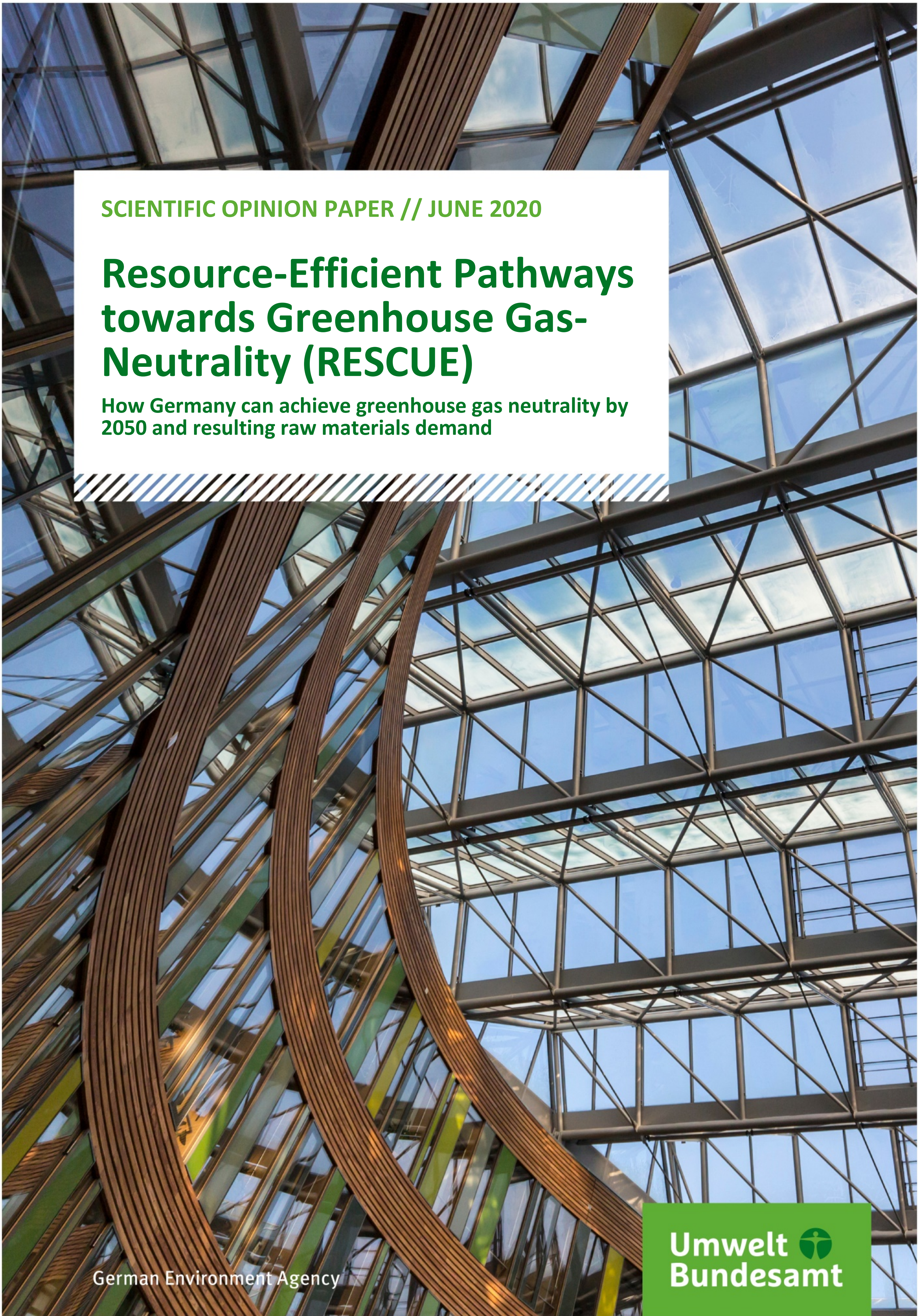

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Resource-Efficient Pathways towards Greenhouse Gas-Neutrality (RESCUE)

How Germany can achieve greenhouse gas neutrality by 2050 and resulting raw materials demand

German Environment Agency

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Section I 1.1 “Fundamental Aspects, Sustainability Strategies and Scenarios, Sustainable Resource Use”
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Section V 1.2 “Strategies and Scenarios for Climate and Energy”
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Resource-Efficient Pathways towards Greenhouse Gas-Neutrality (RESCUE)

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by

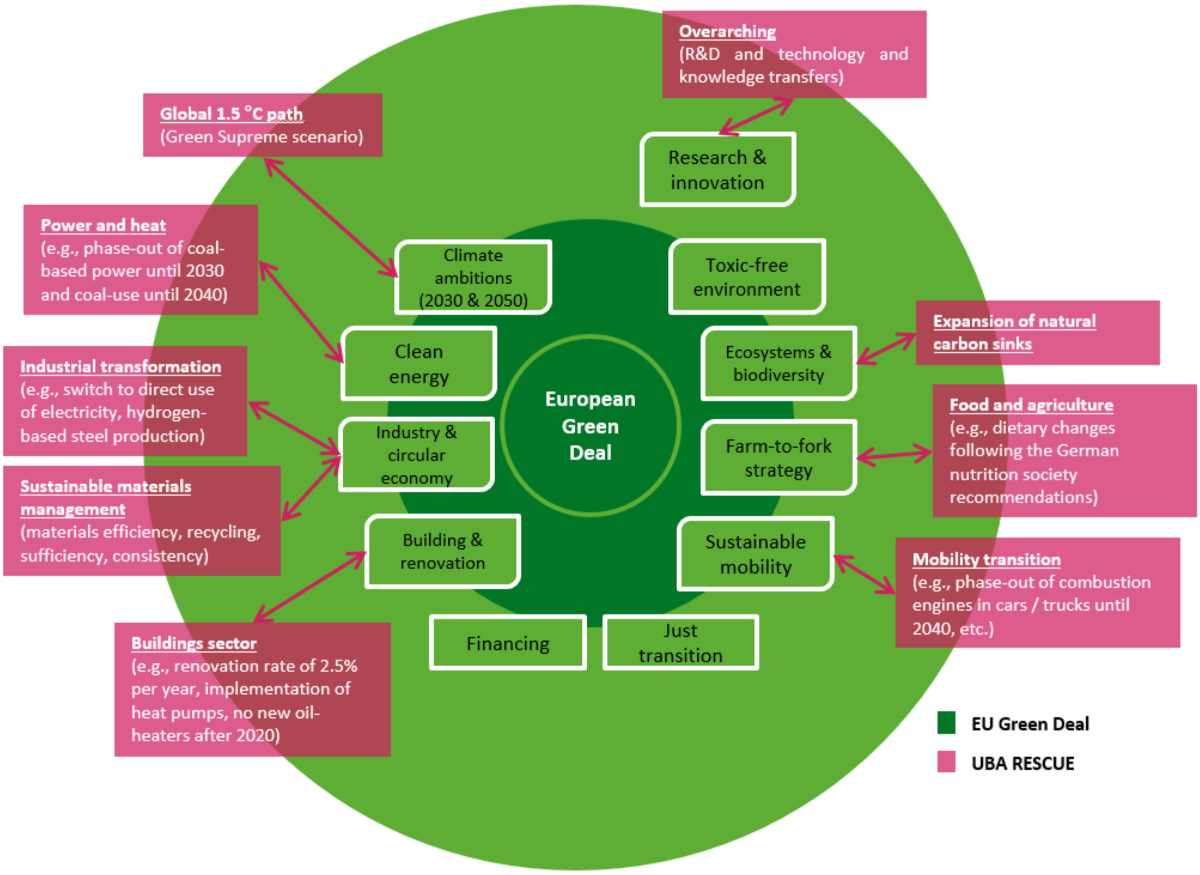
Philip Nuss, Jens Günther, Katja Purr and Guido Knoche

German Environment Agency

Abstract

Drawing on earlier work of the German Environment Agency (UBA), we introduce six transformation pathways towards Germany in 2050 as a greenhouse-gas (GHG) neutral and resource-efficient country in Europe, and discuss the required transformations across key sectors of the economy (RESCUE-study[1]). One transformation path (the GreenSupreme scenario) achieves the reduction of emissions along a global 1.5 °C path towards GHG-neutrality by 2050, while at the same time substantially lowering Germany's material footprint. With its "European Green Deal" the new EU Commission calls for deep transformations in key sectors towards a climate-neutral[2] and resource efficient European economy. The examined transformation areas within our study correspond to eight out of the eleven elements of the European Green Deal (Figure 1) and indicate concrete examples and guidance for decarbonization and more sustainable materials management within the German economy. Results also highlight that a cross-sectoral and systemic perspective is essential for enabling a sustainability transition that avoids burden shifting and fosters collaboration between different branches of government.

Figure 1 Transformation areas in RESCUE and linkages to the European Green Deal.



Source: German Environment Agency (Umweltbundesamt)

[1] **Res**our**c**e-Efficient Pathways towards Greenho**u**se-Gas N**e**utrality (RESCUE)

[2] Climate neutrality refers to the definition given in the Proposal for a Regulation to achieving climate neutrality (European Climate Law, (EU) 2018/1999) of the European Commission, Document COM/2020/80 final.

1 Introduction

Recent literature points to multiple threats to the resilience of the earth system. Crossing the planetary boundaries carries a rapidly increasing risk of irreversible environmental changes (Rockström et al. 2009; Steffen et al. 2018, 2015). Today, four out of nine planetary boundaries have already been surpassed, namely climate change, biosphere integrity, land-system change, and biogeochemical cycles (Steffen et al. 2015). Limiting climate change to 1.5°C as stipulated in the Paris Climate Agreement (UNFCCC 2019, 2015) and preventing its devastating consequences is a defining task for societies (Hoegh-Guldberg et al. 2019). Globally, greenhouse gas (GHG) emissions were found at 36 Gt (billion metric tons) CO_2-eq in 1990 and have since risen to about 51 Gt CO_2-eq in 2015 (Climate Action Tracker 2020). The extraction and processing of raw materials (biomass, metals, minerals, fossil fuels) make up about half of global GHG-emissions and more than 90% of land- and water related impacts (Cabernard et al. 2019; UNEP 2019). Global raw materials extraction has increased to around 90 Gt in 2017 and is expected to further double to ca. 160 – 180 Gt by around mid-century (OECD 2019; UNEP 2019). Managing raw materials and other natural resources more sustainably and reducing absolute demands, therefore, is an essential lever also for climate change mitigation.

Safely achieving the temperature objectives of the Paris Agreement requires a **global transformation to GHG-neutral societies within the next 30 years**. This translates into approximately halving global GHG emissions every decade until 2050 (Rockström et al. 2017). Such emissions reductions require a significant decarbonization of the energy and transport sectors, industrial production, agriculture and land use, buildings, and waste management (Davis et al. 2018; IRENA 2019; Purr et al. 2014; Ram et al. 2019). Associated with this is a **tremendous shift in the materials basis of our economies** including the rapid phase-out of fossil fuels and increased use of metals for low carbon technologies (Kleijn et al. 2011; Sovacool et al. 2020), biomass for buildings (Churkina et al. 2020), energy and chemicals (Cherubini 2010) and minerals for construction and infrastructure. Increasingly, sustainable development pathways are being investigated considering the 17 sustainable development goals (SDGs) until 2030 and planetary boundaries until 2050 (Allen et al. 2019; IIASA 2017; van Soest et al. 2019).

The **European Green Deal** provides a roadmap for Europe to foster a resource-efficient and competitive economy in which climate neutrality is achieved by 2050, economic growth is decoupled from resource use, and no person and no place is left behind (EC 2019). This includes, e.g., a regulatory proposal to achieve climate neutrality by 2050 ("European Climate Law" (EC 2020a)), a new circular economy action plan (EC 2020b), and an industrial strategy (EC 2020c). The Green Deal is also seen as an important cornerstone in the EU´s response to the **COVID-19 pandemic** by channeling future investments toward a sustainable and climate-neutral society (Gibis et al. 2020). The European Council has endorsed the objective of a climate-neutral EU by 2050 (European Council 2019) and communicated this to the UN Framework Convention on Climate Change (EU 2020). **Germany**, in continuing efforts of the **Climate Action Plan** (BMU 2016), has recently set the objective of GHG-neutrality by 2050 in its **Climate Law** (German Federal Government 2019a) and aims at reducing GHG-emissions by at least 55% by 2030 (German Federal Government 2019b). The **German Resource Efficiency Program** (BMU 2012; BMUB 2016) specifies targets and approaches to the conservation of natural resources, and the Raw Materials Strategy looks specifically at raw materials provisioning and use (BMWi 2020).

It is clear that an integrated **view across multiple economic sectors, policy fields, and natural resource categories is essential** in designing narratives and scenarios for achieving GHG-neutrality by 2050. This paper provides the UBA's perspective on how such scenarios might be developed and presents implications and lessons-learned for the national and EU-level.

2 Integrated Climate & Raw Materials Scenarios until 2050

2.1 Scenarios towards Greenhouse – Gas - Neutrality for Germany in 2050

Sketching sustainable development pathways toward a society that acts within the planetary boundaries is possible using scenario analysis. The **RESCUE-study** ("**Res**our**c**e-Efficient Pathways towards Greenho**u**se-Gas N**e**utrality") explores in six scenarios ("Green-scenarios") different transformation paths towards a material-efficient and GHG-neutral Germany 2050 by systematically examining all key economic sectors and quantifying both GHG-emissions and raw materials demands (biomass, fossil fuels, metal, and minerals) (Günther et al. 2019; Purr et al. 2019).

In all scenarios, Germany continues to be embedded in the EU and the world through trade, and has a modern and competitive industry. A common understanding of the need for climate protection and decarbonization, energy efficiency, and sustainable resource use exists within society. All Green-scenarios reach overall GHG reductions of at least 95% until 2050 and at least 55% until 2030 (compared to 1990). Associated raw materials demand is quantified. GHG-neutrality can be achieved in almost all scenarios by 2050 if domestic natural carbon sinks (e.g., sustainable forestry and wetland renaturation) are considered. **In all scenarios, the energy system is based entirely on renewable energy by 2050 which is used through sector coupling[3] across sectors.** Nuclear power and carbon capture and storage (CCS) are not considered as they carry non-manageable environmental risks (UBA 2015).

The **GreenEe1** and **GreenLate** scenarios are characterized by increasing production capacities and an export-oriented industry. However, they differ in their level of ambition with regard to decarbonization and both energy- and material-efficiency gains until 2050. In GreenLate, the speed of the transformation and associated technological innovation is slower than in the other scenarios. Hence, conventional technologies (e.g., combustion engines in heavy-duty vehicles or gas combustion technologies for heat supply) remain partly in use in 2050 resulting in lower economy-wide levels of electrification. With respect to GHG-reductions, GreenLate follows the target corridor of the German Climate Action Plan (BMU 2016), i.e., 55 % reductions until 2030, 70% until 2040, and 95 % by 2050, while GreenEe follows a more ambitious path.

In **GreenEe2, GreenMe**, and **GreenLife,** a more balanced trade situation is assumed. The effects of more sustainable lifestyles (e.g., healthier diets and increased public transport) and wider implementation of technical/technological solutions for climate protection and material efficiency are investigated. Similar to **GreenEe1**, the **GreenEe2**-scenario focuses on a high level of technological innovation including the integration of efficient sector coupling technologies and the use of energy efficiency potentials. In **GreenMe**, further gains in material efficiency and a high level of material substitution are assumed. **GreenLife** is characterized by a widespread implementation of more sustainable individual lifestyles, e.g., shifting towards healthier and low-meat diets or the enhanced use of repairable, long-lasting, and material-efficient products.

Finally, in **GreenSupreme** a combination of the most effective measures from GreenEe2, GreenMe and GreenLife are considered and assumed to be implemented more rapidly compared to the other scenarios. Therefore, the phase-out of coal for electricity (by 2030) and in other general uses (by 2040) is initiated in the short term. While the other scenarios assume an average annual GDP (gross domestic product) growth rate of around 0.7 %, in GreenSupreme

[3]Direct electricity use (e.g., power to heat, electro-mobility) or indirect use via power to gas (PtG) and power to liquid (PtL) for fuels for transport, chemical feedstock, and process heat in industry.

the annual GDP growth is assumed to be zero after 2030 (but the per capita GDP will continue to rise given decreasing population projections until 2050 (Destatis 2015)).

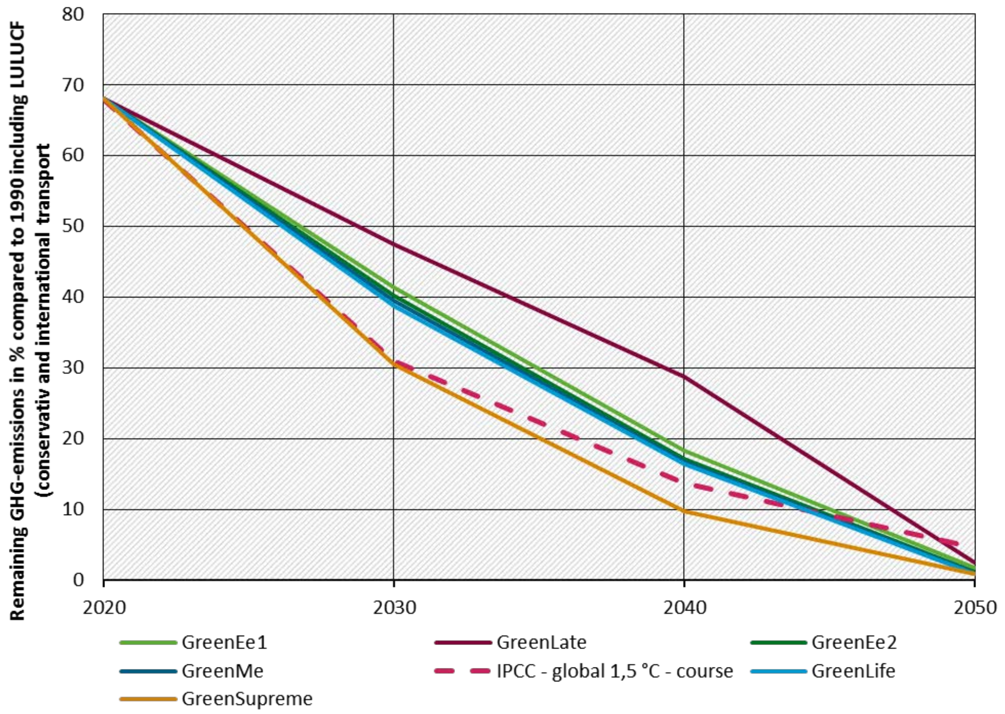
2.1.1 Territorial Greenhouse Gas (GHG) Emissions

The overall GHG reduction target for **2030** of 55 % compared to 1990 (BMU 2016) is met in all scenarios, in particular as a result of the significant progress in the energy sector. With the exception of GreenLate, all other scenarios reach GHG reductions of even above 55%, namely 60% in GreenEe1, 61 to 63% in GreenEe2, GreenMe, and GreenLife, and 69% in GreenSupreme (compared to 1990 levels). However, not all individual sectoral targets are reached. The emissions reductions are dominated by the phase-out of coal-fired power generation (e.g., completed in GreenSupreme already by 2030).

In all scenarios, a shift towards 100% renewable energy (electricity, fuels, and chemical feedstock) takes place until **2050**. By 2050, GHG-reductions of 95 % (GreenLate) to 97 % (GreenSupreme) are achieved which meets or even exceeds German climate targets (BMU 2016). Despite a shift towards healthier (low-meat) diets, 60 to 67 % of the remaining GHG-emissions originate from agriculture. Another 27 % (GreenSupreme) to 37 % (GreenLate) of emissions are generated by industry (i.e., cement, lime, and glass production). Through the use of natural carbon sinks (e.g., sustainable forestry and wetland renaturation), GreenLife and GreenSupreme achieve net zero emissions by 2050 and even GreenLate comes close to this. Natural carbon sinks also provide synergies with other environmental goals such as biodiversity protection. The Green scenarios, thus, show that no CCS and nuclear power are required for GHG-neutrality in Germany by 2050.

However, comparing the scenarios of RESCUE with **a global average 1.5 °C emissions path of the Intergovernmental Panel on Climate** Change **(IPCC)** (IIASA 2019)) shows that only GreenSupreme follows corresponding emissions reductions (Figure 2).

Figure 2: Development of GHG-emissions reductions in RESCUE considering land use, land-use change, and forestry (LULUCF), and the CO_2-emissions of international transport



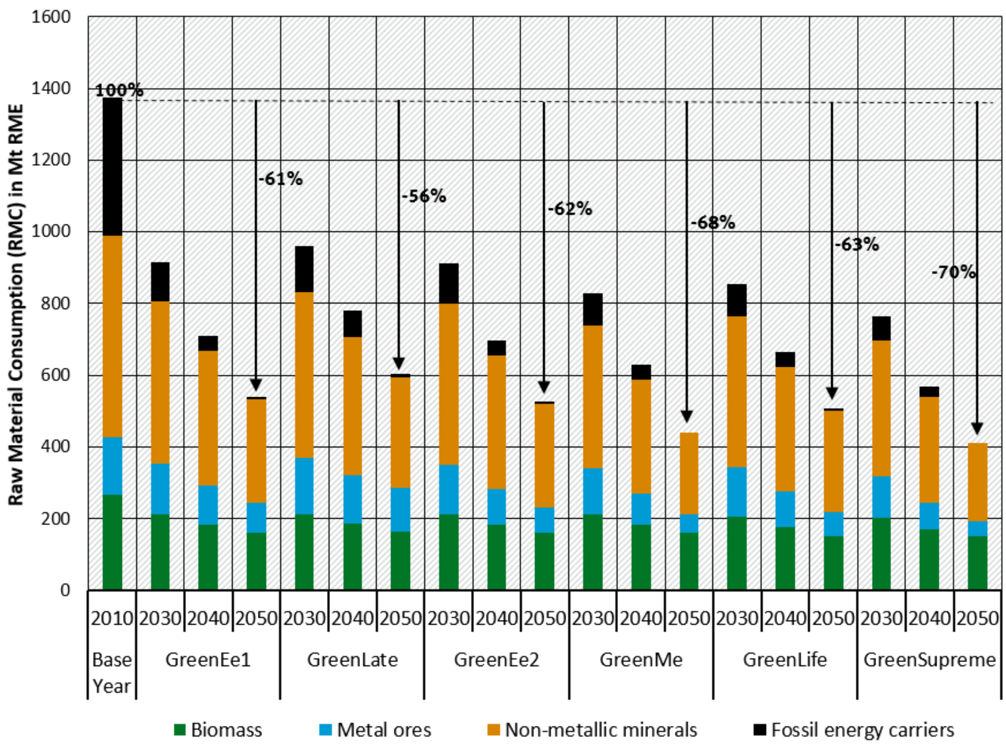
Source: own illustration based on (IIASA 2019; Dittrich et al. 2020a, 2020b, 2020c, 2020d, 2020e)

Therefore, **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**.

2.1.2 Material Footprint

The transition to a GHG-neutral economy based on renewable energy leads to tremendous changes in the demand for raw materials. We use the **material footprint** (raw material consumption (RMC)[4] also used by Eurostat[5]) to quantify the global demand for material extractions (fossil energy carriers, biomass, metal ores, minerals) triggered by consumption and investments in Germany until 2050 (Figure 3).

Figure 3: Raw material consumption (RMC) by raw materials category for all Green-scenarios (2010-2050). RME: raw material equivalents, Mt: megatons



Source: own illustration based on (Dittrich et al. 2020a, 2020b, 2020c, 2020d, 2020e)

In 2010 (base year), Germany's RMC equals 1.37 Gt and is dominated by fossil fuels and non-metallic minerals. In all scenarios, the RMC is reduced through the phase-out of fossil energy carriers. Other crucial leverage points include, e.g., regional development policy to reduce the size and number of new settlement areas, increased energy efficiency, increased recycling and materials efficiency, optimization of manufacturing processes, and life-style changes. Already in **GreenLate** 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 such as, e.g., **GreenEe**). Tapping into additional measures to increase both energy and material efficiency (e.g., using the full recycling potentials for materials, materials substitution, using innovative materials such as textile-reinforced concrete and timber constructions) allows for a

[4] RMC is composed of domestic raw material extraction and imports minus exports. It is expressed in raw material equivalents (RME) which expresses a unit of product traded into the amount of material extraction needed, anywhere in the world, to produce the traded product.

[5] https://ec.europa.eu/eurostat/cache/metadata/en/env_ac_rme_esms.htm

further reduction of the RMC (**GreenMe**). Additional life-style changes (e.g., a reduction of per-capita living space compared to today, increased public transport, use of more durable goods offered within a sharing economy) allows for further RMC reductions (**GreenLife**). Finally, through a combination of energy- and material-efficiency, life-style changes, and the liberation from annual economic growth raw materials use can be reduced further but only by a few percentage points (**GreenSupreme**).

In 2010, **RMC per person (RMC/cap)** in Germany equals 16.8 t/cap and is, thus, clearly 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.

However, the envisaged transformation is also associated with a **stark increase in the demand for individual raw materials such as cobalt and lithium** (Purr et al. 2019) some of which are also termed "critical" at EU-level (EC 2017). In RESCUE, this is a result of the widespread implementation of these materials in electric vehicles which might, however, be mitigated through improved reuse and recycling of batteries. Against the background of a globally just use of raw materials, **an ambitious transformation path such as GreenSupreme should be followed** in order to keep raw materials demand as low as possible.

2.2 Lessons-learned for the European Dimension and beyond in 2050

In the meantime, as calls for the development of and the discussion on long-term transformational pathways in line with the Paris Agreement are not only limited to national activities, some think-tanks and research consortia have elaborated pathways for net-zero GHG developments on the EU level (CLIMACT 2018). In addition, the European Commission – on invitation of the European Council (European Council 2018) - presented in November 2018 its Strategic Vison "A Clean Planet for All" for EU long-term GHG-emissions reductions in accordance with the Paris Agreement (EC 2018). This was accompanied by an "in-depth-analysis" (IDA) to inform the political debates.

The IDA builds on an integrated assessment and is concerned in particular with **two net-zero GHG emissions scenarios by 2050 (1.5TECH and 1.5LIFE)**. As the IDA considers pathways for relevant sectors and GHGs as well as economic and social implications, the **economic feasibility of a transformation to net-zero GHG emissions can be seen as robust** due to the variety of models used (Wachsmuth et al. 2019). Although the IDA serves in particular as a basis for deliberations within the EU, its merit can be seen in the extensive efforts taken (e.g., depth of the analysis, extensive consultations, member states discussions, etc.) which may be helpful to other countries as well. However, though very ambitious GHG emission reductions early on in the net-zero scenarios are required (in particular provided by vastly increasing relevance of renewable energy sources (RES)), the IDA lacks pathways with maximized shares of RES.

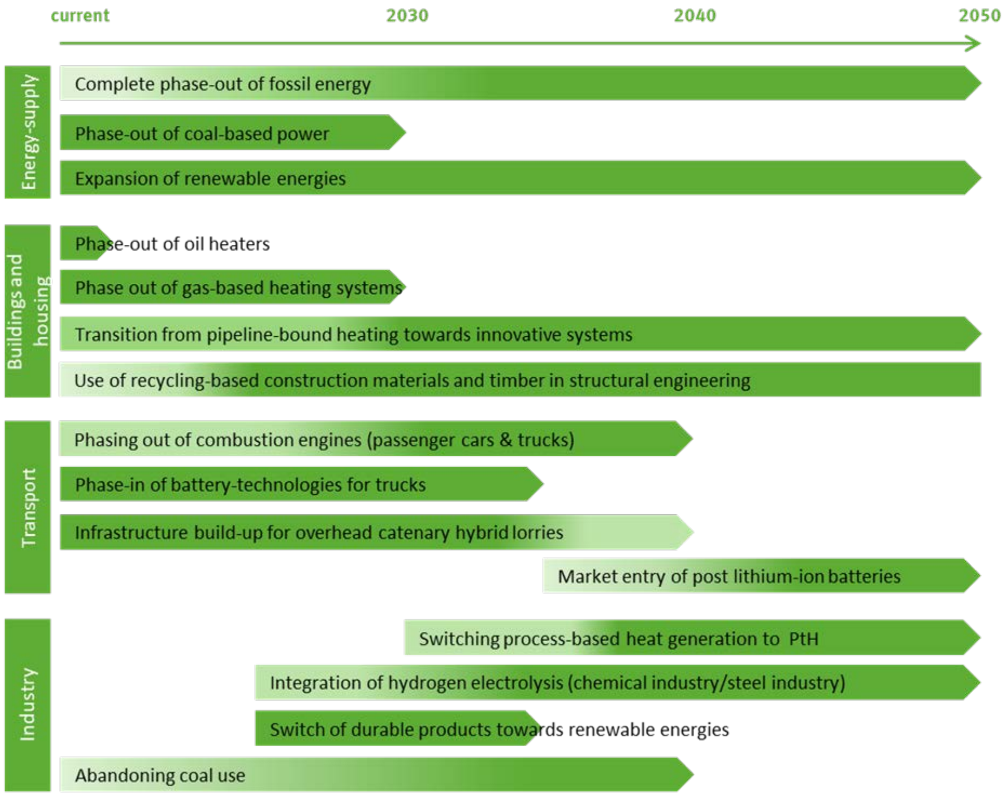
In contrast, the German Environment Agency commissioned a scenario for the EU called "GHG-neutral EU2050" that balances GHG-emissions and sinks for the time horizon until 2050 (Duscha et al. 2019) based on a nearly complete RES supply and further stringent sustainability criteria (i.e. no extension of nuclear power plants with only a small share remaining, no bio-energy with carbon capture and storage (BECCS), and no CCS). However, "**GHG-neutral EU2050" paints only one possible picture of an EU with net zero GHG emissions in 2050.** There are different options for how this can be achieved, e.g., concerning the use of novel fuels (i.e., fuels based on renewable electricity) vs. biogenic fuels and the extent of lifestyle changes, or the electrification vs. use of renewable fuels (i.e., the total of biogenic and novel fuels). In comparison with other scenarios, the GHG-neutral EU2050 scenario is at the very high end with regard to electrification, and even more so with regard to the use of novel fuels. This is due to the fact that the scenario focuses on the technical feasibility of net-zero GHG-emissions under limited biomass availability and current sectoral demand trends. The use of novel fuels is increased even more by the fact that the scenario considers feedstocks and international shipping in the scenario calculations. Supplying such huge amounts of novel fuels will pose extensive requirements with regard to technological and infrastructural scale-ups and investments. These requirements can be significantly reduced if the remaining leeway across all energy-related sectors is exploited, in particular with regard to reducing the demand in air transportation, and implementing a circular economy to the largest possible extent, especially a cascading use of wood and chemical feedstocks. These aspects need to be further explored in future research. Finally, the study focused on an EU with net-zero GHG emissions in 2050 and not on the pathways leading to this. In particular, cost considerations and infrastructure lock-ins played only a minor role.

3 Decarbonization Roadmap for Germany

RESCUE highlights that ambitious efforts 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 more equitable use of raw materials. **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.** A broad range of strategies and measures are required for lowering GHG-emissions and raw materials use until 2050.

Substitution is comprised largely of technical measures aiming at the replacement of GHG- and raw materials-intensive technologies/products with their environmentally friendlier counterparts. For this, 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 chemical feedstock in industry) by 2040 at the latest. All fossil fuels should be phased out completely by 2050. A cross-sectoral switch towards renewable energy technologies and phase-in of alternative technologies (e.g., electric vehicles) is required (Figure 4).

Figure 4 Selected examples of substitution measures in the GreenSupreme scenario.



Note: The different arrows indicate the time period of the recommended action. The different shades stand for the urgency of implementation. The end of each arrow indicates the successful and completed implementation of the recommended action.

Source: German Environment Agency (Umweltbundesamt) (Purr et al. 2019)

Furthermore, it is necessary to **avoid** the overall demand for natural resources in order to reduce energy and material throughputs and related adverse environmental impacts. On the demand side, this includes a societal transition towards more environmentally conscious life-styles (e.g., healthier diets or increased use of public transportation) supported by suitable regional planning[6], regulatory[7], and educational policy measures. On the supply side, cross-sectoral energy- and materials-efficiency measures (e.g., enhanced building sanitation, reduced fertilizer use, or higher performance energy technologies) and considerations of natural resource- and carbon- footprints when selecting and implementing new technologies and infrastructures are important leverage points (Figure 5).

Figure 5 Selected examples of avoidance measures in the GreenSupreme scenario

Note: The different arrows indicate the time period of the recommended action. The different shades stand for the urgency of implementation. The end of each arrow indicates the successful and completed implementation of the recommended action.

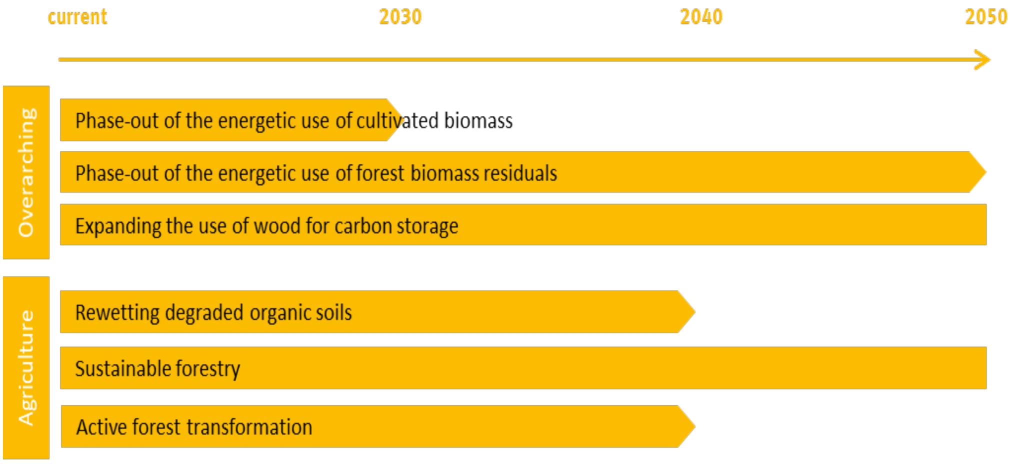
Source: German Environment Agency (Umweltbundesamt) (Purr et al. 2019)

However, given our current state of knowledge, some GHG-emissions cannot be avoided such as from the glass or cement industry, and from agriculture and land-use changes. Therefore, **natural carbon sinks** (i.e., through sustainable agriculture and forest management, carbon storage in wood and forest biomass, and the phase-out of the energetic use of virgin biomass) are also required in order to reach GHG-neutrality in 2050 (Figure 6). Natural carbon sinks allow already today the sustainable removal of CO_2 from the atmosphere and provide synergies to other environmental policy domains such as biodiversity protection. In contrast, carbon capture and storage (CCS) would prolong conventional fossil fuel use, carries environmental risks, and lacks public acceptance in Germany (IPCC 2005; Vögele et al. 2018) and should therefore be avoided.

[6] e.g., compact cities/cities of short distances, EU-wide and fast train networks, or widely-spread teleworking possibilities.

[7] e.g., taxes on the use of fossil and other natural resources and financial incentives to support efficient processes and low-impact products.

Figure 6 Selected examples of natural carbon sinks measures in the GreenSupreme scenario



Note: The different arrows indicate the time period of the recommended action. The different shades stand for the urgency of implementation. The end of each arrow indicates the successful and completed implementation of the recommended action.

Source: German Environment Agency (Umweltbundesamt) (Purr et al. 2019)

4 Implications on the EU and International Level and Transformational Project Management

4.1 Acting beyond Germany

The successful transformation towards GHG-neutrality and materials efficiency within Germany depends strongly on both European and global developments and requires close monitoring of associated raw material demands. GHG-neutrality in Germany until 2050 and the reduction of GHG-emissions compatible with a global 1.5 °C path are prerequisites and still only one part of a reasonable contribution by Germany to fighting global climate change.

In addition to increased climate action domestically, Germany should pave the ground internationally so **that other countries are enabled to also become GHG-neutral around mid-century.** The transition towards GHG-neutrality by other countries is essential in order to mitigate global climate change and because Germany is embedded into global supply chains by trade. Through consumption-based accounting, emissions and raw materials uses are allocated to the country of final consumption.

Hence, **Germany needs to support a global transition towards GHG-neutrality through financial aid, technology support, and knowledge transfer**. Environmental and social implications of the associated raw materials requirements need to be closely monitored and materials use designed in an efficient manner across all economic sectors. **The focus here should be on phasing out fossil energy carriers, eliminating environmentally harmful subsidies, reducing overall material footprints, and the protection and extension of natural carbon sinks.** Given that GHG-emissions associated with raw materials extraction and processing make up a significant part of global GHG emissions (UNEP 2019), climate and resource policies need to work jointly to also increase materials efficiency and **reduce overall materials demands, e.g., though life-style changes and sustainable consumption.**

The Green-scenarios implicitly assume a global transferability of developments in Germany, but do not explicitly quantify the associated demand for raw materials at European and 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-transfers**, in order to be able to contribute to tailor-made solutions also outside of Germany and Europe.

In order to reduce supply risks and ensure expansion of environmental technologies worldwide, substitution has to be increasingly applied to replace raw materials which are prone, e.g., to environmental and social risks and diversify the materials base. Due to the long lead times in development and market diffusion, regularly updated **substitution roadmaps** (Buchert et al. 2019) are important instruments for the orientation of industrial policy and could **increasingly be used in the context of the EU criticality assessment** (EC 2017). **Environmental implications are another important aspect that we recommend should be increasingly considered in supply risk evaluations** such as criticality studies (Manhart et al. 2019).

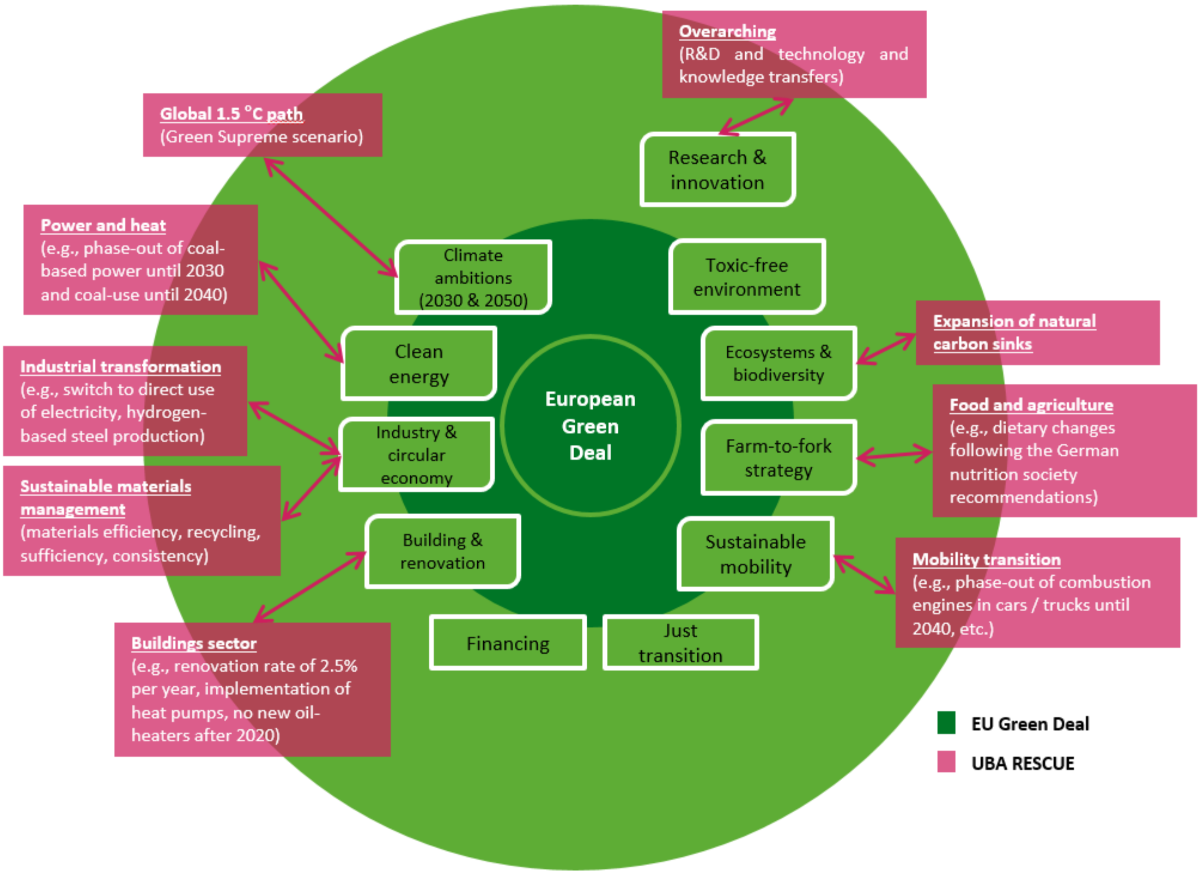
Finally, the results of RESCUE highlight that **the closure of material flows until 2050 is physically limited even under high recycling assumptions**. This is a result of, e.g., further growth in material wealth and unavoidable material losses. Against this background, it is important that through avoidance measures (see previous chapter), the overall demand for (raw) materials is decreased and the absolute size of the circular economy cycle reduced. Circular economy policies with a focus on recycling and product design (EC 2020b) often do not focus on the overall size of the material loop.

4.2 Linkages to the European Green Deal

RESCUE focuses on multiple economic sectors and provides detailed scenario storylines outlining the required comprehensive transition to achieve GHG-neutrality and increased materials-efficiency in Germany. By doing so, RESCUE provides implicitly a range of ideas of how elements of the European Green Deal (EC 2019) might be translated into actions across sectors and fields of action, e.g., of the German economy. Furthermore, RESCUE could inform relevant European and international experts' fora as well as the scientific community itself when developing and discussing ideas for cross-sectoral transformations.

The Green Deal calls for deep transformations in key sectors of the integrated European economy. **The transformation areas examined in RESCUE correspond to currently eight out of the eleven elements of the European Green Deal** (Figure 7).

Figure 7 Transformation areas in RESCUE and linkages to the European Green Deal.



Source: German Environment Agency (Umweltbundesamt)

For example, RESCUE provides detailed roadmaps at the national scale related to the elements of the Green Deal such as **climate objectives, renewable energy, industry and circular economy, building and renovation, sustainable mobility, and the farm-to-fork strategy** (agriculture and food) (see section 2.1 and the detailed RESCUE reports (Günther et al. 2019; Purr et al. 2019)). In the industrial sector, for instance, GHG-emissions are caused directly during the use of carbonaceous fuels (energy-based) and from the non-energetic use of materials (process-based), and indirectly from upstream energy generation. Concrete measures to decarbonize the industrial sector include the phase-out of coal use until 2050 (and 2040 in GreenSupreme) and increases in energy- and material-efficiency. This includes, e.g., primary steel production in hydrogen-based direct reduced iron (DRI) systems and subsequent melting in the electric arc furnace (EAF). Similar examples exist for the other economic sectors.

Furthermore, a focus on natural carbon sinks provides synergies to the element of **ecosystems and biodiversity**. This includes the preservation of the forest carbon sink, conservation of moors and rewetting of drained wetlands, and reduced land take by settlements and transport.

Research and innovation are central for the transformation envisaged by the Green Deal and in RESCUE. While many technical solutions and suitable policy measures already exist, further research is required in order to decarbonize the whole economy. This includes, e.g., the increased design of durable and repairable products and sharing platforms, the phase-out of fossil carbon use in the chemical industry via bio-based solution and Power-to-X paths, increased wood construction, and the development of alternative binding agents and building materials. An open research orientation in the development of new technologies is essential to enable technology and knowledge transfers also outside of Germany and the EU.

Further details on detailed RESCUE recommendations for Germany and in the context of the elements of the EU Green Deal are provided in Table 1.

Table 1 Elements of the EU Green Deal (EGD) and corresponding RESCUE recommendations for Germany based on the GreenSupreme scenario

EGD Elements	RESCUE recommendations for Germany (selected examples)
1.a) Climate target plan (2030) 1.b) European Climate Law (2050)	**Raising the 2030 climate goal and achieving GHG-neutrality by 2050** Reduction of national GHG-emissions by about 70 % until 2030 and nearly 100% by 2050 when compared with 1990 levels, making use of natural carbon sinks to achieve GHG-neutrality, close monitoring of raw materials demands for renewable energy technologies.
2. Clean energy	**Energy, heat, industry, raw materials, and mobility** Phase-out of coal-based power until 2030 and general coal-use until 2040, increasing yearly expansion of wind on land and photovoltaic to 6 gigawatts (GW) per year.[8]
3. Industry & circular economy	**Industry sector** Restructuring of the industry sector towards renewable energy (energy- and process-based as well as upstream), hydrogen-based steel production, chemical industry based on power-to-gas and power-to-liquid routes, supporting R&D activities for alternative binding agents and building materials (substitution of cement).
4. Building and renovation	**Building and housing** Increasing the renovation rate of buildings to min. 2.5% per year (from currently around 1% per year), Implementing heat pumps and residential heat networks for the delivery of heat based on renewable power, phase-out of oil heating systems after 2020 and gas heating systems after 2030. Increase wood construction of housing and using modular building methods.
5. Sustainable mobility	**Mobility** Traffic avoidance and modal shift to eco-mobility via CO_2 pricing and by abolishing environmentally harmful subsidies (e.g., the diesel tax privilege, company car allowance, commuter tax relieve),

[8] Adjustment to the RESCUE publication (Purr et al. 2019) according to the actual data used.

EGD Elements	RESCUE recommendations for Germany (selected examples)
	no inland flights from 2030, walkable neighborhoods, only electric vehicles (cars and small trucks) from 2040 onwards for new vehicle permissions, implementation of battery-electric drive trains for light good vehicles and lorries up to 12 tonnes gross vehicle weight (GVW).
6. Farm-to-fork strategy	**Food and agriculture** Reduction of meat consumption to 300 g per week and person until 2040 (lower limit of the German nutrition society recommendations) and reductions in the livestock number (especially ruminants), reduction of the nitrogen (N) excess to max 50 kg N per ha until 2030).
7. Ecosystems and biodiversity	**Agriculture and LULUCF[9] (natural carbon sinks)** Rewetting of drained wetlands (5% of agricultural lands per year from 2020), preservation of forests as carbon sinks, reduction of new land take to 10 ha per day in 2030 and 0 ha per year by 2050.
8. Toxic-free environment	Not specifically addressed (single examples exist, e.g., no cadmium-telluride (CdTe) photovoltaic cells due to toxicity of cadmium).
9. Research and innovation	Various (see individual sectors)
10. Financing	Not addressed
10. Just transition	Not addressed

Source: German Environment Agency (Umweltbundesamt).

4.3 Implementation and Management of Transformational Projects/Policies

Implementing and managing research projects or policies that aim at a deep transformation of multiple fields of the economy requires collaboration among functions, offices, and organizations. This requires the development of a common vision and of detailed story lines outlining how to achieve the vision's objectives. Yet different stakeholders (governments, business, civil society, and science) have varying views of the required depth and speed of the transformation. To realize the required transformation towards GHG-neutrality and materials efficiency, government agencies must remove silos and get people working together across boundaries (Figure 8).

The RESCUE-study provides an example of a horizontal research project that involved a number of staff from different units and areas of expertise within the German Environment Agency. The following present a few lessons-learned from RESCUE that might be of interest also for other ongoing activities aiming to investigate possible pathways for the transformation of multiple fields of the economy while capturing resource demands and environmental implications:

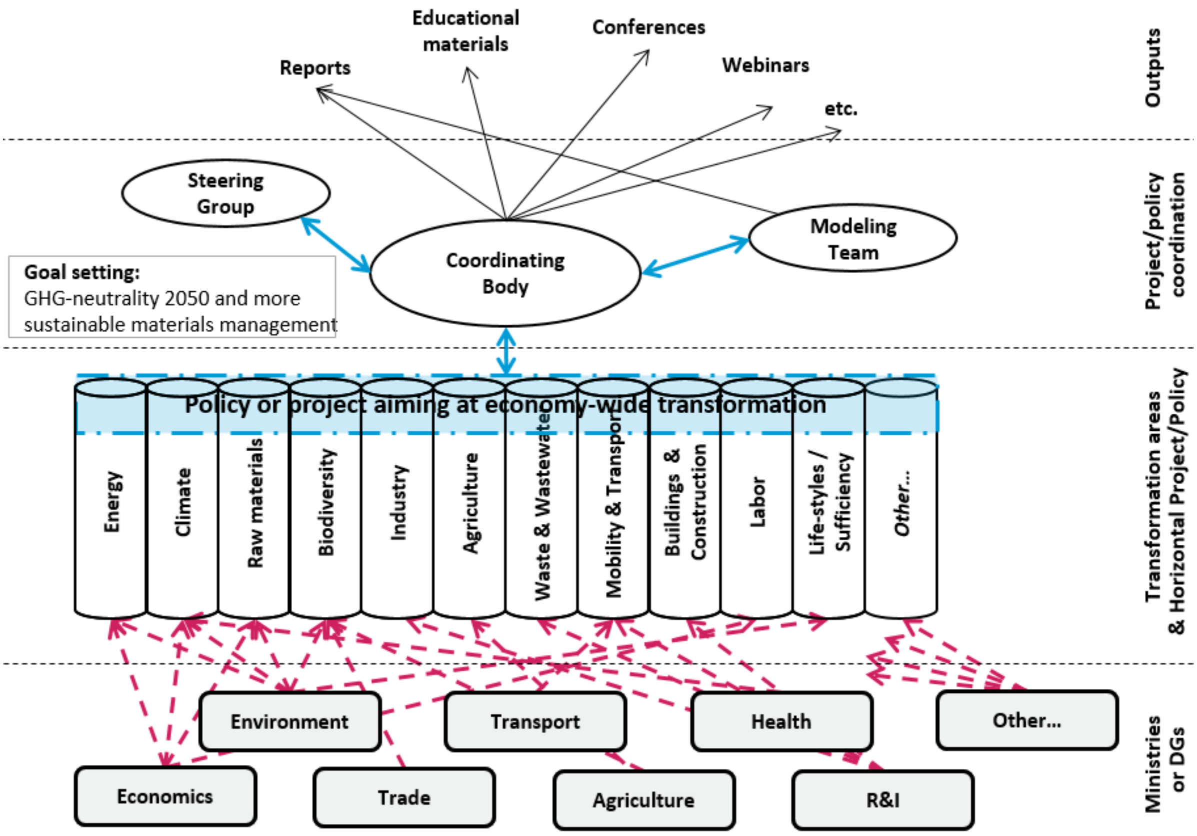
- Developing scenario narratives across all major sectors of the economy can help to **focus expertise from different branches of government** (different ministries (national level) or Directorate Generals (DGs) (EU level)) **in the context of a common vision** (here: GHG-neutrality and sustainable materials management by 2050). This is particularly relevant if

[9] Land use, land-use change, and forestry

multiple natural resource requirements ("resource nexus") are being examined as these are often investigated by different teams or departments within policy and scientific institutions.

- Combining scenario narratives with concrete goals (in RESCUE: GHG reduction targets over time) allows for the formulation of **time-bound benchmarks for different sectors** (e.g., phase out of coal-based electricity by 2030). This, in turn, helps to specify the narratives for subsequent scenario modelling in order to quantify whether the scenario assumptions (narratives) are sufficient to meet the specified goals.
- A **systems-wide perspective across multiple sectors can help to avoid burden shifting**, e.g., if the use of materials and energy is made more sustainable in one sector but at the expense of increased impacts elsewhere in the economy. However, in RESCUE, the focus is on Germany and international supply chains are not generally considered. Furthermore, only a subset of natural resources (raw materials) and environmental impacts (GHG-emissions) are quantified. Both needs to be improved in the future, e.g., through additional studies and modelling efforts.

Figure 8 Schematic representation of a horizontal project or policy which requires expertise across multiple levels of government and possible coordination and outputs



Source: German Environment Agency (Umweltbundesamt). R&I: Research and Innovation. DG: Directorate General

5 Conclusions

The RESCUE study highlights that GHG-neutrality in Germany together with a reduction of the material footprint is possible through a combination of ambitious measures focusing on the economy-wide phase-out of fossil energy carriers and transition to renewable energy, energy- and materials efficiency, and life-style changes. However, the described transformation pathways will also increase demands for individual raw materials like lithium and cobalt. The six Green-scenarios illustrate that significant progress at multiple levels across sectors and institutions as well as considering a broad range of strategies and measures for lowering GHG-emissions and raw materials use 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 and the magnitude of raw materials use 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. Implementing and managing research projects or policies that aim at a deep transformation of multiple fields of the economy requires collaboration among functions, offices, and organizations, and the development of a common vision. In addition, the study "GHG-neutral EU2050" provides one option of a European Union with net-zero GHG-emissions under stringent sustainability criteria. The newly endorsed goal of climate neutrality at EU-level should be increasingly used to develop joint visions and quantitative assessments targeting the sustainable use of multiple natural resources in the context of climate protection.

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