Global Scenarios of Resource and Emissions Savings from Systemic Material Efficiency in Buildings and Cars

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Article

Abstract

Material production now accounts for 23% of global greenhouse gas (GHG) emissions. Resource efficiency and circular economy policies promise emission reductions through reducing material use, but their potential contribution to climate change mitigation has not yet been quantified. Here we present a high-resolution approach for tracking material flows and energy use of products throughout their life cycles, focusing on passenger vehicles and residential buildings. We estimate future changes in material flows and operational energy use due to increased yields, light-weight designs, material substitution, increased service efficiency, extended service life, and increased reuse and recycling. Together, these material efficiency strategies can reduce cumulative global GHG emissions until 2060 by 16-39 Gt CO2e (passenger vehicles) and 28-72 Gt CO2e (residential buildings), depending on climate policy assumptions. The use of wood and more intensive use are promising strategies in residential buildings. Ride sharing and car sharing are best for residential buildings.

Main Text

Achieving the Paris agreement goal of limiting global warming to well below 2°C requires a rapid decarbonization of the economy, which, according to most climate-economic models, can only be done with the use of costly carbon removal technologies[1,2]. Decarbonization is rate-limited given the technological and organizational change and the large investment needs into novel energy infrastructure and factories[3]. Greenhouse gas (GHG) emissions from material production have risen from 5 Gt CO_2e in 1995 to 11.5 Gt in 2015[4] and now 23% if global GHG emissions. The median remaining lifetime of existing production facilities for cement and steel stretches to 2045, causing substantial lock-ins[5]. Decarbonizing material production requires further technological development[3,5–8] and will compete with other applications of low-carbon energy, including electric transportation and low temperature heat[9]. Given the anticipated slow pace of decarbonizing material production, the reduction of material demand through i) more efficient use of materials at all stages of the material cycle[10] and ii) the decoupling of services like mobility from the number of material-intensive products like vehicles[11] may result in more immediate emissions reductions and can lower the cost of supply-side mitigation. Governments are hence assessing or implementing policy frameworks to reduce materials use[12], variously referred to as material efficiency[13,14], resource efficiency[15], a sound material-cycle society[16], sustainable materials management[17], and the circular economy[18]. Policy development could be better targeted if the potential GHG emissions reductions associated with different material efficiency strategies were better understood.

Here, we investigate material efficiency strategies addressing product design (light-weighting and material substitution), fabrication efficiency (lower yield losses and re-use of scrap), the use phase (more efficient use of products and lifetime extension), and waste management (re-use and recycling). Material efficiency strategies in fabrication and waste management aim at prolonging the technical lifetime of engineering materials; they are also termed value retention strategies and form the core of the circular economy vision[19]. While single materials or products have been studied extensively[13,20], there is a gap

between the detailed mechanisms and the more aggregate representation of the industrial system in the climate-energy-economic models used in integrated assessments[2,21]. The former tend to overlook the changing technology landscape outside of material processing, while the latter lack a representation of mass balances to capture engineering innovations reducing material demand or the availability of materials for recycling[22]. Both simplifications adversely impact the ability of these models to represent the role of material cycles and material efficiency in an industrial system on a pathway towards deep decarbonization. Industrial ecology literature to bridge that research gap is emerging[23–25] but has, to this date, not combined detailed scenario descriptions of service provision with material efficiency studies.

We demonstrate the use of engineering-based product-archetype models (representative and scalable product descriptions) to describe prospective material cycles and energy demand for the manufacturing, operation, and recycling of future product cohorts[26]. We do so through global case studies quantifying potential emission reductions from material-efficient residential buildings and passenger vehicles. The production of materials used in residential buildings and cars in 2015 was estimated to have caused GHG emissions of 2.4 Gt and 0.8 Gt CO_2e, respectively[4,12], while in 2018, the operational energy use of these products caused emissions of 6 and 7.5 Gt CO_2e, respectively, and accounted for 21% and 18 % of total final energy consumption[27]. Our analysis covers the entire world comprised of 20 countries/regions, loosely grouped into the Global North (high and medium income OECD, former USSR countries, China) and the Global South (low-income countries in Asia, Africa, and the Americas). It considers three socioeconomic scenarios, a low energy demand (LED) scenario [28] and two of the shared socioeconomic pathways, SSP1 and SSP2 [29]. Two policy scenarios are considered for each socioeconomic pathway, one with no new energy and climate policy after 2020 and one decarbonizing the energy supply to limit average temperature rise to 2°C (i.e. the representative concentration pathway of 2.6 W/m² additional forcing, RCP2.6) [30]. The model captures the production, demand, use, and recycling of six major climate-relevant materials (aluminum, cement, copper, plastics, steel, wood) for the period 2016- 2060, starting from 2015 as the last year with complete empirical data. The material efficiency strategies include supply-side measures (higher yields in fabrication and scrap recovery, reuse of fabrication scrap, product light-weighting through better design or material substitution) and demand-side measures (reuse of products and product lifetime extension, and sufficiency-related measures including more efficient use of cars via car-sharing and ride-sharing, and more efficient use of dwelling space resulting in less floor space per person).

Based on the storylines of the scenarios[31], an expert consensus approach was used to estimate the future service level (passenger-km delivered by cars, residential floor area utlilized) and the share of the different drive and building technologies used[32]. Future service levels were subject to several rounds of consensus-building and refinement. While the LED values were only slightly modified when breaking them down from the Global North/South split to individual countries, the SSP2 values continue (Global North) or extrapolate to (Global South) service levels currently enjoyed by citizens in the Global North. The SSP1 values typically were a compromise between the LED and SSP2 trends. Technology description was

based on high-resolution engineering models of 48 vehicle and 52 building archetypes, the latter with region-specific energy demand for heating and cooling. The effect of each material efficiency strategy on the life cycle performance of each archetype was assessed. The archetype scale-up was determined as a function of future population, service level per capita, stock turnover, and storyline-consistent parameters to split total new product demand into different archetypes. Assuming a full implementation of material efficiency strategies by 2040, the model calculated the material and product cycle turnover needed to expand and maintain the required building and vehicles stocks that deliver the services to the end users over time. It also determined use phase energy demand as well as direct and indirect GHG emissions.

Results

The considered supply and demand-side material efficiency strategies offer a reduction of the direct and indirect GHG emissions of the vehicle and building sectors across all world regions and climate policy scenarios (Fig. 1). Deep vehicle fleet decarbonization is attainable only through a large-scale electrification of the fleet and with the low-carbon electricity supply of the RCP2.6 scenarios (Fig. 1, top row). The vehicle sector in high-income countries/regions experiences a moderate decline in GHG emissions if no additional climate policies are issued, and substantial decline with stringent climate policy. Developing countries are poised for further growth in sectoral emissions, but stringent climate policy and material efficiency can mitigate emissions growth to enable an earlier and lower peak (around 2035 instead of 2050). Emissions reductions are more pronounced for residential buildings, as the electricity supply is decarbonized, efficiency is increased e.g. through building stock turnover and retrofits resulting in better insulation and heat-recovery ventilation, and replacement of oil and gas furnaces with heat pumps. In industrialized countries, emissions are set to decline even under current policies.

Fig. 1: Regional GHG patterns (in Gt CO_2-eq./yr) by region and time for passenger vehicles (top row) and residential buildings (bottom row) for the SSP1 shared socioeconomic pathway (easy adaptation and mitigation) and two climate policy scenarios, with no material efficiency strategies considered, and the full spectrum of ten strategies considered. Grey shaded areas highlight periods of regional carbon negativity, which is due to forest carbon uptake as a consequence of previous timber harvesting and regrowth. See the SI for scenario results for LED and SSP2.

Using wood from sustainable forestry as long-lived construction material where available [33,34] can lead to additional emissions savings of 1-2 Gt/yr. In some regions of the Global South, the regrowth of forest in response to sustainably harvested timber for residential buildings can more than offset the emissions from the production of other construction materials for years after 2050 (grey shaded area in Fig. 1). Next to wood use in buildings, a development towards more intense use of buildings (modelled as lower average floor space per capita) is a highly effective mitigation strategy that combines sufficiency with large energy and material savings.

Overall, the different material efficiency (ME) strategies can reduce annual global emissions in 2050 by 22-61%, depending on ME stringency, energy sector decarbonization, and anticipated growth in services (Fig. 2, bottom row). ME alone could reduce cumulative emissions by 13-18% over the period 2016-2050 (Fig. 2, top row). ME can make an important contribution to reducing anthropogenic GHG emissions to within the remaining emissions budget available for limiting global warming below 2°C, while, at the same time, reducing the risk and magnitude of emissions overshoot and the need for negative emissions technologies. Annual emissions cuts from ME in 2050 are smaller in absolute terms but more important (as a share of the total) in the 2°C scenario with a low-carbon energy supply, than if there is no additional policy to drive further decarbonization. In a low-carbon energy future, ME-induced reductions of the difficult-to-mitigate GHG emissions in material production have a relatively high impact in the system's GHG balance compared to energy supply impacts.

Fig. 2: Total global cumulative (top) and annual 2050 (bottom) emissions reductions of the technical potential of ten industrial and demand-side material efficiency strategies, by socioeconomic and climate policy scenario and material efficiency strategy for the passenger vehicle and residential building sectors combined.

The impact of ME on primary and secondary material production at the global level is substantial, due to massive reductions in demand for primary (produced from virgin natural resources) steel, cement, copper, and plastics (Fig. 3). Reduced primary production will also lower industrial use of mineral resources, land, water, and energy, as well as associated emissions, thus yielding multiple co-benefits which have yet to be quantified [24]. Primary aluminum production increases due to vehicle light-weighting. The vehicle material substitution scenarios are based on aluminum because a large-scale supply of low-carbon aluminum requires only a change in the electricity source and is hence expected to arrive earlier than low-carbon steel, which requires entirely new facilities and production processes that are not expected to reach commercialization before 2035[8].

For wood, the increased demand from timber-based buildings is more than compensated for by the overall reductions from other ME strategies, and more intense building use, in particular. The same trade-off applies to secondary materials, where overall throughput reduction from – amongst others – product light-weighting and lifetime extension is larger than the increase from higher recycling ratios for steel, copper, and wood.

 For aluminum, cement, and plastics, the full implementation of ME will increase global secondary production but for different reasons: much higher recycling rates (plastics), higher in-use stocks of aluminum and thus higher scrap flows, and re-use of concrete elements (cement).

Fig. 3: Global material production for six major materials in SSP1 and a 2°C energy supply mix. In 2016, the two sectors studied accounted for ca. 28% and 25% of the global steel and cement production, respectively. Implementing material efficiency at full technical scale does not mean that we use less of each material. Contrarily, there will be higher demand for substitution materials like aluminium or wood. Copper demand grows due to the electrification of the passenger vehicle fleet.

The model-estimated contribution of specific strategies to combined emissions reduction depends on their sequencing. In Fig 4., energy efficiency and low carbon energy supply are introduced first, and ME strategies are then applied on an already decarbonized system, yielding higher savings from decarbonization and lower savings from ME than if the sequence was reversed. After seizing the energy efficiency (green) and energy supply transformation (blue) potentials, the share of remaining global emissions reduced through ME is smaller in SSP2 (32%) than in LED (61%) due to the lower ambition level in SSP2, reflecting the storylines of those scenarios. Given the additional contribution of ME-based emissions reductions even in face of a largely decarbonized energy supply, ME offers a crucial contribution to bridging the gap between a 2°C and 1.5°C future (Fig. 4).

Fig. 4: Breakdown of emissions reduction into end-use energy efficiency, energy supply, industrial and demand-side material efficiency, for passenger vehicles and residential buildings combined, at the global level (a), the Global South (b), and the Global North (c). The two red-colored segments cover the ten material efficiency (ME) strategies. Industrial ME includes: recovery ratios for recycling, fabrication yield and scrap diversion, re-use, and material choice. Demand-side ME includes product light-weighting/downsizing, lifetime extension, car-sharing, ride-sharing, and more intense use of buildings.

This study provides the first comprehensive global assessment of ME strategies in a changing socioeconomic and energy supply context. The high-resolution material and product lifecycle model allowed us to quantify the overall impact of ME strategy bundles at scale, taking into account both the mutual dependencies among strategies (e.g., product light-weighting means that less material is available for recycling) and development of service demand over time. To quantify these effects, our model captures the interaction of product design and life-cycles, of material cycle dynamics, and of macro-level changes in the service demand and the energy system. It hence demonstrates how detailed knowledge about technological change can be relevant for, and used in, global assessments. While service, product, and material cycle modeling is largely absent from integrated assessment models, which are the work-horses of global climate mitigation assessment, the present modeling can be soft-linked to and possibly be integrated into such models [22] similar to how land-use modeling has recently been integrated [31]. Soft-linking would establish ME strategies and material cycle constraints in climate mitigation scenarios, and integration would allow for including material efficiency into optimization routines. The findings confirm that for deep emissions reductions in the residential building sector, low

carbon electricity by itself will not be sufficient [35] but additional demand side efficiency and sufficiency measures are required [36]. The same holds for the vehicle fleet, where electrification and a transformation to low-carbon electricity must go hand in hand, as confirmed by our results.

Lifting material efficiency to similar prominence as energy efficiency increases the feasibility of attaining the Paris goal of limiting global warming to well below 2°C and may reduce the dependency on negative emissions technologies. As countries struggle to implement and update their nationally determined contributions (NDCs) to the Paris climate agreement, new mitigation options and co-benefits with other sustainable development goals (SDGs) are needed to get them back on track[37]. Material efficiency – due to its co-benefits in savings of raw materials, energy, and GHG emissions, can become part of the solution spectrum.

Materials And Methods

The analysis shown here is based on the resource efficiency and climate change (RECC) framework [26], which tracks material cycles over time and links the services provided (individual motorized transport and shelter) to the operation of in-use stocks of products (passenger vehicles and residential buildings). It calculates the expansion and maintenance of products in use over time, and estimates the material production needed and the potential for recycling. A key innovation of RECC is the upscaling of representative single product descriptions ('archetypes') with different degrees of material and energy efficiency. The product archetypes were simulated with engineering tools that model building energy balance and vehicle driving cycles. We define future scenarios for passenger vehicle and residential building operation by augmenting the storylines of the shared socioeconomic pathways [32] to describe future service demand in the passenger vehicle fleet and residential buildings and calculate associated material requirements, covering the entire globe in 20 countries/regions until 2060. The GHG mitigation potential of ten material efficiency strategies at different stages of the material cycle is quantified by ramping up their implementation rates to the identified technical potentials by 2040. Each material efficiency strategy can be implemented separately or as part of a cascade of strategies. The model allows for calculating the impact of one strategy at a time (which is mostly used for sensitivity analysis) or a bundle of strategies in different orders of implementation, each for different socioeconomic and climate policy scenarios.

The RECC model framework

Services are linked to material cycles via a stock-flow-service nexus [38] (Fig. SI1-1). The scheme shown in this figure is based on the energy service cascade [39] that relates human values to services to functions to products (and their operation). From future scenarios for providing functions to people (like transport-

km), we determined the amount of vehicles and building area needed in a given year, and used RECC routines for stock-driven modelling [40] to translate product in-use stock demand into production of new and recycling of old products. Using product material composition data that are part of the product archetype description, RECC converts the flows of new and old products into material flows, thus representing a dynamic material flow analysis (MFA) [41,42]. It also calculates all energy demand from material production, recycling, and product operation, and estimates related GHG emissions via environmental extensions as done in previous work [43].

Overall, RECC generates a set of what-if scenarios [44] for material efficiency in the vehicle and building sectors and the related major material cycles against different socioeconomic, technological, and climate-political backgrounds [31]. RECC does not assess the likelihood of realization of any of the scenarios studied but checks if mass balance constraints (e.g. by long product lifetimes or limited scrap supply) render some scenarios unfeasible from a material cycle point of view.

The RECC Database

The RECC v2.4 database contains 104 model parameters. Parameters range from static values (direct emissions of combustion per MJ of energy carrier) to highly detailed and uncertain and thus scenario-dependent datasets (e.g., the future energy carrier split of buildings by region, time, and demand (heating/cooling/hot water).

The RECC database was compiled as a community effort involving many experts. Its scope is unprecedented in the industrial ecology community. Data templates and project-wide classifications were used to facilitate the compilation of the various types of information. Depending on data availability, we applied several pathways of data compilation:

- Extract mostly socioeconomic parameters from existing scenario models (scenario reference)
- Compile own plausible scenario estimates for socioeconomic parameters in line with the different scenario narratives where results from established model frameworks are not available (group consensus scenarios)
- Extract process-, product, and material-specific data from the engineering and industrial ecology literature ('bottom-up' data)
- Extract quantitative estimates of resource efficiency strategy potentials, mostly related to prototypes and case studies, from the literature (strategy potentials)
- Simulate energy consumption and material composition of building and vehicle archetypes with specialized software, which are then used as bottom-up product descriptions with and without implementation of ME strategies (product archetype descriptions)

Scenario reference and group consensus storyline extension

For the socioeconomic parameters, the Shared Socioeconomic Pathways (SSP) database and model results as well as available data from the World Energy Outlook and Energy Technology Perspectives models were used wherever possible, e.g., for future population, future GHG intensity of energy supply, or share of electric and hybrid vehicles [29,31,45]. Data were parsed and reviewed by the RECC team, then aggregated, disaggregated, and/or interpolated to fit the project-wide classification. For each parameter file the data gathering process is documented both in the respective template files in the RECC database (whenever only Excel was used), in custom scripts (for more comprehensive datasets that required pre-processing).

For some parameters like the future stock levels or the split of residential buildings into different types, no detailed SSP-consistent scenario calculation was available that we could refer to. Hence, we assumed a set of plausible target values for a number of socioeconomic parameters in line with the storylines of the individual socioeconomic scenarios, fully documented by Fishman et al. [32]. This process has been used when translating broad storylines into parameters with high product- and regional resolution and sector-specificity, cf. Riahi et al. [31] and Grübler et al. [28]. The chosen target values for 2020, 2030, 2040, 2050, and 2060 and the rationale for their choice are documented in scenario target tables, one for each parameter. An overview is given in Table 1.

Table 1: RECC framework data aspects and their resolution.

Model and data aspect	Resolution
Time	2016-2060 in steps of 1 year
Age-cohorts/Vintages	Vehicles: 1980-2060, residential buildings: 1900-2060
Regions	20 countries and world regions, covering the entire world.
Products	6 passenger vehicle drive technologies (with in total 48 vehicle archetypes), 13 residential building types with in total 52 archetypes
Engineering materials	construction grade steel, automotive steel, stainless steel, cast iron, wrought Al, cast Al, copper electric grade, plastics, wood and wood products, zinc, cement and concrete aggregates
Waste and scrap types	heavy melt, plate, and structural steel scrap; steel shred; Al extrusion scrap, auto rims, clean; Al old sheet and construction waste; Al old cast; copper wire scrap; construction waste, concrete, bricks, tiles, ceramics
Chemical elements	C, Al, Cr, Fe, Cu, Zn, 'other'
Energy carriers	Electricity, coal, hard coal, diesel, gasoline, natural gas, hydrogen, fuel wood
Service categories	Driving (vehicles), heating, cooling, domestic hot water (residential buildings)
Scenarios	Socioeconomic: Low energy demand (LED), SSP1, SSP2 Climate policy: No policy after 2020 (reference scenario), 2 degrees Celsius (66%), corresponding to RCP2.6 forcing pathway.

Bottom-up data on technology

For the energy intensity, emissions intensity, and material composition of products and processes, detailed but representative product or process descriptions were compiled from the literature and available databases. These data include the material composition and specific energy consumption of vehicles and buildings [46–48], e.g., the loss and recovery rates for the manufacturing and waste management industries, e.g., [43,49], and the specific energy consumption and process emissions for the manufacturing, waste management, and primary material production industries [45,50]. While the data can be regarded as representative of current average global technology, their main limitation is that they are static and no information on their change under different socioeconomic and climate policy scenarios is given. To become more realistic, a scenario reference was made wherever possible (cf. above), e.g., for the changing GHG intensity of the supply of different energy carriers, for which a combination of MESSAGE IAM [31] results and IEA Energy Technology Perspective results [45] was used. Also, for the

average GHG intensity of primary metal production, emissions from ecoinvent [50] were updated to take into account scenario-dependent changes of the GHG intensity of electricity generation.

For some material efficiency parameters, including the improvement potentials for fabrication scrap, end-of-life recovery efficiency of scrap, re-use of steel components in buildings, or product lifetime extension, previous estimates can be used [43,51].

Building and vehicle archetype descriptions

Here, 'archetype' refers to an idealized representative and scalable description of the physical properties (energy intensity of operation and material composition) of a product with a certain functionality, assuming typical user behavior in a given region.

For passenger vehicles, drive technology, segment (car size), and material design choice together determine the archetypes' material composition, and the three properties above plus the assumed driving cycle determine its specific operational energy consumption (specific = per km driven).

For residential building, building type, energy standard, material intensity (conventional or lightweight design), material design choice, and stylized climate conditions (heating and cooling degree days by region) together determine the archetypes' material composition and specific operational energy consumption (specific = per m^2).

For the final product categories residential buildings and vehicles, the product-specific simulation tools BuildME (https://github.com/nheeren/BuildME), GREET (https://greet.es.anl.gov/) and FASTSim (https://www.nrel.gov/transportation/fastsim.html) were used to model the archetype descriptions by deriving model estimates for both the material composition and energy intensity of operation for different building and vehicle configurations. For each of the nine building and six vehicle types, four archetypes, representing maximal potential for change, were simulated: a standard product without special consideration of material efficiency, downsizing, or material substitution, a downsized product, a product with ambitious material substitution, and a downsized material-substituted product.

Open science project

The RECC framework is open (https://github.com/YaleCIE/RECC-ODYM) and modular. Third parties can modify the scenario assumptions and to run calculations with custom parameters and storylines. A detailed description and definition of all model aspects, the classifications used for them, the system variables and parameters, the model equation and their division into modules and the data compilation, (dis)aggregation and formatting process is contained in the model documentation (supplementary material 2). The project's entire database is archived on Zenodo (dataset DOIs [to be inserted for final publication]).

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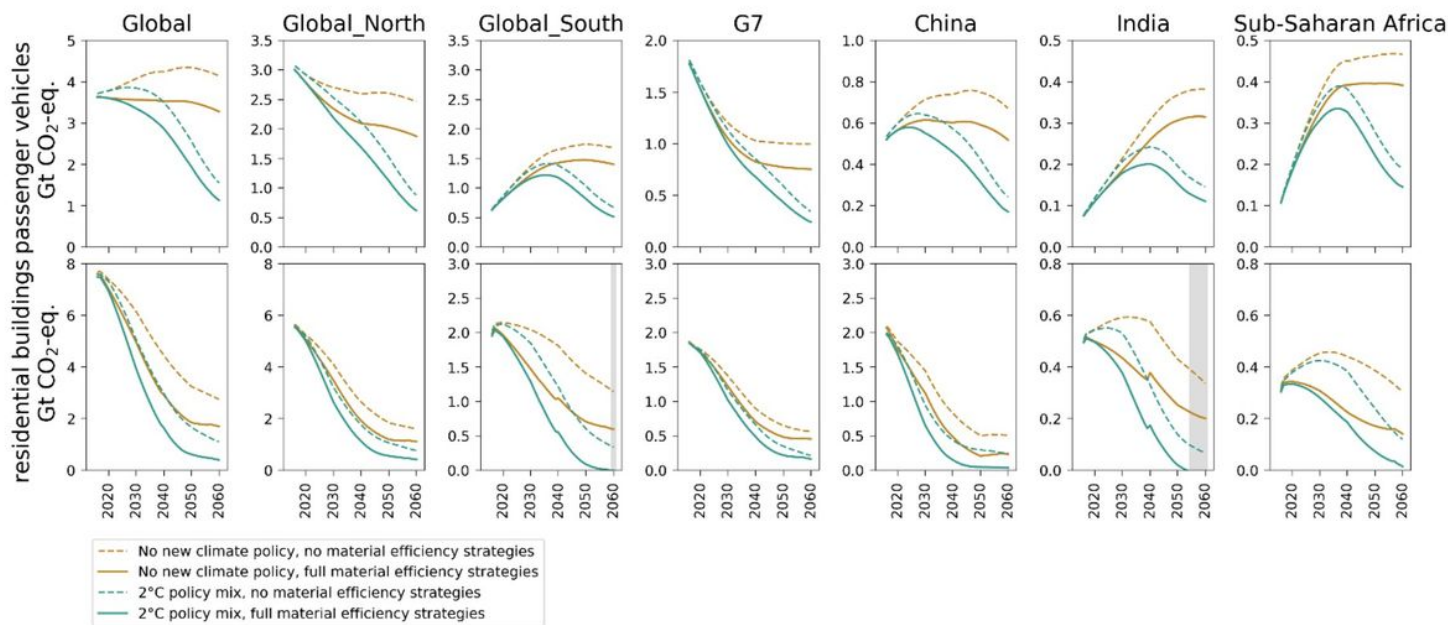
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Declarations

Author Contributions

S.P., N.H., T.F. and E.H. designed the research, N.H., S.P. and E.H. managed the project workflow, T.F. designed the scenario formulation approach, and – together with N.H. and the rest of the team – ensured overall scenario consistency. Q.T and P.W. contributed the modelling of the vehicle archetypes and scenarios, N.H. developed the building archetype model. A.N., N.H., A.N. and P.B. contributed building archetype and scenario formulations. S.P. implemented large parts of the model framework, compiled the database, and conducted the scenario calculations. All authors contributed to analyzing the results and writing the paper.
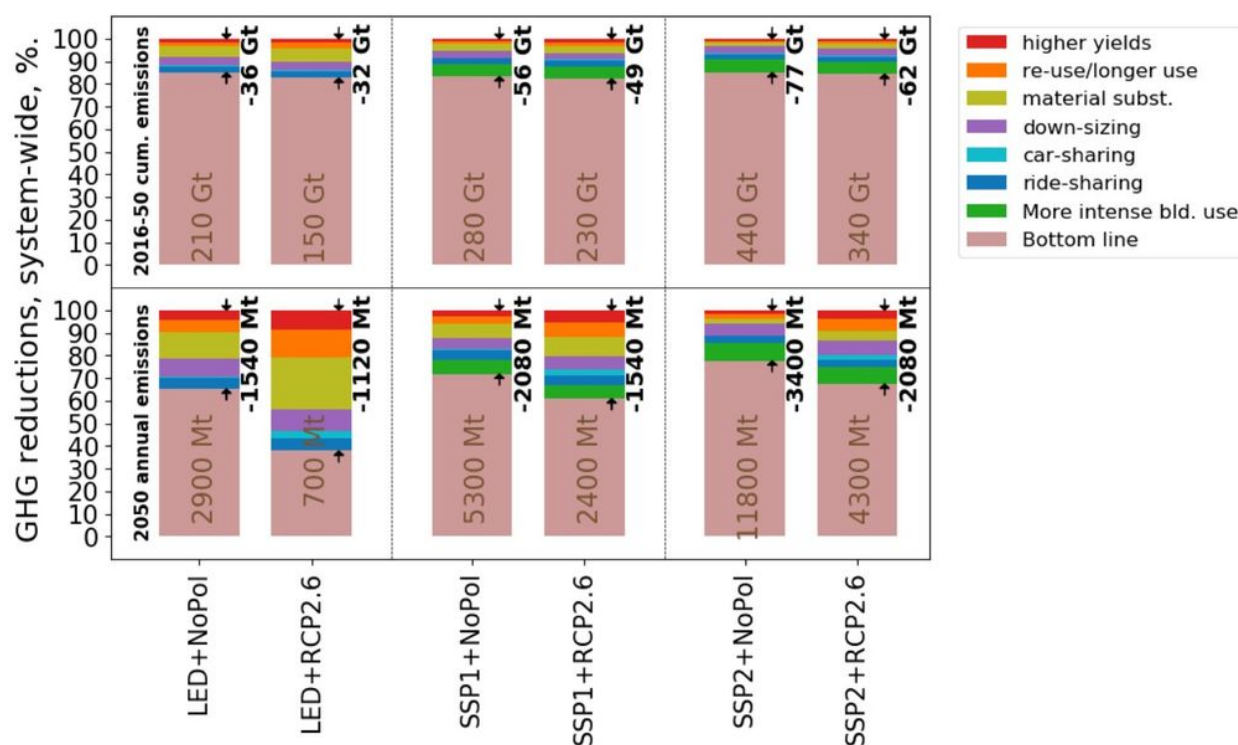
Competing Interest Statement

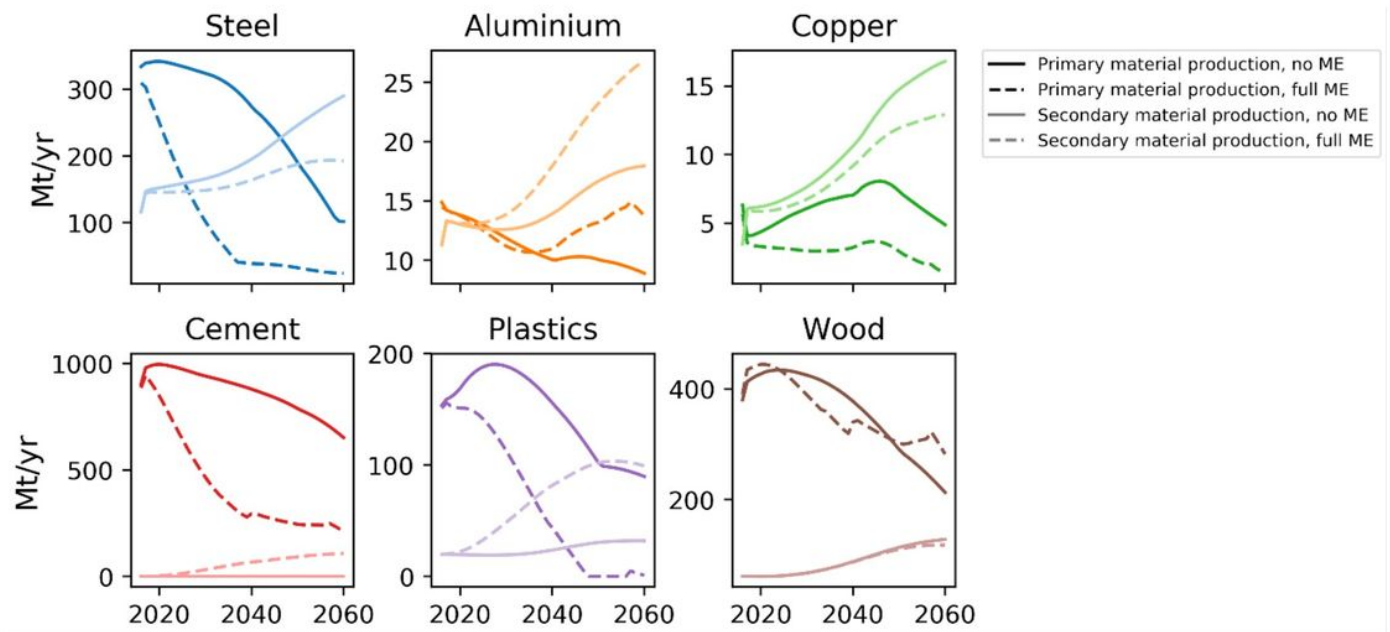The authors declare no competing interests.

Figures

Figure 1

Regional GHG patterns (in Gt CO2-eq./yr) by region and time for passenger vehicles (top row) and residential buildings (bottom row) for the SSP1 shared socioeconomic pathway (easy adaptation and mitigation) and two climate policy scenarios, with no material efficiency strategies considered, and the full spectrum of ten strategies considered. Grey shaded areas highlight periods of regional carbon negativity, which is due to forest carbon uptake as a consequence of previous timber harvesting and regrowth. See the SI for scenario results for LED and SSP2.
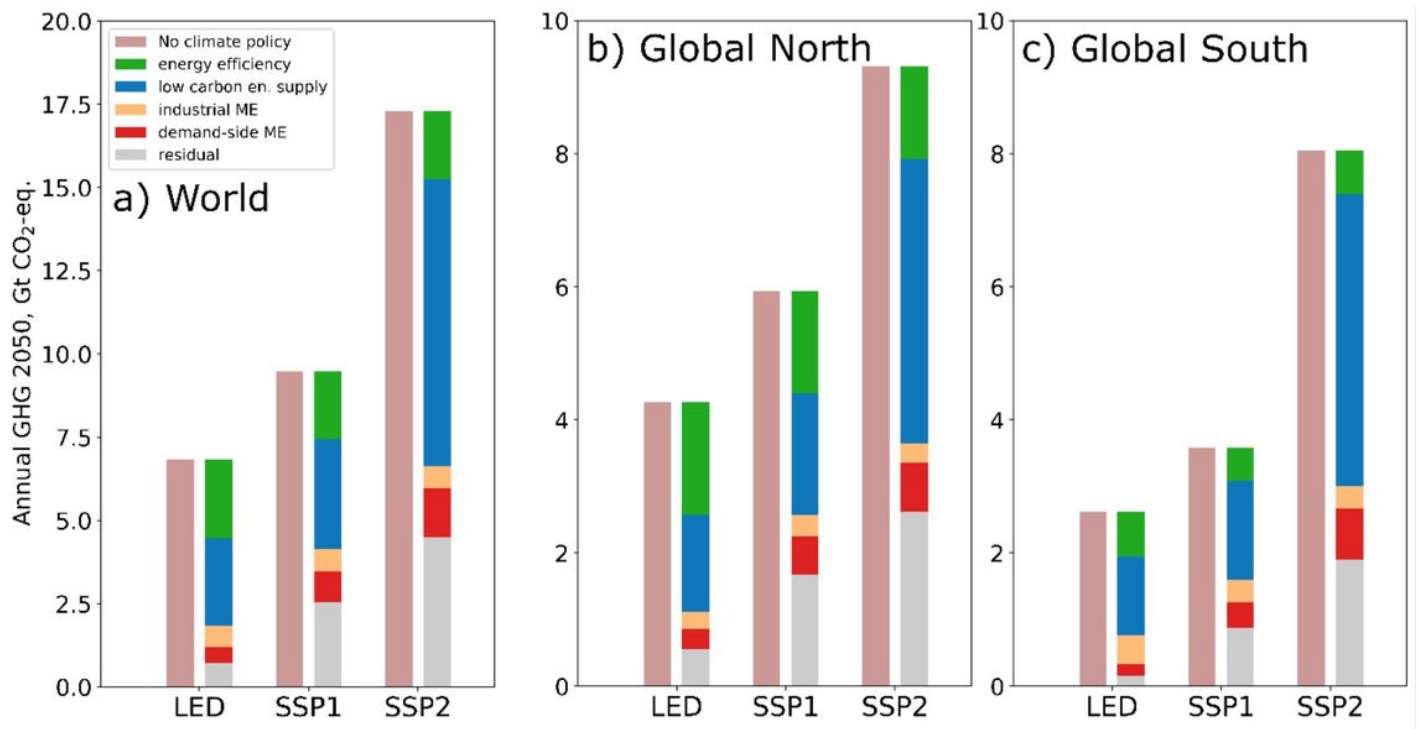
Figure 2

Total global cumulative (top) and annual 2050 (bottom) emissions reductions of the technical potential of ten industrial and demand-side material efficiency strategies, by socioeconomic and climate policy scenario and material efficiency strategy for the passenger vehicle and residential building sectors combined.

Figure 3

Global material production for six major materials in SSP1 and a 2°C energy supply mix. In 2016, the two sectors studied accounted for ca. 28% and 25% of the global steel and cement production, respectively. Implementing material efficiency at full technical scale does not mean that we use less of each material. Contrarily, there will be higher demand for substitution materials like aluminium or wood. Copper demand grows due to the electrification of the passenger vehicle fleet.

Figure 4

Breakdown of emissions reduction into end-use energy efficiency, energy supply, industrial and demand-side material efficiency, for passenger vehicles and residential buildings combined, at the global level (a), the Global South (b), and the Global North (c). The two red-colored segments cover the ten material efficiency (ME) strategies. Industrial ME includes: recovery ratios for recycling, fabrication yield and scrap diversion, re-use, and material choice. Demand-side ME includes product light-weighting/downsizing, lifetime extension, car-sharing, ride-sharing, and more intense use of buildings.

Supplementary Files

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