12 Pathways to a resource-efficient and greenhouse-gas-neutral Germany¹

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Introduction

Natural resources such as raw materials (biomass, metals, non-metallic minerals, and fossil fuels), water, land, and ecosystems provide the backbone of modern society. Their use enables the provisioning of feed and food, buildings and infrastructure, transportation, communication, and an almost infinite array of products and services. The extraction and processing of raw materials result in more than half of global greenhouse gas (GHG) emissions and over 90% of global biodiversity loss and water stress (IRP 2019). Currently, an estimated average of 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). However, raw materials play a central role in renewable energy technologies, sustainable building materials and infrastructure, modern communication systems, and low-carbon mobility (Mancini et al. 2019) and their use are expected to further increase in the coming decades.

Despite an increasing number of measures to mitigate climate change, global GHG-emissions have nevertheless increased from 27 to 49 Gt CO₂-equivalents (CO₂-eq) 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. In 2019, the global mean temperature was found at approximately 0.95 °C above the long-term average of the 20th century and 1.1 °C above pre-industrial levels (UBA 2020). The United Nations Framework Convention on Climate Change (UNFCCC) 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, 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).

Goal and scope of this project

Against this background, countries need to urgently transition towards GHG-neutrality by phasing out fossil-based energy carriers, significantly increasing energy and material efficiencies across all sectors, and by promoting more sustainable lifestyles. Furthermore, given the foreseen demands for a number of materials and potential supply risks, and environmental and social pressures associated with this, careful examination of the requirements and possibilities to reduce demand for individual materials is necessary.

The RESCUE ('Resource-efficient Pathways towards Greenhouse-Gas-Neutrality') study presented in this chapter explores different transformation pathways for Germany towards a raw material-efficient and GHG-neutral society considering all economic sectors. It 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 essential 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) to zero. A central building block is sector coupling with direct electricity use (e.g. the 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, feedstocks for the chemical industry, and process heat for 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.

Scenario storylines

In this study, ambitious climate protection and materials management are being considered together across all economic sectors. For this, six scenarios are developed which show possible development paths for Germany until 2050. The goal 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.

In all scenarios, Germany continues to be a country with a high population density and competitive industry and is embedded in the European Union (EU) and the world. Today's economic structures are assumed not to change fundamentally until 2050. 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. Furthermore, all scenarios follow population developments from currently 83 million people to about 72 million people in 2050 (option V1 of Destatis 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. 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 2015) and, therefore, do not represent sustainable future strategies for Germany. The scenarios include those described in the following sections.

GreenEe1 and Ee2 (Germany – resource-efficient and greenhouse gas neutral – energy-efficiency)

The development of GHG-emissions and raw materials demand is modelled on the basis of assumptions made in previous work (UBA 2014). Raw materials demand simulations include materials such as biomass, fossil fuels, metal ores and non-metallic minerals, as well as a number of individual raw materials (e.g. lithium, cobalt, nickel, iron, copper, among others.). The ambitious increase of energy efficiency, including the tapping of yet unrealised energy efficiency potential throughout all economic sectors, is the main characteristic of this scenario. Other countries in the world follow Germany's developments but at a slower pace (~10-year time delay). While in GreenEe1, 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). Economic growth equals 0.7% per year. 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. 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 (late transition)

GHG-emissions are cut by 95% in this scenario as well. However, the transitions process sets in at a later point in time compared to GreenEe. Also, energy efficiencies are raised in a less ambitious manner. Consequently, GHG-emissions have to be reduced more radically and within a shorter time window. 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 entirely 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, for example., 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 (material efficiency)

This scenario focuses on raising material efficiency in an ambitious manner and throughout all economic sectors. The restructuring of the energy system and of sectors such as transport, industry, and building and housing develops similar to GreenEe2. However, technologies with a smaller material footprint are favoured. For example, for photovoltaic (PV) systems an increasing number of

roof-top thin-film PV modules are installed (smaller material footprint and land requirements than conventional ground-based PV systems). Similarly, foundations and wind towers are designed with durability in mind, so that their service life can be significantly increased. Additional material efficiency measures include, for instance, the light-weighting of vehicles, use of alternative materials (e.g. textile-reinforced concrete for construction), the widespread use of timber buildings, or the use of biotic materials as insulating materials. Assumptions with regard to agriculture and healthy diets follow the GreenEe scenarios.

GreenLife (lifestyle changes)

GreenLife analyses how additional lifestyle/behavioural changes influence GHG-emissions and raw material consumption. Current trends, as well as smaller niche tendencies, are scaled up in this scenario. For example, 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. 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 urbanisation results in the use of fewer cars. Instead, a mix of public transport, walking and biking, and ridesharing are used. Electro-mobility and electrified public transportation outside of urban centres are 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 essential 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 GreenEe.

GreenSupreme (minimising future GHG-emissions and raw material consumption)

In this scenario, the most effective measures from the previous scenarios are combined. In summary, 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 net zero after 2030.

Methodology

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. Modelling of the transport sector is based on the Transport Emission Model (TREMODO) which analyses the GHG emissions and energy uses of all means of passenger and freight transportation on a yearly basis (ifeu 2019a; UBA 2019). The energy consumption for space heating and hot water in buildings under the assumption variations in the scenarios is based on the Building Model (GEMOD) (ifeu 2019b). Modelling of the agricultural sector is based on the Agriculture and LULUCF model (ALMOD) (Dittrich et al. 2020a). The cross-sectoral build-up and optimisation 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 optimisation 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).

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). The headline indicator is the RMC (Raw Material Consumption) 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 (for example, metals) are assessed in this project.

Further information on the methodology and detailed results are provided in (Dittrich et al. 2020a, 2020b, 2020c, 2020d, 2020e). A summary of the results is also provided in (Günther et al. 2019).

Results

GHG emissions. In all scenarios, the overall GHG mitigation target for 2030 of the German Climate Action Plan (reduction of 55% compared by

2030 compared to 1990) is reached, in particular, due to the significant progress in the energy sector. With the exception of GreenLate, all other scenarios are able to reach even higher emissions reductions until 2030, namely 60.3% (GreenEe1), 61.4 to 62.6% (GreenEe2/Me/Life), and 69% (GreenSupreme) (all compared to 1990 levels). 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 (reduction of 80–95% by 2030 compared with 1990). 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. 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.

The development paths of the Green-scenarios are compared with a global average transformation path of the Intergovernmental Panel on Climate Change (IPCC) which should be approximately followed in order to limit global warming to 1.5 °C compared to pre-industrial levels (IPCC global 1.5 °C; IIASA 2019; Figure 12.1). The comparison highlights that in order to develop along the lines of the Paris Agreement, national GHG-emissions should be reduced by around 70% by 2030 compared with 1990 levels as outlined in GreenSupreme. 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 pathway. 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.

Raw material consumption (RMC). The transformation towards a largely GHG-neutral Germany has considerable effects on the demand for raw materials. The 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, optimisation of manufacturing processes via substitution and increases in material efficiency, and lifestyle 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 (see scenario details above).

In 2010 (base year), Germany's RMC equals 1.37 Gt and is dominated by non-metallic minerals and fossil fuels (Figure 12.2). Already in GreenLate it is

Figure 12.1 Development of the remaining GHG-emissions in the Green scenarios taking into account LULUCF (conservative) and the CO₂ emissions of international transport.

Source: Günther et al. (2019).

assumed that energy efficiency potentials across all sectors are unlocked and ambitious sustainable resource policy is implemented (with a time delay compared to the other scenarios). This includes the increased use of secondary materials (see also our companion paper in this book) and material substitution as well as changes towards more sustainable lifestyles (e.g. less meat consumption and changes in transport via avoidance and relocation). 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 (e.g. lower per-capita living space or changes in personal mobility) allow for a reduction of RMC by a further 12% (GreenMe). This includes, 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 lifestyle 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

Figure 12.2 Raw material consumption (RMC) by raw materials category for all Green scenarios (2010–2050). RME: raw material equivalents.

Source: Günther et al. (2019).

and the liberation from annual economic growth (GreenSupreme) are capable of reducing RMC by an additional 2% until 2050 (GreenSupreme).

The largest reduction of RMC is associated with the phase-out of fossil energy carriers. Durable products from the chemical industry are produced from 2030 onwards using feedstock obtained through PtX 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.

Dietary changes such as reduced meat consumption as well as the assumption that no virgin biomass is used for energy purposes after 2030 contribute significantly to the decline in biomass use. 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). 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 equalled 16.8 t/cap and is thus above the global average of 11.1 t/cap (IRP 2019). 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 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 the technological and economic level of well-being.

Finally, also the demand for several individual raw materials was examined in this project. Results show that while for a number of materials such as, e.g. iron, copper, aluminium, zinc, and nickel demand decreases over time (due to efficiency gains and lifestyle changes), the demand for a range of speciality metals such as lithium and cobalt is expected to significantly increase in the future, for instance as a result of the widespread implementation of electric vehicles. This is examined in further detail in our companion paper in this book (Dittrich et al. 2020f).

Recommendations

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. However, the sketched transformation pathways will also increase demands for individual raw materials (see also our companion paper). 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. Against the background of a globally equitable use of raw materials and to follow the IPCC's average global 1.5°C emissions pathway, a transformation path analogous to GreenSupreme should, therefore, be pursued.

Abbreviations

ALMOD	agriculture and land use model
CCS	carbon capture and storage
EW-MFA	economy-wide material flow accounts
GDP	gross domestic product
GEMOD	Gebäudeenergiemodell (building energy model)
GHG	greenhouse gas emissions
IPCC	Intergovernmental Panel on Climate Change
LULUCF	land use, land use change and Forestry
PtG	power to gas

PtL	power to liquid
PtX	power to X
RMC	raw material consumption
TREMOD	transport emissions model
URMOD	Umweltökonomisches Rohstoffmodell (environmental-economic raw material model)

Note

- 1 This chapter is based on a technical report published first by the authors as “Günther J., Lehmann H., Nuss P. and Purr K. “Resource-Efficient Pathways towards Greenhouse-Gas- Neutrality — RESCUE: Summary Report” at https://www.umweltbundesamt.de/en/rescue/summary_report.

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