of planning law. The resulting land bottleneck for the areas that can actually be used should promptly lead to ambitious designation targets in the Länder and regions. Furthermore, social acceptance is needed (above all at the local level) in order to allow for a further expansion of renewable energy systems and thus to achieve the expansion path outlined in the scenarios.

3.1.3 Fuels and raw materials supply

Renewable fuels, power, and raw materials or PtG/PtL products are needed in the long term for national passenger and freight transport (incl. inland water transport), international air and sea transport, the chemical industry, for heat supply (in particular process heat in industry), and for stable power supply (e.g., storage) (Figure 11).

The demand and therefore pressure to act differs by area. For example, in the Green-scenarios it is assumed that in 2030 relevant applications in industry and international air traffic will first be

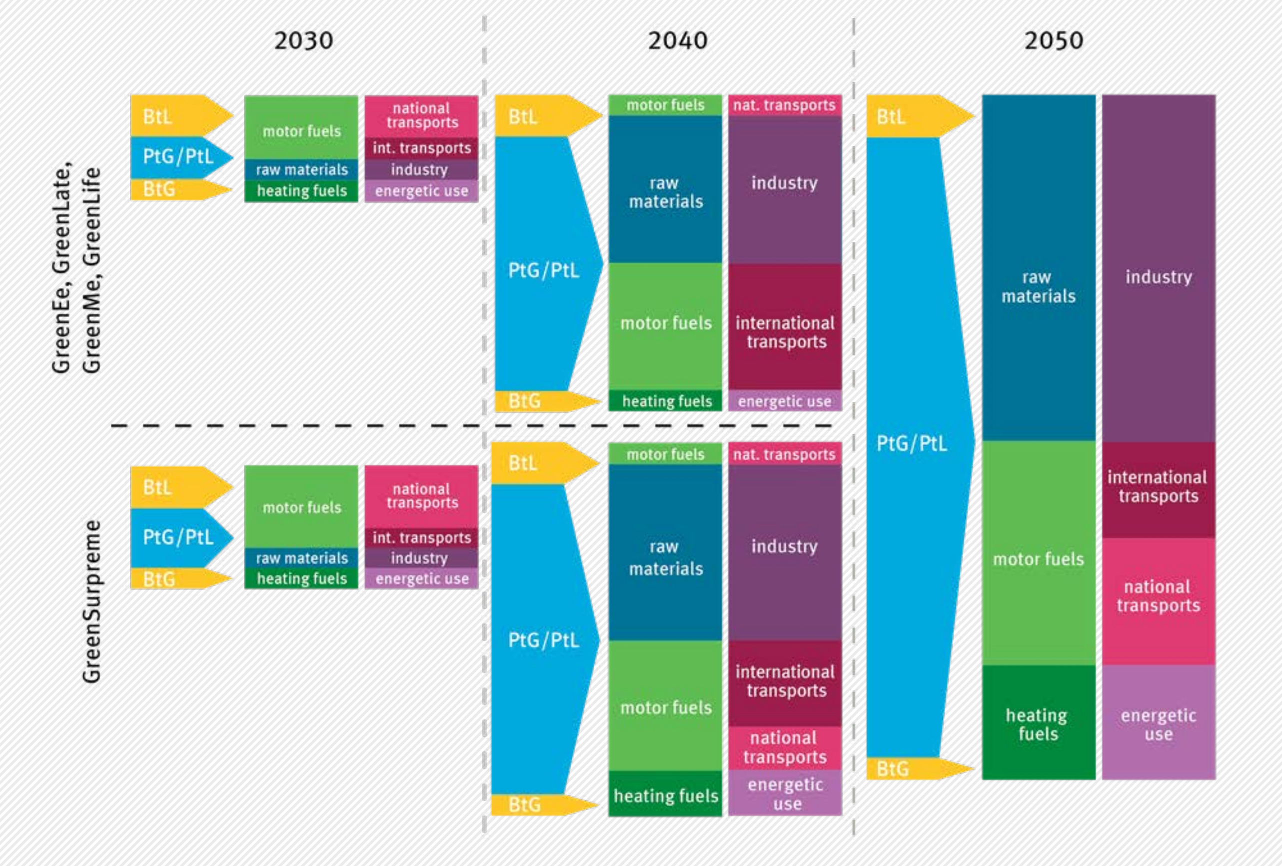
12 With a service life of 20 years, as in the EEG (Renewable Energy Sources Act). In order to conserve resources, 25 years were assumed in the Green scenarios. The impact is shown in detail in Chapter 5.2.3.2.1.2 in the RESCUE full report (UBA, 2019e).

13 Uncertainties include, e.g., that 34.4 GW are attributable to areas which have not yet been finalized and 11 GW to areas resulting from urban land-use planning for which no information on status, age, or possible height restrictions can be obtained. Furthermore, the fact that designated areas (e.g. for economic, licensing, or private-law reasons) cannot be used plays a major role. So far, no renewable energy systems have been installed on 23 % of the areas designated by the end of 2014.

14 Around 14 GW between 2021 and 2025.

Figure 11

Qualitative illustration of Germany's renewable fuel, power, and raw material supply in the Green scenarios



Source: Umweltbundesamt

supplied with renewable PtG/PtL products (to equal shares) coming from imports. In the chemical industy, products with long life-times are already from an early stage onwards substituted with similar products obtained using renewable energy. If this were not the case, these products would after a cascading use pattern still lead to fossil GHG-emissions around 2050 or even after this. In aviation, there is an urgent need for action to ensure that the ICAO (International Civil Aviation Organisation) goal of GHG-neutral growth from 2020 onwards does not rely on the use of biofuels from cultivated biomass next to global market-based measures. This also means that in all scenarios (except GreenSupreme) no PtG/PtL products find use in applications until 2040 that are subject to national reporting under the UNFCCC or the climate targets of the German government. So this assumption on distribution can be regarded as conservative for the climate protection targets set by the Federal Government. In GreenSupreme, an accelerated transformation process is assumed in which renewable energy systems are developed at a faster pace so that all markets based on renewable fuels, power, and raw materials can be supplied at an earlier stage.

A renewable energy supply based completely on renewables is achieved only in the last decade prior to 2050 in the Green-scenarios. This means that for the supply of electricity and fuels the use of natural gas will only be phased out in this last decade of the scenarios. Depending on the level of reduction of the final energy demand for electricity and the availability of internationally competitive locations, domestically produced electricity-based fuels are also generated to a limited extent. Due to the more rapid decarbonization of the national electricity supply assumed in GreenSupreme, domestically sourced PtG-methane for the gas supply is already widely in use in 2040. On the other hand, in the other

Table 2

Development of renewable imports for fuels and raw materials supply*

		renewable net electricity generation for imports	imported renewable PtG/PtL products								
			sum in TWh	fuels (international transport) in TWh	share of requirements in %	fuels (national transport) in TWh	share of requirements in %	fuels (energetic use) in TWh	share of requirements in %	feedstocks in TWh	share of requirements in %
2030	GreenEe1	54	24	12	9	0	0	0	0	12	4
	GreenLate	64	28	8	7	0	0	0	0	8	3
	GreenEe2	51	22	11	8	0	0	0	0	11	4
	GreenMe	53	23	12	9	0	0	0	0	12	4
	GreenLife	44	19	10	8	0	0	0	0	10	3
	GreenSupreme	143	63	21	19	21		0	0	21	7
2040	GreenEe1	504	233	108	100	0	0	0	0	125	44
	GreenLate	725	336	121	86	0	0	0	0	99	35
	GreenEe2	476	220	108	100	0	0	0	0	113	40
	GreenMe	490	227	105	100	0	0	0	0	122	43
	GreenLife	415	192	87	100	0	0	0	0	105	37
	GreenSupreme	595	275	83	100	42		0	0	151	53
2050	GreenEe1	1.066	494	92	100	112	100	25	21	264	94
	GreenLate	1.778	823	134	100	199	100	225	71	264	94
	GreenEe2	1.008	467	92	100	110	100	0	0	264	94
	GreenMe	1.038	480	89	100	98	100	29	23	264	94
	GreenLife	878	406	57	100	90	95	0	0	264	94
	GreenSupreme	802	371	52	100	54	70	0	0	264	94

Note: Rounded values.

Source: UBA, 2020a, 2020b, 2020c, 2020d, 2020e

* In a global renewable energy market, a large number of locations are conceivable that could provide low-cost electricity-based renewable PtG/PtL products. These can be transported to Germany via existing infrastructures such as the gas network or tankers. Each individual generation site has different characteristics with regard to electricity generation, full load hours, carbon source, mode of transport, transport distance, etc. In order to obtain an idea of the required renewable power generation and PtG/PtL production capacities, production in North Africa was simulated as an example for all Green scenarios. These results form the basis of the quantities presented.

Green-scenarios the widespread use of PtG-methane only takes place a decade later and to a lesser extent (UBA, 2019e).

However, similar to today also in the future a considerable proportion of the gaseous and liquid final energy carriers are imported. In 2050, around 8 % of the demands for liquid/gaseous fuels and raw material are provided domestically in GreenLate and up to 24 % in GreenSupreme. In 2050, import dependency is thereby reduced to about 50 % of net electricity generation in GreenSupreme. With 65 % in 2050, import dependency is highest in GreenLate and approximately at today's level[15]. The integration of renewable imports for fuels and raw materials is given in Table 2.

The results highlight that less "electrification" takes place if energy efficiency potentials are not consistently tapped and conventional technologies remain in operation[16] (as in the GreenLate scenario). As a result, significantly more renewable electricity generation is required in GreenLate when compared to the other scenarios. Between 2030 and 2040, in GreenLate an average of 10 GW of onshore wind energy and 11 GW of photovoltaics are required per year. This further increases after 2040[17] to an average of 16.8 GW of onshore wind energy and 18.1 GW of photovoltaics per year in GreenLate. In 2050, in GreenLate around 1800 TWh of renewable electricity are needed to cover imported PtG/PtL demands, whereas in GreenSupreme only 800 TWh are required.

3.1.4 Conclusions

On the basis of the Green-scenarios, the following conclusions can be drawn for a resource-efficient transformation path. Additional details can be found in in the full RESCUE report (UBA, 2019e).

The final energy demand significantly influences the demand for renewable energies, raw materials required for the build-up of power plants, energy import dependency, and natural resource consumption (e.g., land area). In addition, a reduction in energy demand supports the integration of renewable energies and makes a significant contribution to GHG-reductions in the transformation paths.

- Ambitious measures to increase energy efficiency must be taken quickly across all economic sectors considering also the associated raw material requirements. Both, regulatory measures and support programs for energy-efficient technologies and the better monitoring of energy management schemes must be implemented.

- Each individual needs to develop a greater awareness of how energy use can be reduced in a sustainable manner.

Sector coupling is the central building block for the success of a GHG-neutral energy supply. When integrating new electricity consumers using renewable electricity to supply fuels and raw materials in a GHG-neutral manner, efficiency and effectiveness must be ensured from the outset.

- The climate-friendly integration of PtX technologies should be the top priority given their substitution potential and effective GHG-reduction. For this, efficient technologies such as electric vehicles and heat pumps must be promoted and encouraged immediately via a broad mix of policy instruments.

- The framework conditions consisting of, e.g., taxes, cost allocations, and levies (incl. CO_2 pricing) must be designed quickly and in such a way that efficient PtX technologies are less costly than fossil fuels and their inefficient PtX counterparts.

- For decentralized heat supply a number of renewable alternatives to current fossil-based heat as well as PtG routes exist. Therefore, the use of PtG should not be promoted for decentralized heating.

The complete phase-out of the use of fossil energy sources for energetic and non-energetic applications is crucial both from the perspective of climate protection and natural resource conservation. Continuation in the use fossil energy carriers leads to an increase in GHG-emissions in the atmosphere and in the consumption of primary raw materials.

15 Currently, about 70 % of primary energy supply is based on imports.

16 This means that efficient technologies enabling sector-coupling (e.g., heat pumps and electric vehicles) are not consistently integrated. Instead, conventional technologies remain in use and are operated using renewable PtG/PtL products in the medium- to long-term.

17 Similar to domestic production capacities, this is partly also due to the replacement of capacities that reach their end-of-life starting from 2040.

- The complete phase-out of the use of fossil fuels is technically possible and should become a declared goal to be realized by 2050 at the latest.
- Framework conditions must be designed quickly across all sectors in such a way that the use of fossil fuels is not economically viable in the medium and long term considering also the climate and environmental costs of current energy provisioning and use.
- The phase-out of coal-fired power generation must be implemented quickly until 2030 in order to reduce cumulative emissions into the atmosphere and thus meet our international obligations.
- The phase-out of coal-fired power generation must be quickly extended until 2040 to a phase-out of coal across all economic sectors.
- The phase-out of fossil-based hydrogen must be supported by pilot projects of PtG hydrogen plants in the short term, so that the integration of PtG hydrogen plants can take place in the decade after 2030.
- The phase-out of fossil carbon use in the chemical industry must be tackled as quickly as possible with research and development (R&D) projects. In particular, production routes for the synthesis of durable and long-lived product should be considered.

The expansion of renewable energies towards an energy-supply based entirely on renewable energy sources is indispensable from a climate protection perspective.

- The annual gross expansion of onshore wind energy must be increased to at least 4 GW per year and preferably to 5.5 GW per year.
- The looming shortage of land for the use for onshore wind energy should be quickly addressed by designating more land area at Länder- and regional-level in order to ensure that Germany´s climate targets are met in the medium term.
- The annual gross expansion of photovoltaics must be increased to at least 3.5 GW per year. In order to meet the targets of the Paris Agreement, an expansion of at least 4.8 GW per year would be required.
- Consistent and foreseeable expansion paths for renewable energies should be implemented, taking into account the decommissioning of old power plants and expected future electricity consumption. Sudden policy changes thereafter should be avoided.
- The phase-out of the energetic use of cultivated biomass should take place in the medium term in order to strengthen the environment, nature, and biodiversity. The energetic use of biogenic waste and residual materials, on the other hand, should be strengthened if there are no negative impacts on the environment.

Above all, an energy supply completely based on renewables in Germany will succeed only if there is a common and ambitious understanding of climate- and natural resource protection. In view of the limited number of feasible locations for renewable energy systems in Germany under current economic considerations, a large proportion of GHG-neutral fuels, power, and raw materials will continue to be imported in the future.

- Germany should quickly work internationally and at European level to ensure that other countries also become GHG-neutral by 2050 at the latest.
- Germany should rapidly intensify sustainable partnerships with other countries on R&D, knowledge transfer, and implementation related to PtG/PtL production sites. Already at an early stage, globally favorable locations for the expansion of renewable energy systems and PtX systems need to be determined and developed. This should consider environmental protection and the conservation of natural resources as well as equal partnership. A prerequisite for the design of international cooperation should also be to promote the complete transformation of the domestic energy system in the countries where PtX production sites will be located.

3.2 Building and housing

Buildings shape our everyday lives through their architectural design and functional construction. Against the background of demographic change, changing societal trends, e.g., with regards to consumption, urbanization, mobility or digitalization, buildings are constantly being modernized, renovated, and rebuilt. The construction, conversion and expansion of traffic routes, energy infrastructures, water and sewage supply are also subject to changes in both societal and technical requirements. Construction and living have therefore always been subject to constant change which must meet the demands of society. In addition, the buildings and housing sector is an important sector for the reduction of GHG-emissions and resource consumption thereby counteracting the effects of climate change. In principle, this can be done by:

- Reducing the final energy demand through renovation and modernization of buildings and via high energy standards in new construction,
- Increasing energy efficiency through the use of energy-efficient technologies,
- Substitution of fossil fuels by renewable energy sources,
- Reduction of new land take through space-saving constructions and inner urban development as well as
- Increasing the use of secondary raw materials and increased material substitutions in construction and civil engineering.

The technologies for avoiding energy-related GHG-emissions from existing buildings are essentially introduced and available on the market. The efficiency potentials can be increased technically and the remaining energy demand can be covered with renewable energies. The long modernization and renewal cycles require rapid action. However, taking into account the different interests of the stakeholder groups involved, a consistent and rapid implementation of effective measures to reduce GHGs in the buildings sector is a major challenge.

Table 3

Characteristics of the building and housing sector in the different Green-scenarios

	GreenEe1/ GreenEe2	GreenLate	GreenMe	GreenLife	GreenSupreme
Average renovation rate per year	very high	high	very high	very high	very high
Average target level of refurbishments	very high	high	very high	very high	very high
Per capita living space	initially increasing	increasing continuously	initially increasing	decreasing in the long-term	decreasing in the long-term
Ratio SFH/TFH vs. MFH	constant	constant	constant	higher share of MFH	higher share of MFH
Share of pipeline-bound heat supply	medium	medium	medium	high	high
Share of new constructions using wood	increasing	constant	rises sharply	increasing	rises sharply
Composition Insulation materials (compared to today)	no change	no change	changing	no change	changing

Note: SFH: single-family-home, TFH: two-family-homes, MFH: multi-family-homes

As already shown in Chapter 3.1 in Figure 5, a complete avoidance of GHG-emissions is possible by switching to renewable energies. However, given current knowledge the use of primary raw materials cannot be completely avoided. The choice of technologies and materials for buildings, both in new construction and in refurbishment, determines the magnitude to which raw materials are used and the individual raw materials required in each case. Similarly, the raw material requirements are also influenced by the necessary conversion and expansion requirements of transport and supply infrastructures, which in turn have a decisive influence on the development of land-take, especially with regard to new soil sealing. Therefore, it is also important to consider aspects of space-saving construction in all scenarios in order to make the transformation to a largely GHG-neutral society smooth and efficient also with regard to the additional demand for land areas.

By varying various influencing parameters, the six Green-scenarios cover a wide range of solution spaces as shown in Table 3 which provides an overview of the characteristics of the building and housing sector in each scenario.

In addition, it is assumed for all scenarios that new land take can be reduced to 30 ha/day by 2020. In GreenLife and GreenSupreme, the assumed development of living space and the somewhat higher density (Table 4) lead to a reduced need for additional settlement and transport space. Among other things, this can reduce the increase in settlement and transport area to 10 ha/day by 2030. In the other scenarios, a reduction to 20 ha/day will be implemented by 2030. According to the Federal Government’s Climate Action Plan 2050 in all scenarios land use is also part of the circular economy and there is “no net land take” by 2050 at the latest.

Table 4

Development of important parameters for the building and housing sector in the six Green-scenarios

<table>
<tr><th></th><th>GreenEe1/ GreenEe2</th><th>GreenLate</th><th>GreenMe</th><th>GreenLife</th><th>GreenSupreme</th></tr>
<tr><td colspan="6">Average renovation rates per year</td></tr>
<tr><td>2030</td><td>2,4 %</td><td>1,7 %</td><td>2,4 %</td><td>2,5 %</td><td>2,5 %</td></tr>
<tr><td>2040</td><td>3,1 %</td><td>1,8 %</td><td>3,1 %</td><td>3,3 %</td><td>3,3 %</td></tr>
<tr><td>2050</td><td>3,4 %</td><td>1,8 %</td><td>3,4 %</td><td>3,9 %</td><td>3,9 %</td></tr>
<tr><td>From today until 2050</td><td>2,6 %</td><td>1,6 %</td><td>2,6 %</td><td>2,8 %</td><td>2,8 %</td></tr>
<tr><td colspan="6">Average room heating requirement in kWh/m²</td></tr>
<tr><td>2030</td><td>52,6</td><td>61,1</td><td>52,6</td><td>52,2</td><td>52,2</td></tr>
<tr><td>2040</td><td>32</td><td>48,9</td><td>32</td><td>30,9</td><td>30,9</td></tr>
<tr><td>2050</td><td>25,6</td><td>42,4</td><td>25,6</td><td>24,4</td><td>24,4</td></tr>
<tr><td colspan="6">Building space</td></tr>
<tr><td>Inhabited living space per person in m²</td><td>49,4</td><td>53,0</td><td>49,4</td><td colspan="2">41,2</td></tr>
<tr><td>Residential living space total in 2050 in billion m²</td><td>3,55</td><td>3,83</td><td>3,55</td><td colspan="2">2,96</td></tr>
<tr><td>Usable space non-residential buildings in 2050 in billion m²</td><td colspan="5">2,54</td></tr>
</table>

Source: UBA, 2020a, 2020b, 2020c, 2020d, 2020e

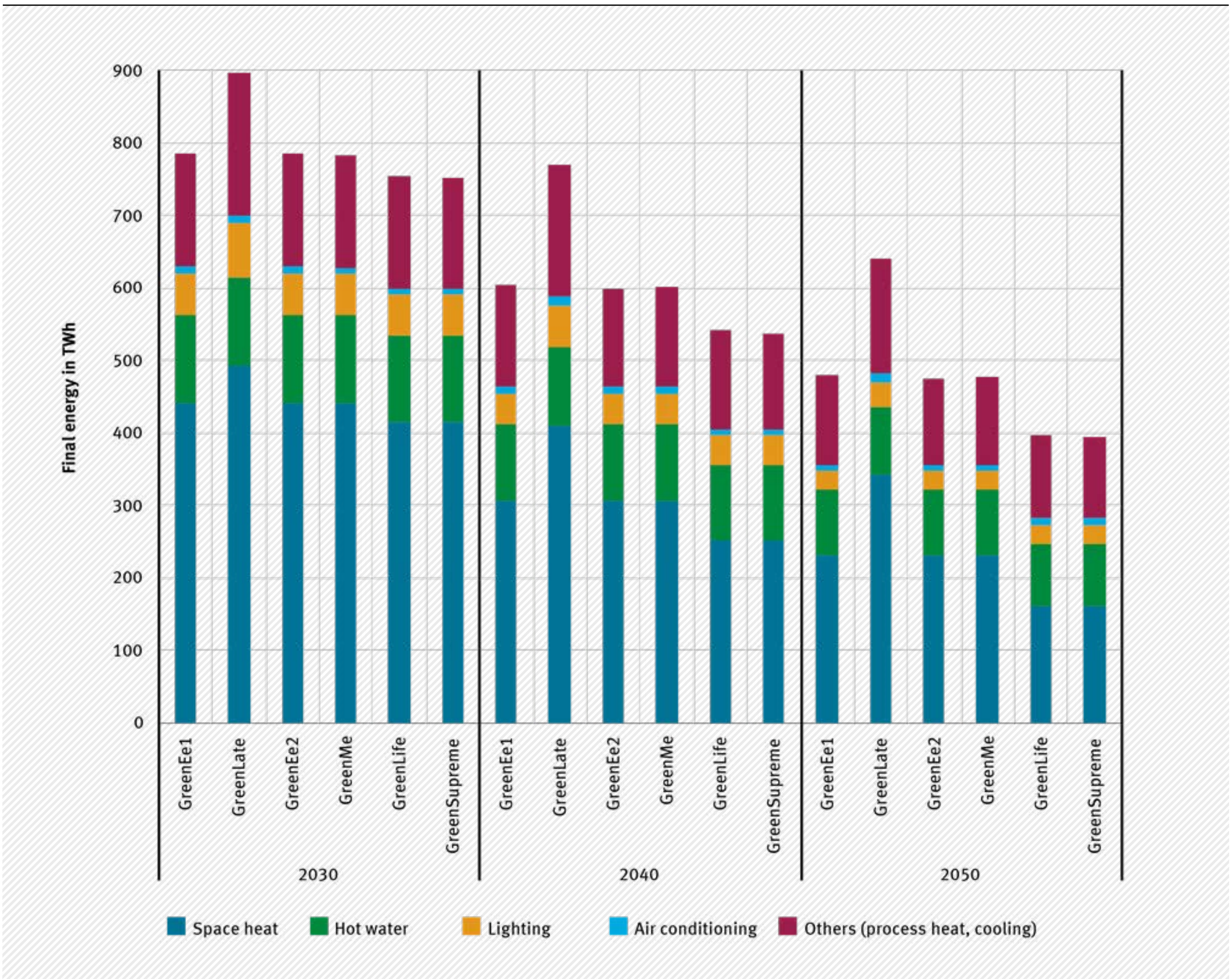
3.2.1 Development of energy demand and supply

Renovations and modernizations take place out of different interests. This does not always go hand in hand with an energetic renovation and reduction of demand. Against the background of longer renewal and investment cycles, however, this is often a missed opportunity. It is assumed in all Green-scenarios that the regulatory framework and financial incentive mechanisms will be designed in such a way that by 2030 at the latest no renovation or modernization of the building shell and building components will take place without simultaneous energetic refurbishment. Through a combination of regulatory measures, incentive and subsidy policies and internalization of climate costs, increasing refurbishment activity will also be combined with a high level of ambition with regards to the level of refurbishment in all Green-scenarios. The level of ambition with regards to the renovation rate speed of implementation are assumed to be highest in the GreenLife and GreenSupreme scenarios following the overall scenario characteristics. On the other hand, GreenLate is well below this level despite the fact that a considerable increase in the level of the renovation rate and speed of implementation is also assumed when compared to today. The most important influencing factors are displayed in Table 4.

The resulting required final energy demand in buildings is shown in Figure 12. The variations of parameters and underlying measures assumed in the different Green-scenarios directly influence the remaining quantities of renewable energies that still have to be supplied to the existing buildings in 2050. In all Green-scenarios, efficiency potentials are tapped, particularly through renovation and

Figure 12

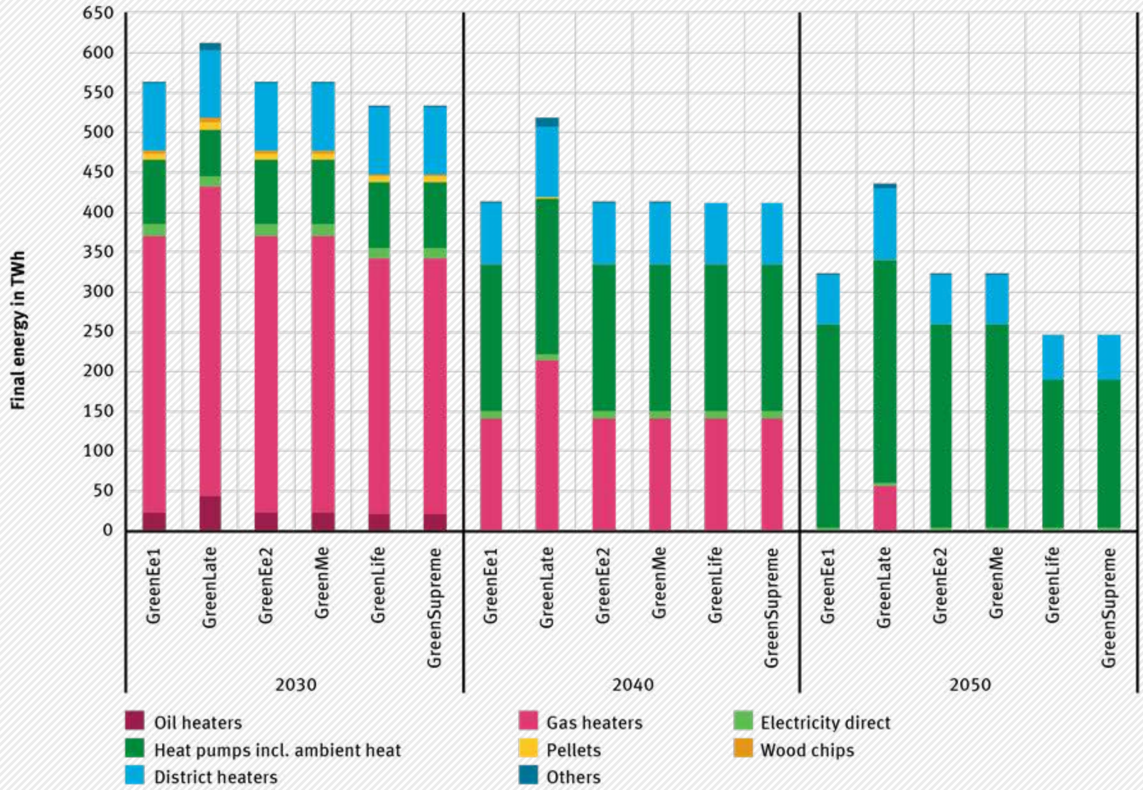
Development of the final energy demand (incl. ambient heat) for buildings across the Green-scenarios

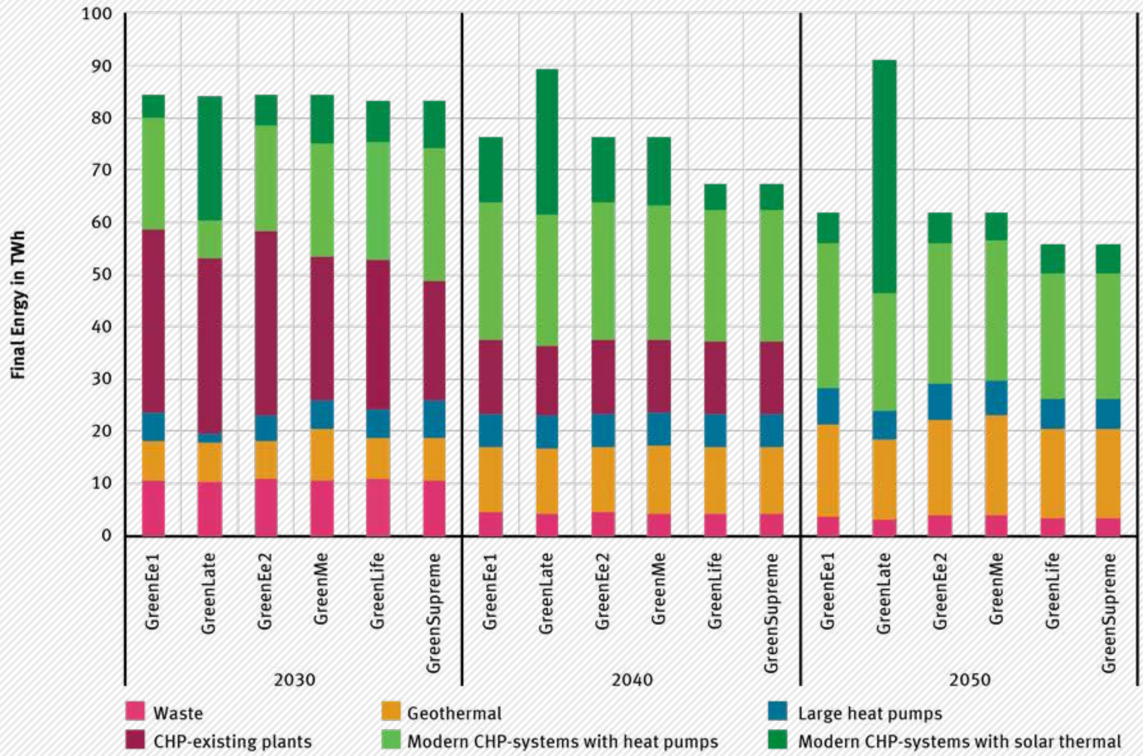


Source: own figure based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

Figure 13

Development of final energy demand by heating technologies (left) and development of the district heating supply (right)





Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e modernization, and the energy requirements are significantly reduced by 2050. The energy demand for space heating is falling more sharply in GreenLife and GreenSupreme when compared to the other scenarios. This a result of the changed societal demand for housing as a results of lower living space per person. Lighting and process heat in private households can also contribute to reductions in energy demand, e.g., by adapting eco-design-requirements, using energy-efficient appliances, and avoiding the standby operation of electrical appliances. However, the potential of these activities to reduce overall energy demand is much smaller when compared to other possible measures.

Against the background of an efficient use of resources including renewable energies, the Green-scenarios exclude (apart from GreenLate) the majority of conventional heating technologies. Instead, a combination of heat pumps and heating networks based on renewable energies are preferred in the future to supply buildings with heat. The development in the supply of space heating and hot water requirements can be seen in Figure 13. In all Green-scenarios, the use of biogenic materials such as pellets, forest residues, or wood chips for energy generation in decentralized heating systems is successively reduced in order to foster environmental protection and nature conservation, biodiversity, and the preservation of natural carbon storage. It is assumed that no decentralized heating systems using biogenic fuels are installed even prior to 2030. Again, the GreenLate scenario pictures a slower exchange of heating technologies so that even after 2040 small amounts of biogenic material are still used. In the five other scenarios, biomass heating technologies have already been replaced a few years after 2030. Furthermore, it is assumed in all Green-scenarios that no new oil heating systems will be installed from 2020 onwards. Gas heating systems including condensing boilers will also no longer be installed in the decade after 2030. Only in GreenLate, such technologies are still in operation in 2050 and will then cover 13 per cent of the space and hot water demand on the basis of renewable PtG.

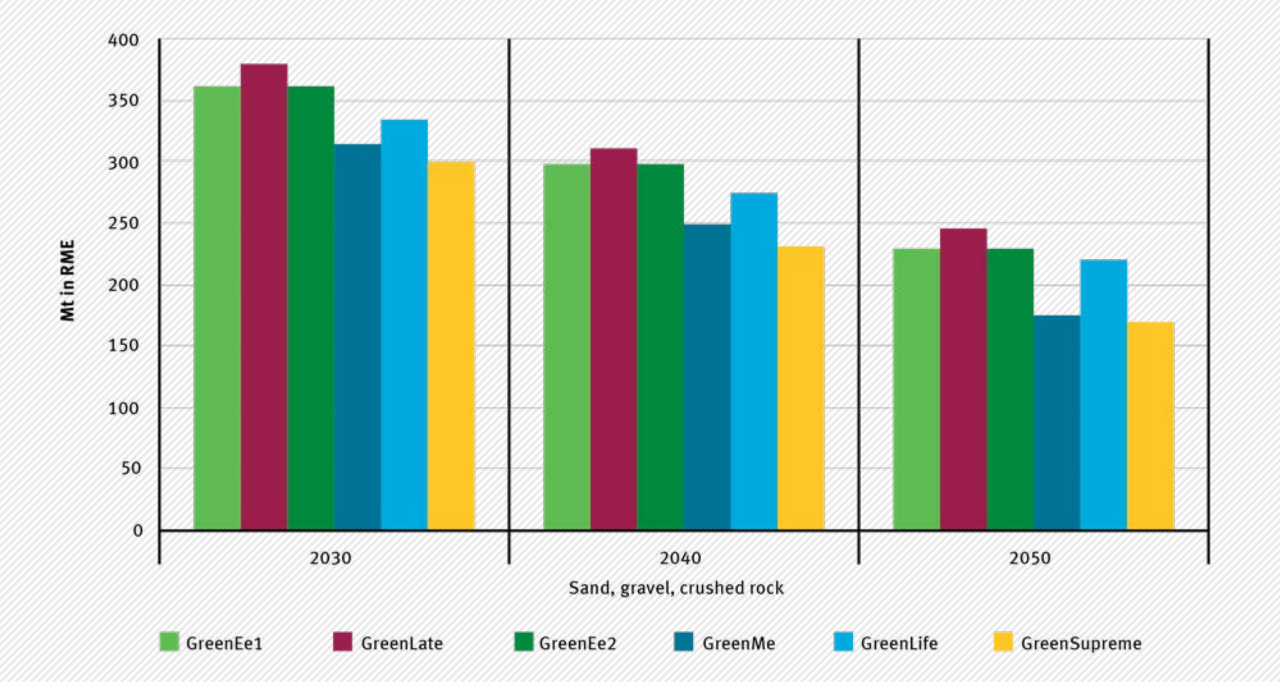
In view of the renovation and modernization of buildings, in particular heat pumps are replacing conventional technologies. In the two GreenEe scenarios, 79 % of the space heating and hot water supply in 2050 comes from heat pumps. In particular, near-surface borehole heat exchangers[18] are dominant, on which almost 50 % of the room heating supply in 2050 is based. In urban areas, the supply of heat via pipelines dominates. It is assumed that the connection rate in four scenarios increases significantly to at least 20 % of the space heating and hot water supply and in GreenLife and GreenSupreme to around 24 % of the building heating supply. Due to the reduction in demand, the absolute value decreases to 91 TWh in GreenLate by 2050, to 62 TWh in GreenEe1, GreenEe2 and GreenMe and to around 56 TWh in GreenLife and GreenSupreme, see Figure 13 on the right. The combined heat and power systems are changing in all Green scenarios. While in 2030 the supply of heat via pipelines is still dominated by the continued existence of today's CHP plants with just under 35 TWh, these are increasingly replaced in subsequent years by innovative and modern combined heat and power systems and will completely replace these by 2050. Modern combined heat and power systems are characterized by a high share of renewable energy (large heat pumps or solar thermal energy), flexible gas-based CHP generation and flexible use of storage tanks and PtH. In GreenSupreme, this change takes place even faster. Deep geothermal energy is constantly being expanded so that in 2050 it will contribute between 26 % and 31 % to the supply of heat via pipelines. In GreenLate, the share is lower due to the higher heat demand and amounts to just under 17 %. Against the background of changed lifestyles, greater waste avoidance and a decline in waste production in line with population growth, the energy contribution of waste combustion is reduced to around 6 % in all scenarios by 2050 and to just under 4 % in GreenLate due to the higher demand for heat.

3.2.2 Development of raw materials requirements
Implementing the modernization and refurbishment measures as well as the conversion of the heat supply to renewable energies described above will initially require increasing amounts of raw materials. However, the need for, e.g., insulation materials will soon be overcompensated by savings in raw materials for energy provisioning including initially fossil fuels and later on raw materials for the development of the renewable energy system (UBA, 2018b;

18 On average, these reach an seasonal performance factor of 4.5. Air heat pumps in 2050 have an seasonal performance factor of 4.

Figure 14

Development in the RMC for sand, gravel, and crushed rock across the Green-scenarios



Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

Ritthoff et al., 2015). For example, with 48.7 million tonnes (UBA, 2018b) the annual cumulative raw material consumption associated with the heating of buildings can be reduced by at least 70 % in the Green-scenarios compared to 2010, see also Chapter 5.3.6 in the full RESCUE-report (UBA, 2019e).

The developments in construction (shaped by the developments in the residential building stock) and in civil and underground engineering (shaped by infrastructures such as for transport including bridges and tunnels, and supply and disposal networks[19]) determine the required raw material demands. The assumptions made both for the development and design of the building stock and the infrastructures in connection with land-take influence the RMC for building sand, gravel, and crushed stone (Figure 14).

The significantly lower demand for these building materials in GreenMe compared with the other scenarios (with the exception of GreenSupreme) can be explained, amongst other things, by the significantly higher proportion of timber construction. While in GreenEe1, GreenEe2, and GreenLife, it is assumed that the proportion of wood in residential construction for detached (single) and semi-detached houses can be increased from 15 % in 2010 to 30 % in 2050, in GreenMe and GreenSupreme the proportion is increased to 80 % in new buildings. For multi-family houses, the share in these two scenarios rises from 2 % in 2010 to 45 % in 2050 and in the other scenarios (except GreenLate) only to 15 % in 2050. In GreenLate, the current share of residential buildings in timber construction (single-family-homes: 15 % / multi-family-homes: 2 %) remains constant in new construction. Further influencing parameters here are the substitution of reinforced concrete by textile concretes and the overall higher raw material efficiency of 1.2 % per year in GreenMe and GreenSupreme. The lower demand for building sand, gravel and crushed rocks in GreenLife compared to GreenEe2 is largely due to the assumed lower living space and the assumed reduction in new land take. Green Supreme has the lowest demand for the building materials because of the effects of GreenMe and GreenLife complement each other.

19 In this study, the energy production plants are also assigned to civil and underground engineering when calculating raw material consumption. More details are provided in the long-version of the RESCUE project report in chapter 5.2 (UBA, 2019e).

3.2.3 Conclusions

Energy efficiency and substitution of fossil fuels are key elements for successful climate protection in the building sector. In combination with measures for sustainable and raw material-saving construction as well as less land-take, a resource-efficient and GHG-neutral transformation can be achieved. Due to the long investment cycles of buildings, timely action is necessary. Already today, new construction, refurbishment and modernization should ideally meet the requirements of the existing building stock in 2050. The temporary increase in raw material requirements for insulation materials is more than offset by savings through less demand for heating and cooling energy. With the current heat supply, the demand for fossil fuels is directly reduced. Furthermore, due to the lower energy requirements in the future, raw materials needs for the expansion of the renewable energy system are reduced (more detailed information are provided in the full RESCUE project reports Chapter 5.3, UBA, 2019e). The following steps are required for implementation:

- In the short term, the renovation rate must be increased to at least 2.5-times the current level of 1 %. Such large increases can only be achieved if very effective policy instruments are established promptly.

- Measures and instruments must be designed or complemented with the goal to make building renovations economically attractive as well as socially acceptable, and in a manner so that properly trained experts are available for implementation.

The energy supply that is still needed for buildings in 2050 should be provided from renewable energies. The complete phase-out of fossil fuels is crucial for success. The following steps are necessary to enable an energy- and resource-efficient fuel switch:

- Rapid action to reduce the need for space heating (as described above) increases synergies for the integration of particularly efficient climate-friendly technology for heat supply, such as heat pumps, and in urban areas for the integration of pipeline-based heat supply with renewable energies.

- All subsidies for heating technologies based on fossil fuels must be stopped immediately.

- No new oil heating systems should be installed. Starting In the decade after 2030 also no new gas heating systems should be installed.

- Accompanying the above changes, efficient and decentralized heating technologies such as heat pumps are to be promoted.

- In GreenLate, the delay in action combined with less ambitious measures implemented in the building sector lead to higher final energy needs and a delayed exchange of heating technologies. With the use of PtG a GHG-neutral heat supply is possible. However, this goes hand in hand with lower efficiencies, higher operating costs, higher economic costs (ifeu et al., 2018)and higher energy and raw material requirements. Therefore, remaining with conventional technologies does not appear to be target-oriented.

- The sustainable energetic use of biomass is limited. For reasons of resource conservation, wood should be primarily used for material purposes and for energy uses only at the end of a cascading use cycle. Decentralized biomass use should be gradually reduced as this is usually accompanied by high local emissions of particulate matter and other air pollutants.

- In urban areas, pipeline-based heat supply must be economically attractive and greenhouse gas-neutral. Modern and flexible electricity-heat systems, e.g. in combination with large heat pumps, seem to be robust future options.

- Today, financial support for heat networks via the combined heat and power act (KWKG)is still very strongly linked to fossil-fired combined heat and power. Instead, the promotion of grid-bound heating infrastructure must increasingly be geared toward the integration of heat from renewable energies.

Against the background of current discussions on the need for living space and rent increases in growth regions, the Green-scenarios (in particular GreenLife and GreenSupreme) envisage a number of ambitious changes to existing residential buildings and associated living space. They also show that, next to growing building stocks, the type and magnitude of future building activities have a high relevance for the demand of raw materials. For example, material substitutions, such as increased wood construction instead of concrete, and the increased use of secondary materials will significantly reduce the consumption of raw materials. The reduction of living space per capita is also an important factor for the reduction of primary material input.

- Increased wood construction, especially in multi-story residential constructions, promises positive effects for climate and resource protection. The Federal Government must continue its research and advisory activities on timber construction, including within the framework of the Charter for Wood 2.0. At the same time, possible negative ecological effects need to be examines and properly monitored. In particular, there are uncertainties regarding the availability of wood when considering the necessary forest conversions and changes in the share of forest vs. wood product for carbon storage.

- Constructions with a small land-footprint, inner urban development and brownfield redevelopment reduce the use of new land area and increase the efficiency of land use. This is also and especially true in smaller towns and rural communities, where the use of new land in relation to the number of inhabitants is higher than in large cities.

3.3 Mobility

Transport within Germany has steadily increased over the past decades. Further strong growth is currently forecasted for the future as well – especially regarding freight transport. As of 2017 transport, with 168 million t CO_{2eq}, was recorded as the only sector showing higher GHG emissions compared to the 1990 level. Thus transport accounted for around 18.5 % of Germany's GHG emissions in 2017 – and the trend is rising. Moving towards a GHG-neutral and resource-efficient transport system is therefore imperative and can be successfully achieved if

- a **transport transition** which brings a reduction of transport performance and of final energy consumption
- is combined with an **energy transition in transport**, i.e., a changeover to alternative drivetrains and GHG neutral fuels.

Measures within the transport transition comprise the areas avoidance, modal shift, and improvement of energy efficiency. Only through an integrated approach with a mix of measures can the goal of sustainable transport be achieved. In this, so-called non-technical measures are of crucial importance, for example economic instruments or integrated settlement and transport planning. Regarding resource demand, environmental impacts and costs, until 2050 at the latest, a drastic lowering of energy consumption by 40 % to 60 % is absolutely necessary. At the same time, demand for required renewable energies in transport declines and the successful implementation of the energy transition is likely to be achieved.[20] A transport transition on its own, however, is not enough. As a further building block, energy-based GHG transport emissions in their entirety must be avoided through an energy transition that includes all-encompassing conversion to GHG-neutral energy carriers.

Within the energy transition in transport internal combustion engines, as technically feasible, must be replaced by electrical drivetrains, and fossil fuels gradually replaced with GHG-neutral ones. Due to the advantages of electrification in terms of energy and cost efficiency, it makes sense to implement electrification as far as possible before, for further GHG reductions, a much more elaborate conversion to GHG-neutral fuels (mainly to power-to-liquid (PtL)) ensues[21]. Despite this, considering long-term high demand for GHG-neutral liquid fuels first steps into utilizing PtX fuels should coincide with an electrification of means of transportation. Furthermore there are areas of transport which even in the long term cannot at all or only be partially electrified, such as international maritime transport and aviation (UBA, 2015b). Here, GHG-neutral fuels play an essential role (UBA, 2015b; UBA, 2016a). To facilitate the required GHG-reductions, the appropriate advancement in the area of energy supplies is necessary, see Chapter 3.1.

20 International maritime transport and aviation are considered in the scenarios, however their GHG emissions are not added into national reporting inventories.

21 Biogenic fuels can only contribute marginally due to limited volume potential, existing usage competition, only partial GHG neutrality and usage alternatives.

Table 5

Characteristics of the transport sector in the different Green-scenarios

<table>
<tr><th></th><th>GreenEe1</th><th>GreenLate</th><th>GreenEe2</th><th>GreenMe</th><th>GreenLife</th><th>GreenSupreme</th></tr>
<tr><td>Change in individual mobility behavior*</td><td>high</td><td>medium</td><td colspan="2">high</td><td colspan="2">very high</td></tr>
<tr><td>Modal shift in freight transport</td><td>very high</td><td>high</td><td colspan="4">very high</td></tr>
<tr><td>Improvement of vehicle efficiency</td><td>high</td><td>medium</td><td>high</td><td>very high</td><td>high</td><td>very high</td></tr>
<tr><td>Shift to electric drives</td><td>high</td><td>medium</td><td colspan="3">high</td><td>very high</td></tr>
</table>

*By choosing the mode of transportation, the size of the vehicle as well as the place of work and residence.

In all Green scenarios a development of traffic is shown in which the two above-mentioned reduction approaches (traffic and energy turnaround) are pursued to varying degrees. Common to all scenarios is the avoidance of energy-related GHG emissions from transport by 2050. Depending on the scenario characteristics, see Table 5, it is possible to make a significant contribution to GHG reduction in transport, for example through change of mobility behavior, a transport shift in freight transport towards climate-friendly means of transportation and efficiency improvements in vehicles. All Green-scenarios result in a relatively marked transition to electric drivetrains. In freight transport this happens, aside from GreenLate, also through overhead catenary hybrid lorries, in part as overhead catenary battery-electric lorries. To completely avoid energy-related GHG emissions, until 2050 greenhouse-gas neutral fuels are being integrated, mainly PtL. Changes in air traffic usage patterns in some Green scenarios, which lead to fewer air travel overall, should also be highlighted. Domestic flights are completely shifted to land transport in these scenarios.

3.3.1 Development of transport

The development of the entire transport performance for passengers and goods is a major driver regarding GHG emissions from transport. Important is also the distribution among different means of transportation. In the Green-scenarios there is a generally assumed change in mobility behavior of the population regarding passenger transport.

In GreenLife and GreenSupreme – beyond the other scenarios – further changes for the urban population are facilitated through a "city and region of short distances". Car- and ride sharing as well as a strengthening of public transport thus additionally help to shape this trend. As a result, there is no more noteworthy passenger-car ownership in cities by 2050. The number of passenger cars, counting ride sharing as well as car sharing vehicles and taxis, is reduced to 150 vehicles per 1000 inhabitants (UBA, 2017a) and thus by approx. two third. For longer distances, the urban population uses rail and intercity coaches much more than today. Shortened distances resulting from settlement consolidation in combination with altered choice of means of transportation, are leading up to 2050 a decline in the share of motorized individual transport and also overall passenger transport performance.

The delayed trend reversal in GreenLate according to the scenario characteristics, on the other hand, means that the MIV share remains higher and that overall transport performance is higher than in the other scenarios.

The development of freight transport mirrors the changes in economic development and manufacturing structure in Germany and related changes in freight transport demand. Transport demand and its development affect, among others, the development of transport performance in freight transport. Thus, trends existing far beyond the realm of transport nonetheless affect freight transport performance. This

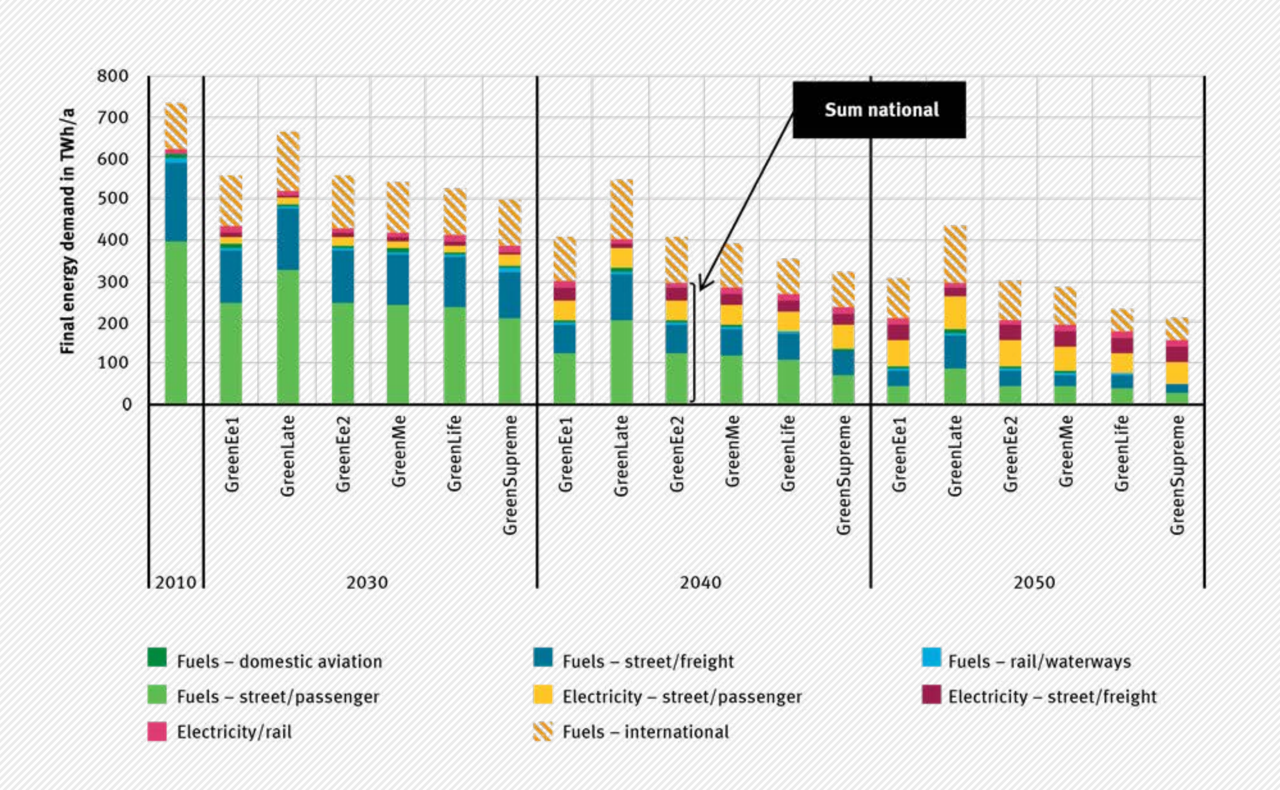
Figure 15

Development of the transport performance in passenger and freight transport

Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

Figure 16

Development of the final energy demand in transport



Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

include declining demands for fossil energy carriers and increased recycling of materials. In all scenarios, aside from GreenSupreme, the overall transport performance of freight transport for 2050 lies above the 2010 value, which is in part caused by shifting over to inland waterways and rail and thus longer transport routes. The on-road transport performance however drops in all scenarios up to 2050 below the level of 2010. The shifting of goods from road to rail and inland waterways will be greatly accelerated towards the year 2050, so that in all scenarios aside from GreenLate more than 42 % of goods are then transported in a climate-friendly way. Today this amounts to only approx. 28 %. In GreenLate the share up to the year 2050 rises at least to 37 %.

Successes of transport transition in passenger and freight transport are also mirrored in final energy consumption (see Figure 16). The successes of improving the efficiency of vehicles and aircraft as well as ships, which are taking place with varying degrees of progress in all Green scenarios, are particularly evident here. Even more important is electrification, specifically in regards to land transport. While in 2010 almost no electricity is used in road passenger and freight transport, the share increases markedly leading up to 2050. Aside from GreenLate-scenario, electricity in national passenger as well as freight transport will be, with 56 % to 67 %, the most-used final energy source. One kilowatt hour of electricity delivers an approx. three times bigger transport performance compared to use of PtL. Electricity dominates transport thus even more clearly than what meets the eye. The demand for fuels markedly decreases in all scenarios with at least 85 %.

In order for electricity to be able to play such an essential role in the energy supply of transport the energy transition must be initiated in good time, and electric vehicles must establish themselves on the market as an alternative to vehicles with combustion engines as quickly and as strongly as possible. In the passenger car sector this means that by 2030, apart from GreenLate, at least 40 % of new passenger cars will already be electric vehicles (as pure battery-electric passenger cars or plug-in hybrids).

Table 6

Number of electric vehicles in the 2030 passenger car fleet

in million passenger cars	GreenEe1	GreenLate	GreenEe2	GreenMe	GreenLife	GreenSupreme
Plug-in-Hybrid (PHEV)	3,1	2,5	3,1		3,0	4,7
Battery-Electric (BEV)	4,5	2,3	4,5		4,4	7,3
Sum	**7,5**	**4,8**	**7,5**		**7,5***	**12,1***

* In GreenLife and GreenSupreme, the total fleet of vehicles is smaller. As a result, the number of electric vehicles is also smaller, but their share of the overall number of vehicles stays the same.

Source: based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

From 2040 only electric cars will be newly registered in the scenarios other than GreenLate, and in GreenLife and GreenSupreme partly as car- and ridesharing vehicles. In GreenLate market run-up takes place with a delay of about 5 to 10 years, in GreenSupreme much quicker than in all other scenarios, so that in 2030 already approx. 12 million electric cars are in the vehicle fleet. Likewise in lorries with up to 12 tonnes GVW electric drivetrains analogue to passenger vehicles become established. With heavier lorries and articulated vehicles conversion to electric drivetrains happens at first slower than with passenger cars, until 2030 mainly through plug-in hybrid lorries. From 2040 onwards, apart from GreenLate, also only electric lorries will be newly registered – mostly as overhead catenary hybrid lorries and overhead catenary battery-electric lorries. In GreenLate only electric lorries that don't use a catenary exists as the catenary options in this scenario were unable to be established and thus a catenary infrastructure does not exist.

Looking at the different means of transportation, it becomes apparent that the greatest reductions of final energy consumption can be realized in motorized individual transport. Reasons for this are especially the strong electrification in passenger-car transport as well as the effects of measures for avoidance and shifting of passenger transport. In on-road freight transport between 2010 and 2050 the transport performances cannot be reduced to the same extent. The shift towards electric drivetrains however must be initiated in both areas as early as possible, meaning significantly ahead of 2030.

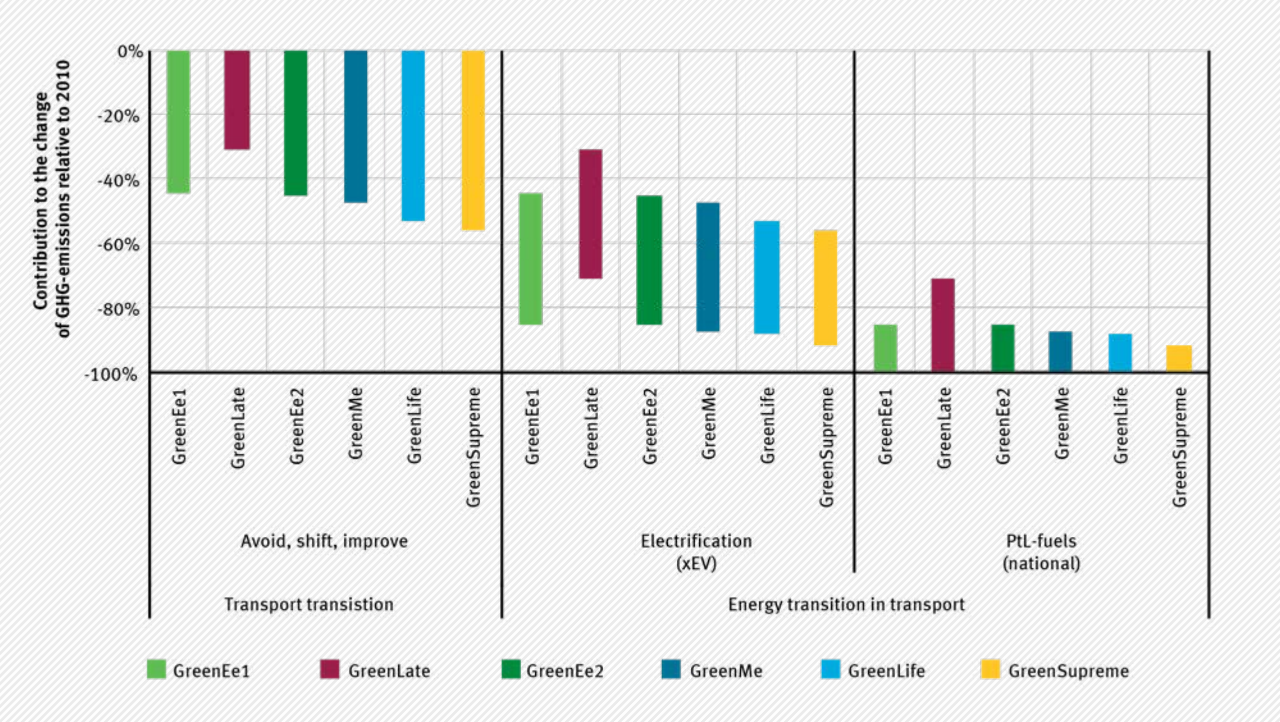
Due to high growth rates in traffic performance, the share of air traffic in the final energy consumption of total traffic is increasing significantly in some green scenarios. Due to the changes in air traffic usage patterns achieved only in GreenLife and GreenSupreme and the different ways of improving efficiency, there are major differences between the Green scenarios with regard to the influence on demand for PtL fuels. Aviation dominates final energy consumption of international means of transportation in all scenarios, even taking into account the change in usage patterns up to 2050. Even by the year 2050 international maritime transport and aviation will exclusively be using fuels and no electricity as energy carriers. Rail and inland waterways still – despite their significant contribution to transport performance based on high energy efficiency per ton kilometer – show only insignificant shares of final energy consumption.

In all scenarios fuels in 2050 are made based on renewable electricity. They are thus GHG-neutrally produced, enabling achieving necessary GHG reductions despite usage of fuels in internal combustion engines. In order to achieve this in aviation, the tax advantage enjoyed by air transport should be reduced, such as the exemption from kerosene tax and the exemption from value added tax for cross-border flights. In addition, the regulatory and economic framework conditions must be created for the integration of renewable energy-based fuels. In the UBA study (UBA, 2019j), a CO_2 price for kerosene via European emissions trading is proposed along with regulatory measures such as a PtL admixture quota.

In Figure 16 the contribution of the transport and energy transition – split into electrification and PtL fuels – to GHG reduction of 2050 versus 2010 is shown. Delayed implementation of the transport

Figure 17

Contribution of the transport transition and the energy transition in national transport to climate protection (change in 2050 relative to 2010)



Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e and UBA, 2016a. The contribution was calculated from left to right. If one would start with electrification and would calculate the contribution of the transport transition, the contribution of the electrification would be higher and of the latter smaller. The same effect would occur for the PtL-fuels as result of the approach for the calculation.

transition first and foremost leads to a significantly higher demand for PtL fuels in order to achieve GHG neutrality of transport by the year 2050.[22]

The design of the scenarios over time leads to greatly varying demands for raw materials. Especially the trend toward electrification of means of transportation, most importantly as battery-electric mobility, leads to massive changes regarding type and amount of requested raw materials. Further trends comprise of lightweight design of vehicles, technical efficiency increases on vehicles and the use of other fuels and propellants.

The integration of electric mobility is foreseen at different speeds in the Green-scenarios[23]. Furthermore until 2050 a change in cell types is foreseen, from the initially dominating lithium-ion battery towards lithium-sulfur batteries with about twice the energy density. Hereby as well the demand for materials[24] is altered, and altogether less materials and thus battery weight is necessary, see Figure 17. In GreenMe and GreenSupreme the latter is supported by a tight network of fast charging points so that batteries with less range – and thus less material requirement – are sufficient.

This causes the demand for cobalt and graphite for car batteries to return to zero by the year 2050 as both materials are no longer used in lithium-sulfur batteries. Similarly the for 2050 predicted lowered total demand for lithium, except in GreenLate, can be attributed in part to the changes in cell types.

Market run-up and stock of electric vehicles also have an impact on the demand for lithium. While in 2030 GreenLate shows the least demand of all the scenarios, in 2050 it is nearly three times as high as the demand within GreenSupreme. The lowest

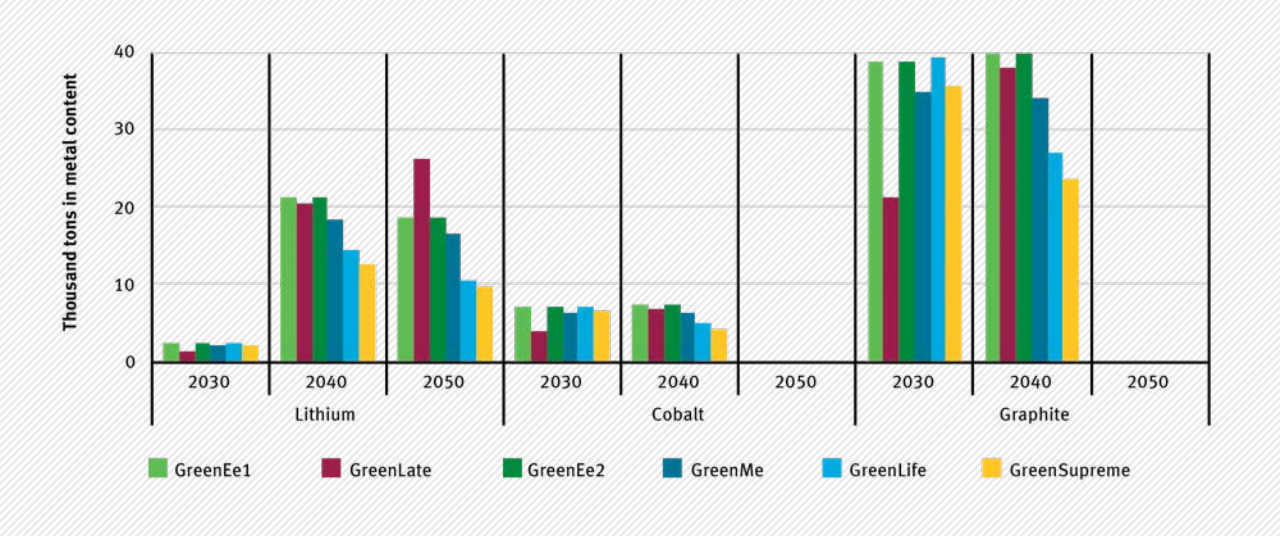
22 Aside from the target point in the year 2050 in particular the energy demands and GHG emissions running up to 2050 are crucial.

23 Hereinafter the vehicle battery is reflected, not the drivetrain of the (electric) vehicles.

24 Lithium-ion batteries compared to lithium-sulfur batteries show higher fractions of metals and lithium compounds.

Figure 18

Demand for materials relevant for traction batteries of vehicles in the Green-scenarios



Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

absolute number of electric vehicles in GreenLife and GreenSupreme results from 2040 on in the lowest demands for battery raw materials. Aside from lithium, cobalt and graphite shown here the demand for other metals, especially copper, is boosted through electric mobility.

The resource analyses of the Green-scenarios do not assume explicit recycling of vehicle batteries, rather they are assumed to be used in second-life applications within the energy system. Recycling concepts are currently in development. Assessments regarding extraction of secondary resources, however, cannot be made. Based on anticipated market run-up over the next few years it can be posited that demand, especially assuming an ambitious transformation such as in GreenLife or GreenSupreme, can also be met through secondary materials.

3.3.2 Conclusions

The key to from an economic point of view effective structuring of a GHG-neutral and resource-efficient transport can be found in a combination of a transport transition and an energy transition in transport. For their implementation the following steps are to be implemented as soon as possible:

- Transport avoidance and shifting over to ecomobility play a central role in passenger transport. To achieve this, on the one hand, CO_2 pricing must be implemented on fossil fuels and environmentally harmful subsidies must be abolished (for example diesel tax privilege, company car allowance, commuter tax relief). On the other hand, incentives must be created to shorten distances travelled and to cover more trips via ecomobility.

- A transport shift for freight towards rail and inland waterways should be promoted by increasing appeal of on-road alternatives on one hand, and on the other hand by making on road freight transport more expensive by adding charges for environmental costs. In addition, by furthering sustainable and climate-compatible economic development the growth of transport volume resp. the volume overall must be reduced.

- As part of the transport transition conventional vehicles resp. airplanes and ships must be primed for greater fuel efficiency. Especially regarding airplanes and ships which will in the long run use fuels, this is of great importance.

- The demand for kerosene for German-based international flights and related GHG emissions will continue to grow strongly in the future if aviation isn't swiftly converted to renewable PtL fuels. In addition, the rail network needs to be expanded in order to improve accessibility to the densely populated areas and avoid domestic flights in Germany.

- Electric mobility is the central building block of an energy transition in transport. Only for modes of transport where according to what we know today the direct resp. exclusive use of renewable electricity to satisfy mobility demands isn‘t feasible technically, should greenhouse-gas neutral fuels be employed. For significant reductions of GHG emissions in passenger transport a speedy market run-up of electric cars is necessary.

- In order to efficiently achieve the climate objectives, from the year 2040 at the very latest only electric cars should be newly approved. In on-road freight transport the implementation of battery-electric drive trains for light goods vehicles and lorries up to 12 GVW must be paramount.

- Implementation of overhead catenary hybrid lorries and overhead catenary battery-electric lorries will enable stronger reduction of final energy consumption compared to plug-in hybrids for lorries over 12 tonnes GVW as well as road trains and articulated vehicles. For the implantation of catenary technology, infrastructure alongside highly-frequented sections of motorway must be constructed as soon as possible.

- The speed of the run-up of electric mobility is crucial with regards to (primary) raw materials demand. It is preferable to create a uniform run-up; however, this needs to be synchronized with the target of low cumulative GHG emissions.

- PtL fuels in 2050 will still be responsible for large parts of energy consumption in transport. Thus the use of renewable PtL fuels in transport must be set up in a timely manner to ensure the market run-up which generally would take place after 2030. PtL fuels should find preferred use in international modes of transport.

- For aviation the development and implementation of an international deployment strategy for renewable PtL is time-critical.

- Following a complete shift of international aviation towards use of PtL fuels there will be no more direct GHG emissions. Other, non-CO_2 climate effects of aviation will continue to exist as long as drivetrains are combustion-based. Climate-neutral aviation in conjunction with current drive technology – even using PtL – isn’t feasible, necessitating a stronger focus than before on measures and instruments to avoid flights altogether or optimise flight paths in order to reduce non-CO_2 effects.

3.4 Industry

Industry and commerce are important components of our society. Against the background of technological progress, changing needs of the population, and shifting economic framework conditions, industry and commerce are subject to a continuous change. The transformation pathways toward GHG-neutrality examined in this study consider Germany as an industrial nation in a globalized world. Achieving resource- and climate protection requires significant changes to today´s industrial processes and operations.

In industrial processes, GHG-emissions are caused in various ways:

- Direct (energy-based) emissions from the use of carbonaceous fuels for energy supply (e.g., process heat, steam, mechanical work),

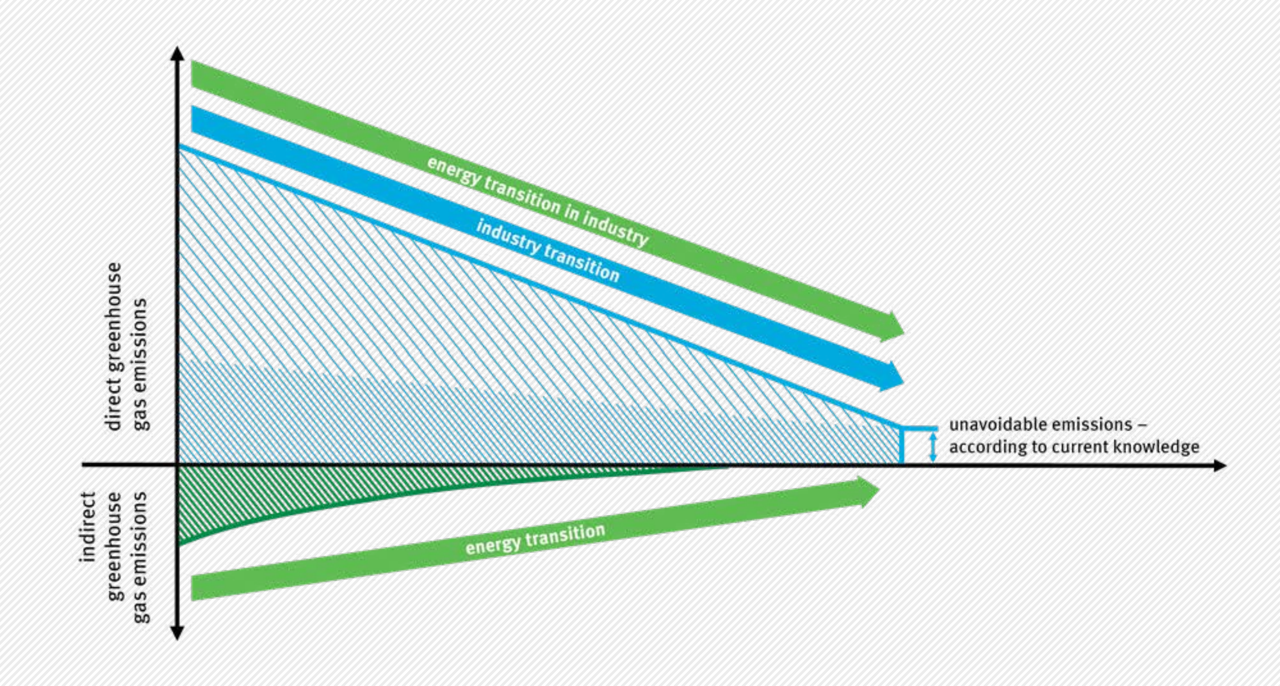
- Direct (process-based) emissions from the non-energetic use of carbon-containing energy sources and other raw materials, or from the process-based release of GHGs other than CO_2, and

- Indirect energy-based emissions from upstream energy generation (electricity, heat, or cooling).

In 1990, the direct GHG-emissions from industry amounted to 283.8 Mt (megaton = million tonnes) CO_{2eq}. Until 2016, total emissions from industry could be reduced to 188.2 MT CO_{2eq}.(BMU, 2019b) The main contributors to GHG-emissions are the iron and steel industry (including coking plants and rolling mills), the cement industry, the lime industry, the chemical industry, the glass industry, the pulp and paper industry, and the non-ferrous metals industry. In addition, the use of solvents and fluorinated gases also generates significant GHG-emissions in other manufacturing sectors. Direct energy-based GHG-emissions account for the largest share. Process-related emissions, e.g., from reduction processes, the use of raw materials containing carbonates, or

Figure 19

Qualitative illustration of the reduction of industrially emitted greenhouse gases



Source: Umweltbundesamt

solvents and fluorinated gases, account for about one third of direct GHG-emissions. The reduction of direct GHG-emissions requires different approaches depending on the source and type of emissions the industrial sector, and specific process under consideration.

GHG-emissions can be reduced by increasing materials efficiency, reducing consumption, and through the substitution with less GHG-intensive products and services, thereby reducing overall demand for GHG-intensive products and associated production requirements. This is reflected in the decreasing production amounts over time in the individual scenarios. In order to reduce direct energy-based emissions, the following basic approaches exist:

- Increasing energy efficiency with energy-efficient technologies, by optimizing processes and procedures, and through the consequent use of waste heat.
- Switching to less GHG-intensive and renewable energy sources and making direct use of renewable electricity (where technically possible).

The main challenge is the reduction of direct process-related GHG-emissions, which requires industry- and product-specific approaches:

- Avoiding materials or products which are associated with high GHG-emissions during their production or to substitute them with less GHG-intensive materials and products.
- Avoiding raw material-related or process-based emissions through fundamental process switches where possible.

Indirect energy-based GHG-emissions can be reduced mainly by a shift to renewable energies and by improving energy efficiencies.

Figure 19 illustrates the development of direct and indirect GHG-emissions when moving towards GHG-neutrality in the industrial sector. The envisaged energy transition reduces the indirect GHG-emissions (e.g., products source from other sectors upstream) towards zero while in parallel the energy transition in industry helps to reduce direct energy-related emissions in industry. Decarbonization of industrial

Table 7

Characteristics of the Green-scenarios for the industry sector

	GreenEe1	GreenLate	GreenEe2	GreenMe	GreenLife	GreenSupreme
Phasing out coal use	until 2050					until 2040
Energy efficiency potential realized	very high	intermediate	very high			
Material efficiency of technologies applied	high	intermediate	high	very high	high	very high
Production quantities	constant		model output (generally decreasing)			
International trade pattern	trade surplus		trade balanced			

processes reduces the process-based GHG-emissions even if a small amount of unavoidable emissions (according to current knowledge) will remain.

The narratives of the Green-scenarios describe a development in the industrial sectors which ensure a proper contribution to GHG-neutrality across all emission source groups, without the use of cultivated biomass for energy and without the use of CCS. For an overview, general variations in the Green-scenarios are shown in Table 7.

3.4.1 Development within industry

In the two GreenEe scenarios it is assumed that technical measures to increase energy and materials efficiency and the switch to renewable energies are implemented. Electricity is used directly to supply process heat wherever technically possible (power to heat). In GreenMe, additional ambitious measures are included to increase materials efficiency.
In GreenLife, the transition as described in the GreenEe scenarios is complemented by additional assumptions regarding sustainable consumption towards more durable and repairable products. GreenSupreme combines the positive measures supporting climate and resource protection from the other scenarios. In addition to phasing out of coal-based power generation by 2030, GreenSupreme assumes a complete phase-out of coal uses across all applications, which means a faster changeover of process technologies is required compared to the other scenarios. GreenLate is characterised by slower and less ambitious actions so that the renewal of production technologies is not completed by 2050. Instead, conventional technologies are still in operation and supplied by more inefficiently produced renewable fuels.

In all Green-scenarios, energy and raw material-related GHG-emissions from industry are reduced by around 96 % by 2050 compared with 1990 levels (Figure 20)[25]. The remaining emissions originate from the cement, lime, glass industries, and chemical industry. Iron and steel production contribute only up to 1.2 % to the remaining raw material-related GHG emissions.

GreenLate achieves the lowest reductions in energy demand. In 2050, around 900 TWh of final energy are still required which equals only a small reduction of around 9 % compared with 2015 levels (Figure 21).

On the other hand, due to better energy- and materials-efficiency as well as decreases in overall demands a reduction of 33 % to around 660 TWh is achieved in the GreenSupreme scenario. In all scenarios, energy efficiency measures have the largest impact on emissions reductions until 2030. From 2030 onwards also the conversion of process technologies toward more efficient sector-coupling-technologies show a visible effect on the final energy requirements. GreenSupreme follows a more ambitious transformation path from the outset, so that higher energy and material efficiency measures and the conversion of process technologies

25 According to the Climate Action Plan 2050 of the German government.

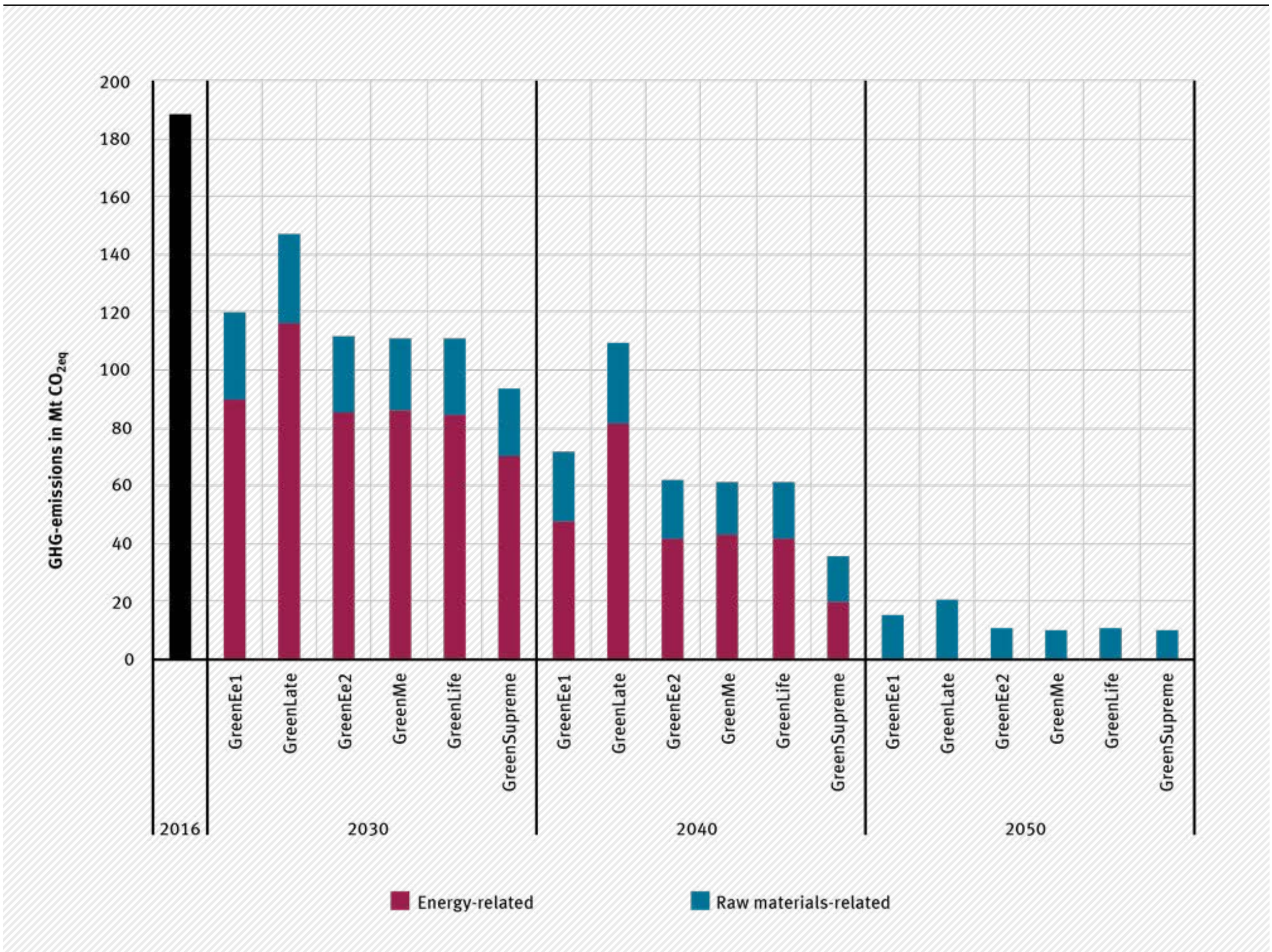
can be implemented at an earlier stage. Additional information on the specific changes assumed within each industry branch are provided in the full report Chapter 5.5 (UBA, 2019e) and briefly below.

Steel industry

In the production of pig iron in blast furnaces, the considerable CO_2-emissions resulting from the use of coke cannot be avoided due to the process. In order to meet climate protection targets, it is therefore unavoidable to switch primary steel production in the long term from the oxygen steel/blast furnace route to other production processes with a lower carbon-footprint. Secondary steel production via the electric arc furnace (EAF) route offers a possible alternative because the final energy requirement can be completely provided by electricity. GreenEe1, GreenEe2, GreenMe, and GreenLife therefore make the optimistic assumption that the scrap volume will increase from currently 45 % of crude steel (Wirtschaftsvereinigung Stahl, 2019) to 67 % by 2050. GreenLate only assumes an increase to 50 %. In GreenSupreme, an even higher share of 67 % is assumed by 2040. If renewable electricity is used in the EAF production route, this only leaves the specific CO_2-emissions from electrode burn-up in 2050, which will then be about half as high as today. The remaining demand for crude steel 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 hydrogen-based direct reduced iron (DRI) systems and subsequent melting in the EAF. It is assumed in all scenarios except GreenLate that primary steel is produced via this route from 2030 onwards and increases until 2050 when all primary steel is

Figure 20

Development of the GHG-emissions across all sub-sectors of industrial production

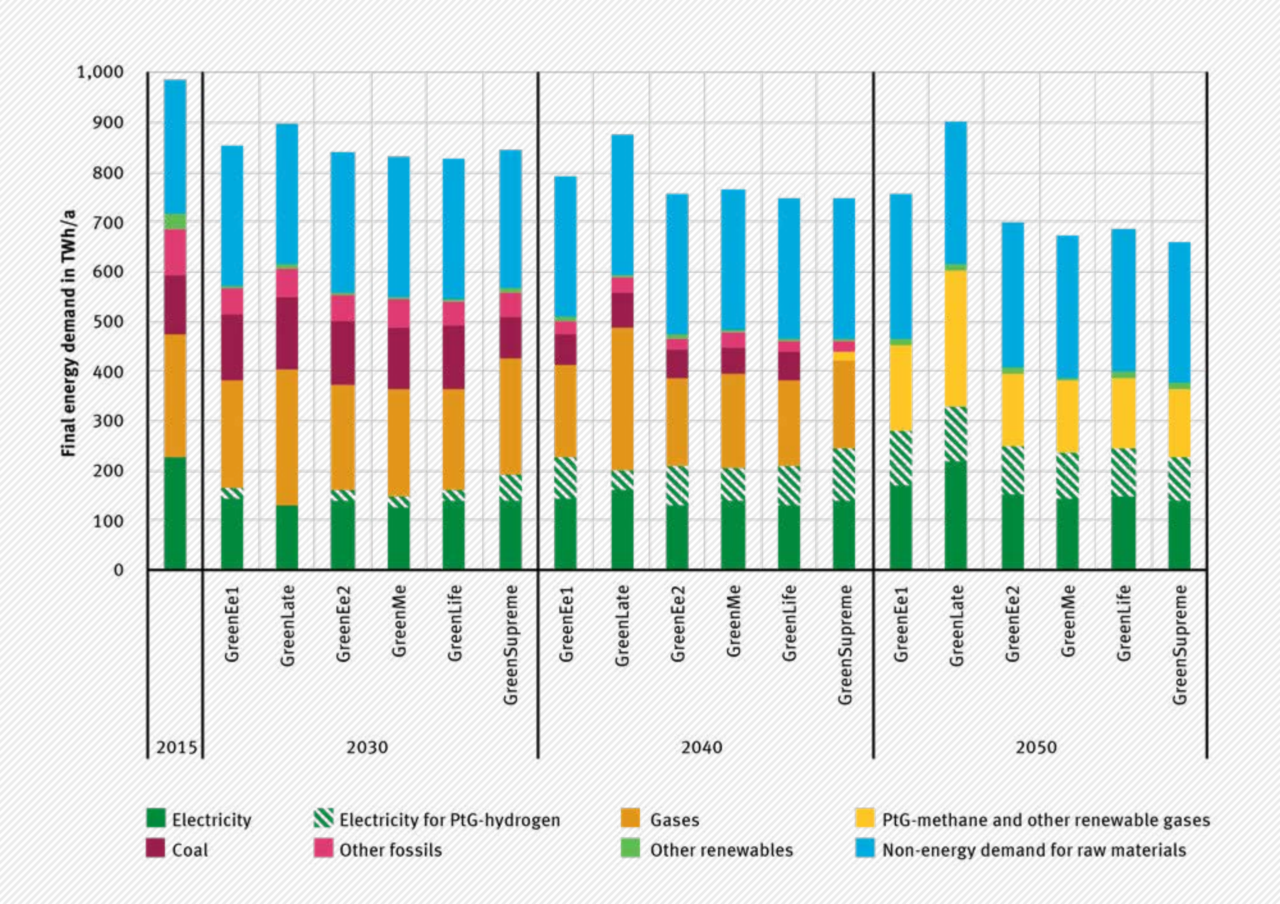


Note: Estimates include the emissions from the use of fluorinated GHGs as well as solvents and other chemical products.

Source: Umweltbundesamt based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e and historical data from BMU, 2019b

Figure 21

Trends in the final energy demand of the industrial sector



Source: Umweltbundesamt based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e and historical data from BMU, 2019b

produced via renewable hydrogen-based DRI. In GreenSupreme, the technology conversion will take place between 2025 and 2040 in order to phase out the use of coal by 2040. A complete process change is also assumed in GreenLate, but it is assumed that the DRI plants will still use 75 % natural gas or renewable electricity-based gas in 2030 and 25 % in 2050. Further details and assumptions on efficiency improvements can be found in Chapter 5.5.2 of (UBA, 2019e).

Chemical industry

As an energy-intensive sector, the chemical industry is characterised by a large number of different products and production processes. Starting materials are generally fossil fuels such as crude oil, natural gas, and coal. It is assumed that the final energy demand by 2050 will be provided entirely from renewable energy. By 2050, the raw material requirement (e.g., for the production of plastics) will be essentially provided via PtG and PtL routes powered with renewable energy. Conservatively, it is assumed that the demand for staring materials does not change over time. This corresponds to an energy equivalent of 282 TWh per year[26]. With regard to the efficiency of the overall system consisting of power generation, PtG/PtL generation and their further processing, it appears necessary to convert the process chains in the chemical industry to different PtG/PtL products as starting materials, depending on the product, in order to limit the conversion losses and thus the considerable electricity requirement for the provision of raw materials. There is still a need for research in this area. By 2030 at the latest, the hydrogen economy can switch to renewable energy (PtG hydrogen electrolysis).

26 In the scenarios GreenEe2, GreenMe, GreenLife, and GreenSupreme, the demand-side changes would lead to a decrease in the demand for raw materials. In the project, the complex production structures in the chemical industry could not be adequately modelled. For more Information see chapter 5.2, Textbox 5-2 in (UBA, 2019e).

It is assumed that as early as 2030 parts of the chemical industry operate without fossil energy sources and are based on PtG/PtL products. As a result, no additional fossil CO_2 emissions arise during the disposal (combustion) of the end products produced in 2050 or later[27].

Cement industry

The production of cement is inevitably associated with the release of CO_2. As in other industrial sectors, the energy-related GHG-emissions from production processes can be avoided by a complete switch to renewable energies, albeit only partially through the direct use of electricity. GHG-emissions from raw materials provisioning and use can only be reduced if alternative binding agents and building materials are found. It is assumed that research and development (R&D) work will be successful, so that conventional cement will increasingly be replaced by alternative binders reaching a share of 50 % in 2050. In contrast, in GreenLate the R&D activities are not sufficiently pursued or are not successful so that no switch to alternative binding materials takes place.

Due to changes in buildings & construction and infrastructure combined with the shift towards alternative construction materials, the production volumes in the Green-scenarios decrease significantly in some cases (for more information see Chapter 5.5.6 in the full RESCUE study (UBA, 2019e). For example, changing demands combined with gains in material and energy efficiency as well as shift towards alternative binding agents/ construction materials result in reduction of GHG-emissions of 80 % compared to 2010 in the GreenSupreme scenario.

3.4.2 Conclusions

In order to achieve the climate targets, the industrial plants need to be completely operated using renewable energy by 2050 and retrofitted using low-GHG technologies and processes. When undertaking the necessary conversions of the existing stock of power plants, the expenditures for new investments should be kept to a minimum and carried out in line with existing renewal cycles. To achieve this, the switch in the energy supply needs proceed and the necessary research and development (R&D) activities should be initiated at an early stage. Only by doing so can a complete conversion of all industry installations with long renewal cycle (e.g., blast furnaces) be carried out by 2050.

The central building block on the way to an industrial sector with low GHG-emissions is the complete phase-out of fossil fuels for energetic and non-energetic industrial applications.

- As far as technically possible, fossil fuels should be substituted by the direct use of renewable electricity (e.g., for process heat generation) in order to limit the overall energy requirement for the energy system. There is still a need for R&D in some industrial sectors.

- Renewable fuels should only be used in industries where electricity cannot be used for technical reasons (e.g., for heating solid and poorly heat-conducting feedstocks).

- The fossil-based hydrogen economy in Germany (possibly with a short-term focus on petrochemicals) should be restructured starting from 2030 onwards towards the use of renewable energy through the integration of hydrogen electrolysis.

- The raw material requirements of the chemical industry (organic chemistry) must also be completely covered by renewable energies (PtG/ PtL) by 2050 at the latest. Against the background of long life-times and increased recycling rates, durable products must be replaced by renewable energy sources in the chemical industry as early as 2030.

Until 2050, all industrial processes have to be completely switched to renewables. A large part of the industrial installations also has to be converted into GHG-neutral processes and further developed so that raw materials-related and process-based emissions are reduced.

- Industrial processes with low GHG-emissions should quickly be brought from the pilot stage to mature installations at large industrial scale. In the case of plants with long life-times or renewal

27 For more information see chapter 5.2 (UBA, 2019e). It is assumed that the electricity concerned is additional fully renewable electricity.

cycles (e.g., blast furnaces), the conversion should be carried out as soon as possible (starting in 2030 at the latest).

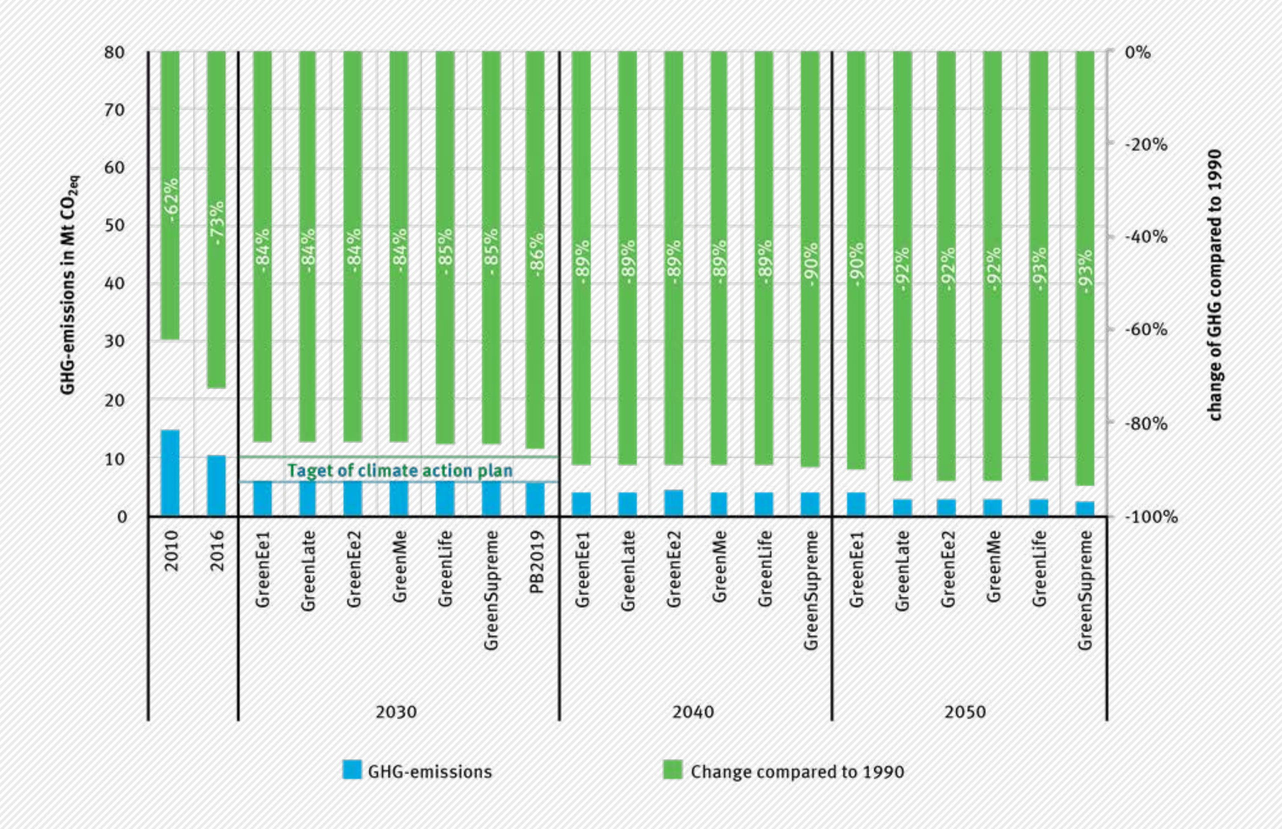
- Alternative low- or zero-carbon products for the substitution of conventional products associated with the release of high GHG-emissions (e.g., cement production) should be developed and be put on the market.

The implementation of ambitious measures for energy- and material-efficiency alters the required final energy demand and supports the integration of renewables into the energy mix. Efficiency gains also can make an important contribution to GHG-reductions and help to lower raw materials requirements in the long-term. In parallel to the retrofitting of industrial installations, the following mitigation and avoidance approaches should be pursued:

- Increase energy efficiency through the use of energy-efficient technologies, energy management, the optimization of processes and procedures, and the consistent use of waste heat.
- Increase material-efficiency in manufacturing processes.
- Increase recycling rates by enhanced secondary raw materials collection, efficient processing, and preferably high-quality utilization,
- More widespread use of substitution technologies, including through regularly updated substitution roadmaps,
- Increase the production of and demand for durable and repairable products,
- Foster sustainable consumer behavior.

Figure 22

Trends in greenhouse gas emissions in the sector Others for the Green-scenarios up to 2050



Source: own figure based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

3.5 Waste and Wastewater

The disposal and treatment of waste and wastewater are pivotal parts of both, health and environmental protection. In order to limit unwanted environmental emissions, the wastewater and waste sector will also play an important role in the future. However, the mandatory disposal and treatment processes emit GHGs. These emissions depend, among other factors, on lifestyle and nutrition, the used technology on the plant level, upstream processes of product production and the recycling rates and waste/wastewater collection rates.

The amount of emitted GHG decreases from over 38 Mt $CO_{2Äq}$ in 1990 to under 3 Mt $CO_{2Äq}$ in 2050. The differences between the Green-scenarios are only minor. GreenMe presumes a higher material efficiency, GreenLife postulates attitude changes (e.g. with respect to packaging materials and a reduced protein intake) and Green Supreme includes both assumptions. Substantial measures for the reduction of GHG emission in the waste and wastewater sector are:

- retrofitting existing waste treatment plants to mechanic-biological treatment plants,
- avoiding all waste streams, which are not based on renewable energies,
- ambitious cascade utilization of resources,
- maximizing GHG emission reduction through a flexible use of sewage gas, that is beneficial to the energy system.

3.6 Agriculture and LULUCF

With the production of healthy food, agriculture has a special significance for society. However, it is also a source of GHG-emissions and at the same time particularly vulnerable to the consequences of climate change. Due to the natural, physiological processes, greenhouse gas emissions in agriculture, e.g. methane from the digestion of ruminants or nitrous oxide from the use of agricultural land, can only be partly avoided by technical measures. This means that in addition to the technical measures, such as the fermentation of farm fertilizers and increases in the efficiency of fertilization, changed production systems, such as organic farming, but also more far-reaching structural measures are necessary in order to achieve the climate protection goals in Germany by 2050. In order to reduce emissions from agriculture as far as possible, the agricultural and food system needs to be restructured. The focus is on reducing livestock numbers (especially ruminants) and reducing the consumption of animal products to a healthy level in accordance with the recommendations of the German Nutrition Society. The reduction of food waste also has the potential to save GHG if less production is required due to fewer losses. Closely linked to agriculture are other types of land use. While agriculture will always remain a source due to the processes mentioned above, (remaining) land use can also act as a sink. According

Table 8

Characteristics of the green scenarios in agriculture and LULUFC

	GreenEe1/GreenEe2	GreenLate	GreenMe	GreenLife	GreenSupreme
changes in meat consumption	high	high	high	very high, very fast	very high, very fast
changes in milk consumption	none	none	none	reduction by 2050	reduction by 2050
ambition level for changes in production capacities	medium/ very high	medium	medium	very high	very high
ambition level in the use of wood products	medium	medium	very high	medium	very high
moor rewetting	5 % p.a. from 2020 onwards	5 % p.a. from 2022 onwards	5 % p.a. from 2020 onwards	5 % p.a. from 2020 onwards	5 % p.a. from 2020 onwards

to international climate reporting, natural sinks, as well as land-related emissions, are included in the land use, land-use change and forestry sector (LULUCF) in addition to arable land also forests, grassland, wetlands, settlement areas and other land. In the LULUCF sector, emissions must therefore be avoided and sinks must be maintained or restored, for example through

- preservation of the forest carbon sink
- conservation of moors and rewetting of moor soils
- halting the conversion of organic soils into residential and transport areas.

By varying the different parameters, the Green scenarios span a solution space for development in the agriculture and LULUCF sectors according to their characteristics, as described in Table 8.

In all Green scenarios, the technical climate protection measures are fully implemented. The energetic use of cultivated biomass will end in all Green scenarios by 2030. In addition, all scenarios will achieve a 20% share of organic farming by 2050[28].

3.6.1 Development of agriculture

Emissions from agriculture are mainly due to the use of agricultural land and animal husbandry. While technical measures are the most effective in soil management, the potential in animal husbandry lies in changing existing structures in the agricultural and food system.

In agricultural land use, large quantities of nitrous oxide and indirect greenhouse gases, e.g. ammonia, are released as a result of nitrogen fertilization with mineral and agricultural fertilizers. This means that there is great potential for reducing emissions in nitrogen fertilization and farmyard manure management. In all green scenarios, increased nitrogen efficiency (e.g., achievable by optimizing fertilizer planning and application techniques) and a lower mineral fertilizer requirement reduce the total nitrogen surplus to a maximum of 50 kg N per ha by 2030. This will above all enable direct and indirect nitrous oxide emissions to be reduced[29]. The storage and application of manure primarily releases methane, but also nitrous oxide. These emissions can be reduced by fermenting manure in biogas plants and storing the fermentation residues in a gastight manner. It is therefore assumed that by 2030 all fermentation residue storage facilities will be covered and that by 2050 all detectable quantities of liquid manure and manure will be fermented in biogas plants. Due to competition for cultivated land, no renewable raw materials will be cultivated in Germany for energy purposes from 2030 onwards. As a result, the emissions of fermentation residues from NaWaRo biogas will drop to zero from 2030. According to the scenario characteristics, the implementation of these measures in GreenLate will be delayed.

Our eating and consumption patterns have a significant impact on the level of greenhouse gas emissions. Changes in consumption and eating habits, if they affect the production of domestic agricultural goods, are one of the key factors in reducing emissions. In Germany, for example, around 11 million tonnes of edible food are currently disposed of as waste each year. This leads both to avoidable greenhouse gas emissions and to avoidable use of resources, especially water and land. Therefore, in all Green scenarios, food waste will be reduced by 50% by 2050. The resulting decline in demand is taken into account.

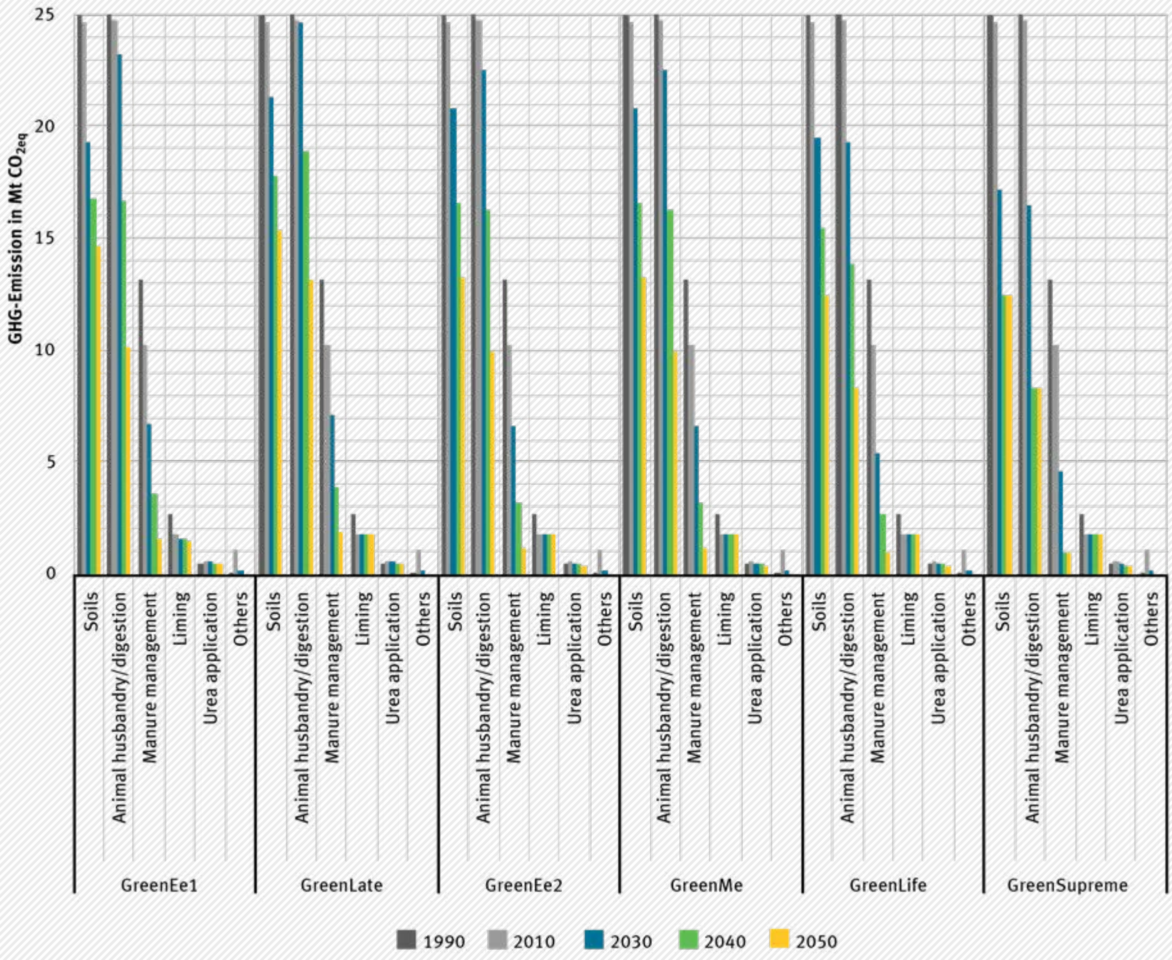
The production of animal food and the increasing degree of food processing cause high emissions. The cultivation of animal feed not only requires the production of additional energy-intensive fertilizers and pesticides, its cultivation also causes large-scale changes in land use (uprooting of grassland and deforestation) and thus further high emissions (Grünberg et al., 2010). In addition to direct and indirect emissions from animal feed cultivation, ruminants in particular emit the very climate-intensive methane. A healthier diet through reduced consumption of animal products is therefore one of the most effective measures to reduce GHG emissions from agriculture. In the Green scenarios, the German

28 The methodological and data-specific basis for the calculation of this partial aspect is (UBA, 2014). In the present study and the ALMOD model used here, it was not possible to vary the proportion of organic farming in 2050 in an acceptable cost-benefit ratio, although this would have been expedient if the area had been considered due to the lower GHG emissions of organic farming.

29 The production of mineral fertilizers also causes considerable greenhouse gas emissions. According to international climate reports, however, these are not attributed to agriculture but to the chemical industry. This attribution is also maintained in the present study.

Figure 23

Source group specific results of the modelling of agriculture



Source: Umweltbundesamt based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

Nutrition Society recommendations (DGE, 2017) for plant (fruit, vegetables, cereal products, potatoes, legumes) and animal products (meat, milk and eggs) are therefore used as the basis for the diet of the German population in 2050. The level of ambition and the timing of achieving this target vary. In the scenarios GreenEe1, GreenEe2, GreenLate and GreenMe it is assumed that meat consumption will be reduced to 30 % of today's consumption of approx. 1150 g per person per week by 2050. In the GreenLife and GreenSupreme scenarios, which are characterized by changes in lifestyles, the lower limit of the DGE recommendation for meat consumption from 2040 is assumed. This corresponds to a weekly intake of 300 g per person. At the same time, these two scenarios assume that consumption of fresh milk will fall by 15 % by 2040 as more people eat vegan and milk is partly replaced by soy milk from locally grown soy. The change in eating habits, in particular the significant reduction in meat consumption, is accompanied by a corresponding reduction in domestic meat production in the Green scenarios[30]. As a result, the livestock numbers are reduced to different degrees according to the scenario characteristics in the green scenarios and

30 In (UBA, 2014) a degree of self-sufficiency in meat of 345 % is achieved under the assumptions made in the ECO20% scenario. Since the assumptions of this scenario also form the basis of the GreenEe1 and GreenLate scenarios, this means that an adjustment in meat demand cannot be directly reflected in reduced meat production in these two scenarios. In the scenarios GreenEe2, GreenMe, GreenLife and GreenSupreme, the self-sufficiency share of animal demand was assumed to be 150 % under the overarching premise of balancing trade balances more strongly. The balance is essentially achieved by adjusting the pig and poultry herds.

the reduction is realized at different speeds. While in the GreenLate scenario it is assumed that a missed start will initially only lead to a moderate reduction in livestock numbers, the omissions will be made up for later and livestock numbers will be continuously reduced linearly from 2030 to 2050. In the GreenLife scenario, a linear decline in livestock numbers from 2020 is assumed in order to reach the target value, nutrition in accordance with the lower limit of the German Nutrition Society recommendation, in 2050. GreenSupreme, this target will already be reached in 2040, resulting in an even stronger reduction of livestock. In GreenEe1 and GreenEe2 it is assumed that livestock numbers will decline only slightly by 2030. Thereafter, a steady decline in livestock numbers to around one third of current levels will be achieved by 2050. The decline in livestock numbers will be accompanied by lower emissions from the digestion of ruminants and lower amounts of manure.

The measures described above lead to greenhouse gas emission reductions in agriculture of 59 % (GreenLate) to 70 % (GreenLife/GreenSupreme) compared to 1990 being achieved in the Green scenarios. As a result of a healthier diet and implementation of the DGE recommended intake for meat, while at the same time reducing animal numbers, emissions from the currently largest agricultural source, animal husbandry, are falling to such an extent that in GreenLife and GreenSupreme they are already lower than emissions from the soil for the first time in 2030, see Figure 23. In GreenLate, soils do not become the main source of emissions until the decade after 2040, as livestock numbers in the cattle, pig and poultry categories are reduced to varying degrees and rates in the various scenarios. Closely related to animal husbandry is the amount of manure available. In all scenarios, emissions from manure management are reduced to a minimum through complete fermentation and gas-tight coverage of the fermentation residue storage (residual emissions amount to around 1 million tonnes CO_{2eq}).

3.6.2 Development of the sinks

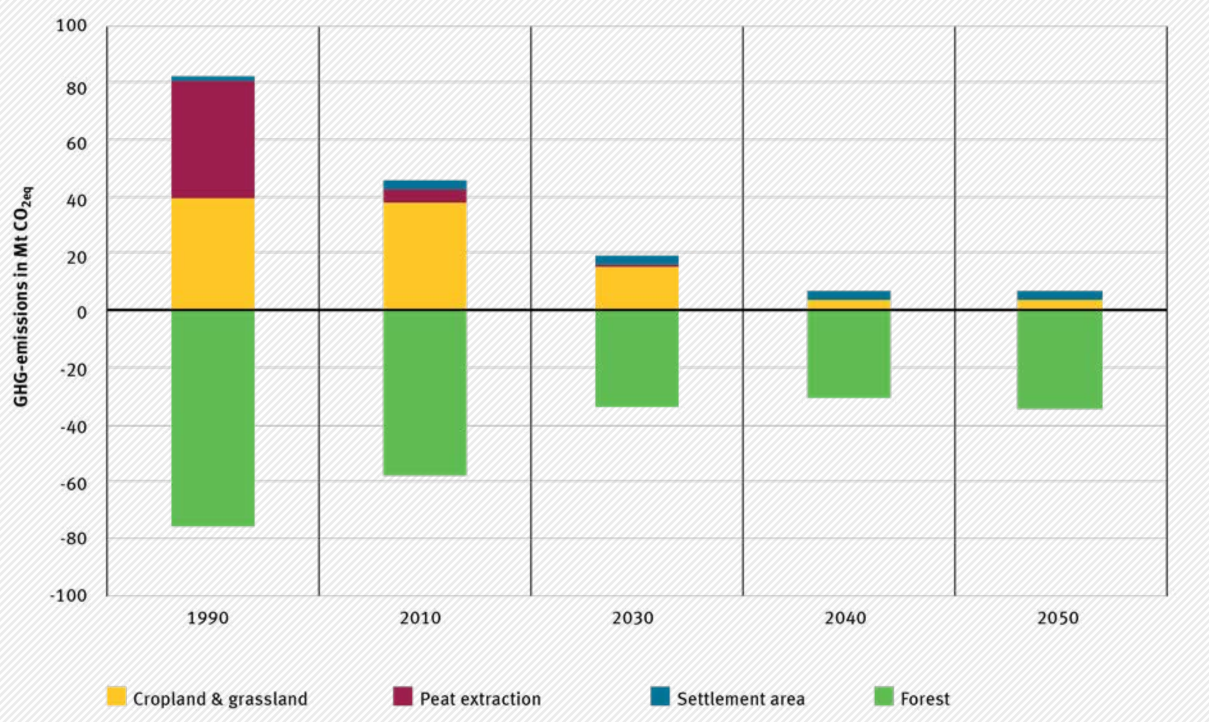
Around 6.5 % of agricultural land use in Germany takes place on drained moors (approx. 1 million ha). However, approx. 92-97 % of the CO_2 emissions from agricultural soils are attributable to this area (UBA, 2019a). The rewetting of drained bogs is therefore one of the most effective land use measures. With the exception of the GreenLate scenario, the Green scenarios assume that 5 % of agricultural land on drained moorland will be restored annually from 2020. The aim is to use only about 180,000 ha of former moorland close to settlements and infrastructure by 2050. This will reduce greenhouse gas emissions to 4 million tonnes by 2040. In the GreenLate scenario, the rewetting of the moors reflects the scenario-specific lower level of ambition at the beginning of the path. By 2021, around 100,000 ha of moorland will have been rewetted. From 2022 to 2030, the rewetted area will also grow by 5 % each year. Achievement of the target will thus also be ensured in this scenario by 2040. The resulting restrictions on agricultural production are taken into account by a reduction in livestock numbers, as this releases land that was previously used for the cultivation of animal feed. About 1 million hectares of intensively used arable land are affected. In order to preserve and restore existing peatlands, peat products will gradually be completely replaced by alternative substrates, thus stopping peat extraction by 2040.

In all Green scenarios, the forest is preserved as a net carbon sink. The green scenarios are based on the current “nature conservation scenario” of the model for forest development and timber production (Oehmichen et al., 2018). Accordingly, the rotation times in mixed hardwood stands in particular are extended and the unused forest area (process protection) is increased to 6.9 %. At the same time, forest stands that do not correspond to a natural potential vegetation (predominantly coniferous stands) are actively converted, which initially leads to more intensive forest use. These measures are based on the assumption that the overall volume of timber will be reduced, which will reduce the amount of timber product stored. However, the reduced timber volume is also countered by a reduced timber demand, in particular due to the continuous decline in the energetic use of residual forest wood until its complete abandonment in 2050.

In order, among other things, to minimize further pressure on land used for agriculture and forestry, land-take by settlements and transport is gradually decreasing. In the scenarios GreenEe1, GreenEe2, GreenLate and GreenMe, the land-take will be about 20 ha per day in 2030 and 0 ha net by 2050. In the GreenLife and GreenSupreme scenarios, a land-take of 10 ha/day is already achieved in 2030, which will

Figure 24

GHG-emission reduction in land use in the GreenEe1-scenario*



* The presentation of all scenarios is omitted here, as deviations between the scenarios are hardly graphically representable

Source: Umweltbundesamt based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

then fall linearly to 0 ha net by 2050. The reason for the faster achievement of targets in these two scenarios are the more sustainable lifestyles and the associated reduction in living space (cf. 3.2.1) and the demand for infrastructure (e.g. road networks). The already converted areas on organic soils will continue to emit 2.5 million t CO_{2eq} in 2050 despite the complete halt of the net new use. GreenLife and GreenSupreme, with faster target achievement, will lead to approx. 2 and 1 million t CO_{2eq} respectively less in 2030 and 2040.

As a result, the Green scenarios reduce the sources of emissions in the LULUCF sector, in particular the use of organic soils and peat extraction, from over 40 million tonnes in 2010 to about 6.5 million tonnes by 2050. At the same time, the carbon sink in the forest remains large enough to offset these remaining emissions fivefold (Figure 24). According to the nature conservation scenario of the WEHAM model (Oehmichen et al. 2018), in 2050 the forest removes about 35 million tonnes of CO_2 from the atmosphere. By rewetting a total of 80 % of the organic soils, it is possible in all scenarios to reduce the largest emission source of the LULUCF sector from approx. 38 million tonnes in 2010 to 4 million tonnes by 2050. In the GreenLate scenario, the delayed rewetting measures will lead to higher emissions of organic soils by 2030, but these will be accelerated before 2030, so that GHG emissions will also be reduced to 4 million tonnes CO_{2eq} by 2040. Although sealing can be stopped in all scenarios by 2050, there are still about 2.5 million tonnes of CO_{2eq} emissions from settlements. This is due to the continuing emissions of drained bog soils on these areas. In the GreenLife and GreenSupreme scenarios, there is an accelerated reduction in emissions from residential areas, but residual emissions of 2.5 million tonnes also remain in 2050.

3.6.3 Conclusions

GHG reduction targets in agriculture and land use can only be achieved with great efforts. Due to physiological processes, emissions from agriculture cannot be reduced to zero, so the relative share of agricultural emissions in total emissions will increase.

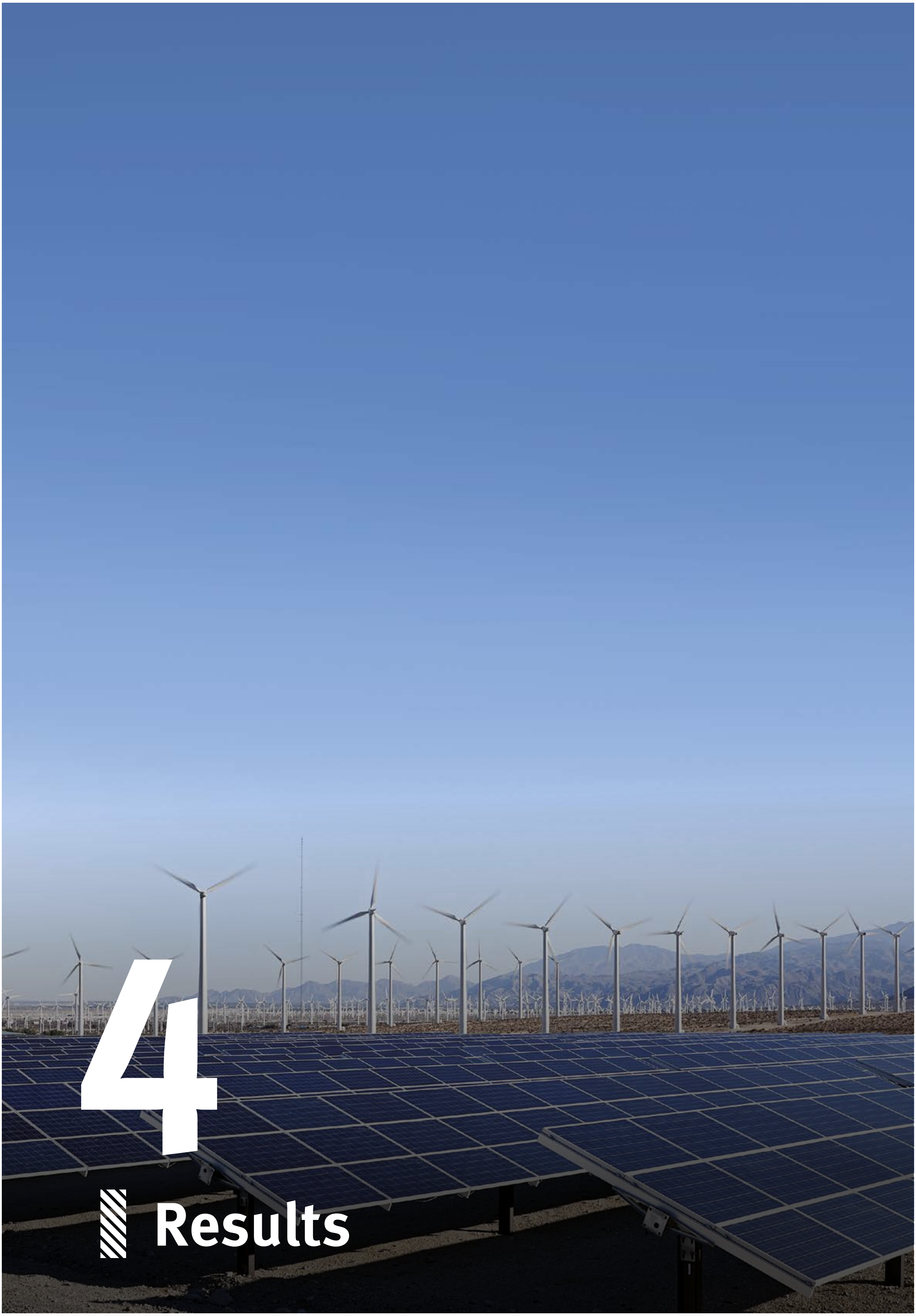
- Purely technical reduction measures (increased efficiency, slurry fermentation, etc.) can reduce emissions by around 20–25 %. These should therefore be implemented quickly.

- Around 60 % of agricultural emissions results from livestock farming. The reduction of livestock therefore plays a key role in effective climate protection in agriculture and land use. However, a reduction in domestic livestock is only possible if eating habits change at the same time and the consumption of animal products is reduced to a healthy level in accordance with the German Nutrition Society recommendations. In addition, meat exports must be reduced.

- A reduction in livestock numbers – achieved in particular through a reduction in regions with particularly intensive animal husbandry – would not only benefit climate protection, but would also have positive effects on biodiversity and on air and water quality. In addition, dependence on feed imports would be reduced, thus reducing the virtual import of land.

- Furthermore, other GHG reduction measures are only possible through cattle reduction. In order to restore the drained moors, 6.5 % of the agricultural land must be taken out of use or converted into paludiculture. This will reduce emissions from arable and pasture land by 80 %. Without reducing livestock production, however, this goal is difficult to achieve.

- Natural forest management is necessary both for nature conservation and for climate protection and adaptation. In order to preserve the carbon sink in the forest, a forest conversion is urgently necessary. The high proportion of coniferous forest monocultures makes the forest and thus the carbon reservoir susceptible to direct and indirect consequences of climate change. Mixed deciduous forests increase resilience.



4 Results

4.1 Territorial Greenhouse Gas (GHG) Emissions

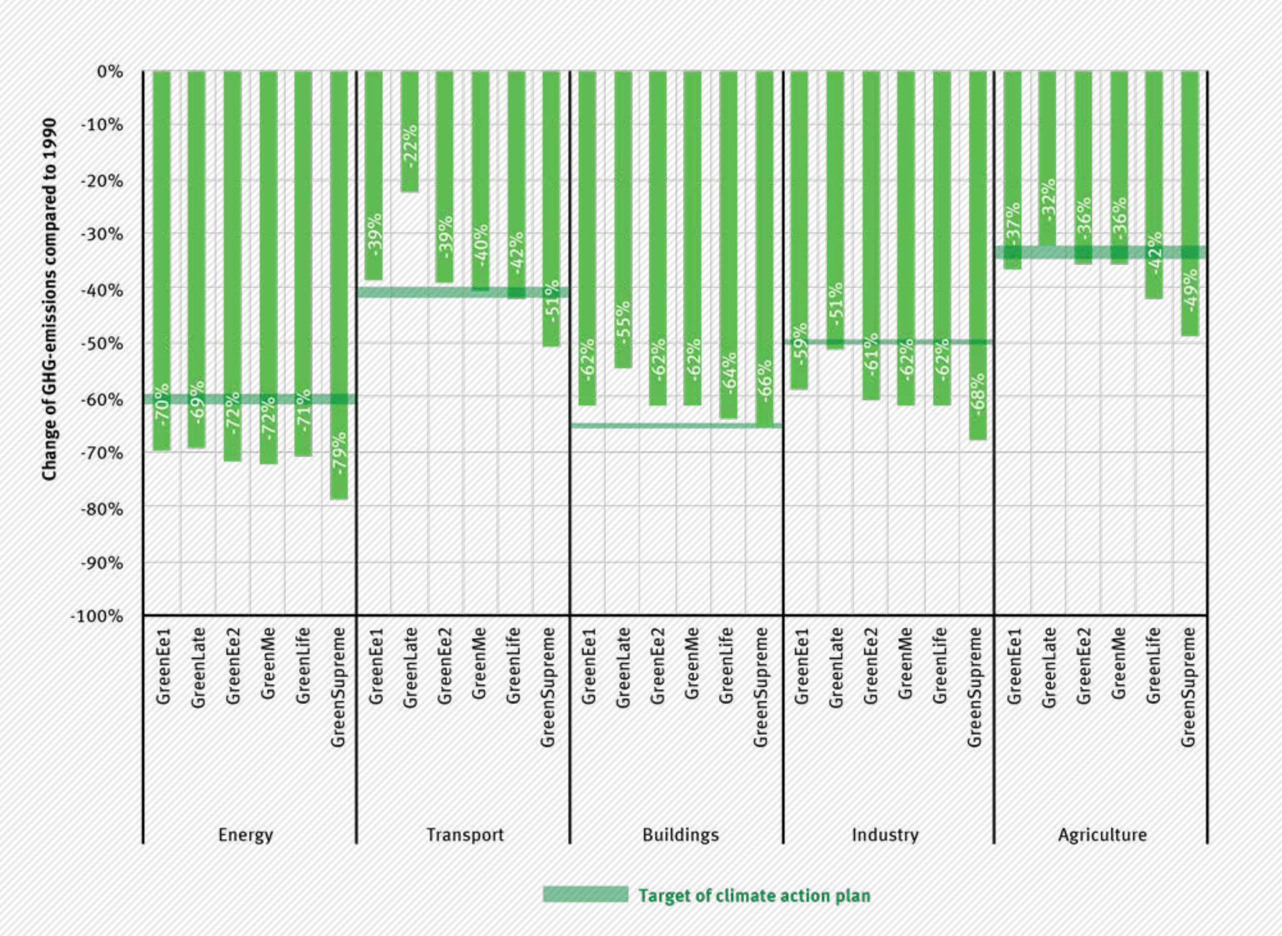
In order to limit climate change and its adverse effects, the German government has set itself in 2010 the target of reducing GHG-emissions by 80 to 95 % by 2050 compared with 1990 levels. This is in compliance with the two-degree limit. The Climate Action Plan 2050 further specifies the German climate targets, i.e., a reduction in GHG-emissions of 55 % until 2030 compared with 1990 levels, sectoral contribution to emissions reductions, and Germany's long-term goal to become "nearly" greenhouse gas-neutral by 2050 (BMU, 2016). Despite the Paris Convention of 2015 and its long-term climate protection targets, the German government confirmed the existing reduction corridor of 80 to 95 % by 2050 compared with 1990 levels (UBA, 2016c). In September 2019, the German government has set "greenhouse gas neutrality" as a new environmental action target for Germany by 2050 with the "Eckpunkte für das Klimaschutzprogramm 2030" (Bundesregierung, 2019). However, there is no increase in the level of ambition for the 2030 time horizon. Against this background, all Green-scenarios incorporate this target (i.e., a 95 % reduction in GHG-emissions compared to 1990 levels), but highlight different development paths for achieving this target including the implications on other national and international climate protection targets.

4.1.1 2030 – On the Path towards Greenhouse Gas Neutrality

The Green-scenarios cover development across all emission source groups. **Despite the fact that some of the individual sectoral climate protection targets are not met, the overall GHG-reduction target for 2030 is reached in all Green scenarios.**

Figure 25

Greenhouse-gas mitigation in the Green-scenarios until 2030 by individual sectors



Note: The "other" sector is listed in Chapter 3.5 and is not shown here due to its small contribution to overall emissions.

Source: Umweltbundesamt based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

This is a result of a fast transition in the energy sector, shown in Figure 25. Only the GreenLate-scenario remains within the target range of the Climate Action Plan (reduction of 55 % compared by 2030 compared to 1990). However, the other scenarios go well beyond this target. For example, **in GreenEe1 a reduction in GHG-emissions of 60.3 % is achieved compared with 1990 levels. In GreenEe2, GreenMe, and GreenLife, GHG-emissions are reduced to around 61.4 to 62.6 %. Furthermore, given its higher level of ambition, in GreenSupreme a reduction of 69 % in 2030 can be observed.** This highlights that emissions reductions above the existing target laid out by the German Federal Government can be achieved, but only if additional and even more ambitious measures are implemented. As a result, this should also be defined and put into action in the context of Germany's international and European obligations.

Energy

The energy sector aims to reduce GHG-emissions by at least 61 % in comparison to 1990 levels (see the target of the Climate Action Plan). This equals a reduction to at least 183 Mt CO_{2eq} by 2030. With the measures initiated by May 2019, a reduction to 263 Mt CO_{2eq} is (BMU, 2016, 2019b) expected. Across all Green-scenarios, the energy sector contributes a disproportionately high share to the GHG-reductions and this can compensate somewhat for smaller contributions by other sectors (Figure 25). **The sectoral -target for 2030 in the energy industry is achieved in all Green-scenarios. The GHG-reductions are dominated by the initiated phase out of coal-fired power generation. And in GreenSupreme, the phase-out of coal-fired power generation has already been completed by 2030.** In addition, measures to reduce the overall energy demand further support the reduction of energy-related GHG emissions.

Transport

Transport is the only sector for which almost no GHG-reductions were achieved between 1990 and 2018. In 2018, a total of 163 Mt CO_{2eq} were caused by transport. The emissions caused by Germany in international air and sea traffic are not yet included. According to the Climate Action Plan, GHG-emissions from national transport should be reduced by at least 40 % compared with 1990 levels to a maximum of 98 Mt CO_{2eq} (UBA, 2016c) by 2030.

In GreenLate, the GHG-reduction equals only 22 % by 2030 and clearly misses the sectoral target put forth by the Climate Action Plan. In the two GreenEe-scenario, the emissions are reduced by 39 % and therefore already come close to the sectoral target of 40 %. In GreenLife and GreenMe, additional measures, e.g., to avoid and shift traffic towards sustainable alternatives lead to a reduction in motorized private transport. Furthermore, about 7.5 million electric cars are in use which contribute to lowering GHG-emissions in 2030. In GreenSupreme, a stronger shift towards active forms of mobility (walking, cycling, etc.), the use of public transport, faster integration of electric vehicles (12 million electric cars in the fleet by 2030), and the limited use of renewable PtL fuels in conventional road traffic are assumed. This leads to a **reduction of GHG-emissions of 51 % until 2030 which is beyond the** Climate Action Plan-**target of 40 % by 2030 in the GreenSupreme-scenario**.

Buildings

In the buildings sector, GHG-emissions from the operation of residential and non-residential buildings are considered together with GHG-emissions from the "commercial, trade and services sector" (including also the military). The target for 2030 equals a reduction of at least 66 % compared to 1990 to a maximum of 72 Mt CO_{2eq} (BMU, 2016). It is assumed that by 2030 the phase-out of the energetic use of biomass, especially the inefficient use of decentralized wood heating technologies, have significantly advanced. This is assumed to conserve resources and reduce air pollution. **In GreenSupreme**, due to advances in the refurbishment and modernization of buildings, **a reduction in GHG-emissions of 65.7 % is achieved**. With GHG-reductions of 64.2 %, GreenLife just missed the intermediate target of the climate action plan. However, **by 2035 (at the latest) all Green-scenarios meet the sectoral GHG-reductions target for 2030 in spite of the phase-out of decentralized biomass use.** The GreenLate-scenario meets the target only in 2035, while for the other scenarios this happens a few years earlier.

Industry

In the industry sector, all GHG-emissions from the direct use of energy carriers, process-based emissions from the use of raw materials, and the use of fluorinated gases are accounted for.

According to the targets of the Climate Action Plan, emissions have to be reduced by 2030 to at least 143 Mt CO_{2eq} (i.e., by at least 49 % compared to 1990, BMU, 2016). **The sectoral target is met in all Green scenarios (and clearly exceeded with the exception of GreenLate). The main driver is a consistent energy efficiency strategy** which helps to drive down emissions especially in the GreenEe1, GreenEe2, GreenMe, and GreenLife scenarios where reductions of 59-62 % compared to 1990 are achieved. In addition, **GHG-emissions are decreased even further to 68 % in GreenSupreme as a results of the already initiated phase-out of coal as a fuel until 2040.**

Agriculture

The agriculture sector[31] in the climate action plan includes next to the GHG-emissions from agriculture also the direct emissions associated with the auxiliary use of equipment, e.g., the use of fuels in agricultural vehicles. In 2016, GHG-emissions in agriculture amounted to 71.8 Mt of CO_{2eq}. The target according to the climate action plan is to reduce emissions by at least 31 % to 61 Mt CO_{2eq} compared to 1990 levels (BMU, 2016). **The modeled Green-scenarios all meet this sectoral target.** Among the contributions to GHG-reductions are changes to a healthier diet and therefore reduced animal numbers. This happens at a faster pace in GreenLife and GreenSupreme when compared with the other scenarios. In combination with the technical measures assumed, GreenLife and GreenSupreme show a reduction in GHG-emissions of 42 % to 49 %, respectively, compared to 1990 levels.

4.1.2 2050 – Greenhouse Gas Neutrality

In the further transformation path from 2030 up to 2050, the Green-scenarios continue to unfold according to their story lines. With GHG-emissions reductions of 70 % by 2040 and 95.4 % by 2050, GreenLate follows the targets of the German federal government. However, in all other Green-scenarios emissions reductions are higher. This is largely a result of the ambitious transformation in the energy sector. By 2040, the difference between GreenLate and the other scenarios widens. The scenarios GreenEe1, GreenEe2, GreenMe and GreenLife show reductions of 80 % to 81.9 % until 2040. Because of its even more ambitious measures to limit global warming to 1.5 °C, the **GreenSupreme-scenario meets the 2050 climate targets already in 2036 with a subsequent reduction of 88 % by 2040 compared with 1990 levels. In 2050, GHG-reductions in GreenSupreme are found at 97.1 %.** With GHG-reductions of 96.7 to 96.9 % compared with 1990, the scenarios GreenEe2, GreenMe and GreenLife are found in a similar range (Figure 26).

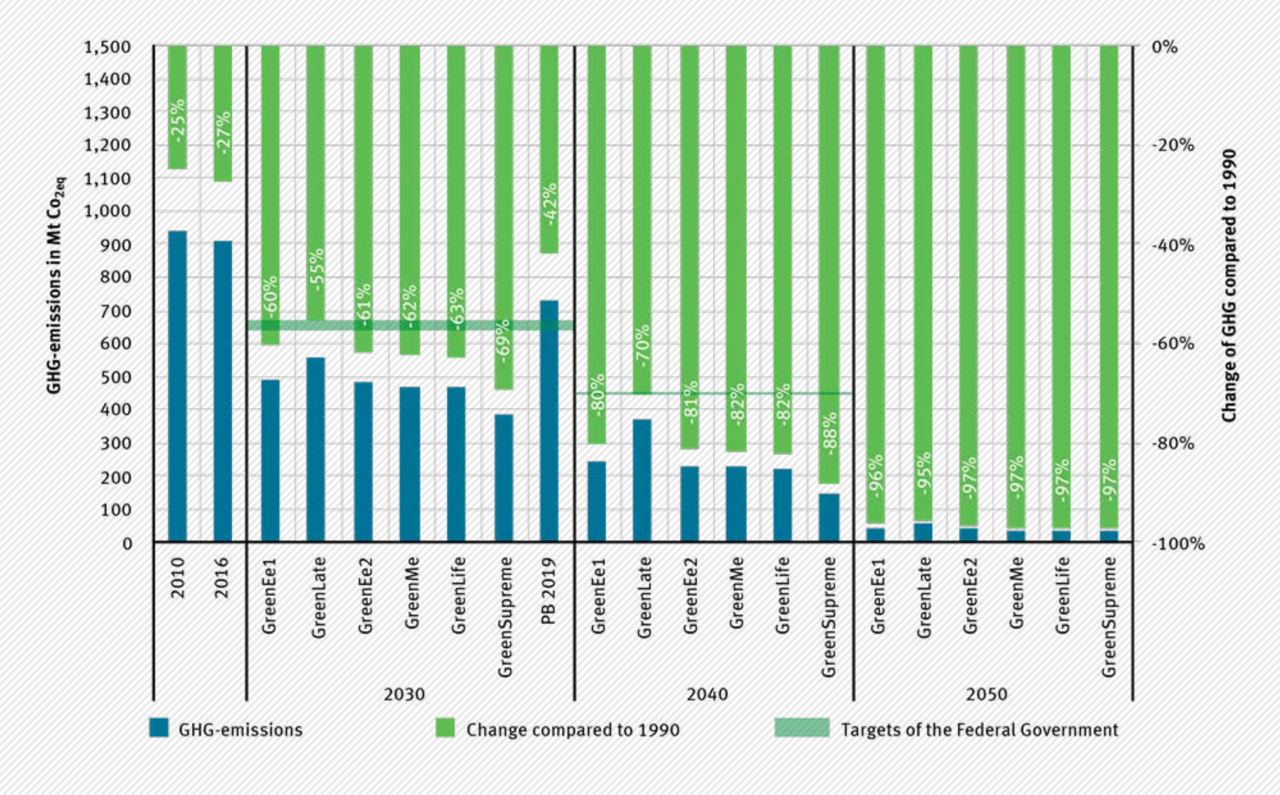
The above Figure includes all GHG-emissions that are also included in the climate targets of the German Federal Government. However, they represent only part of the emissions caused at national level. For land use and land-use changes (LULUC), forest management and national international transport (i.e., the transport of national consumer goods by sea and air), further GHG-emissions must be taken into account. Until 2050 in all Green-scenarios, the LULUC sector is able to reduce GHG-emissions by about 86 % compared to 1990 (see Chapter 3.6). Energy-related GHG-emissions from international transport are completely avoided by 2050 (Chapter 3.3). Against this background, GHG-emissions and the percentage reduction change only slightly compared to the Federal Government's targets.

The natural sinks from with sustainable forest management, wood use, and land use are more relevant. Avoiding the energetic use of residual woody biomass results in more available land area as no biomass crops for energy uses have to be grown. Similarly, reducing the animal numbers through dietary changes reduced GHG-emissions from animals and land transformations. Both strengthen the natural carbon sinks. In this study, no ecosystem accounting was carried out and the reduction potentials of natural carbon sinks could only be estimated on the basis of available literature. Specifically, the FOREST-Timber Preference Scenario ("Naturschutzpräferenzszenario") from WEHAM (Oehmichen et al., 2018) was used according to which the carbon sink potential of forests equals 29.5 Mt CO_{2eq} in 2030, 28 Mt CO_{2eq} in 2040, and 32.5 Mt CO_{2eq} in 2050. However, wood for materials and energy purposes in the Green-scenarios is smaller than in WEHAM and the above numbers are therefore considered to be conservative estimates. A more optimistic estimate is provided by the Greenpeace study "Waldvision" (Greenpeace, 2018)

31 GHG-emissions and measures in the area of LULUCF are not part of the sectoral classification in the Climate Action Plan and are, therefore, not examined in this section.

Figure 26

Greenhouse-gas mitigation in the Green-scenarios until 2050



Note: Only GHG-emissions are shown that are included in the targets of the German Federal Government.

Source: Umweltbundesamt based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e and BMU, 2019b

according to which the carbon sink of the forest equals 90 Mt CO_{2eq} in 2050. The potential carbon sink of newly available agricultural lands could not be quantified in the Green-scenarios. Therefore, it can be assumed that the carbon sinks given in the WEHAM FOREST-Timber Preference Scenario are available in all Green-scenarios. On the other hand, a carbon sink as given in the Greenpeace study is not reached.

For GreenSupreme, this means that GHG-reductions can be further increased through natural sinks to more than 97.1 % in 2050. **If the unavoidable emissions from LULUC and the GHG-reductions of natural sinks are considered, GHG-emissions can be completely avoided in GreenSupreme in 2050.** Using an optimistic assumption, a reduction of more than 103 % compared to 1990 can also be achieved (see Figure 27)[32].

The more ambitious GreenLife- and Green-Supreme-scenarios are able to achieve net zero emissions due to sustainable agriculture and forestry management, and even GreenLate comes close to this result (Table 9). Achieving country-level GHG-neutrality is therefore possible without the use of CCS[33], but instead through fostering natural carbon sinks. This in turn also provides synergies with other environmental goals such as biodiversity protection.

All Green-scenarios show that (almost complete) GHG-neutrality can be achieved. However, the different transformation paths result in varying cumulative emissions between 2010 and 2050. These differences are shown in Table 10. In GreenSupreme, almost half of the GHG-emissions emitted between 1990 and 2015 are released again in the period 2015–2050. The impacts of a delayed transformation are visible

32 The natural carbon sink in 1990 (i.e., 75 Mt CO_{2eq}) is considered when estimating the percentage reduction.

33 Carbon, Capture and Storage (CCS) is limited in its potential and associated with certain environmental risks and is therefore neither a sustainable nor a permanent option.

Figure 27

Greenhouse-gas mitigation in 2050 considering LULUCF

Note: LULUCF – Land Use, Land-Use Change and Forestry; HWP – Harvested Wood Products; Also the energy-based GHG-emissions of international transport are considered in the base year.

Source: Umweltbundesamt based on UBA, 2020e and Greenpeace, 2018

Table 9

Characteristics of the energy sector in the different scenarios

Green-scenario	reduction compared to 1990 without LULUCF	reduction compared to 1990 with LULUCF and HWP – conservative	reduction compared to 1990 with LULUCF and HWP – optimistic
GreenEe1	96,2 %	98,3 %	102,9 %
GreenLate	95,4 %	97,5 %	102,1 %
GreenEe2	96,7 %	98,8 %	103,4 %
GreenMe	96,8 %	98,9 %	103,5 %
GreenLife	97 %	99 %	103,6 %
GreenSupreme	97,1 %	99,1 %	103,8 %

Note: Also the energy-based GHG-emissions of international transport are considered in the base year.

Source: UBA, 2020a, 2020b, 2020c, 2020d, 2020e; Greenpeace, 2018; Oehmichen et al., 2018

in GreenLate where around 4.8 billion t CO_{2eq} (37 %) more are emitted than in GreenSupreme. In the other scenarios, emissions until 2040 are equal to emissions in GreenSupreme until 2050.

This highlights that in order to limit cumulative GHG-emissions, a light tightening of intermediate targets only leads to limited benefits for climate protection. Instead, rapid and ambitious action is needed.

4.1.3 2050 – Greenhouse Gas Neutrality in a global context

With the Paris Agreement, the international community has set the goal of limiting global warming to well below 2 °C and making efforts to possibly limit the rise in global temperatures to 1.5 °C. The IPCC's special report on the 1.5 °C target shows that global warming at 2 °C poses significantly higher risks to humans and nature than previously assumed. In line with the precautionary principle and

Table 10

Cumulative greenhouse gas (GHG)-emissions in the Green-scenarios*,**

In billion t CO_{2eq}	GreenEe1	GreenLate	GreenEe2	GreenMe	GreenLife	GreenSupreme
from 1990 to 2015	26,97					
additional until 2030	10,54	11,04	10,44	10,37	10,32	9,58
additional until 2040	3,61	4,6	3,46	3,39	3,35	2,45
additional until 2050	1,39	2	1,28	1,25	1,23	0,84
Total 1990–2050	42,51	44,61	42,15	41,98	41,87	39,84

* Simplifying, a linear development between the years was assumed.

Source: UBA, 2020a, 2020b, 2020c, 2020d, 2020e

** Without LULUCF and international traffic.

the sustainability goals, the necessary climate protection measures must be initiated quickly and in a socially, economically, and environmentally compatible manner. In IPCC SR1.5 (IPCC, 2018), 53 scenarios highlight possible global GHG-emissions pathways that limit global warming to 1.5 °C compared with pre-industrial levels[34]. On the basis of these different global emissions paths, an average path (IPCC global 1.5 °C) is presented below[35] and the development of the Green-scenarios compared to this (Figure 28). This global 1.5 °C emissions pathway represents an average transformation path which should be approximately followed with regards to human-induced GHG-emissions[36]. It does not mean that each individual nation must follow exactly this path.

Figure 28 clearly illustrates that **the high level of ambition reflected in GreenEe1, GreenEe2, GreenMe and GreenLife (especially until 2040) does not meet the requirements of the IPCC's average global 1.5 °C emissions pathways. Similarly, the current targets of the German Federal Government and the GreenLate-scenario until 2040 are insufficient to limit global warming well below 2 °C. On the other hand, GreenSupreme, represents a compatible transformation path.**

It should also be noted that a number of other relevant emissions caused by humans (such as non-CO_2 effects in aviation) cannot yet be properly quantified. As a result**, the GHG-emissions reductions likely need to be more stringent than shown above. Simply considering the precautionary principle therefore requires rapid action in order to reach a trend mirroring the 1.5 °C emission pathway put forth by the IPCC.**

With the Paris Agreement there is also agreement that wealthy countries are of particular importance (see Article 4(1) of the Paris Agreement). Given that Germany's prosperity and economic performance are based on GHG-intensive technologies and the use of fossil fuels, Germany should aim for ambitious GHG mitigation measures (see also (Climate Analytics, 2018; Höhne et al., 2019)). **A transformation path such as GreenSupreme requires the comprehensive and rapid implementation of national climate protection measures. Furthermore, this requires ambitious international cooperation, financing and implementation of climate protection measures also outside Germany.**

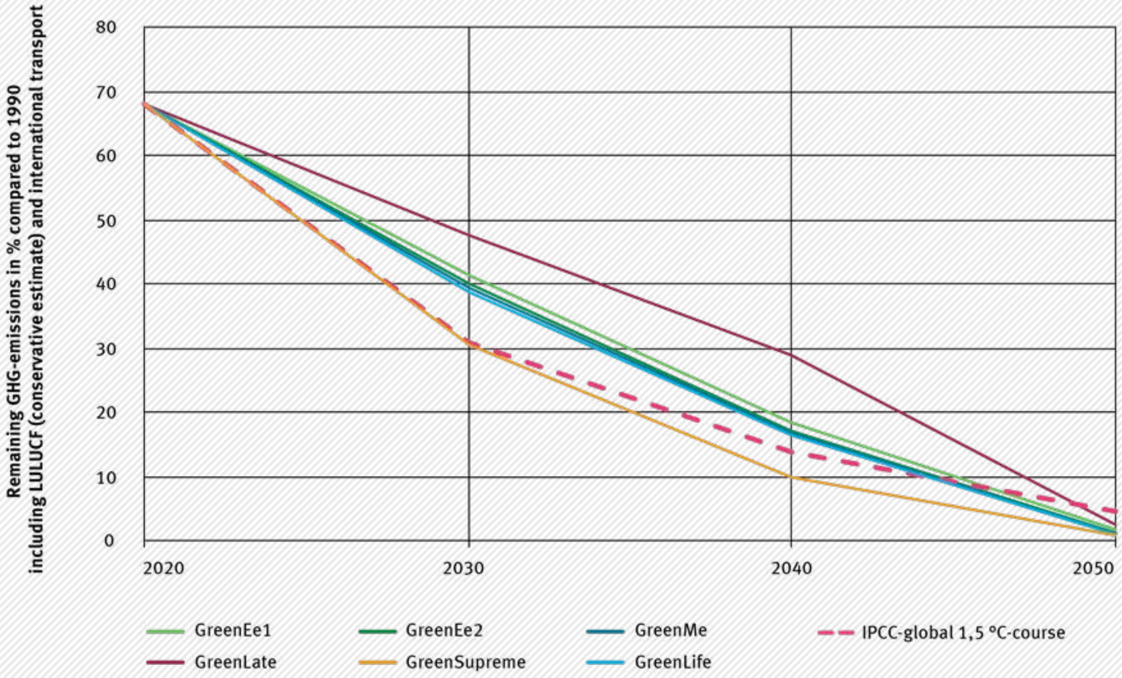
34 The 1.5°C emission pathways in IPPC SR1.5 are defined as those that either continuously limit warming to a maximum of 1.5°C or briefly exceed the target by 0.1°C and stabilize at 1.5°C within a decade following an overshoot.

35 These different IPCC scenarios have some common features. Two of the most important features of the scenarios used for the average path (IPCC-global 1.5 °C) are the development of GHG-emissions until 2030 and 2050. In all 1.5 °C scenarios, CO_2 emissions are halved by 2030 when compared to 2010. The global GHG-mitigation scenarios achieve CO_2-neutrality by ~2050. GHG-gases other than CO_2 are significantly reduced in the global scenarios but never completely avoided. Instead, emissions are offset through measures targeting CO_2 removal, so that net GHG emissions are found even below zero after 2050. The exact emissions trajectory between today and 2030/2050 varies within the global IPCC scenarios. Fewer "negative emissions" are required after 2050 the faster GHG mitigation takes place.

36 This global pathways thus represents the average GHG mitigation rates of the IPCC scenarios towards the 1.5°C target (considering no or only short-term exceedance of this target).

Figure 28

Development of the remaining GHG-emissions in the Green-scenarios taking into account LULUCF (conservative) and the CO2 emissions of international transport



Source: Umweltbundesamt based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e and IIASA, 2019

4.1.4 Conclusions

The Green-scenarios show alternative paths towards GHG-neutrality by 2050. They all have in common that considerable technical/technological developments and innovations, social change and a deep awareness of each individual for sustainable action will be necessary in the coming years.

- In order meet global commitments/targets to limit global warming to 1.5 °C, national GHG-emissions must be reduced by about 70 % until 2030 when compared with 1990 levels.
- GHG-neutrality must be achieved until 2050 at the latest by consequently avoiding anthropogenic GHG-emissions (according to current knowledge) and by strengthening natural sinks.
- Climate mitigation measures to reduce anthropogenic GHG-emissions must be prioritized and implemented quickly. They also need to be designed with a higher level of ambition than today.
- Both GHG-neutrality and sustainable resource management benefit from the rapid phase-out of fossil fuels across all sectors of the economy and this should be implemented as soon as possible.
- Sustainable agriculture and forestry management allow for the natural removal of CO_2 from the atmosphere and should be implemented in addition to other GHG mitigation measures.
- The use of CCS is not necessary for achieving GHG-neutrality at national level. Instead, natural carbon sinks should be leveraged as these also have synergies to other environmental challenges such as biodiversity protection.
- Raising awareness about climate and resource protection in people´s everyday life is at the core of sustainable development. A change in daily consumer behavior is necessary to relieve the pressure on natural resources.

- In addition to climate action at national scale, Germany needs to act internationally to ensure that other countries also become GHG-neutral by 2050 at the latest. For example, this should include financial support, technological aid, and knowledge transfer to support climate mitigation efforts. In this context, a special focus should be the phase-out of fossil fuels as well as the protection and expansion of natural sinks.

- Products used in Germany (including imported products) should meet high requirements for GHG-emissions, including emissions in the upstream supply chains and material efficiency, so that global change towards more climate and natural resource protection is also encouraged.

4.2 Raw Materials

In the Green-scenarios, the material flows into the German economy (i.e., domestic extraction, imports, and secondary material inputs) and exports are determined using economy-wide material flow accounts (EW-MFA, UBA, 2020a, 2020b, 2020c, 2020d, 2020e). The **headline indicator** is the **RMC (Raw Material Consumption)**[37] which represents the primary raw material use for domestic consumption and investments. The RMC is divided into the following raw material categories: biomass, metal ores, non-metallic minerals, and fossil energy materials/carriers. The use of raw materials for internationally traded goods is expressed in raw material equivalents (RME) in order to equally assess raw materials extraction domestically and abroad. RME represents the weight of raw materials used for the manufacture of goods including all raw materials used in the production of these goods both at home and abroad. In addition, a number of single raw materials (e.g., metals) are assessed in this project.

4.2.1 Development of Raw Materials Consumption (RMC) by Raw Materials Categories

The transformation towards a largely GHG-neutral Germany has considerable effects on the demand for raw materials. RMC can be reduced through the phase-out of fossil energy carriers when transitioning towards a renewable energy system. Other important leverage points include, e.g., structural policies that reduce the number and size of new settlement areas, increased energy savings, enhanced use of secondary materials, optimization of manufacturing processes via substitution and increases in material efficiency, and life-style changes. In all scenarios, continuous improvements in materials efficiency and in the technological development in Europe and the rest of the world (RoW) are assumed (section 2).

In 2010 (base year), Germany's RMC equals 1.37 Gt and is dominated by non-metallic minerals and fossil fuels (Figure 29).

Already in GreenLate it is assumed that energy efficiency potentials across all sectors are unlocked and an ambitious sustainable resource policy is implemented (with a time delay compared to the other scenarios). This includes the increased use of secondary materials and material substitution as well as changes towards more sustainable life-styles[38]. As a result, the RMC decreases in GreenLate already by -56 % until 2050 compared to 2010 levels. Additional measures to increase both energy and material efficiency (GreenEe2 + material efficiency) supplemented by additional sustainable life-styles changes[39] allow for a reduction of RMC by a further -12 % (GreenMe). This include, e.g., tapping the full recycling potentials for materials, additional material substitutions, and the use of innovative materials such as textile-reinforced concrete and timber constructions. In addition, it is assumed that at global-scale efforts towards increased materials efficiency (similar to Germany) also take place and this is reflected in the lower material footprint of imports. Further life-style changes (i.e., a reduction of per-capita living space compared to today and consumer preference for more durable goods offered within the framework of a sharing economy) of the GreenLife-scenario combined with a more ambitious transformation of the energy system and the liberation from annual economic growth (GreenSupreme) are capable of reducing RMC by an additional -2 % until 2050 (GreenSupreme).

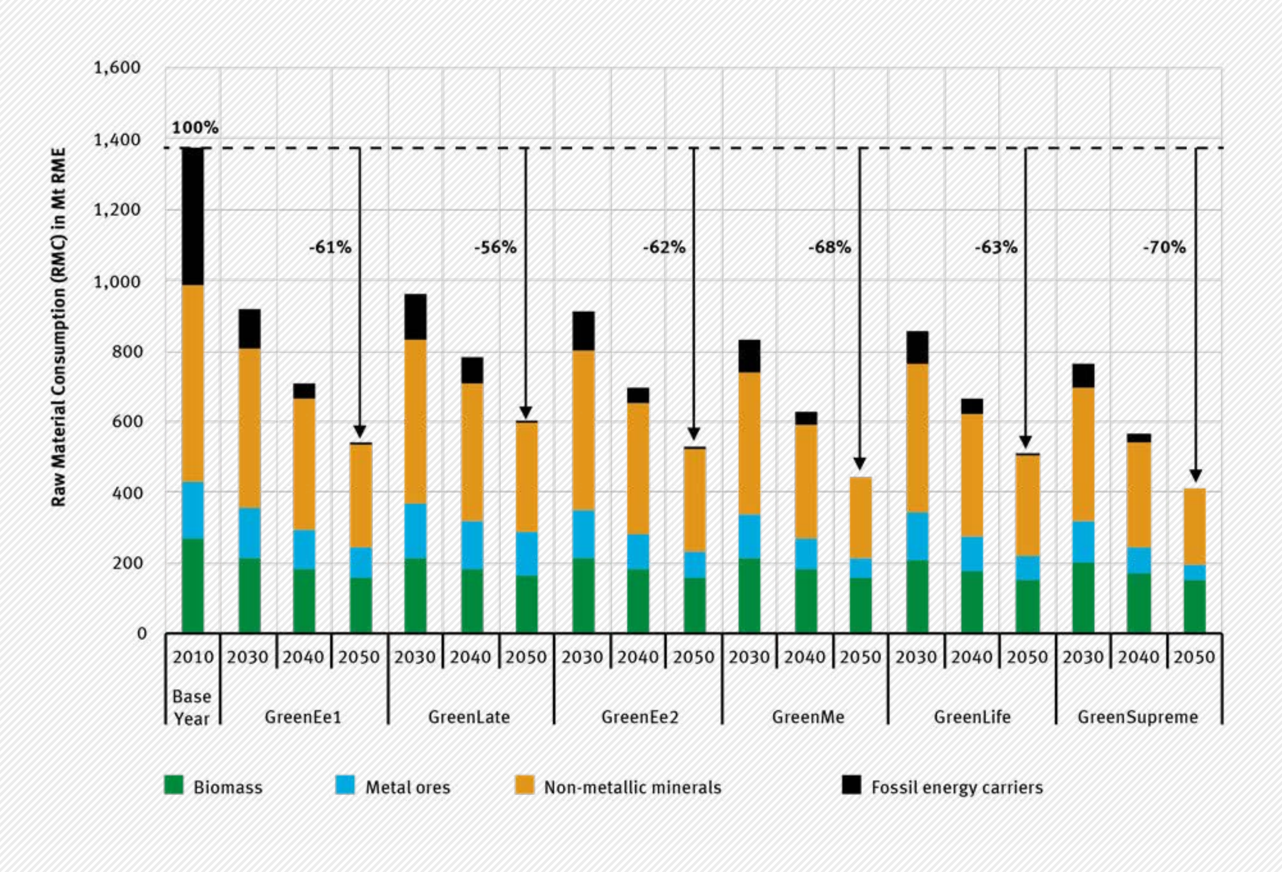
37 RMC (Raw Material Consumption) is composed of domestic raw material extraction and imports minus exports. In order to calculate indirect imports (raw material equivalents (RME)) use is made of input-output and linkage tables from URMOD together with data on imports and exports in the German economy. RME represent conversion factors to express a unit of product traded into the amount of material extraction needed, anywhere in the world, to produce the traded product.

38 Since the GreenLate scenario focuses on technical/technological measures, only a few aspects of more sustainable lifestyles are included. This includes, e.g., less meat consumption and changes in the transport system through avoidance and relocation. However, it is assumed that these measures are implemented with a delay compared to the other scenarios.

39 This includes, e.g., a lower per-capita living space or changes in personal mobility.

Figure 29

Raw material consumption (RMC) by raw materials category for all Green-scenarios



Note: All numbers expressed in raw material equivalents (RME).

Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

The largest reduction of RMC is associated with the phase-out of fossil energy carriers. The economy-wide shift towards renewable energy (i.e., also in areas where fossil energy carriers are used for raw materials purposes such as naphtha) reduces the use of **fossil energy carriers** by 2050. Durable products from the chemical industry are produced from 2030 onwards using starting materials obtained through PtG/PtL routes using renewable electricity. In 2050, only small amounts of fossil raw materials are still consumed in GreenEe1, GreenLate, GreenEe2 and GreenLife (approx. 5.5 to 8.1 Mt). This is a result of the delayed switch to renewable energies in the rest of the world and imports of products to Germany (footprinting perspective). On the other hand, due to the assumed global phase out of fossil fuels by 2050 in GreenMe and GreenSupreme, no fossil energy carriers are part of the RMC in 2050 in both scenarios.

In 2010, the use of **non-metallic minerals** (e.g., sand, gravel, limestone) amounted to about 0.56 Gt (41 % of the RMC). Non-metallic minerals use decreases in all scenarios and is found at 0.22 Gt to 0.31 Gt in 2050 in GreenSupreme and GreenLate, respectively mostly as a result of the decreased demand from the building and housing sector (section 3.2). In particular, assumptions with regard to the development of living space and the reduction of land take from settlements and transport in all scenarios to 0 ha/day by 2050 (section 3.2) influence the amounts of non-metallic minerals use. Furthermore, assumptions with regard to the share of secondary materials, material substitution (e.g., wood for non-metallic minerals), and increasing material efficiency affect the demand for non-metallic minerals.

Dietary changes such as reduced meat consumption (section 3.6) contribute significantly to the decline in **biomass** use from 266 Mt in 2010 to around 150 Mt (GreenLife and GreenSupreme) and 163 Mt (GreenLate) in 2050. For example, a lower demand for food products (due to a declining population) reduces biomass use by 24 Mt and switching to a healthier diet by 42 Mt until 2050 in GreenEe.

Furthermore, the assumption that no biomass is used for energy purposes after 2030 (Chapter 3.6) also contributes to the decline in biomass consumption (62 Mt in GreenSupreme to 54 Mt in GreenLate). In contrast, increasing wood construction in all Green scenarios except GreenLate and the substitution of abiotic materials by wood (e.g. insulating materials) increase the biomass demand (especially in GreenMe and GreenSupreme). However, this effect decreases continuously after 2030 due to the assumed living space developments (Chapter 3.2).

Metals and metalloids are central for the transition towards a GHG-neutral and resource-efficient economy. For example, iron and steel are central for infrastructures and energy-efficient buildings, copper and aluminum for power lines, electric vehicles, and renewable energy systems. A variety of specialty metals are required in future applications, e.g., batteries (lithium, cobalt, graphite), magnets for generators (rare earths), as alloying metals (nickel, niobium, beryllium, cobalt, gallium, etc.) and in electronic devices and systems (e.g. tantalum in capacitors, silicon in photovoltaic systems). In the scenarios, the RMC for metal ores declines from 162 Mt in 2010 to a range of around 124 Mt (Greenlate) and 43 Mt (GreenSupreme) in 2050 (reduction of -24 % to -74 %). Due to the additional demands for metals for restructuring the economy and the energy system, the decrease in the consumption of metal ores equals only -4 % to -29 % until 2030, whereas a reduction of -16 % to -53 % can be achieved by 2040. In GreenLate, the transformation of the economy is delayed and does not pick up speed until after 2030.

In 2010, **RMC per person (RMC/cap)** in Germany equals 16.8 t/cap and is thus above the global average of 11.1 t/cap (UNEP, 2019b). In the Green scenarios, a reduction to 5.7 (GreenSupreme) to 8.4 tons/cap (GreenLate) is achieved in 2050. All scenarios, with the exception of GreenLate, thus reach the corridor of sustainable resource use of 5 to 8 t/cap/year discussed in the literature in 2050 (Bringezu, 2015; IRP, 2014; Lehmann (Ed.), 2018; UNEP, 2011). **The comparison shows that reaching a significantly lower RMC per capita in Germany in 2050 might be possible, while at the same time remaining a high standard of technological and economic level of well-being.**

4.2.2 Level of circularity of the German economy

An important indicator for the level of circularity of an economy is the share of secondary materials used compared to the total materials use either for all materials categories combined or for single materials. The share of secondary materials for domestic consumption and investments in RME in the base year 2010 in Germany equals around 11 % (Figure 30).

This corresponds to the indicator DIERec (Direct and Indirect Effects of Recovery), which assesses the conservation of primary raw materials through recycling. The indicator highlights the extent to which primary raw materials would need to be extracted globally (assuming the same production patterns and technologies are in place) if secondary raw materials were not recycled (UBA, 2019f).

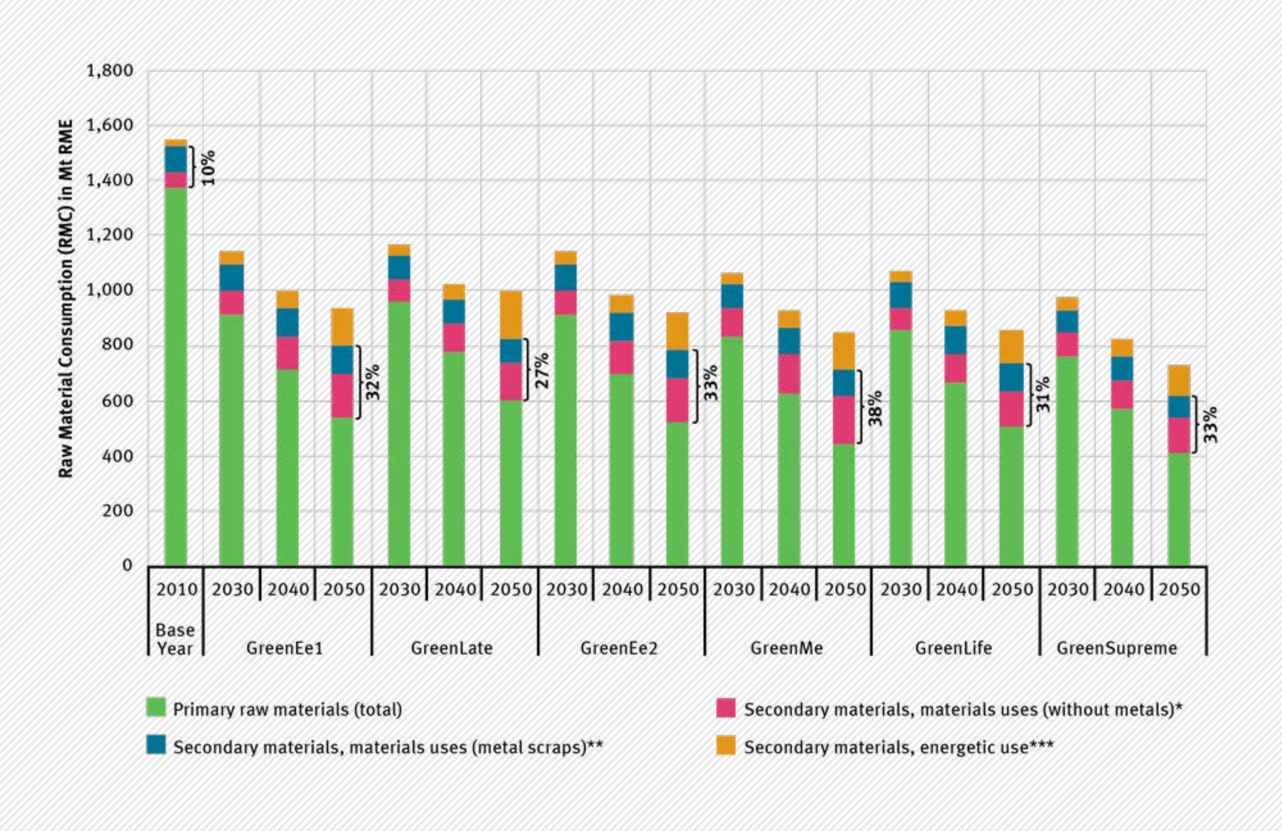
Over time, the share of primary raw materials substituted by secondary materials increases significantly. On the one hand, higher recycling rates and recycled contents are assumed for some material flows (see UBA, 2019e). This applies equally to the rest of the world and the goods exported from there to Germany. On the other hand, domestic consumption of primary raw materials is falling significantly. By using secondary materials, domestic material consumption in RME can be avoided by 27 % in GreenLate and 38 % in GreenMe by 2050. The higher share of recycled materials in GreenMe compared to GreenSupreme is due to a lower overall demand for materials in the GreenSupreme scenario. If energy recovery is also taken into account, this share rises to about 40 % to 48 %.

These results show that, given high recycling rates worldwide and reduced material demands, Germany can achieve a much higher degree of circularity by 2050[40]. The phase-out of the energetic (dissipative) use of fossil energy carriers already leads to a significant reduction in RMC and increased share of recycling. Nevertheless, even in 2050 primary raw material inputs are still necessary due to growth effects and residence times of materials and goods in the anthropogenic stock (Lanau et al.,

40 This does not take into account whether sufficient amounts of secondary materials will in fact be available globally (both in terms of quantity and under temporal considerations) to meet the high recycling input rates assumed for certain materials.

Figure 30

Raw material consumption (RMC) and share of secondary materials input for all Green-scenarios



* Wood, paper, plastics, and mineral wastes for use in high and civil engineering (without wastes) which are utilized directly on the construction site (closed loops)

** Iron-, copper-, and aluminum scraps

*** Tonnes of (raw) oil equivalents (toe) (theoretical value to quantify substitution effects).

Note: All numbers expressed in raw material equivalents (RME).

Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e

2019; UBA, 2017b), functional losses, downcycling, and dissipative uses (Mayer et al., 2019). Such losses can be minimized, but cannot be completely avoided from a technological and thermodynamic standpoint (Cullen, 2017).

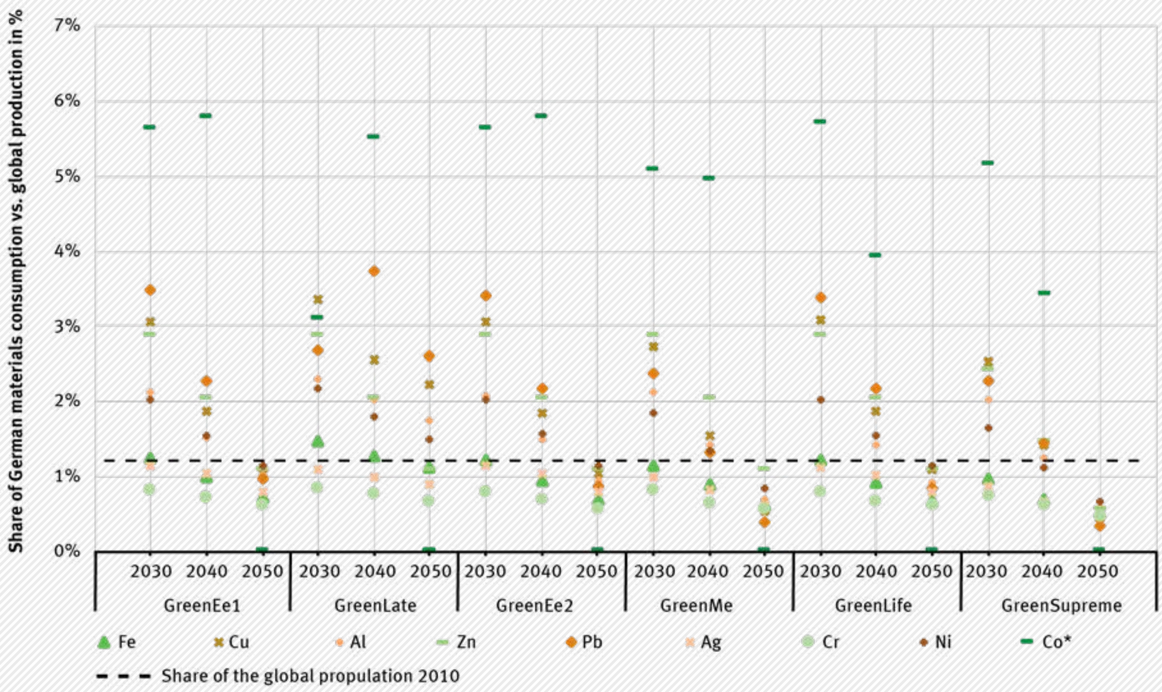
4.2.3 Overview of single raw materials

The consumption of selected materials is given in Figure 31 and compared with their annual global production in 2015/2016 (depending on data availability).

Germany's consumption of iron (Fe), chromium (Cr), silver (Ag), and nickel (Ni) in 2030 to 2050 is around 0.5 % to 2 % when compared with current global production. This corresponds roughly to Germany's share of the global population (dotted line). For copper (Cu), aluminum (Al), zinc (Zn), and lead (Pb) Germany's consumption of primary raw materials is slightly higher at about 1 % to 4 % of global production in 2015/16. On the other hand, the consumption of primary cobalt (Co) in batteries is estimated at about 3 % to 6 % of current global production in 2030 and 2040, respectively, and thus significantly higher than Germany's current share of the global population. Similarly, the German Raw Materials Agency (DERA) estimates that the demand for cobalt could increase further in the coming decades (up to 120,000 tonnes globally in 2035 are estimated for future technologies, which corresponds to 90 % of world production in 2013) (Marscheider-Weidemann et al., 2016). In the Green scenarios, the final demand for primary cobalt equals 7,287 tonnes per year in 2040 (GreenEe1 and GreenEe2) and could thus account for a significant share of global primary production (126,000 tonnes in 2016 (metal content)).

Figure 31

Final demand of selected raw materials in 2030, 2040, and 2050 as a share (%) of global primary production in 2015/2016



* Estimate only for batteries used in transportation.

** Germany's population in 2010 was 81.75 million people and the global population equaled 6.96 billion people (81.75 million people / 6.96 billion people = 1.17 %).

Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e. Global production estimates were taken from the US Geological Survey for the latest year available USGS, 2019. For chromium, the production data from chromite was used and a metal content of 30 % assumed.

For **lithium (Li)**, global primary production was around 26,000 tonnes (metal content) in 2016 (USGS, 2016). Lithium is currently mined mostly in Australia, Chile and Argentina. In the Green-scenarios, a significant increase in the use of lithium-batteries in transportation is assumed (Figure 32)[41].

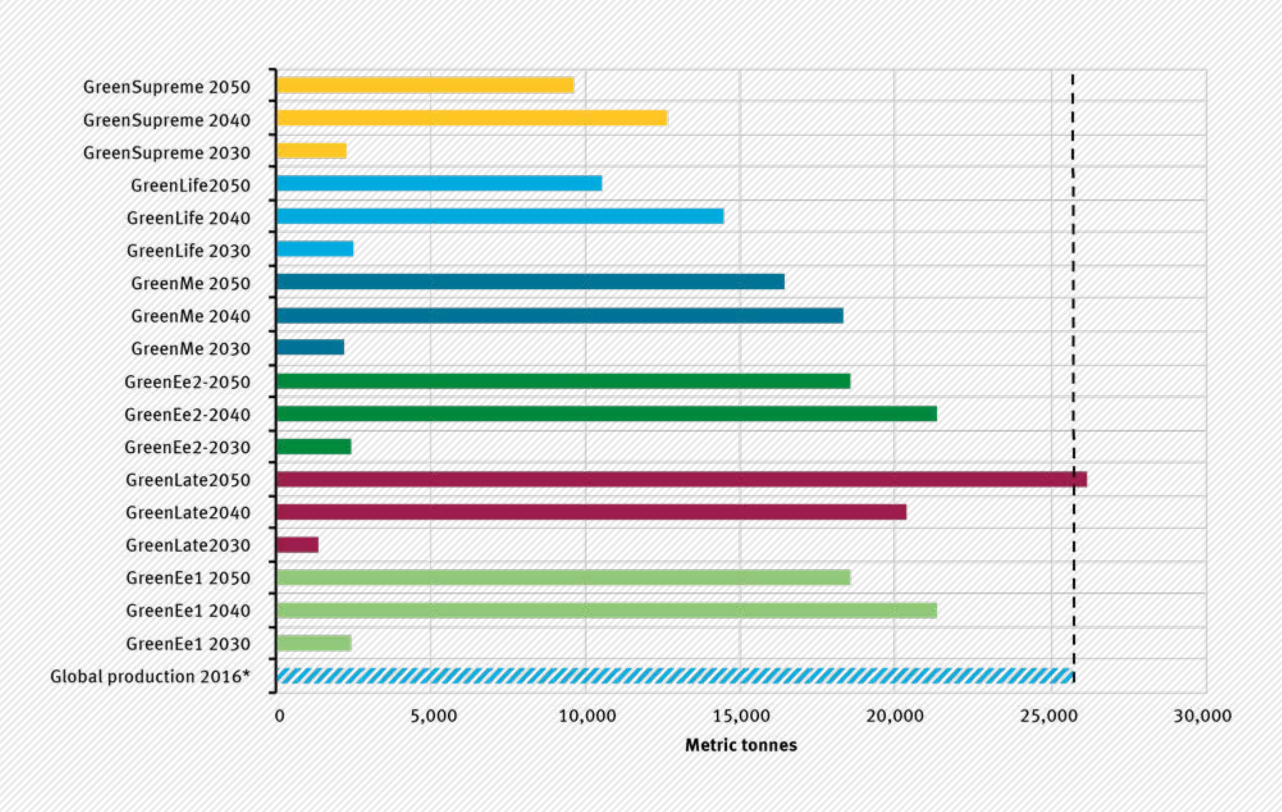
In 2050, the demand for lithium in Li-Ion batteries used in Germany amounts to approx. 9,600 t in GreenSupreme to 26,200 t in GreenLate. This corresponds to a share of 37 % to 102 % of current global lithium production. Assuming that the rest of the world develops similarly to Germany, this would require an enormous expansion of lithium production capacity. Also DERA assumes that the global demand for lithium in 20135 in a subset of future technologies alone (i.e., Li-Ion batteries and airframe lightweight structures) could reach up to 110,000 tons, i.e., more than four times the current annual production (Marscheider-Weidemann et al., 2016).

However, the estimates for the Green scenarios shown above do not take into account the possible recovery of lithium from secondary sources, e.g., from vehicle batteries. Instead, in the scenarios, second-life batteries are assumed to be used firstly as storage in the energy sector so that the quantities of lithium in 2050 are still largely bound in the in-use stock (i.e., most batteries have not yet reached their end-of-life and can be recycled). In addition, recycling concepts for vehicle batteries are only currently being developed, so that no estimates could be made with regards to the possible recovery of lithium and other materials. However, it can be assumed that in the next years corresponding concepts and plants will be developed and that the demand for lithium (and other materials such as cobalt) can thus be partially covered by secondary sources. A further limitation of the above

41 This is an extra calculation only for lithium used in batteries. Other usage paths (e.g. ceramics and glass, greases, etc.) were not considered.

Figure 32

Final demand for lithium (Li) in batteries in the different Green-scenarios in comparions to global annual production figures (in metal content) in 2016



* Globale production data for 2016 were taken from the US Geological Survey (USGS, 2019) (excluding the USA). Production figures for lithium minerals and brine were converted into metal contents based on Graedel et al., 2015.

Source: own compilation based on UBA, 2020a, 2020b, 2020c, 2020d, 2020e.

estimates of lithium and cobalt is that only use in vehicle batteries was taken into account. The demand for these raw materials in other applications could further increase the demand for both raw materials.

Even if the numerous environmental technologies considered in the Green scenarios are consistent for Germany from today's point of view, their actual global expansion could be significantly different if substitution technologies (UBA, 2019h), which are not yet ready for the market or which have not yet been developed, are taken into account. As a result, the estimated requirements for individual raw materials in 2050 are subject to larger uncertainties than the estimations by material categories. However, they can help to identify possible issues of high raw material criticality at an early stage.

4.2.4 Development of total raw materials productivity until 2050

In all scenarios, raw materials use (RMI[42] and RMC) decreases between 2010 and 2050 (see UBA, 2019e). At the same time, a continuous economic growth of about 0.7 % per year (all scenarios except GreenSupreme from 2030) leads to an increase of the gross domestic product (GDP) and thus of the total raw material productivity[43]. With an annual average increase of total raw material productivity of 2.3 % to 3.0 % across all scenarios, the observed trend is above the target of ProgRess II (BMUB, 2016) and the German Sustainability Strategy (Bundesregierung, 2018). But even in the GreenSupreme scenario, in which average economic growth declines to zero

42 RMI: Raw Material Input. The RMI includes domestic extraction and imports expressed in raw material equivalents (RMI).

43 Total raw material productivity = (GDP + imports)/RMI, with GDP: Gross Domestic Product and RMI: Raw Material Input. In the indicator, imports are taken into account not only by weight of imported goods but with the associated total primary raw material inputs (Raw Material Equivalents = RME).

percentage points between 2020 and 2030 and stays at this level in the decades thereafter, (total) raw material productivity continues to rise by 2.6 % per year between 2030 and 2050 due to the continuous decline in primary raw material use.

4.2.5 Conclusions

The Green-scenarios show that Germany can reduce its consumption of primary raw materials by up to 70 % until 2050 through a combination of energy- and material-efficiency measures, sustainable life-style changes, and the transformation to a renewable energy system without fossil energy carriers. However, the sketched transformation pathways will also increase demands for individual raw materials and this was only partly quantified. Against the background of a globally equitable use of raw materials, a transformation path analogous to GreenSupreme should therefore be pursued. For this, the following aspects need to be considered and implemented:

- The consistent closure of material cycles considering technical potentials is one of the biggest leverage points for lowering RMC, alongside the phase-out of fossil energy carriers. Both should be promoted much more ambitiously than before. In the long term, also the net increase of anthropogenic material stocks must be slowed down, as otherwise the cyclical use of secondary materials will continuously be overcompensated by physical materials growth.

- The technological changes necessary from a climate protection perspective, such as the development of the renewable energy system or changes in the industrial sector, e.g., alternative steel production routes, also help to reduce demand for primary raw materials in the medium to long term. In addition to promoting material efficiency, resource policy should therefore also foster policy measures for technological change and innovation.

- The assumption in the Green-scenarios that other countries also pursue an ambitious climate and resource policy is central to success within Germany (given that Germany is reliant on imports and climate change is a global challenge). Hence, the German resource policy should actively support the necessary transformations of trading partners.

- The Green-scenarios implicitly assume a global transferability of developments in Germany, but does not explicitly quantify the associated demand for raw materials at global scale. The envisioned transformation requires a broad technology mix in order to diversify materials demands. This calls for an open research orientation in the development of new technologies, especially with regard to technology- and knowledge-transfer, in order to be able to contribute to tailor-made solutions also outside Germany.

- In order to reduce supply risks and ensure expansion of environmental technologies worldwide, substitution will have to be increasingly applied to replace the corresponding technological raw materials. Due to the long lead times in development and market diffusion, regularly updated substitution roadmaps such as those proposed by the German Environment Agency are important instruments for the orientation of industrial policy.

- Next to material efficiency approaches, changes to our consumer behavior are important in reducing the overall consumption of primary raw materials. Germany's resource policy should therefore promote sustainable consumption on the basis of the National Program on Sustainable Consumption.

5 Conclusions

The RESCUE study highlights that GHG-neutrality in Germany together with a significant reduction of primary raw material consumption is possible through bold and ambitious actions. The six Green-scenarios illustrate that significant progress at all levels is necessary to ensure sustainable climate protection and natural resource conservation. Implementing only technical solutions for lowering GHG-emissions and raw material consumption is not sufficient. Instead, a broad range of strategies and measures targeting substitution, avoidance, and natural carbon sinks to influence GHGs in the atmosphere are needed.

The use of natural carbon sinks is central for successful climate protection. However, sinks do not replace substitution and avoidance. Natural carbon sinks (i.e., sustainable agricultural and forest management) allow already today the sustainable removal of CO_2 from the atmosphere and provide synergies to other environmental policy domains such as biodiversity protection. For a completely GHG-neutral Germany, these natural sinks must be used to a greater extent in the future. Technical sinks, e.g., CCS, can and should be avoided. All Green-scenarios pursue a mix of strategies for substitution, avoidance, and sinks, but with varying levels of implementation and differing by action field and sector.

The scenarios highlight that limiting the rise in global temperatures to 1.5 °C and enabling a more equitable use of raw materials requires bold efforts at national scale similar to the GreenSupreme-scenario. Acting in a timely and ambitious manner would allow for a more balanced combination of strategies to target substitution, avoidance, and sinks which are necessary for enabling joint climate protection and natural resource conservation. **For this, the necessary steps have to be taken globally and at national-level without further delay within the next few years.** Otherwise, climate protection will exceed a point beyond which the goal of GHG-neutrality can no longer be achieved.

Following developments for Germany as outlined in the Paris Agreement requires the reduction of territorial GHG-emissions by 70 % until 2030 compared with 1990 levels. Tightening the short-term GHG reduction targets (2030) only by a small margin will be insufficient for meeting the necessary national contributions of Germany toward limiting cumulative GHG-emissions and global warming to 1.5 °C. Current policies and targets of the German Federal Government lack behind the necessary actions for achieving this goal and are not enough for Germany to live up to its responsibilities.

The interdependencies between climate protection and natural resource conservation require a common overarching way of thinking and integrated action. For example, all Green-scenarios have in common that fossil fuels in all areas (i.e., for electricity, fuels, and raw materials/feedstocks) will be phased out. The technically feasible rapid phase-out of coal-fired power generation has benefits for both mitigating climate change and reducing the consumption of raw materials, and should therefore be pursued. The temporary additional demand for raw materials for the transformation of the energy system can be reduced by a technology mix and corresponding technological developments for substitution and avoidance.

The phase-out of coal-based power generation should take place by 2030 and the complete phase-out of coal use (including for heat and raw materials/feedstocks in industry) by 2040 at the latest. All fossil fuels should be phased out completely at least by 2050. For this, all production and consumption sectors have to be involved to pursue these developments. As discussed in the previous chapters, the necessary technical/technological developments for the substitution and avoidance of GHG- and resource-intensive processes and products as well as the expansion of the required infrastructure should be tackled in an ambitious and timely manner.

In addition, a societal transition towards more environmentally conscious life-styles is needed, considering both the supply and demand side. In order to initiate such a transition, policy-making needs to create the suitable regulatory and economic framework conditions as well as educational policy measures.

A clear commitment towards ambitious climate protection and resource conservation policy by policy-makers is needed. In addition to setting ambitious policy goals (both for climate

protection and natural resource conservation) the necessary policy and economic framework conditions for achieving these goals needs to be created. This would ensure that all actors at all levels of society (e.g., industry, building owners, etc.) can plan ahead. In addition, corresponding European and international efforts are required that are in line with the Paris Agreement and Agenda 2030. In particular, resource conservation needs to be anchored in bilateral and multilateral agreements (e.g. commodity partnerships, trade agreements, etc.), and internationally binding targets need to be agreed on the use and efficiency of raw materials.

Measures must be taken by Germany to support global GHG-reductions and the use of raw materials through financial aid, technological support, and knowledge transfer. The phase-out of the use of fossil fuels and the protection and expansion of natural carbon sinks should be high on the priority list.

Products placed on the German market (including imported products) should meet high requirements in terms of low GHG-emissions and material efficiency, referring to the entire supply chain, in order to strengthen global change towards climate protection and natural resource conservation.

Even if the RESCUE study might be ambitious given current trends, political decisions, and societal discussions, it clearly highlights that climate protection and natural resource conservation need to be jointly pursued and implemented. However, the question of whether and when individual contributions should be made, and related changes enacted, is no longer relevant. Instead, **the study clearly highlights that urgent action is required and that every contribution (considering both production and consumption) is important!**

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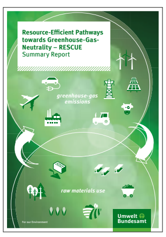

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