Material efficiency and its contribution to climate change mitigation in Germany
A deep decarbonization scenario analysis until 2060

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Abstract
Germany’s greenhouse gas emissions have declined by 35% since 1990, and the national policy ambition is to become largely carbon-neutral by 2050. A change of the industrial landscape and a partial transformation of energy supply have contributed to reductions so far, but for deep reductions, a deep transformation of the country’s industrial metabolism is needed.

While energy efficiency is well established, the same cannot be said for material efficiency, which includes product lightweighting, lifetime extension, more intense use, and value retention strategies like higher recycling rates, remanufacturing, and reuse. Sector-specific research showed substantial energy and emissions savings potentials of material efficiency, but the overall material efficiency potential for most world economies, including Germany, is unknown.

We applied an open-source and modular dynamic material flow analysis model of the transformation of passenger vehicles, residential buildings, and commercial and service buildings in Germany (together ca. 50% of national greenhouse gases) to a material-efficient system, covering the time span 2016–2060. The potential impact of the above-mentioned material efficiency strategies was studied for the climate-relevant materials concrete, steel, timber, aluminum, and plastics.

Once the potentials of energy-efficient products, electrification of end-use sectors, and energy system transformation are seized, supply and demand side material efficiency and sufficiency can reduce remaining 2050 emissions by an additional 19–34% (passenger vehicles), 27–31% (residential buildings), and 14–19% (non-residential buildings). The 2016–2050 cumulative savings can be up to 750 Mt (million metric tons) CO₂-eq. Material efficiency can be a key contributor to deep emissions cuts like a 95% target. This article met the requirements for a gold-gold JIE data openness badge described at http://jie.click/badges.

Keywords
buildings, climate change mitigation, industrial ecology, material efficiency, material flow analysis (MFA), passenger vehicles
Despite substantial efforts at the national and European levels, salient environmental pressure indicators in Germany remain at high levels, including greenhouse gas (GHG) emissions, material use, and soil sealing (Figure 1). For a substantial reduction of environmental pressures and for reaching the different national policy targets, a more profound transformation of the country’s industrial metabolism is needed than what has been achieved with a change of the industrial landscape (Tukker et al., 2014) and a partial transformation of energy supply system (AGEB, 2019).

Substantial efforts went into decoupling economic development from GHG emissions (Gawel et al., 2014), and as a consequence, Germany’s greenhouse gas emissions have declined by 35% since 1990, and a national policy goal to become largely carbon-neutral by 2050 was installed in response to the Paris Agreement (BMU, 2016).

To achieve such deep reductions in GHG emissions, a wide spectrum of mitigation strategies (Bashmakov et al., 2014) is needed that covers both, supply and demand side (Creutzig et al., 2018). Moreover, due to the interlinkage of the different environmental challenges (Liu et al., 2015), strategies that achieve environmental and social co-benefits are particularly effective and potentially easy to implement (Stechow et al., 2016).

1.1 Material efficiency and climate change mitigation

Material efficiency (Allwood, Ashby, Gutowski, & Worrell, 2011) seeks to achieve similar service outcomes of provisioning systems with the use of less materials (Allwood, Ashby, Gutowski, & Worrell, 2013; Zhang, Chen, & Ruth, 2018). Material efficiency (ME) is a core element of the “circular economy” (BSI, 2017; Su, Heshmati, Geng, & Yu, 2013) and includes the light-weighting, lifetime extension, and more intense use of products, buildings, and infrastructure as well as different value retention strategies like higher recycling rates, higher fabrication yield, fabrication scrap diversion, remanufacturing, and reuse (Allwood et al., 2012). From a systems perspective, material efficiency strategies can be divided into three groups: supply side (industrial efficiency and product design), demand-side (re-use and lifetime extension), and sufficiency (using fewer products more intensively). Material efficiency has the potential to lead to substantial co-benefits, as resource extraction and waste generation can be reduced (Allwood et al., 2011) and additional social and employment benefits can arise from implementing value retention strategies in “circular business models” (Bocken, de Pauw, Bakker, & van der Grinten, 2016).

The production of five major materials (iron and steel, aluminum, cement, chemical products, and pulp and paper) alone is directly responsible for 26% of global final energy use and 18% of CO₂ emissions from fossil fuels and industrial processes (in 2014) (OECD/IEA, 2017). Given the significance of these emissions in the global carbon budget, it stands to reason that the climate change mitigation potential of material efficiency is large.
1.2 | Previous work on material-related decarbonization

To quantify the emissions mitigation potential of material efficiency (ME) and understand potential co-benefits and obstacles to its implementation, model-based assessments are needed. Material production is included in all scenario models that cover the entire industrial energy consumption. Often, however, only material-related energy demand and no explicit description of the material cycles is contained in incumbent energy system and integrated assessment models (Pauliuk, Arvesen, Stadler, & Hertwich, 2017). That means that the different material efficiency strategies cannot be correctly depicted in these models, as they do not contain the material stocks and flows that are directly affected by these strategies.

This gap in modelling is now slowly being filled, and due to their potential, material efficiency strategies are now systematically included in various large-scale mitigation assessment both at high levels of sectoral aggregation (e.g., the global resources outlooks by the OECD (OECD, 2019) and the IRP (UNEP-IRP, 2019)) and high levels of technology detail (such as the IEA’s Energy Technology Perspectives (OECD/IEA, 2017) and an EU-based study by Material Economics (Enkvist & Klevnäs, 2018)). A recent review of the ME-GHG linkage (Hertwich et al., 2019a) finds that “the largest potential emission reductions quantified in the literature result from more intensive use of and lifetime extension for buildings and the light-weighting and reduced size of vehicles”. Also, the authors highlight that “there can be a systematic trade-off between material use in the production of buildings, vehicles, and appliances and energy use in their operation, requiring a careful life cycle assessment of ME strategies”.

For Germany, the recent RESCUE study on carbon neutrality by the German Environment Agency contains a “GreenMe” (“Germany – resource efficient and greenhouse gas neutral – Material efficiency”) scenario, which captures different use patterns for passenger vehicles, vehicle light-weighting, increased use of wood as construction material and resource-efficient buildings (Günter et al., 2019). Bürger et al. couple a dynamic model of the German building stock with energy system model to describe energy efficiency, energy carrier and the cost structure of energy supply in great detail (Bürger et al., 2018).

1.3 | Research gap, goal, and scope

A detailed scenario analysis of the climate change mitigation impact of material efficiency in the material cycles supporting the major end-use sectors in Germany is still lacking. With “detailed,” we mean a stock-flow consistent depiction of the climate-relevant major materials and a representation of all the different material efficiency strategies identified in the literature. This study aims at filling this gap for the three end-use sectors passenger vehicles, residential buildings, and non-residential buildings for Germany. Together with their material- and energy-supplying industries, these three sectors are responsible for ca. 400 Mt (million metric tons) of CO₂-eq, ca. 50% of the 2019 national emissions (Statista, 2020). The following research questions are addressed:

- How large is the reduction of GHG emissions resulting from implementing the different material efficiency strategies, both at the sector level and for the supporting material cycles?
- How do in-use stocks of materials, and primary and secondary material production change under the implementation of material efficiency at all stages of the material cycles?
- How big is the potential contribution of supply-side and demand-side material efficiency to GHG emissions reductions in relation to the potential of energy efficiency and low-carbon energy supply?

Below, we address these questions for the three major end-use sectors in Germany with a timeframe spanning from 2015 to 2060 in steps of one year. We describe the model setup and the Germany-specific scenario assumptions and results.

2 | METHODOLOGY AND DATA

To address the research questions, a multi-layer dynamic physical model of the energy service cascade (from end-use functions to products to in-use stocks of products and their operation (Kalt, Wiedenhofer, Görg, & Haberl, 2019)), from product stocks to the manufacturing and waste management industries (Bergsdal, Bratteba, Bohne, & Müller, 2007), and from there to the material industries is needed. The following layers need to be covered: function (e.g., person-km), product stock operation (e.g., vehicle-km), product stocks (e.g., passenger vehicles), materials (e.g., automotive steel), energy (e.g., electricity), as well as process and direct GHG emissions. To calculate the total contribution of material efficiency to the national GHG reduction target and to quantify the actual extent of future recycling, the model needs to work at the sector scale, not at the level of individual products. The different material efficiency and sufficiency strategies need to be included.
2.1 The RECC framework

The RECC model framework (Pauliuk et al., 2020) was developed to meet the above criteria, and it can be applied to different countries and sectors both individually and as a collective. Here, the low energy demand scenario (LED, (Grubler et al., 2018)) based on demand-side solutions and the shared socioeconomic pathways SSP1 (easy adaptation to and mitigation of global warming) and SSP2 (moderate adaptation to and mitigation of global warming) (O’Neill et al., 2014) are analyzed and the corresponding model parameters are quantified for these three scenarios as part I of the RECC model framework. Existing product archetypes for future passenger vehicles (Wolfram, Tu, Heeren, Pauliuk, & Hertwich, 2020a), residential (Heeren et al., 2020), and non-residential buildings (part II) are scaled up in the different scenarios. ODYM-RECC v2.4 (open dynamic material systems model for the resource efficiency-climate change nexus) calculates the system linkages from service demand to the material cycles, energy demand by process, and related GHG emissions (system definition: Figure 2). It also depicts the implementation of ten different material efficiency strategies and represents part IV of the RECC framework. The energy-, GHG, and impact-related parameters (part III of the framework) are also included in ODYM-RECC.

2.2 The RECC Germany database

The RECC Germany database contains 104 model parameters and comprehensive documentation is available in the model description (Supporting Information S1) and the individual parameter template files. The reference year of the database is 2015, and some of the input data (vehicle kilometrage, energy/km and building energy/m², and lifetime) are calibrated by ODYM-RECC to reproduce the reported energy consumption of each sector. UN population prospects (UN, 2019), multiplied with SSP- and LED-consistent assumptions on future per capita service levels (Table 1) drive the total service demand, which is the input to the stock-driven model of the different products (6 vehicle drive technologies, 13 residential building and 24 non-residential building types). The inflow of new products (2016–2060) is split into the individual types using a type split parameter, that is sourced from the RESCUE study for vehicles (Günter et al., 2019), and from expert consensus (SSP1/SSP2, (Fishman et al., 2020)) and the LED study (Grubler et al., 2018) for the two building categories (Table 1). Product inflow, outflow and in-use stocks are translated to the material and energy consumption layers by multiplying them with the material composition (kg/vehicle and per m² residential floor area) and specific energy consumption (MJ per km driven and per m²·yr) of the products. These per-product-values are determined from product archetypes that were simulated in dedicated engineering tools (Heeren et al., 2020; Wolfram et al., 2020a). The yield factors of the material cycle industries (processes 3, 5, 9, and 17 in Figure 2) are taken from the MFA literature (Cullen, Allwood, & Bambach, 2012; Liu, Bangs, & Müller, 2012; Mantau, 2015; Pauliuk, Milford, Müller, & Allwood, 2013; Zheng & Suh, 2015), and the specific energy demand and direct process emissions parameters from
| Scenario definition overview for the material efficiency study of Germany, 2015–2050/60 |
|---------------------------------------------------------------|
| **Table 1** |
| **All values BEFORE implementation of ME** | LED | SSP 1 | SSP2 | **Product scope** |
| 2050 population (M) | 79.2 | 79.2 | 79.2 | 6 Vehicle drive technologies |
| Passenger-veh. km/cap 2015 | 10,438 | 10,438 | 10,438 | 13 Residential building types |
| Passenger-veh. km/cap 2050 | 8,434 | 10,000 | 12,000 | 24 Nonresidential building types |
| Resulting pass. vehicles/cap, 2050 | 0.40 | 0.46 | 0.62 | |
| El. Vehicle share (new), 2030, NNCPol | 23% | 23% | 23% | Material scope |
| El. Vehicle share (new), 2030, RCP2.6 | 86% | 86% | 86% | Steel (4 types) |
| Residential m²/cap, 2015 | 41.6 | 41.6 | 41.6 | Aluminum (2 types) |
| Residential m²/cap, 2050 | 32 | 41.6 | 47 | Copper |
| Share of zero energy buildings (new), 2050 | 80% | 50% | 40% | Zinc |
| Res. building stock, 2050, million m²² | 2,536 | 3,296 | 3,724 | Cement |
| Nonresidential m²/cap, 2015 | 21.3 | 21.3 | 21.3 | Concrete aggregates |
| Nonresidential m²/cap, 2050 | 20 | 23 | 28 | Plastics |
| Share of zero energy buildings (new), 2050 | 50% | 20% | 0% | Wood |
| Nonres. building stock, 2050, million m²² | 1,585 | 1,822 | 2,219 | |

| **ME strategy and cascade step no. in parentheses** | **Industry** | **Demand-side** | **Description** |
|-----------------------------------------------------|---------------|-----------------|-----------------|
| Higher yields: EoL recovery (1) | X | | Increase from current to max. realistic values |
| Higher yields: Fabrication yield (1) | X | | Increase from current to max. realistic values |
| Higher yields: new scrap diversion (1) | X | | For automotive steel scrap only |
| Re-use (2) | X | | Max. 29% for construction steel, max. 27% for concreteslabs |
| Lifetime extension (2) | X | | 20% for electric vehicles, 90% for buildings |
| Material substitution (3) | X | | Substitute automotive steel with aluminum, concrete with wood |
| Lightweight design/downsizing (4) | X | | Car segment shift, lean building design |
| Car-sharing (5) | X | | Up to 30% of all passenger-km provided by car sharing |
| Ride-sharing (6) | X | | Up to 40% of all passenger-km provided by ridesharing |
| More intense use of buildings (7) | X | | Up to 20% less floor space per capita |

ME = material efficiency, EoL = End-of-life. Three socioeconomic scenarios (LED = low energy demand and the shared socioeconomic pathways SSP1 and SSP2) and two climate policy scenarios (NNCPol = NoNewClimPol and RCP2.6-compatible climate policy) are considered. Values below are valid for both climate policy scenarios if not indicated otherwise.
2.3 | Material efficiency analysis

2.3.1 | Overview

Ten different material efficiency strategies are studied for Germany (Figure 2, Table 1). They are divided into industrial (material processing and product design/technology strategies) and demand-side (end user strategies, including sufficiency strategies mediated via consumption and lifestyle changes).

2.3.2 | Material efficiency at the demand side

Different modes of service provision, such as shared mobility and housing, can make substantial contributions to resource throughput and emissions reductions (Creutzig et al., 2018; Steinberger & Roberts, 2010). In ODYM-RECC, we model a shift to smaller car segments as well as an adoption of car-sharing (reduced fleet size) and ridesharing (reduced vehicle-km) of up to 30% of the total delivered passenger-km. A detailed rationale for these choices is provided in the scenario documentation (Fishman et al., 2020) and the transport model documentation (Wolfram et al., 2020b). For both residential and non-residential buildings, a gradual reduction of per capita floor space of up to 20% is modelled. It is made sure that the new target floor space does not fall below the stock curve of the LED scenario (i.e., 32 and 20 m²/cap for residential and non-residential, see Table 1), the bottom line of our framework. This reduction factor was deemed both realistic and relevant in the expert consensus process that was part of the SSP storyline adoption (Fishman et al., 2020). Floor space reduction can be achieved by number of measures, including attractive urban settings, shared kitchens and other infrastructure, or parents who downsize their living space when their kids move out (Hertwich et al., 2019a). For the LED scenario, the future residential and nonresidential stock levels are given and we used these values as a lower bound in our scenario suite. The split of the construction of all new nonresidential buildings into the different buildings types is modelled after latest historic data (Müller, Hummel, Kranzl, Fallahnejad, & Büchele, 2019). Product lifetime extension is also considered. Based on estimates from previous studies (Milford, Pauliuk, Allwood, & Müller, 2013), vehicle lifetime can increase by up to 20% and building lifetime by up to 90%, and we applied these estimates to electric vehicles and efficient building types only.

2.3.3 | Industrial material efficiency (material processing, product design, and technology)

For each of the six vehicle types, four segments (size classes) times two material composition options are considered (Wolfram et al., 2020a). For each of the 13 residential building and 24 nonresidential building types, two design times two material composition options are considered. The residential building archetypes were transferred from previous work (Heeren et al., 2020) and the non-residential building archetype description follows below. The weighting of the 48 vehicle, 52 residential building, and 96 nonresidential building archetypes into the average type material composition and energy consumption of a given model year depends on the implementation levels of the material substitution and lightweight design/downdsizing parameters. The former is part of supply-side material efficiency, as engineering and not user perception aspects dominate the implementation of this strategy. The latter is part of the demand-side strategies, as smaller vehicles and lightweight buildings directly affect the status aspect of the products. Re-use is included for construction components and materials, for which estimates could be compiled from literature studies on steel (Milford et al., 2013) and concrete (Shanks et al., 2019), and for vehicle components, for which own scenarios were built (Wolfram et al., 2020a, 2020b). Up to 29% of end-of-life (EoL) construction steel and 27% of EoL concrete can potentially be re-used in new buildings, and for vehicles, the re-used potential varies by type and material, ranging from 62% for cast aluminum components in EoL vehicles in Japan down to 17% for cast iron parts from electric vehicles globally.

Due to the lack of detailed archetype simulations, material composition and heating energy demand of multi-family house were used as proxy for the different nonresidential building archetypes, whereas cooling and hot water requirements were assumed to be constant and 2015 values from the European Union (EU) Hotmaps project were used (Müller et al., 2019). The same data source was used to quantify the 2015 in-use stock and
its energy consumption by age-cohort, and the split of the total energy consumption in to energy carriers was taken from background data for the Energy Technology Perspectives 2017 (OECD/IEA, 2017). The material composition data for the historic nonresidential building stock were taken from Ortlepp et al. (Ortlepp et al., 2016) and Deetman et al. (Deetman et al., 2019) and re-formatted to the age-cohorts used by ODYM-RECC.

While material substitution in products is described by the different archetypes and their respective market shares, the industrial yield parameter improvement potentials were compiled from a number of case studies and industry estimates for the improvement potentials for the EoL recovery rates for the different metals (Liu et al., 2012; World Steel Association, 2008; Zheng & Suh, 2015), for fabrication yield (Milford, Allwood, & Cullen, 2011), and for fabrication scrap diversion (Milford et al., 2013). For some metals and some parameters, plausible assumptions were made based on the available information and expert consultation input (see the parameter files for details).

2.3.4 | Implementation of material efficiency in the RECC scenarios for Germany

ODYM-RECC can be configured to run each ME strategy and each sector individually (sensitivity analysis) or in combination. The ten different strategies are grouped into a cascade of seven steps (vehicles) and six steps (buildings) to simulate the currently perceived ease of implementation, from technical strategies first to lifestyle changes last, and to facilitate the visualization of the results (see Table 1). Each ME strategy is described by a scenario-independent parameter quantifying its technical potential to change the relevant system parameters and by a scenario-dependent parameter that reflects the strategies’ actual implementation levels over time. Some of these parameters are described above, and a full documentation of the 104 model parameters is available in the model description (Supporting Information S1) and the individual parameter template files.

3 | RESULTS

For all three sectors, the 2°C-compatible use of more efficient products, shift of energy carriers to electricity, building renovation, and energy supply transformation will lead to a substantial decrease of the direct use phase emissions (Figure 3a). For the building sectors, scope 2 (electricity and heat) emissions are highly relevant, too, and also these will decline sharply. Additional emissions reductions from material efficiency (Figure 3b) can become relevant contributors to ambitious mitigation targets from around 2030 onwards. For passenger vehicles, the largest contributions stem from the sufficiency-related ME strategies ridesharing, carsharing, and downsizing. For buildings, more intense use, material substitution (wood), lifetime extension, and higher yields are particularly relevant (Figure 3b, c). The same strategies will have a particularly strong effect on reducing GHG in the material cycle industries (Figure 3c), where they can lead to additional 2050 emissions cuts of up to 56% (vehicles), 93% (residential buildings), and 67% (non-residential buildings).

In all three sectors, the circular economy strategies higher fabrication and EoL recovery yields, longer product life, and re-use of components can reduce the difficult to mitigate material cycle emissions by an additional 40–55%, highlighting the relevance of the co-benefit between value retention and emissions mitigation.

In Figure 3a, the scope 1 and 2 emissions are shown already for 2015, the year of the latest historic data. The material cycle model runs from 2016 onwards. In the vehicle materials plot in Figure 3c one can see that material substitution actually leads to higher emissions (from aluminum production), which leads to different shading colors. For the building plots in Figure 3c, the more-intense-use-wedge shows some irregularities, which is a consequence of the stock-driven model applied (inflow is proportional to derivative of stock curve). The material production emissions changes from more intense use vanish by 2060 (Figure 3c), the year of reaching the assumed 20% reduction, as new construction, which is largely determined by replacement needs, rises to its original value.

Across the three sectors, all ME strategies studied yield relevant contributions to emissions mitigation in the long run (Figure 4, top left). While the model runs until 2060 to ensure that no discontinuities occur right after 2050, central results are reported for or by 2050 as this is a central benchmark year in climate policy. From the 2050 base value, which represents a ca. 83% reduction from 2015 values (from ca. 450 to 77 Mt (million metric tons) CO2-eq), ca. 24% of additional emissions reductions are possible through material efficiency, which thus can be a key factor to achieving deep emissions cuts like a 95% target. In the material cycles, 70–75% of the remaining baseline emissions can be avoided (Figure 4, bottom left), where the largest contributions stem from the value retention strategies higher yields, re-use, and longer use. While reductions of cumulative emissions are usually much lower than annual emissions cuts due to the relatively slow uptake of the ME strategies (Figure 4, top right), it strikes that in the material cycles, ME strategies can lead to a ca. 50% cut in cumulative emissions. Here, the value retention and sufficiency strategies more intense building use, higher yields, re-use, lifetime extension, and vehicle downsizing are the largest contributors.

Also in the future, the in-use stocks of the three sectors will contain substantial material stocks (Table 2). Cement stocks continue to be the largest of the materials studied, surpassed only by concrete aggregates (not shown). If fully rolled out, the ten ME strategies together will cause most in-use stocks of material to decline substantially, for example, steel in vehicles (−50%) or cement in residential buildings (−20%). As a consequence of the shift to lightweight electric vehicles, notable increases are seen for aluminum and copper stocks in passenger cars. Also, the stocks of timber in buildings increase over time.
FIGURE 3 GHG emissions for SSP1 scenario with 2°C-compatible transformation of the energy supply system (RCP2.6). 2016–2060 GHG emissions for passenger vehicles (left), residential buildings (middle), and nonresidential buildings (right). (a) system-wide GHG without material efficiency, (b) system-wide GHG with material efficiency cascade in addition, (c) material cycle industries GHG with material efficiency cascade. The curves labeled “total” in Figure 3a, b are the same. Emissions “wedges” in the stacked area plots in Figure 3b, c may overlap, leading to different color shades, as not all strategies lead to emissions reduction in any given year (in particular, material substitution in vehicles). Underlying data used to create this figure can be found in Supporting Information S2.

For future primary and secondary material production (the latter including re-use), different patterns emerge for the materials studied (Figure 5). Due to the relatively high variation of material production, which is typical of stock-driven models, the 2040–2050 annual average is plotted. As a result of energy efficiency and lifestyle changes, the total demand for primary aluminum, cement, plastics, and wood can be expected to decline slightly in the SSP1 scenario without ME. For steel and copper, a slight increase was observed. When ambitious ME is included, a drastic decline in primary production demand will occur for steel, copper, cement, and plastics. Primary aluminum will increase slightly and wood harvesting decline by ca. 40% only (compared to the no ME scenario), both as a consequence of these two materials being the main substitutes for steel and concrete, respectively.

Recycling quantities undergo less drastic changes than primary production, largely because the increasing recycling yields and reuse quantities compensate for the general dematerialization decline. For steel, the 2020 and two 2040–2050 scenario values stay within a rather narrow range of +/− 10%. For aluminum, copper, and wood, future secondary material availability from the three sectors studied will increase. For cement and plastics, larger changes will occur in the ME scenario, as current recycling and re-use are at very low levels.

4 | DISCUSSION

The scenarios presented for future material use and related GHG are the results of a novel modelling approach with high resolution of services, products, materials, and material efficiency strategies. They convey new insights into the relevance and magnitude of material-efficiency-induced emissions cuts.
FIGURE 4  Material efficiency cascades for the three sectors passenger vehicles, residential buildings, and nonresidential buildings combined. Top row: system-wide GHG, bottom row: material cycle industry GHG (processes 3 and 9 in Figure 2 and related energy-supply GHG), left column: 2050 annual emissions, right column: 2016–2050 cumulative emissions. Underlying data used to create this figure can be found in Supporting Information S2
### Table 2

Material stocks, by sector and material, SSP1 scenario with RCP2.6 climate policy, Germany, 2020, 2050 without implementation of material efficiency strategies, and 2050 with implementation of material efficiency strategies. Steel comprises automotive, construction, and stainless steel but not cast iron. Aluminum comprises wrought and cast alloys. Mt stands for million metric tons.

| SSP1                    | Mt  | Steel | Aluminum | Copper | Cement | Plastics | Wood |
|-------------------------|-----|-------|----------|--------|--------|----------|------|
| **Passenger vehicles**  |     |       |          |        |        |          |      |
| 2020                    | 32.8| 2.9   | 1.2      | 0      | 8.1    | 0        |      |
| 2050, no ME             | 26.7| 3.0   | 3.9      | 0      | 6.7    | 0        |      |
| 2050, full ME           | 13.3| 4.9   | 2.7      | 0      | 4.6    | 0        |      |
| **Residential buildings** |   |       |          |        |        |          |      |
| 2020                    | 170 | 1.3   | 0.6      | 418    | 101    | 116      |      |
| 2050, no ME             | 185 | 1.5   | 0.6      | 470    | 134    | 146      |      |
| 2050, full ME           | 148 | 1.1   | 0.4      | 381    | 108    | 109      |      |
| **Non-residential buildings** | |       |          |        |        |          |      |
| 2020                    | 257 | 8.4   | 6.4      | 336    | 77     | 85       |      |
| 2050, no ME             | 208 | 8.4   | 6.4      | 301    | 77     | 115      |      |
| 2050, full ME           | 187 | 7.3   | 5.6      | 259    | 68     | 102      |      |

**Figure 5** Annual material production for the three end-use sectors studied, SSP1 scenario for Germany with 2°C-compatible climate policy. Left (darker colors): primary production from virgin sources, right (bright colors): secondary production from scrap and re-use of materials in components. Due to the relatively high variation of material production, which is typical of stock-driven models, the 2040–2050 annual average is plotted. Underlying data used to create this figure can be found in Supporting Information S2.

### 4.1 Comparison to other studies

The RECC approach is currently unique in its depth of representing material cycles and material efficiency. Part of the strategies are also covered by other scenario assessments for deep decarbonization. For example, in the “GreenMe” (“Germany – resource efficient and greenhouse gas neutral – Material efficiency”) scenario, the recent RESCUE study of the German Environment Agency describes a complete decarbonization of the German economy, whereas our scenarios show residual direct emissions of ca. 8 Mt (million metric tons) CO₂-eq due emissions from material production, which are not substantially decarbonized according to our SSP scenario storyline expansion. While the RESCUE study is cross-sectoral and takes...
FIGURE 6 Breakdown of 2050 system-wide GHG emissions reductions into end-use energy efficiency (green), energy supply (blue), industrial and demand-side material efficiency (apricot and red) for the three end-use sectors in Germany. The two red-colored segments cover the ten ME strategies covered by ODYM-RECC v2.4. Industrial ME includes: recycling efficiency, fabrication yield, material choice, and re-use. Demand-side ME includes lifetime extension, product lightweighting and segment shift, car-sharing, ride-sharing, and more intense building use. Underlying data used to create this figure can be found in Supporting Information S2.

into account sector-coupling effects like a decline in freight transport volumes due to dematerialization, the description of material efficiency is not as detailed as in the RECC study, as reuse, product lifetime extension, and fabrication yield improvements are not or only partly covered. More intense use of cars and buildings is implemented in both studies as part of their vehicle fleet and building stock scenarios.

For their scenario analysis, Bürger et al. (2018) find sectoral GHG reductions of 82–83% by 2050, which is a higher reduction than what we calculated for scope 1 and 2 emissions for both the residential and nonresidential building sectors. The RESCUE study models a virtually complete decarbonization of all sectors and arrives at even higher emissions reductions. The reason for that our results are higher lies in i) the different energy supply mix for the RCP2.6 scenario, which, according to IEA results, still contains 33% of natural gas in 2050 (OECD/IEA, 2017) and ii) the residual emissions from material production.

The RESCUE study finds a decline of raw material consumption by up to 68% (2010–2050) and a decline for the primary production of all bulk materials (Günter et al., 2019), which is with the exception of aluminum, the same qualitative result as obtained from our study. Since RESCUE partly assumes future targets for the recycled content, an age-cohort-based dynamic stock approach yields endogenous and hence more accurate estimates of future secondary and thus also primary production levels than an exogenously specified split between primary and secondary production.

4.2 Interpretation of scenario results and policy relevance

Comparing the deep decarbonization scenarios with counterfactual model runs without a switch to energy-efficient products, electrification of end-use sectors, and energy system transformation shows that material efficiency can become particularly relevant, once the emissions mitigation potential of the former has been seized (green and blue segments in Figure 6). In such a situation, industrial and demand side material efficiency can reduce the remaining emissions by an additional 22–25%. If that technological potential of ME is seized, it can make a substantial contribution to reaching both the sectoral and the national emissions reduction target.
Limitations of the study and outlook on future research

The results presented here are estimates of the technical potential and system-wide feedbacks of material efficiency and the impact of the different strategies on the material cycles, energy consumption, and GHG emissions. The what-if scenarios are contingent on a number of assumptions on the future development of service demand and product choice and the implementation speed of material efficiency and hence, they do not represent predictions of future material cycle, they rather illustrate possible futures. Instead of conducting some form of (always incomplete) optimization to determine cost-efficient implementation pathways of ME, we followed the simpler scenario approach, combined with an open science paradigm, to make the results traceable. The RECC model framework offers a platform for modifying the ME scenarios for Germany to fit them to specific settings or match them to other scenario exercises of sustainable development as the systems level. Still, integrating costs into the material cycle model, as common in energy system modelling (Pfenninger, Hawkes, & Keirstead, 2014) and already implemented in the MARKAL-MATTER project (Gienel et al., 1998), is urgently needed to study the physical/engineering and business model aspect of the circular economy transition from an integrated perspective. Adding consumer behavior, for example, via agent-based modelling (Niamir, Filatova, Voinov, & Bressers, 2018), could help estimate the rebound effects of the sharing strategies for cars and dwellings (Ludman, 2019) and derive the strategy potentials from lifestyle and behavioral parameters.

A number of model parameters had to be quantified using expert consensus and a dialogue-based extension of the SSP storylines (Fishman et al., 2020). Subjective choices and small group bias could not be entirely avoided and the scenarios may need refinement in light of future debates. Moreover, many scenario parameters, such as the exact improvement potential for the scrap recovery rate of different metals from different end-of-life goods, the exact technology mix and energy use of future material production, or future product lifetimes are inherently uncertain, and part of that uncertainty is captured by the scenario analysis. Still, more accurate and consistent estimates of future material-related model parameters will help increase the robustness of the policy-relevant claims extracted from the scenario analysis. Also here, the open science nature of ODYM-RECC helps speed up the refinement process. In the future, different stakeholders should be able to modify individual scenario parameters and systematic and consistent linkages to other assessment frameworks need to be developed, as it is already the case with the GHG emissions factor from the MESSAGE implementation of the SSPs (Riahi et al., 2017). A parallel analysis for other world regions shows that countries with economic development status similar to Germany can expect a similar impact of ME on their GHG emissions (Hertwich et al., 2019b). For developing economies, the lock-in from existing in-use stocks and supporting infrastructures is smaller, and hence, the impact of a timely roll-out of ME on GHG emissions can be substantially higher than in most OECD countries, as case studies for India and China show (Hertwich et al., 2019b).

The ODYM-RECC model traces different chemical elements through the metal life cycles. With the element-specific remelting yield, the scenarios contain a quantification of the average remelt element contamination of the secondary materials in different material efficiency scenarios. This application is particularly relevant for steel and aluminum, for which ODYM-RECC already distinguishes between four and two material qualities, respectively. Going down to the element level and the already implemented product-specific description of recycling chains will help to produce realistic scenarios for material cycles across all sectors that are largely based on secondary resources. In this work, remelt element contamination is not an issue since the intra-sector recycling assumptions are conservative and excess secondary material is exported to other sectors and regions. When describing intricate remelting and purification processes with a liquid metal, slag, and gas phase, thermodynamic analysis and understanding are required to produce accurate estimates of the process yield factors. Our work, however, contains an aggregate representation of these...
processes at a level where relatively pure scrap (e.g., aluminum sheets and not shredded mobile phones) is sorted and remelted into aggregate scrap and secondary material quantities. At this level of aggregation, it is sufficient to know the average yield rates and their (conservative) improvement potentials which in many cases are available from the literature.

A full picture of material efficiency in all its facets can only be obtained if all relevant chemical elements used by technology are traced through the system of production and consumption, so that the linkages and constraints by co-production (mining), alloying, product material mix, scrap blending, and remelting thermodynamics can be considered. To this end, more end-use and industrial sectors need to be included to capture all relevant material end uses. One can, as a first step, create rather simple scenarios by building on existing work for electricity generation (Deetman, Pauliuk, Van Vuuren, Van der Voet, & Tukker, 2018; Elshkaki, 2019; Elshkaki & Graedel, 2013; Elshkaki & Shen, 2019; Grubler et al., 2012; Tokimatsu et al., 2017, 2018), appliances (Deetman et al., 2018), and nonresidential buildings (Deetman et al., 2019). Such an assessment is well possible within the ODYM-RECC framework but is beyond the scope of the current work.

Integration these features describe above will make the scenarios and resulting assessments and indicators more interdisciplinary (costs, element-level) and thus potentially more relevant to decision makers. Opening up the scenario-formulation approach to stakeholders can create a transdisciplinary exchange where the scenario results can directly lead to practical insights and consequences and multiple levels, from consumers to industry to policy makers.

ACKNOWLEDGEMENT

The authors thank the members of the resource efficiency and climate change mitigation (RECC) team for their input to the model framework and database, which is published in this special issue and elsewhere. In particular, our thanks goes to Tomer Fishman, Peter Berrill, Qingshi Tu, Paul Wolfram, and Edgar G. Hertwich. Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTEREST

The authors have no conflict to declare.

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How to cite this article: Pauliuk S, Heeren N. Material efficiency and its contribution to climate change mitigation in Germany: A deep decarbonization scenario analysis until 2060. Journal of Industrial Ecology. 2021;25:479–493. https://doi.org/10.1111/jiec.13091