A comprehensive set of global scenarios of housing, mobility, and material efficiency for material cycles and energy systems modeling

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Abstract
Scenario-based assessments are a useful tool to explore unknown futures and inform decision makers and the public of the consequences of different courses of action. Scenario developments in industrial ecology have focused on disparate components of the socioeconomic metabolism and case studies, and few efforts of comprehensive and cumulative scenario formulation are documented. Many important, empirically derived relationships between material cycles, end-use services, and energy use are relevant to global scenario modeling efforts, for example, of integrated assessment models (IAMs), which do not routinely describe material cycles or the life-cycle impacts of various technology shifts. These inconsistent depictions of material cycles and their environmental impacts hinder the assessment of sustainable development strategies such as demand-side sufficiency, material efficiency, and energy efficiency. We developed three highly detailed scenarios covering 20 global regions to 2060 for the service provisioning of dwelling area and personal transport grounded in salient building and vehicle operation parameters. Our scenarios are based on, and interface with, the Low Energy Demand (LED) and Shared Socioeconomic Pathways (SSP1 and SSP2) narratives. The results comprise scenario-, region-, and period-specific narratives and corresponding parameter values, including per-capita floor space and vehicle stocks, building and vehicle archetype mixes, passenger-km, vehicle-km, vehicle occupancy rates, and implementation potentials of nine material efficiency strategies. The explicit storyline extension approach presented here is an alternative to the aggregate GDP-driven or historical trend extrapolations of service or energy demands. We describe the scenario formulation processes, resulting parameters, their applications, and offer an outlook for prospective sustainability models. This article met the requirements for a Gold-Gold JIE data openness badge described at http://jie.click/badges.
INTRODUCTION

1.1 Scenarios in industrial ecology and integrated assessment models

Scenario modeling is a method to explore a highly uncertain future and chart out possible development trajectories. Scenario-based assessments of bundles of sustainable development strategies inform decision makers and the public of their overall potential, impacts, and consequences. Scenarios show how the current, fossil-fueled development pathway with its massive resource requirements, emissions, and land use change will result in rapid global warming (IPCC, 2018), mass extinction of species (Brondizio et al., 2019; Pereira et al., 2010), and resource depletion (Schandl et al., 2018; Schipper et al., 2018). Other scenarios, however, suggest that market-based solutions can address these problems to some extent (Tilton et al., 2018). While the large sustainability challenges are global (Jaramillo & Destouni, 2015), the solutions are local and highly diverse. They include a myriad of technological solutions, business models, regulations, economic incentives, and behavioral shifts.

Prospective scenarios have been employed in various guises in industrial ecology to study questions of future developments towards sustainable production and consumption (Pauliuk & Hertwich, 2015). For example, scenarios have been used to evaluate the introduction of technologies on a country or global level (Fukushima et al., 2004; Hertwich et al., 2014) or sectoral end-use level (Fishman et al., 2018). Scenarios have also been used to assess the impact of changes in the energy mix on life cycle impacts (Bauer et al., 2015; Mendoza Beltran et al., 2018), or to investigate life-cycle impacts in energy and material scenarios (Heeren & Hellweg, 2018; Luderer et al., 2019; Pehl et al., 2017; Treyer & Bauer, 2016). Material efficiency (ME) strategies are diverse and applicable at different life-cycle phases of materials and products (Allwood et al., 2011), and what-if scenarios include the investigation of the environmental impact of material efficiency strategies in an input-output framework (Scott et al., 2019; Wiebe et al., 2019). The role of technology choices on future resource use (Deetman et al., 2018) and of emission reductions resulting from various efficiency measures (Cabrera Serrenho et al., 2019; Milford et al., 2013b) have also been explored. Scenario assessments for specific material cycles are common in industrial ecology. (Fishman et al., 2014; Kao et al., 2019; Hatayama et al., 2010; Liu et al., 2013; Müller, 2006; Voet et al., 2019) and beyond (van Ruijven et al., 2016), but these assessments start with material consumption or in-use material stocks, not necessarily directly linked to end-use services. These examples, while not exhaustive of the growing number of such scenario analyses, illustrate the various research questions that can be answered by scenarios. They also demonstrate the wide variability of scenario premises: scenarios are often formulated on an ad hoc, case-specific basis, to answer a certain study’s research questions, with little common ground with other studies’ scenarios. This fact hinders comparability between results, potential for follow-up studies, and synthesis of findings, all of which are crucial for informing policy.

Furthermore, to study the system-wide implications of the different sustainable development and decoupling strategies at each stage from service provision to emissions, a detailed depiction of system linkages is needed. Such depiction traces the environmental impacts of material and energy supply to demand for products, which occur for building up and maintaining in-use stocks, and which in turn exist to provide fundamental societal services. In particular, the services provided to end-users need to be described in detail, as they are crucial providers of needs satisfaction (Creutzig et al., 2018) and major drivers of environmental impacts (Ivanova et al., 2016) at the same time, forming a nexus of services, stocks, and flows (Haberl et al., 2017). Within industrial ecology studies, many studies do not consider this entire causal chain. For instance, some include service provision scenarios, such as dwelling space, as exogenous model inputs (Müller, 2006) and other stock demand-driven studies following its methods (Lanau et al., 2019; Müller et al., 2014). Others utilize top-level macroeconomic indicators such as GDP as drivers, (Ciacci et al., 2020; Fishman et al., 2014; Schipper et al., 2018; Voet et al., 2019), and others fit curves directly to historical material trends (Fishman et al., 2016; Liu et al., 2013; Pauliuk et al., 2013; Watari et al., 2020).

The longstanding problem of incompatibility of scenarios across studies has been tackled by the integrated assessment models (IAM) community by the definition and specification of the shared socioeconomic pathways (SSP) scenario family, a set of narratives of five futures (O’Neill et al., 2014, 2017), describing different combinations of demographics, economics, policies, technology, and environment, with accompanying quantifiable indicators (Dellink et al., 2017; Kc & Lutz, 2017; Riahi et al., 2017). The SSPs are now a widely accepted and commonly utilized framework for scenario modeling of sustainable development strategy rollout.

However, in energy systems and IAM, representation of end-use services and the technologies and materials needed to supply them is limited (Riahi et al., 2017), so that the different models using them need to generate their own SSP scenario storyline extensions. This is often done individually, sometimes implicitly by different models, but rarely in a transparent fashion. Service levels are often obtained from GDP-based regression or extrapolation models (Pauliuk et al., 2017), due to the historical coupling of GDP with service levels and energy consumption. However, this historical coupling may contradict future scenario narratives, and furthermore given the very high GDP levels in some SSP scenarios (Dellink et al., 2017), this approach could lead to unreasonable service levels that would be hard to translate into actual lifestyles, such as a doubling of per-capita floor
area in developed countries. In energy system modeling, in particular, it is also common to not model services explicitly but to directly relate the socioeconomic drivers to the energy consumption in the different end use sectors (Pauliuk et al., 2017). Skipping the stocks of goods and products that provide service, as reviewed recently for vehicle modeling (Wolfram & Hertwich, 2019). In such a situation, the sustainable development strategies of demand-side sufficiency, material efficiency, and energy efficiency cannot be distinguished, and thus their relative potentials are not well understood.

Alternatives to the aggregate GDP-driven or historical trend extrapolations of service and/or end-use sector energy demand are needed to provide experts and stakeholders with a detailed description of future consumption levels and their environmental impacts under various sustainable development strategies. Deetman et al. (2018, 2020) postprocess the IMAGE IAM model results to back-calculate the product stocks for residential and nonresidential buildings as well as passenger vehicles, but only for one global aggregate region. Furthermore, many IAMs disclose only limited details of their scenarios, requiring researchers to deduce their assumptions. This lack in data transparency hinders scrutiny and cumulative research (Hertwich et al., 2018). A step towards linking the SSP scenarios with material requirements was published recently, a set of comprehensive material consumption scenarios for the five SSPs (Schandl et al., 2020), which also reviews recent relevant scenario modeling efforts. However, it does not directly account for the in-use material stocks in the various scenarios, nor does it quantify the societal services for which materials are extracted and accumulated, and so a suite of SSP-consistent descriptions of future service provision still does not exist.

The authors of the low energy demand (LED) scenario (Grubler et al., 2018) took a different route: As a detailed description of end-use services is crucial to accurately depicting a low energy demand scenario, they used an expert consensus approach to estimate and establish future service levels. The values obtained there can serve as a bottom line for service provision. A similar quantification of service levels associated with SSP scenarios is still lacking. Moreover, the LED scenario storyline extension only covers two world regions, Global North and Global South, and more regional resolution is needed to accurately depict differences due to socioeconomic development, societal trends, technology adaptation rates, and climate.

1.2 | Research goal and scope

In this study we document a large effort towards alleviating ad hoc scenario formulations and gaps in coverage of service provisioning and material cycles hierarchies in widely accepted scenario sets like the SSPs and LED. We describe a comprehensive set of scenario parameters of baseline service provision and material efficiency potentials for two of the major contributing sectors to greenhouse gas emissions and other environmental impacts: residential buildings and private vehicles. Our scenarios describe three potential evolution pathways to 2060 of the services provided by these two sectors, namely dwelling area (in square meters per person) and mobility (in passenger kilometers and number of vehicles), respectively, and accompanying scenario-specific parameters of ME strategy implementation potentials. The scenarios cover the entire globe split into 20 world regions, some of which are individual countries, and conform to three well-regarded scenario frameworks: two of the five SSPs and the LED scenario.

The resulting set of scenario storylines and quantitative socioeconomic and technological scenario parameters form a ready-to-use package for consistent and comparable study of the material and energy cycles in industrial ecology, harmonized with preexisting scenario sets.

We describe the methodologies we developed for the scenario-building process and present the resulting scenarios with their parameters and values, patterns, and configurations in context of their intended role as drivers of models of material cycles and specifically of material and energy efficiency potentials. The formulation of these scenarios is motivated by an objective to create an encompassing platform for detailed multistage decoupling assessments, the RECC (Resource Efficiency-Climate Change mitigation) framework (Pauliuk et al., 2020a). Our scenario parameters are designed to be iteratively further developed and evolved and are available open-access for researchers to use, expand, and refine, as are the RECC framework and other related elements such as the model source code. To facilitate their joint use and expansion by the scientific community, we also include some description of the linking of our scenarios to the RECC framework. The scenarios are nevertheless model-agnostic, and we discuss their applicability and potential contributions to scenario-based modeling in industrial ecology and beyond.

2 | METHODS

2.1 | What-if scenario formulation

In scenario modeling, an internally consistent qualitative narrative of a possible sequence of events is translated into a development of quantifiable variables. Unlike forecasting models which describe a future path together with assessments of its likelihood or probabilities, the scenario-based approach follows a what-if logic (Börjeson et al., 2006): counterfactual possibilities. Our formulation of the scenario storylines was done in an approach similar to the creation of the Shared Socioeconomic Pathway scenarios (O’Neill et al., 2017). Firstly, we identified meaningful counterfactual narratives. We then defined the realization of our parameters of interest with values subject to the scenario narratives, region-specific historical trends, and maximum technical implementation potentials.
2.2 Scenario narratives

We prioritized building our scenarios upon well-regarded existing ones to create continuity with contemporary research and with a vision to link our work to other scenario models. Three different socioeconomic storylines were selected: two of the five storylines of the Shared Socioeconomic Pathway family (O’Neill et al., 2014; Riahi et al., 2017), which were developed to support modeling efforts of 2°C consistent scenarios by the climate research community, namely SSP1 (Sustainability—Taking the green road) and SSP2 (Middle of the road). The third storyline is the Low Energy Demand (LED) scenario, which was developed specifically to explore the possibilities to limit global average temperature rise to 1.5°C above preindustrial temperatures without using extensive carbon-removal technologies and nuclear power (Grubler et al., 2018). The LED scenario builds on the socioeconomic and demographic assumptions of SSP2. These three storylines were selected for their fundamentally different development trends and societal priorities on material cycles, vis-à-vis the potential for advanced implementation of material efficiency strategies in their narratives. Our research priorities called for an analysis of options for climate change mitigation, and hence did not call for a business-as-usual scenario of continued, unabated growth of material consumption. SSP pathways 3, 4, and 5 were hence not investigated in this work.

2.3 Requirements of scenario parameters

The three socioeconomic scenarios (LED, SSP1, and SSP2) were originally designed at the global or global regions levels. We therefore either identified existing scenario-conforming future values in the literature or conducted a process to determine how the different scenario parameters would manifest in 2050 for each region/country considering the three socioeconomic storylines and in light of historical trends. We identified several requirements and qualities that the ideal parameter data should balance:

1. Consistent with scenario narratives. This requirement is not only for harmony with the scenario for which the parameter is defined, for example that material and energy-efficient buildings and vehicles are prominent in the LED scenario, but also for consistency across scenarios, for example ensuring that SSP1 and SSP2 values are not lower than the LED scenario, which is treated as the lower limit in our scenario set.
2. Viable case-specific implementation of ME strategies in light of maximum technical potentials found in the literature, and realistically achievable in the study’s 2015–2050 timeframe in the specific scenario.
3. Consistent with and reasonably continuing the historical trends unique to each region.
4. Smooth time trends, to avoid sudden and unrealistic trend shifts in the first and second derivatives of time series, which manifest as modeling artifacts and edge effects in dynamic stock and flow modeling.
5. Scrutiny for latent or “black box” factors or assumptions that may have been used in the formulation of parameters. Such factors may be inconsistent with the narratives, regions, or historical trends, even if the parameters themselves seem to be consistent. For example, using the year as an explanatory variable in a regression-based parameter means that ceteris paribus the response variable has a path dependency, which may not be consistent with the counterfactual scenario approach.
6. Efficient and parsimonious, balancing the level of complexity and level of abstraction and simplification required of the parameters and the model to the needs and resolution of the study’s aims.

These requirements formed a guideline for the quantitative specification of the scenario-specific parameters.

2.4 Parameter scope and resolution

We set a relatively high spatial resolution of 20 major individual countries (in terms of population and economic power) and world regions: USA, Canada, Japan, France, Germany, Italy, Spain, UK, other EU countries that joined prior to 2004 (here referred to as the Rest of EU15), Poland, other EU countries that joined after 2004 split into medium- and high-income groups (EU12-H and EU12-M), Rest of the OECD, Reforming Economies of Eastern Europe and the Former Soviet Union, China, India, Rest of Asia, non-OECD Latin America, non-OECD Middle East and Africa (MENA), and Sub-Saharan Africa. Details of the 20 regions and constituent countries are found in the Supporting Information S1.

Our scenario parameter set includes socioeconomic parameters and ME strategy implementation parameters. The main socioeconomic parameters are per-capita service demand, intensities of use and operation, product/material stock lifetime curves, and archetype split. The archetypes themselves, such as building types and vehicle drivetrains, are scenario-agnostic. The ten ME strategy implementation parameters are: fabrication scrap diversion rate, fabrication yield improvement rate, end of life recovery rate, reuse rate, lifetime extension, material substitution, downsizing/less material by design, more intense building use, car sharing, and ride sharing. The last two together quantify the more intense vehicle use ME strategy.
2.5 Process of formulation of scenario parameter values

When possible, we directly used available scenario data. Data on future population (Kc & Lutz, 2017) and economic development (Dellink et al., 2017) are from the SSP database. Data on energy mix (Riahi et al., 2017) and vehicle drive technologies were based on 2°C conforming scenarios following the respective storylines. Prospective data on energy technologies were extracted from reports of the IEA (OECD/IEA, 2010, 2017; IEA, 2018). We used previous estimates (Milford et al., 2013a) for several parameters describing material efficiency strategies’ maximum 2050 technical potentials, including the improvement of fabrication scrap, end-of-life recovery efficiency of scrap, re-use of steel components in buildings, or product lifetime extensions. Pauliuk (2020) contains a complete list of data sources used to this end.

Many of our scenario parameters were either only partially quantified by the SSP and the LED scenarios and other literature, or not at all. Chief among these parameters are the per-capita service levels (floor space per capita and passenger-km per capita) which are intended to drive the modeling of service-provisioning product stocks and corresponding material and energy demands. Also missing are the scenario-specific future archetype splits, baseline material efficiency, and peak material efficiency rates which determine the potential effects of ME strategies. Furthermore, some of our regions are more detailed than the geographical resolution of the SSPs and especially the LED scenario and required case-specific parameters. For example, existing SSP-consistent floor space data (Daioglou et al., 2012; Marinova et al., 2020) are available for global regions, not the country-level resolution. To generate values for these parameters we utilized three approaches: a historical data-driven approach, adoption and adaptation of other existing assessments from the literature, and an expert consensus approach.

The data-driven approach applies time-series regression analysis methods to unpack historical dynamics and extrapolate them into the future. Several previous studies used similar approaches to quantify future values for multiple parallel scenarios (Elshkaki et al., 2016, 2018; Schipper et al., 2018). However, this approach inherently assumes that future dynamics will remain consistent with historical ones, and we deemed that this assumption only matches the SSP2 storyline that describes a continuation of historical trends and is inconsistent with SSP1 or LED. Furthermore, this approach requires relatively long historical data, and only the floor space data of the USA and Japan supported this type of analysis. To account for potential time-series data effects, we expanded on Fishman et al. (2016) and Ciacci et al. (2020) and utilized a model with autoregression (AR) errors and GDP and urbanization rates as drivers (covariates). We detail this model and its results in the Supporting Information S1.

For all remaining parameters, historical data was insufficient for the data-driven approach. We therefore employed a semi-quantitative approach to develop storyline-compatible parameter sets through adaptation of other scenarios and a process of expert consensus, similar to the approach used to formulate parameters in the SSPs (O’Neill et al., 2017; Riahi et al., 2017). For each region in each storyline, we established scenarios for services demand (floor area per person and passenger-km per personal travel), their respective service-provisioning products (residential floor space and personal automotive transport), the associated development of these technologies, their product archetype mix (market shares), the degree of potential implementation of material efficiency strategies, and the technological progress to be expected in each scenario in comparison to future maximum technical potential. If existing scenarios and values in other literature were deemed to be applicable to a certain scenario narrative, we adapted them. In the remaining cases, starting with “default” values or qualitative high-medium-low assignments, we developed storyline-consistent target values through expert group consensus, drawing on expertise from both within and beyond our project team. The values went through multiple iterative rounds of definition, rationalization, discussion, consensus-building, refinement, testing, and review.

We set up spreadsheet tables for ease of use by the group of experts. These “scenario target tables” require values for the year 2050 and optionally for 2020, 2030, and 2040 (and 2060), documenting rationales for every value. Setting values for the optional years enabled reaching a maximum value prior to 2050 and curving trendlines to model faster or slower take-up as befitting the scenario narrative (Figure 1). We calibrated all
parameters to historical data, especially for the historical stock that constitutes a lock-in constraint. The year-by-year values between the target years were interpolated to create a full time-series for 2015–2060. A spline interpolation was selected over linear or moving-average approaches to minimize sudden jerks in the first and second derivatives of the curves, which can dramatically influence the results of a dynamic stock-driven model and create model artifacts. The interpolation and conversion to consistently formatted spreadsheet data are done using Python code. The target table format and interpolation and conversion Python code are available in a Github repository (Fishman, 2020), and the resulting parameters are available, with versioning, in Zenodo archives (Pauliuk et al., 2019).

3 RESULTS: SCENARIO PARAMETER STORYLINES AND VALUES

The results of our scenario formulation process are two-fold: qualitative scenario-consistent storylines and accompanying quantitative values. In the following subsections we describe both for the main scenario parameters.

3.1 Dwelling service provision scenarios

Per capita residential floor space varies widely across countries at similar levels of development and economic activity (Ellsworth-Krebs, 2020), shaped by tradition, urban form, as well as land use and building regulations. Scenarios for future floor space were based on the starting point of the country in question, past dynamics, and the climate-friendliness of the underlying scenario, resulting in distinct trends in each scenario (Figure 2).

SSP2 describes a scenario of continued growth of floor space per capita in all regions. Although there has been a large difference in per-capita living space in countries at a similar stage of development, there has been a general trend of increasing floor-space with growing GDP, followed by an eventual slowing of demand (OECD/IEA, 2017). We assumed that this trend continues for SSP2. The values obtained with the data-driven method for the USA and Japan conform to this trend. We used them in SSP2 for 2015–2060 and for formulating the scenario values of countries that were found to have had similar historical trends, for example, Canada and the USA, and Germany and Japan. In SSP2, regions generally converge towards 50 m²/cap by 2050–2060. The exceptions are the USA and Canada which have already exceeded this value, and conversely India and the rest of Asia region which reach an average of 40 m²/cap by 2060, and Sub-Saharan Africa reaching 35 m²/cap due to the infeasibility of them reaching 50 m²/cap by 2060 based on their current levels.

In the SSP1 scenario, if a region has an average floor space per capita of over 40 m²/cap in 2015, its value is held fixed. Regions whose average floor space per capita is below 40 m²/cap in 2015 grow towards this value by 2060 but remain below their projected SSP2 levels. The LED scenario calls for a global convergence of floor space per capita of 30 m²/cap by 2050 (Grubler et al., 2018), but does not provide detail on how that is to be achieved or whether this convergence varies by regions. We deemed all regions to either contract or enlarge their per-capita floor area towards this value of 30 m²/cap by 2060, and do so more rapidly after 2030. Regions that are far higher or lower from this value in 2015 do not reach it by 2060. Nevertheless, comparatively speaking their efforts (e.g., the reduction in the USA) are among the most ambitious. The portion of total floor space that is heated or cooled is assumed to remain the same as in 2015 or increase slightly by 2050 in all regions and scenarios.
3.2 Mobility service provision and intensity of operation scenarios

Contrary to the service levels of residential buildings, which we simply quantify in \( m^2/cap \), we formulated four scenario parameters that together describe the future service provision of mobility in each scenario and are interlinked through Equation (1) and its variation, Equation (2):

\[
PKM = OR \times VKM \times S \tag{1}
\]

\[
S = \frac{PKM}{OR \times VKM} \tag{2}
\]

where PKM is passenger km (average annual kilometers traveled by a person using a passenger vehicle)—the mobility service provision indicator in practice; OR is vehicle occupation rate (average number of persons in vehicle in a given year), that is, the intensity of use; VKM is vehicle km (average annual kilometers traveled by a passenger vehicle) that is, intensity of operation; and S is vehicle stocks (number of vehicles per person). PKM, OR, and VKM values were obtained through the expert consensus process for all countries in all three scenarios, and S is calculated using the equation.

This equation describes the provision of mobility (PKM) by the stock of products (S), required for modeling of product and material cycles. Furthermore, the explicit quantification of these parameters enable our scenarios to be used for modeling the two demand-side mobility ME strategies: ride sharing (which affects OR) and car sharing (which affects VKM). We set scenario values for 2050, assuming a linear and smooth trend from 2015 up to that point and no further changes from 2050 to 2060. The results of our scenario formulation are presented in Figure 3.

2015 values range from 322 annual person-km per capita in India through 10450 km in Germany to 22500 km in the United States. The assumption of the LED scenario is that by 2050, due to modal shift and changes in the urban form, passenger vehicle transport demand in developed countries will reduce to 8434 person-km per capita and year on average (Grubler et al., 2018). We assume that all G7 and European regions converge to this value by 2050 except Japan, which is already lower than this value. Slow growth in PKM occurs in the rest of the regions. In comparison, the SSP2 scenario assumes an increase in PKM in all regions except the already high USA and Canada, and SSP1 a moderate level between the other two scenarios.

Similarly, annual vehicle kilometers are assumed to decrease in the LED scenario in all regions, stay at 2015 values in SSP2, and the SSP1 values are assumed to be in between the other two scenarios. Vehicle occupancy rates in the LED scenario increase dramatically by 2050 in all 20 regions,
3.3 Archetype mixes and product lifetimes

The shares of the different building and vehicle types added to the stock in a given period are used to represent changes in market share over time, reflecting the scenario narratives. For residential buildings, archetypes are defined under two dimensions, type (single-family, multifamily, residential tower, and informal) and energy efficiency level (in order of increasing efficiency: nonstandard, standard, efficient, zero energy building). Scenarios with high use intensity have a higher share of multifamily homes because their occupation is denser, that is, less floor area per person. In general, as shown in Figure 4, we assume a general transition to multifamily residences and residential towers due to increasing urbanization. For urbanization to successfully achieve denser dwellings with higher portions of multifamily homes and residential towers, sprawling growth of low-density urban forms must be limited (Ewing & Rong, 2008; Lee, & Lee, 2014). The transition to dense urbanization is gradual and comparatively weaker in SSP2, stronger in SSP1, and dramatic in the LED scenario. In all countries in SSP2 by 2050 only some buildings are efficient or zero energy, whereas in SSP1 more than 50% are efficient or zero energy. In the LED scenario, by 2050 all buildings are either efficient or zero-energy, and standard buildings are no longer built, except for India, the rest of Asia, Latin America, the Middle East and North Africa, and Sub-Saharan Africa.

In the case of passenger vehicles, the archetypes are characterized by three factors: four size segments (micro car, passenger car, minivan/sports utility vehicle (SUV), and light truck); six drivetrain types (gasoline internal combustion, diesel internal combustion, hybrid electric, plug-in hybrid, battery electric, and hydrogen fuel cell electric); and two production designs (conventional and lightweight), providing a total of 48 archetypes. We adapt the split of drivetrains from the IEA Energy Technology Perspectives (ETP) (OECD/IEA, 2010). The LED and SSP1 archetype split follow the ETP BLUE Map scenario, and SSP2 follows the ETP baseline scenario.

The average lifetimes of products added to the stock 2016–2050 prior to implementation of the lifetime extension ME strategy are assumed to remain the same as 2015 values that were obtained from the literature. These values are 15 years for all vehicle archetypes in all regions. For all building archetypes the average lifetime is assumed to be 75 years in the USA, Canada, the UK, France, Germany, and Italy, 50 years in India, 45 years in Japan, and 40 in China.

**Figure 4** Residential housing archetype mix in 2015 and in the three scenarios (LED, SSP1, and SSP2) for 2050. Abbreviations: SFH, single family house; MFH, multifamily house; RT, residential tower; ZEB, zero energy building. Underlying data used to create this figure can be found in the Supporting Information S2.
### Table 1

Material efficiency implementations by 2050 for the G7 countries. Percentage changes refer to the scenario-specific starting values. Actual values vary slightly by country. Abbreviations: PHEV, plug-in hybrid electric vehicle; BEV, battery electric vehicle; FCV, fuel cell vehicle.

| ME strategy                                      | LED                                      | SSP1                                      | SSP2                                      |
|-------------------------------------------------|------------------------------------------|-------------------------------------------|-------------------------------------------|
| Buildings                                        | End of life recovery                     | 95% recovery of Steel and Aluminum, 93% copper, 70% plastics | 50% of new buildings                      | 10% of new buildings                      |
| Fabrication yield                                | Fabrication yield increase to 10%        |                                           |                                           |
| Fabrication scrap diversion                      | 80% scrap diversion                      |                                           |                                           |
| Reuse                                            | +29% steel reuse, +27% concrete reuse    |                                           |                                           |
| Lifetime extension                               | lifetime extended 90%                    |                                           |                                           |
| Material substitution                            | 85% of new buildings                     | 50% of new buildings                      | 10% of new buildings                      |
| Down-sizing/less material by design             | 85% of new buildings                     | 55% of new buildings                      | 35% of new buildings                      |
| More intense use                                 | (Not implemented in the LED scenario, already at max) | 20% reduction of floor space per capita, down to LED values |                                           |
| Vehicles                                         | End of life recovery                     | 95% recovery of Steel and Aluminum, 82% copper, 70% plastics |                                           |                                           |
| Fabrication yield                                | fabrication yield increase to 10%        |                                           |                                           |
| Fabrication scrap diversion                      | 80% scrap diversion                      |                                           |                                           |
| Reuse                                            | 20–40% reuse                             | 9–20% reuse                               |                                           |
| Lifetime extension                               | Lifetime of PHEV, BEV, FCV extended by 20% |                                           |                                           |
| Material substitution                            | 60% of new vehicles                      | 28–35% of new vehicles                    |                                           |
| Down-sizing/less material by design             | Share of microcars and passenger cars 80–96% | Share of microcars and passenger cars 70–95% | Share of microcars and passenger cars 65–94% |
| Car-sharing                                      | 30% service demand through car sharing   | 25% service demand through car sharing    | 15% service demand through car sharing    |
| Ride-sharing                                     | 40% increase in occupancy rate           |                                           |                                           |

### 3.4 Material efficiency strategies implementation rates

Scenario-consistent future values were assigned for the implementation rates of the ten material efficiency strategies for the three scenarios. Table 1 presents these parameters for the G7 countries. To conserve space, details of the region-specific scenario values and their rationales are included in separate technical reports of the RECC framework for vehicles (Wolfram et al., 2020), buildings (Heeren et al., 2019), and material cycles and material efficiency (Pauliuk, 2020).

### 4 DISCUSSION AND CONCLUSIONS

#### 4.1 Towards common scenarios of services, material cycles, and energy systems

In this study we present a rich set of ready-to-use parameters for different socioeconomic development paths, archetype splits, and material efficiency potentials. As such, our scenarios address several gaps in previous work and contribute to open science. On one level, our approach and its resulting scenario parameter storylines and values form a bridge between the IAM and the industrial ecology research agendas. This set of scenarios is designed to be consistent with existing and well-regarded scenario frameworks, namely the SSP and LED scenarios. Our scenario-formulating methods and resulting parameters complement these frameworks by providing quantifications of parameters detailing anthropogenic material cycles explicitly related to the services provided by the products made of these materials.

On a second level, the purpose of this study is to add detail to the methods and processes we adopted and developed to overcome challenges in which prospective scenario modeling is operating, such as ad hoc approaches, narrative inconsistencies, "black boxes", and an overall data-poor modeling environment. The documentation provided by this study is at a level of detail that allows other researchers to use, refine, and expand the scenarios for future studies. Specifically, the explicit storyline extension approach presented here is a novel alternative to aggregate GDP or curve-fit extrapolations of historical service or end-use sector energy demands. Economic indicators like GDP are both a poor guide for past improvements in service and wellbeing and for meeting needs in a sustainable future (Hoekstra, 2019; Stiglitz et al., 2018). Our approach facilitates detailed, descriptive, and more flexible counterfactual scenarios that allow for expert and stakeholder-based depiction of future consumption levels, their potential environmental consequences, and opportunities to mitigate them.
4.2 | Present and future applications of the scenarios

The scenario space created with our approach describes a wide range of plausible—yet substantially different—futures that are meant to be used as baseline drivers of material and energy cycle studies. Some example applications of our scenario results are already available, which used earlier development versions of the scenarios. In its first major application, a limited iteration of the scenarios was employed with the RECC framework (cf. Section 4.3) in a study for the International Resource Panel (IRP) (Hertwich et al., 2019a). The scenarios were used to quantify the potential greenhouse gas abatement that could be achieved by 2050 through the deployment of different combinations of ten ME strategies for passenger vehicles and residential buildings in the G7 countries, China, and India. This scenario set was similarly utilized in the United Nations Environment Programme’s Emissions Gap Report 2019 (Hertwich et al., 2019b). These projects’ specifications called for a multidimensional scenario space, combined with an ambitious modeling framework that calls for a plethora of scenario-specific variables. Our scenarios and corresponding data balance between consistency across narratives, regions, time, historical trends, and so on, and fidelity to the objectives of such studies. The full range of scenarios for all 20 regions is used in a follow-up study with global scope (Pauliuk et al., 2020b) (preprint). Our scenario formulation processes are also beginning to fulfil their goal as study-agnostic baselines to support and inform independent scenario-based research of material cycles and associated emissions, such as cement (Cao et al., 2020).

We plan to continuously refine, improve, and make available expanded iterations of this scenario set, including expansion to further scenario narratives including SSP 3, 4, and 5. Our approach can also be transferred to other sectors. Other transport modes and nonresidential buildings are obvious candidates for the expansion of the sectoral scope, though the much larger diversity of service-provisioning by these products (vehicle and nonresidential building types) is a foreseen challenge. The same applies to many modern consumer products such as smartphones that offer multiple difficult-to-quantify services. One potential approach to deal with this challenge is to adopt previously published functional unit—reference flow pairings from the LCA literature. Infrastructure can be added, but its depiction hinges on the consistent description of urban and rural settlement structures. Once the major end-use sectors are covered, the industries supplying those sectors with products, energy, and materials also become relevant. Their capacity can be estimated from the manufacturing, material production, and waste management industries throughput determined by the material cycle model.

We identify several limitations and challenges to be addressed in future revisions of our scenario setup and formulation. We employed several methods to develop the scenario parameters, including data-driven methods, adaptation of data originally developed for other uses, and expert consensus. However, our approach employs average values, limiting the scope of assessment to large regional resolutions in which local variability is assumed to be small. Furthermore, in the scenario procedure documented here, the two end-use sectors were largely considered in isolation. That approach can be lacking, especially for scenarios that starkly deviate from current service consumption patterns, as substantial reductions in different sectors may not happen independently of each other but only as a result of integrated policies and other measures designed across sectors. For example, aggressive urban densification towards multifamily housing should affect passenger km (Ewing & Cervero, 2017), or declining housing space and passenger vehicle transport compensated by more attractive job market, leisure activities, and a shift to other, denser transport modes (Hsieh & Moretti, 2019). Linking the different service needs to detailed descriptions of urban and rural forms and lifestyles can help to establish such cross-sector consistency. This way, the rather loose ends of the end-use services can be brought together by linking them to detailed lifestyle descriptions in line with the different macro-level storylines.

Currently, data to properly quantify the 2015 reference state are scarce, especially for most developing countries and sectors other than passenger vehicles and residential buildings. Even where suitable data are available, the effort to obtain, compile, and harmonize them is substantial. Sufficienlty long time series to apply data-driven analysis for future extrapolation as described above are largely not available, yet the provision of these data would allow us to create robust extrapolations of historic socioeconomic trends. Such scenarios would represent a baseline against which the different efficiency and sufficiency strategies can be assessed. Data-driven scenarios can also be created to describe not just average but multiple different lifestyles across different strata, and observations based on big data acquisition such as high resolution time use or expenditure data can help to obtain consistent lifestyle description across sectors and thus validate the scenario assumptions.

4.3 | Linking the scenarios to the Resource Efficiency and Climate Change Framework

The scenario parameters are intentionally model-agnostic to facilitate their adoption to act as drivers and implementation potentials for dynamic material and energy modeling. Notwithstanding, our efforts were developed in tandem with an open-science comprehensive modeling framework to study the influences, tradeoffs, and effects of ten material efficiency strategies (in tandem and individually) on the GHG emissions from different end-use sectors in various regions up to 2050, and we briefly document their linkages in this section.

This modeling framework, Resource Efficiency and Climate Change (RECC), is described in detail in (Pauliuk et al., 2020a). It operationalizes the conceptual chain of links from the societal demand for services (such as dwelling space or passenger travel), through the physical products that deliver them (such as building stocks and vehicle fleets, correspondingly), to the materials these products are composed of, the material flow
cycles involved in delivering these products, and the life cycle energy emissions of the manufacturing, use, and end-of-life phases of these products and constituent materials. The RECC framework employs our scenarios to assess the potential contributions of resource efficiency strategies—the materials-related counterparts of energy efficiency—to reduce environmental impacts on the global and regional levels. The deployment of the various ME strategies and their GHG abatement delivery would differ under different socioeconomic, technical, and climate conditions, and between different regions.

In this regard, our scenarios can form the first of four interlocking parts in the RECC framework (Figure 5). The first three parts produce data and parameter values required for the comprehensive modeling of the services-products-materials-energy-emissions chain: the second part defines scenario-agnostic archetypes of end-use products with their material and energy characteristics and upscaling, documented in (Heeren et al., 2019; Wolfram et al., 2020), and part three quantifies the life cycle energy and emissions of the various process, together with energy-efficiency scenarios that complement our material efficiency scenarios to expand the possible scenario space. The parameter values generated in these three parts are fed to part four, the quantitative modeling of the aforementioned chain of links, with a mass-balanced stock-driven dynamic model at its heart, detailed in Pauliuk and Heeren (2019), which calculates the resulting material and energy cycles.

Specifically, our socioeconomic scenario parameters in part one are input parameters to the model in part four forming a baseline scenario run, and the ME implementation scenario parameters act as interventions that modify the baseline scenario run, conceptually "turning on" these ME strategies (Allwood et al., 2012) to their highest applicable level in the specific region/scenario combination. The ME strategies can be turned on one-at-a-time, forming a sensitivity analysis, or serially, which together enable the model to show the maximum GHG reductions possible through ME strategies in a specific region and scenario. The functions of the socioeconomic parameters, the locations of the intervention by ME strategies in the model in part four, and their order of implementation are marked in Figure 5. For technical details of the usage of the scenario data in the RECC framework, we refer to further descriptions of the RECC framework (Pauliuk et al., 2020a) and the RECC model documentation (Pauliuk, 2020). The scenario values we describe in this manuscript correspond to RECC version 2.4.

4.4 Outlook and conclusion

The roles of service provisioning by products and the built environment, the materials and energy required for them, and the potentials to decouple them from each other are gaining prominence in policy-informing sustainability science. The theoretical foundations of linking societal demands to environmental means (and burdens) through intermediate technological and economic means and ends have emerged and were developed in various sustainability fields including socioeconomic-environment systems, ecological economics, and industrial ecology, including Ayres and Kneese (1969), Meadows (1998), Fischer-Kowalski and Hütter (1999), and Rittel et al. (2002). In recent discourse, the Sustainable Development Goals (SDGs) set targets for improvement of service levels while reducing the environmental and resource cost of economic production. These means-ends links have been utilized to describe a 'safe and just space' for sustainable wellbeing (O'Neill et al., 2018). Service provision levels play important roles in defining sustainable consumption, from recent basic living standards vis-à-vis their material and energetic demands (Rao & Min, 2018; Rao et al., 2019), to sustainable consumption ‘corridors’ (Di Giulio & Fuchs, 2014; Lamb & Steinberger, 2017) that also address social fairness. There are ongoing efforts at the IPCC to develop a chapter specifically on demand-side solutions for climate change mitigation that explicitly detail societal requirements of services (Creutzig et al., 2016, 2018). The specific roles of societal material stocks in relation to services have been delineated in various socioeconomic metabolism studies (Pauliuk & Müllers, 2014). They have been further conceptualized as a stock-flow-service nexus (Haberl et al., 2017) and as part of an ‘energy cascade’ (Kalt et al., 2019), and positioned within a quantifiable implementation of the means-end framework (Tanikawa et al., 2020). All these efforts require explicit quantification of future service provision, and sufficiency and material efficiency potentials, complementing the already available energy efficiency scenarios, to which our scenario results aim to contribute.

We note that quantifiable proxy indicators are limited in their capacity to fully describe societal services that are more complex and abstract, for example passenger kilometers standing in for the concept of mobility. This is a well-acknowledged challenge not only in industrial ecology but in sustainability science in general, as described in pioneering works such as Meadows (1998) and in current discussions such as Fanning et al. (2020). Fell (2017) points out the ambiguous dual-usage of the term ‘services’ in sustainability sciences for both technical functions and societal end-goals, and some suggestions for disambiguation were proposed recently (Kalt et al., 2019; Whiting et al., 2020). In this study we stick to the notion of services to maintain compatibility with existing IAM and IE frameworks, and our scenarios-formulating approach can accommodate other quantifications and definitions of services provisioning systems as these are developed.

Scenario modeling for sustainable development thus needs to cover both the full scale of solutions across the chain of wellbeing-services-products-materials-environment to yield relevant conclusions and high levels of detail to correctly depict the different solutions and interactions between them, including explicit linkages through the intermediaries of material and product cycles and service provision levels, to which this study contributes. Industrial ecology is on the cusp of employing scenario modeling more widely and to contributing to integrated assessment exercises of long-term global scope (Pauliuk & Hertwich, 2015). In doing so, industrial ecology needs to consider the scope and mechanisms covered by present-day models and its own unique topics and strengths. Despite the importance of the underlying assumptions of socio-economic scenarios as the fundamental exogenous variables and drivers of scenario modeling-based results, so far relatively low attention was given to formulating baseline
FIGURE 5  The socioeconomic scenarios in context of the overall Resource Efficiency and Climate Change (RECC) Framework. Our scenarios form part I of this framework, providing scenario parameters (purple hexagons) and material efficiency strategy implementation value parameters (green hexagons and numbered circles). For clarity, Parts II, III, and IV are simplified. For their details, please refer to Pauliuk et al. (2020a), Wolfram et al. (2020), Heeren et al. (2019), and Pauliuk (2020)
socio-economic scenarios, leading to inconsistent storylines and scenario driver parameters within and across studies of material cycles. On the other hand, in a review of integrated assessment models from an industrial ecology perspective, Pauliuk et al. (2017) identified a gap that although materials contribute to more than half of industry-sector GHG emissions, material cycles are not described and the life-cycle impacts of various technology shifts are ignored. As a result, mitigation strategies such as material efficiency and secondary material production were ignored or included in an ad hoc manner. Further, the implications of technology transformation in the energy, transport, or buildings sectors on the demand for construction, manufacturing, and materials production were either ignored or considered only through increased costs.

Scenario-based modeling and analysis is an important tool for sustainability science. The observation of the scenario outcome may provide feedback both on the realism of specific scenario assumptions and on the desirability of certain policy or investment decisions influencing variables in the model. For policy makers, a counterfactual scenario analysis can be particularly informative. Such an analysis assumes a certain baseline scenario and investigates the impact of a specific event, policy, or technology on the outcome of the scenario (i.e., the scenario variables of interest) compared to the outcome when the specific event, policy, or technology is absent. Our detailed, expansive, and open scenarios for service provision- and material efficiency implementation potentials, consistent with the SSP and LED scenarios, aim to serve as a major stepping stone towards bridging this gap.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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REFERENCES
Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E. (2011). Material efficiency: A white paper. Resources, Conservation and Recycling, 55(3), 362–381.
Allwood, J. M., Cullen, J. M., Carruth, M. A., Cooper, D. R., McBrien, M., Milford, R. L., Moynihan, M. C., & Patel, A. C. (2012). Sustainable materials: With both eyes open. UIT Cambridge Limited. http://withbotheyesopen.com/read.php.
Ayres, R. U., & Kneese, A. (1969). Production, consumption, and externalities. American Economic Review, 59(3), 282–297.
Bauer, C., Hofer, J., Althaus, H.-J., Del Duca, A., & Simons, A. (2015). The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. Applied Energy, 157, 871–883.
Börjesson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user’s guide. Futures, 38(7), 723–739.
Brondizio, E. S., Settele, J., Diaz, S., & Ngo, H. T. (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES. https://ipbes.net/sites/default/files/inline/files/ipbes_global_assessment_report_summary_for_policymakers.pdf
Cabrera Serrenho, A., Drewniok, M., Dunant, C., & Allwood, J. M. (2019). Testing the greenhouse gas emissions reduction potential of alternative strategies for the English housing stock. Resources, Conservation and Recycling, 144, 267–275.
Cao, Z., Myers, R. J., Lupton, R. C., Duan, H., Sacchi, R., Zhou, N., Reed Miller, T., Cullen, J. M., Ge, Q., & Liu, G. (2020). The sponge effect and carbon emission mitigation potentials of the global cement cycle. Nature Communications, 11(1), 3777. PMID: 32728073
Ciacci, L., Fishman, T., Elshkaki, A., Graedel, T. E., Vassura, I., & Passarini, F. (2020). Exploring future copper demand, recycling and associated greenhouse gas emissions in the EU-28. Global Environmental Change, 63, 102093.
Creutzig, F., Fernandez, B., Haberi, H., Khosla, R., Mulugetta, Y., & Seto, K. C. (2016). Beyond technology: Demand-side solutions for climate change mitigation. Annual Review of Environment and Resources, 41(1), 173–198.
Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M. L., Bruine De Bruin, W., Dalkmann, H., Edelenbosch, O. Y., Geels, F. W., Grubler, A., Hepburn, C., Hertwich, E. G., Khosla, R., Mattauch, L., Minx, J. C., Ramakrishnan, A., Rao, N. D., Steinberger, J. K., Tavoni, M., Ürge-Vorsatz, D., & Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. Nature Climate Change, 8(4), 260–263.
Daioglou, V., Van Ruijven, B. J., & Van Vuuren, D. P. (2012). Model projections for household energy use in developing countries. Energy, 37(1), 601–615.
Deetman, S., Marinova, S., Van Der Voet, E., Van Vuuren, D. P., Edelenbosch, O., & Heijungs, R. (2020). Modelling global material stocks and flows for residential and service sector buildings towards 2050. Journal of Cleaner Production, 245, 116568.
Deetman, S., Pauliuk, S., van Vuuren, D. P., van der Voet, E., & Tukker, A. (2018). Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. Environmental Science & Technology, 52(8), 4950–4959.
Dellink, R., Chateau, J., Lanz, E., & Magné, B. (2017). Long-term economic growth projections in the shared socio-economic pathways. Global Environmental Change, 42, 200–214.
Di Giulio, A., & Fuchs, D. (2014). Sustainable consumption corridors: Concept, objections, and responses. GAIA - Ecological Perspectives for Science and Society, 23(3), 184–192.

Ellsworth-Krebs, K. (2020). Implications of declining household sizes and expectations of home comfort for domestic energy demand. Nature Energy, 5(1), 20–25.

Elshkaki, A., Graedel, T. E., Ciacci, L., & Reck, B. K. (2016). Copper demand, supply, and associated energy use to 2050. Global Environmental Change, 39, 305–315.

Elshkaki, A., Graedel, T. E., Ciacci, L., & Reck, B. K. (2018). Resource demand scenarios for the major metals. Environmental Science & Technology, 52(5), 2491–2497.

Ewing, R., & Cervero, R. (2017). Does compact development make people drive less? The answer is yes. Journal of the American Planning Association, 83(1), 19–25.

Ewing, R., & Rong, F. (2008). The impact of urban form on U.S. residential energy use The impact of urban form on U.S. residential energy use. Housing Policy Debate, 19(1), 1–30.

Fanning, A. L., O’neill, D. W., & Büchs, M. (2020). Provisioning systems for a good life within planetary boundaries. Global Environmental Change, 64, 102135.

Fell, M. J. (2017). Energy services: A conceptual review. Energy Research & Social Science, 27, 129–140.

Fischer-Kowalski, M., & Hüttrich, W. (1999). Society’s metabolism: The intellectual history of materials flow analysis, Part II, 1970–1998. Journal of Industrial Ecology, 2(4), 107–136.

Fishman, T. (2020). TomerFishman/RECC-scenarios. Zenodo. https://doi.org/10.5281/zenodo.3631878.

Fishman, T., Myers, R., Rios, O., & Graedel, T. E. (2018). Implications of emerging vehicle technologies on rare earth supply and demand in the United States. Resources, 7(1), 9. http://www.mdpi.com/2079-9276/7/1/9.

Fishman, T., Schandl, H., & Tanikawa, H. (2016). Stochastic analysis and forecasts of the patterns of speed, acceleration, and levels of material stock accumulation in society. Environmental Science & Technology, 50(7), 3729–3737.

Fishman, T., Schandl, H., Tanikawa, H., Walker, P., & Krausmann, F. (2014). Accounting for the material stock of nations. Journal of Industrial Ecology, 18(3), 407–420.PMID: 25505368

Fukushima, Y., Shimada, M., Kaines, S., Hirao, M., & Koyama, M. (2004). Scenarios of solid oxide fuel cell introduction into Japanese society. Journal of Power Sources, 131, 327–339.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Sterckhe, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlik, P., Huppmann, D., Kiesewetter, G., Rafaj, P., ... Valin, H. (2018). A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. Nature Energy, 3(6), 515–527.

Haberl, H., Wiedenhofer, D., Erb, K. H., Görg, C., & Krausmann, F. (2017). The material stock-flow-service nexus: A new approach for tackling the decoupling conundrum. Sustainability (Switzerland), 9(7), 1049.

Hatayama, H., Daigo, I., Matsuno, Y., & Adachi, Y. (2010). Outlook of the world steel cycle based on the stock and flow dynamics. Environmental Science & Technology, 44(16), 6457–6463.

Heeren, N., Fishman, T., Tu, Q., Wolfram, P., Berrill, P., Pauliuk, S., & Hertwich, E. G. (2019). Annex C of the UN-IRP report “Resource efficiency and climate change - material efficiency strategies for a low-carbon future” Supplementary material for the in-depth industrial ecology assessment. United Nations Environment Programme.

Heeren, N., & Hellweg, S. (2018). Tracking construction material over space and time: prospective and geo-referenced modeling of building stocks and construction material flows. Journal of Industrial Ecology, 21(2), 253–267. https://doi.org/10.1111/jiec.12739

Hertwich, E., Heeren, N., Kuczenski, B., Majeau-Bettez, G., Myers, R. J., Pauliuk, S., Studler, K., & Lifset, R. (2018). Nullius in verba: Advancing data transparency in industrial ecology. Journal of Industrial Ecology, 22(1), 1–19.

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., & Shi, L. (2014). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences, 120, 6277–6282.

Hertwich, E. G., Lifset, R., Ali, S., Pauliuk, S., Heeren, N., & Tu, Q. (2019a). Resource efficiency and climate change: Material efficiency strategies for a low-carbon future. Summary for policy makers. A report of the International Resource Panel. United Nations Environment Programme.

Hertwich, E. G., Lifset, R., Pauliuk, S., Heeren, N., Ali, S., Berrill, P., Fishman, T., Tu, Q., & Wolfram, P. (2019b). Bridging the gap: Enhancing material efficiency in residential buildings and cars. In Emissions Gap Report 2019 (pp. 56–62). United Nations Environment Programme. resources/emissions-gap-report-2019

Hoekstra, R. (2019). Replacing GDP by 2030: Towards a common language for the well-being and sustainability community. Cambridge University Press. https://www.cambridge.org/core/books/replacing-gdp-by-2030/1583BE07055EAD85CBFECE1FC5EF6442

Hsieh, C.-T., & Moretti, E. (2019). Housing constraints and spatial misallocation. American Economic Journal: Macroeconomics, 11(2), 1–39.

IEA. (2018). World energy model: Documentation. International Energy Agency.

IPCC. (2018). Global warming of 1.5°C An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/src15/

Ivanova, D., Studler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., & Hertwich, E. G. (2016). Environmental impact assessment of household consumption. Journal of Industrial Ecology, 20(3), 526–536.

Jaramillo, F., & Destouni, G. (2015). Comment on planetary boundaries: Guiding human development on a changing planet. Science, 348(6240), 1217.

Kalt, G., Wiedenhofer, D., Görg, C., & Haberl, H. (2019). Conceptualizing energy services: A review of energy and well-being along the Energy Service Cascade. Energy Research & Social Science, 53, 47–58.

Kayo, C., Dente, S. M. R., Aoki-Suzuki, C., Tanaka, D., Murakami, S., & Hashimoto, S. (2019). Environmental impact assessment of wood use in Japan through 2050 using material flow analysis and life cycle assessment. Journal of Industrial Ecology, 23(3), 635–648. https://onlinelibrary.wiley.com/doi/abs/10.1111/jiec.12766

Kc, S., & Lutz, W. (2017). The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change, 42, 181–192.PMID: 28239237

Lamb, W. F., & Steinberger, J. K. (2017). Human well-being and climate change mitigation. WIREs Climate Change, 8(6), e485.
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