Supplementary Material A – Model description and GHG reduction scenarios for G7 countries, China, and India

This document contains the supplementary material for the IRP report "Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future". The table of contents list the items covered here. This document provides a brief description of assumptions and additional modeling results for homes and cars. For detailed description of overall model framework, modules, associated assumptions, scenarios and data for this IRP report, please refer to the following documents:

- "Linking Service Provision to Material Cycles – A New Framework for Studying the Resource Efficiency-Climate Change Nexus (RECC)"
- "Documentation of the transport-sector model within the RECC model framework v1.0"
- "Developing scenarios of resource efficiency and climate change: from conception to operation"

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S1. Material efficient homes

This section describes how the model framework was applied to the residential building sector. First, the scenarios for future floor space demand are described, then the building archetypes, then the material flows for the different scenarios and material efficiency (ME) strategy cascade steps, and finally, additional model results for residential buildings.

S1.1. Future floor space demand

Per capita residential floor space tends to increase with GDP, but varies widely across countries at the same level of GDP, shaped by tradition, urban form, as well as land use and building regulations (International Energy Agency, 2016). The SSP scenarios don't detail the floor space in their documentation, and we formulate values which are consistent with the SSP storylines. In the SSP2 scenario and for the USA and Japan (for which relatively rich historical data exists), future per-capita floor space growth rates are an extension of historical rates to 2050 using a data-driven approach. This extends the methods of Fishman et al., (2016) by incorporating GDP/cap and urbanization rates as drivers. Canada's growth rates are modeled using the USA's 2015-2050 growth rates, and likewise Germany, France, and Italy's growth rates are modeled using Japan's 2015-2050 growth rates, due to similar historical trajectories and current socioeconomic conditions. The remaining regions converge to 50 m^2/cap by 2050 except for India which reaches an average of 40 m^2/cap by 2050. In the SSP1 scenario, if a region has an average floor space per capita of over 40 m^2/cap in 2015, this value is held fixed. Regions whose average floor space per capita is below 40 m^2/cap in 2015 achieve this value by 2050, except for India which reaches only 30 m^2/cap in 2050. The LED scenario calls for a global convergence of floor space per capita of 30 m^2/cap by 2050, but doesn't provide details by regions (Grubler et al., 2018). In our scenarios, all regions either contract or enlarge their floor area to reach this value by 2050, and do so more rapidly after 2030. The two exceptions are the USA, whose starting point at 2015 is significantly higher than the other modeled regions (nearly 70 m^2/cap) and fails to reach the 30 m^2/cap by 2050, only contracting to 40 m^2/cap. In a similar fashion, India's lower per capita floor area values in 2015 compared to the others allows it to only reach 24 m^2/cap by 2050.

For simulating the impact of the ME strategy 'more intensive use' (MIU, see description of strategies in the main report), LED-values present the lower limit. In contrast to vehicles, mechanisms for floor space reduction were not explicitly modeled. However, we assume further urbanization and a higher rate of multifamily over single family residences, which are essential factors to lowering floor space (see Fig. 11 in the main report for per capita material intensity), in addition to improvements in design and furnishing and policies that incentivize efficient floor space utilization.

Urbanization and the portion of people living in multifamily homes will reduce the average area of all house types (Ewing and Rong, 2008). In the past average floorspace per capita has generally increased with GDP up to now (International Energy Agency, 2016; Moura et al., 2015; Weisz and Steinberger, 2010). Better building and urban design are one means to reduce material efficiency by reducing per capita floor area (Weisz and Steinberger, 2010). However, it is unlikely that technical solutions will bring the required reductions. There needs to be some step change in culture or mindset around floorspace requirements. Central tenets of the SSP1 scenario include orienting consumption around low material growth, changing attitudes, and a shift away from economic growth towards broader well-being (O'Neill et al., 2017). We interpret this to mean personal possessions, including less rooms in housing units. This can be achieved through reducing numbers of underutilized rooms in houses, such as guest bedrooms and spare bathrooms, as well as less storage space and basements which will become less valuable as people own fewer possessions. Likewise, there will be less demand for separate kitchens and dining rooms. Some demographic shifts will assist in

the transition. Most G7 countries have a steadily aging population, which is likely to increase the portions of the population living either in some form of assisted living or elderly communities, or next to their families in 'in-law suites' (Rosenberg and Everitt, 2001), with both options having lower floor space requirements than traditional housing units. Another relevant demographic change is the later age at which people are choosing to marry, form new households and have families (Holmans, 2013; Paciorek, 2016). This may lead people in their twenties and thirties to live in urban shared living arrangements for longer, supporting the urbanization trend and the shift from single family to multi-family housing.

For the LED scenario, the above changes are probably insufficient to achieve the required MIU. We therefore consider that a portfolio of regulation options for reducing per capita floor space. Restrictions on house sizes for new construction, restriction or high taxation of secondary homes are some direct measures that would help reduce floor space. Some indirect measures with potential could be carbon taxes or other measures which raise energy prices. There is some empirical evidence which suggests that homes built during times of high energy prices tend to be smaller (Costa and Kahn, 2011). Reducing the tax burden associated with selling or changing ownership of houses may encourage parents to downsize after their children move away from home, reducing the 'over-consumption of housing' by populations over 60 (Clark and Deurloo, 2006). Finally, a policy change which may apply to the US more than other countries is the relaxation or removal of single family zoning in urban areas, which is often framed in discussions around access to and sufficient supply of housing, but also has the potential to increase the portion of multifamily dwellings in urban areas (Chakraborty et al., 2010).

S1.2. Material composition of building archetypes

As described in the main report, the building archetypes are based on (Taylor et al., 2015). Table S 1 summarizes the geometry of single-family and multi-family archetypes (floor, wall, window, roof area). This data is available as energy plus input files and come in three different standards: IECC 2006, IECC 2009, and IECC 2012. The energy demand simulation was calibrated by changing ventilation rate and building envelope thermal insulation so that they represent the following energy standards:

- non-standard: Values ca. 30% above IECC 2006 are used
- standard: IECC 2006 is used
- efficient: IECC 2012 is used
- ZEB: Current best practice values

In order to determine material content, the archetype is equipped with building cross-sections that describe the composition of walls, floors, etc. The cross-sections depend on the energy standard and ME strategy, and for each combination of 'using less material by design' and 'material substitution' a specific archetype is described for each building type, leading to 2 x 2 x 3 = 36 archetypes. Multiplying building component surfaces with material density and cross-sections allows us to determine total material content of the archetype building. This procedure was used to calculate concrete, cement, wood, paper & cardboard, construction grade steel, and "other" materials (including insulation material). Aluminum and plastics content were taken from (Dean et al., 2006) and copper content is based on typical values in (Heeren and Fishman, 2019). The modifications that are applied to the archetypes for the Material Efficiency strategies are described in 2.3.3 of the main report. Once the building materials and construction are selected, its operational energy demand is calculated using Energyplus (Crawley et al., 2001). This allows to account for the effect on energy demand when changing building material composition. For instance, Heeren et al 2015 have shown that space heat demand of timber buildings may be 2–5% increased, compared to concrete buildings (Heeren et al., 2015). Some countries, such as the US or Japan, span different climate zones which have a strong influence on building energy demand.

Table S 1. Prototype characteristics as in (Taylor et al., 2015)

Parameter	Single-family home	Multi-family home
Conditioned floor area	221 m^2 (plus 110 m^2 of conditioned basement, where applicable)	112 m^2 per unit, or 2007 m^2 total (plus 112 m^2 of conditioned basement on ground-floor units, where applicable)
Footprint and height	1.5 m by 6.7 m, two-story, 2.6 m high ceilings	Each unit is 12.2 m wide by 9.1 m deep, with 2.6 m high ceilings. The building footprint is 36.6 m by 19.8 m.
Area above unconditioned space	110 m^2	111 m^2 on ground-floor units
Area below roof/ceilings	110 m^2	111 m^2 on top-floor units
Perimeter length	46 m	113 m (total for the building)
Gross exterior wall area	240 m^2	474 m^2 per story
Window area (relative to cond. floor area)	15% equally distributed to the four cardinal directions	23% of gross exterior wall area, excluding walls facing the interior breezeway
Internal gains	91 MJ/day (2015 IECC, Table R405.5.2)	58 MJ/day per unit, 1038 MJ/day total (2015 IECC, Table R405.5.2)

S1.3. Material consumption for different material efficiency strategies

Figure S 1 illustrates all material inputs for residential construction in the G7. These results are produced by the ODYM-RECC framework, which is coupled to the building archetype model. A remarkable effect in the LED scenario is the decline in material demand until 2045 and the strong increase after that date. This phenomenon is related to the very low floor area demand of that scenario (therefore also visible in SSP1 and SSP2 with more intense use). As seen from Figure 10 in the main report, the building stock has overcapacity in floor area until 2045 and will therefore shrink until then because the population growth can be easily accommodated. Only once the target value of the per capita floor area has been reached, new floor area has to be added to satisfy the demand by new population. The SSP1 scenario has remarkably lower material demand, which is again a consequence of the lower floor area demand, compared to SSP2.

The Material Efficiency cascades 1 to 5 reduce cumulative total material demand 2016–2060 to different extents. The first cascade considers improvements for fabrication yield and improved end-of-life recovery. Both have no influence as they do not influence the total material demand. However, the secondary material flow increases in that cascade from 813 Mt to 1169 Mt, which marks a 44% increase. Lifetime extension leads to fewer new construction, thus reducing material demand by 1% in cascade 2. Material substitution in cascade 3 reduces material demand ***in mass*** by 3% as wood is more lightweight and timber construction more material efficient. Cascade 4 introduces the lightweighting strategy, which leads to 9% less material demand. More intensive use of buildings reduces cumulated demand by 53% in cascade 5.

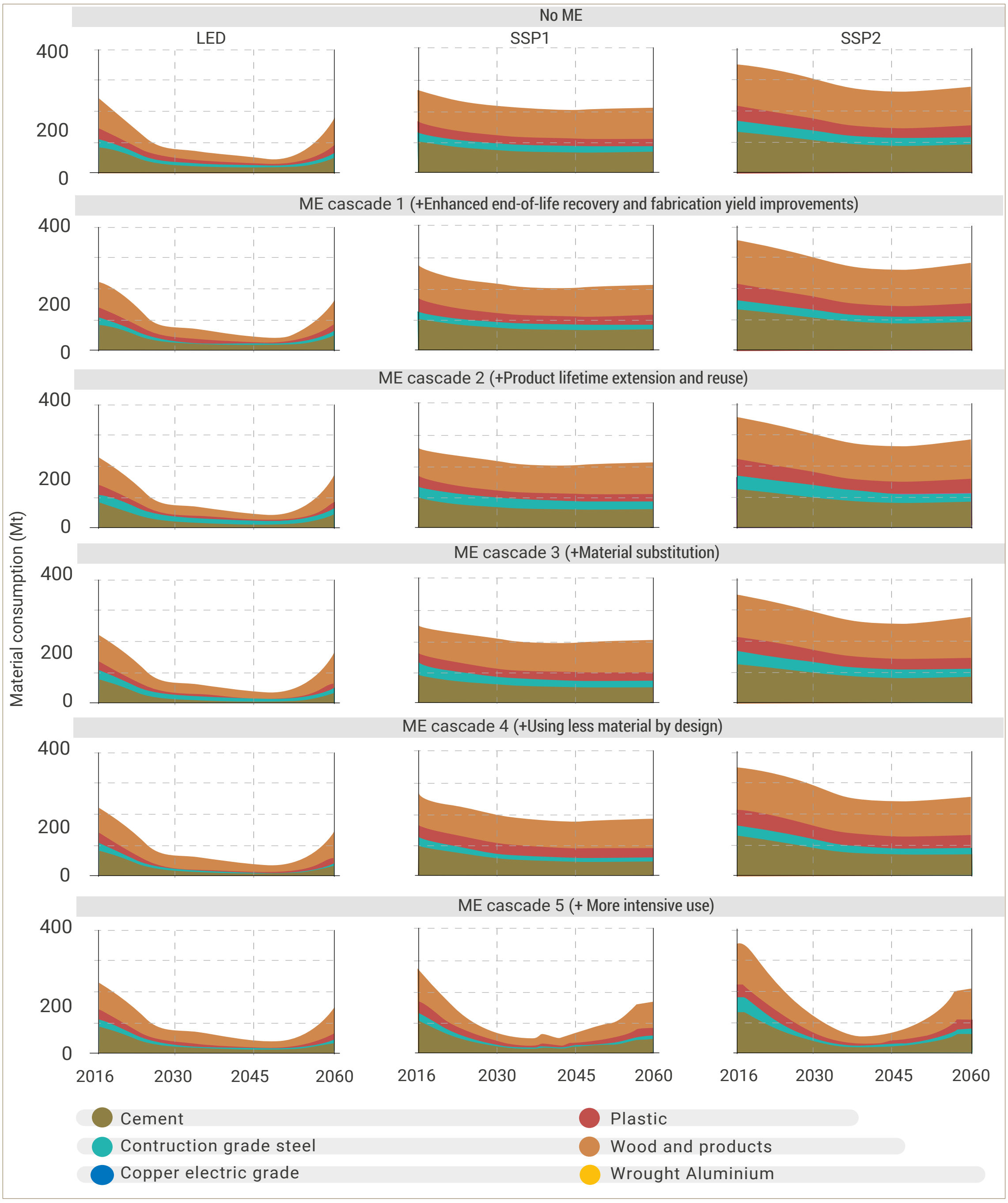
S2. Material efficient vehicles

This section describes how the model framework was applied to the passenger vehicle sector. First, the scenarios for future transportation demand are described, then the vehicle archetypes, then the material flows for the different scenarios and ME strategy cascade steps, and finally, additional model results for vehicles.

S2.1. Future transportation demand

Future person-km for all countries were obtained through the expert consensus process. 2015 values range from 322 person-km per capita and year in in India, through 6350 km in Japan, 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 countries converge to this value by 2050 and that China grows to half this value. For India, we take the LED developing country value of 1350 km per year. In industrialized countries, we assume 2050 passenger vehicle transport demand in SSP2 remains at the 2015 level or converges to the LED

Figure S 1. Primary and secondary materials entering the use phase by material, scenario (columns in figure grid), and ME strategy cascade (rows in figure grid) for 2016–2050.



Construction aggregates are omitted and only the cement fraction of concrete is displayed here. Each cascade includes the ME strategies of the previous cascade. In ME cascade 5, all strategies have been applied. The numbers behind this and all other figures are available for download at https://doi.org/10.5281/zenodo.3542681

scenario target, whichever is value higher. The SSP1 scenario value was chosen to be between the LED scenario and the SSP2 scenario. For China and India and the SSP1 and SSP2 scenarios, we assume a continued, uninterrupted growth of per capita person-km in passenger vehicles to intermediate levels of what is currently observed in the G7 and other high-income countries: ca. 10000 km per person and year. Impacts of modal shift on other transport modes is not part of the current assessment.

Vehicle ownership is then calculated internally by the ODYM-RECC model from the annual service demand for passenger-km and a group of parameters including vehicle occupancy rate and annual vehicle-km. EU's vehicle stock reduces from 239 million in 2015 to 156-207 million units in 2050, depending on the scenario. The baseline vehicle stock in the G7 countries was 441 million units in 2015, it reduces to 180-389 million units by 2050. China from 132 to 159-481 million units. India from 23 to 111 to 730 million. USA from 220 to 73-234 million vehicles.

We compare our results to estimates in the literature in Table S 2. Huo and Wang, (2012) forecast future Chinese vehicle stocks. The authors estimate that the stock of Chinese private light vehicles could reach 465-558 million units by 2050. Sales of new vehicles could reach 23-42 million units by the same year. In 2010, the Chinese light vehicle stock was at roughly 50 million units. The Annual Energy Outlook 2019 published by the US Energy Information Administration forecasts US light vehicle stocks to reach 245-332 million units by 2050, depending on economic growth and oil price development (which does not anticipate a transition to electric vehicles). In 2017, the US light vehicle stock was at 254 million units, and 15.9 million light vehicles were sold in that year. US 2050 sales are expected to range between 12.9 and 19.3 million units according to this study. In 2017, total vehicle miles traveled were at 2.84 billion but in the future, they could range between 2.69 and 4.42 billion, depending on the scenario (U.S. Energy Information Administration, 2019). India's passenger car sales are expected to increase from 2.4 million in 2010 to 6.7 million units in 2025 (Statista, 2019). EU's passenger vehicle stock is forecast to increase moderately from about 250 million units currently to just under 300 million units by 2030 (Nemry et al., 2009)"abstract":"This report presents the results and conclusions of a research carried out by the JRC/IPTS analysing two demand-side measures that can help improving the environmental performance of cars: The first instrument, the feebate system, is a way to differentiate the registration tax according to the CO2 emissions from cars. The second instrument, the scrappage policy is intended to encourage the owners of old cars to scrap their car earlier. The potential and consequences of technical options to reduce car weight are also analysed. The report builds a comprehensive assessment of these policy options at EU level, covering all major environmental life cycle impacts and the different economic impacts. The report is built upon IPTS research work, supported with a study subcontracted to a research consortium led by Transport&Mobility Leuven (TML). At the global level, (Deetman et al., 2018) estimate that global passenger car sales could grow from 120 to 261–276 million units per year by around 2050, based on the SSP storylines.

Estimated vehicle stocks in our study at the higher end of our range compares with the lower end of the range from the literature, and can reach much lower minima compared to the literature. This is a direct consequence of our scenario scope, which includes (with LED, SSP1, and SSP2) the lower part of the entire service consumption (and in-use stock demand) spectrum.

Table S 2. 2050 vehicle stocks by region from this study compared to results from the literature. Unit: Million.

Region	This study (million)	Literature (million)	Source
China	159-481	465-558	(Huo and Wang, 2012)
India	111-730		
G7	180-389		
USA	73-234	245-332	(U.S. Energy Information Administration, 2019).
EU	156-207	300 (2030)	(Nemry et al., 2009)

S2.2. Material composition of vehicle archetypes

Figure S 2 shows the material composition of vehicle archetypes. Steel accounts for a majority of the mass of conventional vehicle archetypes (ca. 65% on average), while the mass of aluminum accounts for an average of 4.1% of total weight. As we assume an Al-intensive solution for lightweighting, the aluminum content of lightweight vehicle archetypes range from 32% to 42%, while the mass of steel drops to 22-37%. As the weight of materials in an LT archetype (e.g., PHEV-LT) is scaled based on the corresponding PC archetype (e.g., PHEV-PC), there is no difference in material composition between the two segments.

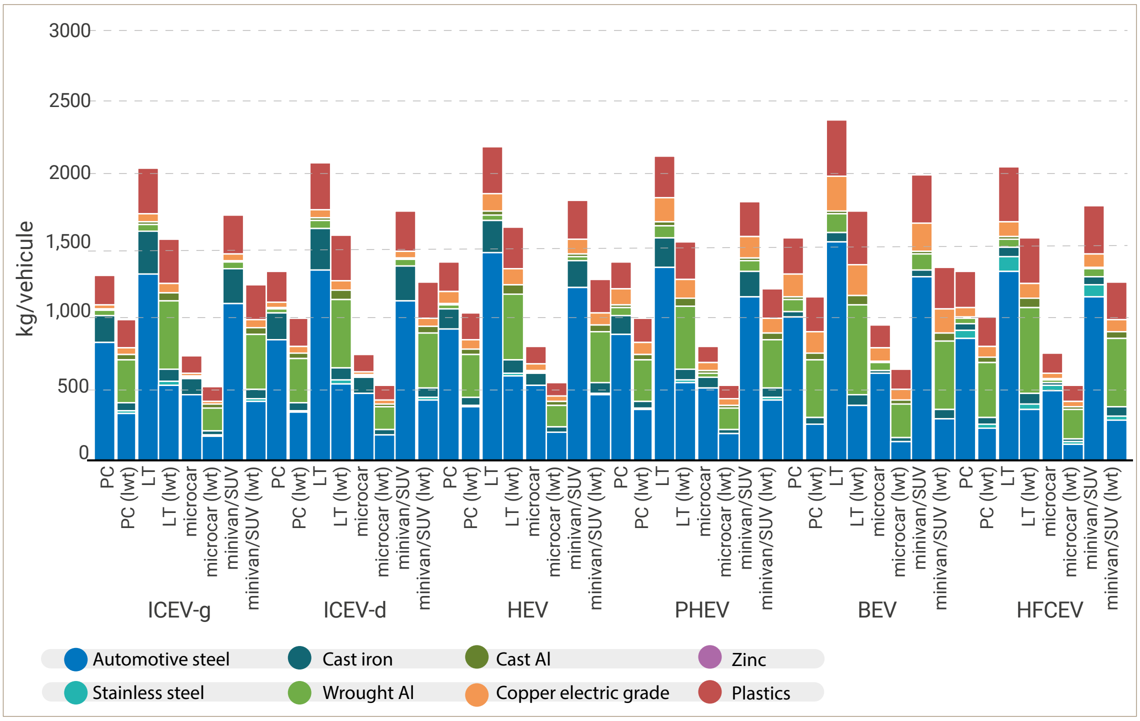
S2.3. Material consumption and GHG emissions under different ME cascades

Material consumption changes at different rates in all scenarios (Figure S 3). Compared to 2016, the material consumption in 2050 decreases by 5.1 Mt in LED, while increases by 0.4 and 3.1 Mt in SSP1 and SSP2, respectively, when no ME strategy is implemented. Reductions are observed when all ME strategies are implemented, approximately 6.7, 5.8 and 2.5 Mt, respectively. Cumulative material consumption (2016-2060) with all ME strategies implemented are 44, 37 and 24% less than with no ME strategies.

GHG emission reductions: Similar to the building modeling results, the technical ME strategies (FYI, EoL and MSu) have rather minor contributions due to limited potentials for improvement over or trade-offs with other strategies (Figure S 4). On the other hand, changes in use patterns and provisioning systems such as ride sharing and car sharing have a higher technical potential. For instance, both MIU and ULD are primarily driven by the behavior changes of customers (e.g., increase in car sharing leads to decrease in vehicle ownership), rather than technical improvement of vehicles.

ME cascade 1: Improving process yields. Increasing EoL recycling rates, fabrication yield improvement and fabrication scrap diversion altogether could reduce the cumulative GHG emissions (2016-2060) related to material manufacturing by 12-14%, compared to no ME strategy. However, from the entire life cycle perspective, the contributions are rather minor

Figure S 2. Material composition of vehicle archetypes



(PC= passenger car; LT= light truck; lwt= lightweight design). Relevant materials from batteries are included (Lead-acid battery for ICEV; Ni-MH for HEV and HFCEV; Li-ion for PHEV and BEV)

Figure S 3. Material flows by category, scenario (columns in figure grid), and ME strategy cascade (rows in figure grid) for 2016–2060.

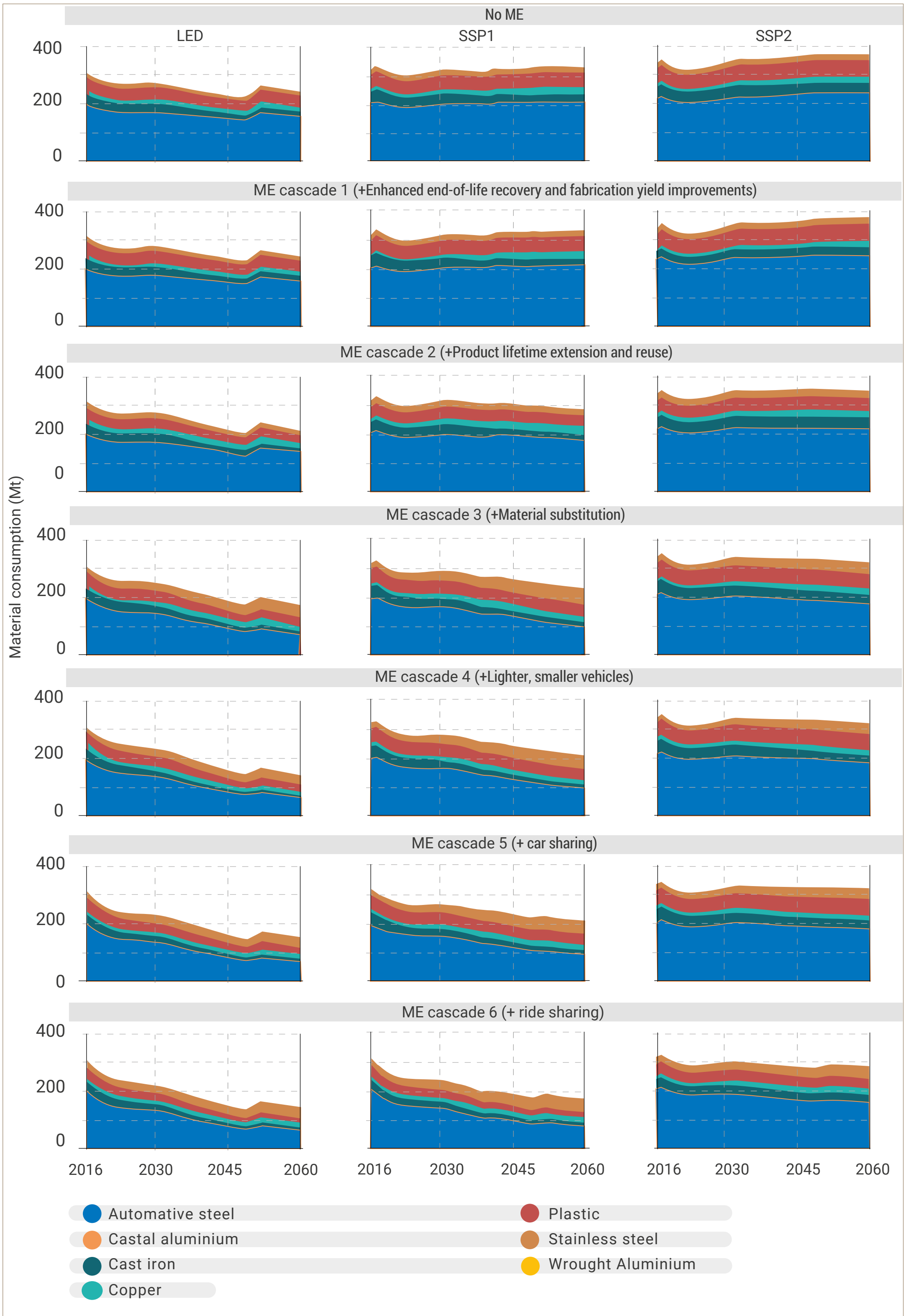
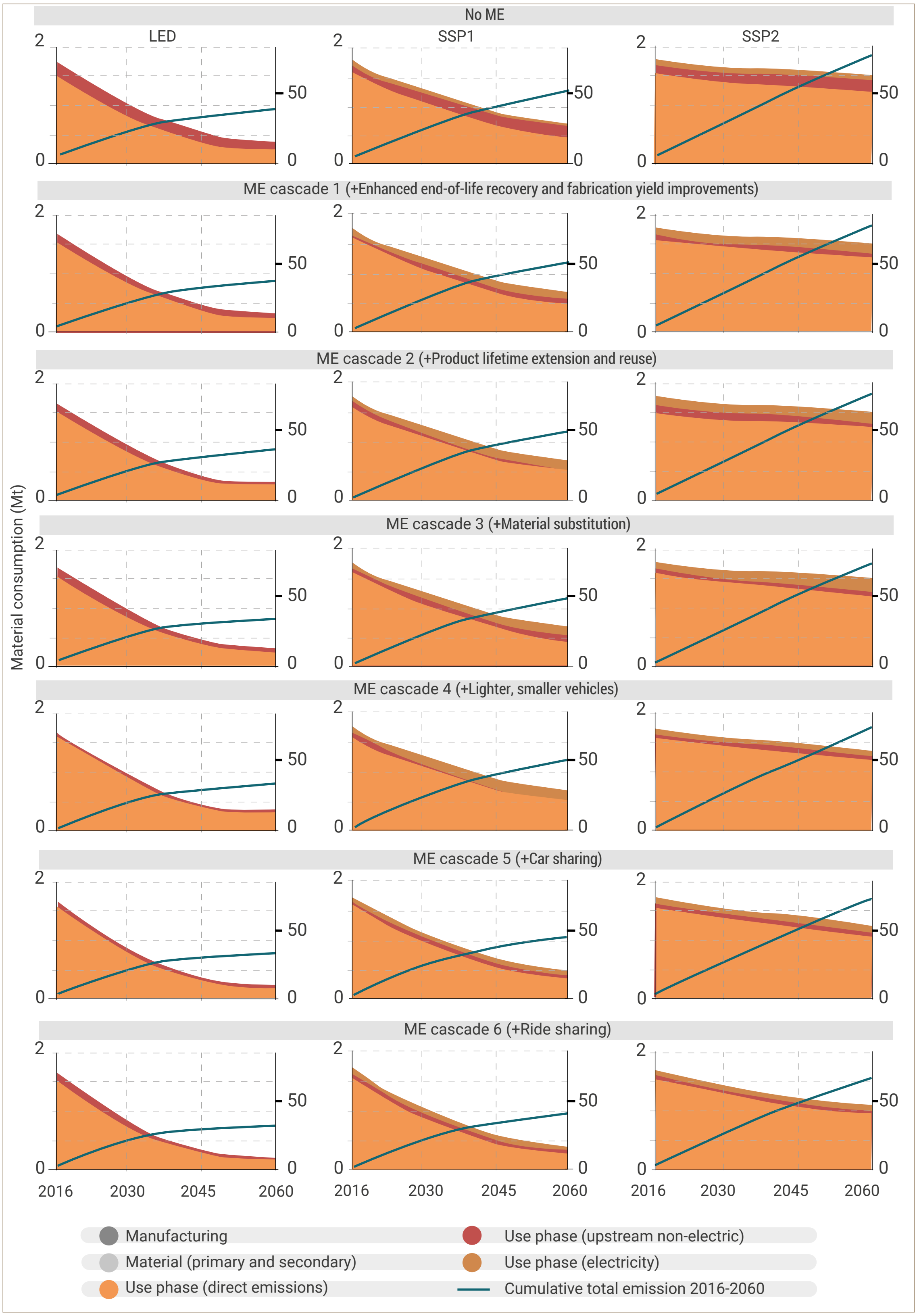
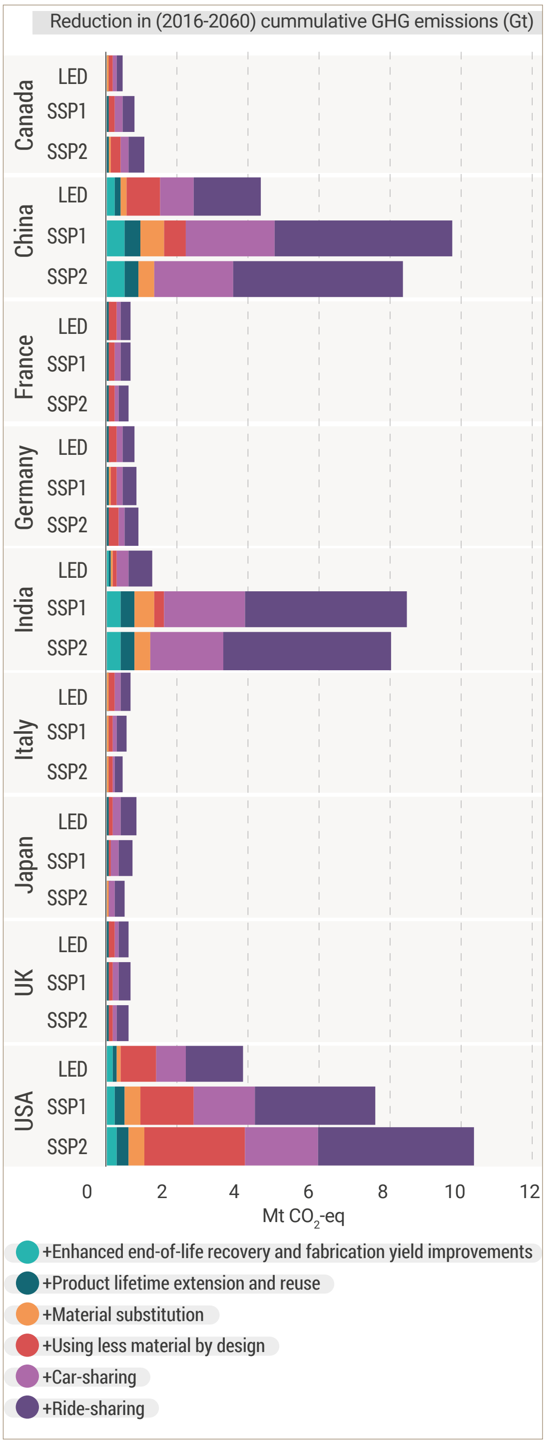


Figure S 4. The areas illustrate annual emissions for the manufacturing and use of vehicles by scope (colors), scenario (columns in figure grid), and ME strategy cascade (rows in figure grid).



The dashed line represents cumulative emissions from 2016 to 2060 and is plotted against the secondary y-axis. For ME abbreviation, please refer to the caption of Figure S 3.

Figure S 5. Contribution of different ME strategies to the overall reduction in GHG emissions for G7 countries, China, and India.



(0.6-1.7%) for all G7 countries due to relatively larger GHG emissions from the use phase. In addition, as the recycling rates of waste materials are already high (e.g., 69% for automotive steel). The additional reduction in GHG emissions by further improving EoL recovery rates of up to 95% is not considerable as a share of the emissions of the entire system. Although significant reduction in fabrication scraps (from currently ca. 20% to 10%) could be achieved by implementing FYI, the corresponding GHG reduction in material manufacturing is not proportionally large, due to the fact that fabrication scraps are an important source of secondary materials for manufacturing and a decrease in its availability could potentially increase the demand for primary (virgin) materials.

ME cascade 2: +Re-use & life time extension. On top of improving process yields, the reuse of vehicle components and extending vehicle lifetime offer a similarly small reduction potential in all countries, when use phase emissions are included. From the material manufacturing perspective alone, the GHG reduction potentials could be large, although a considerable variation is observed (4.0-23%) among G7 countries and scenarios.

ME cascade 3: +Material substitution increases the cumulative GHG emissions related to material manufacturing by 1.9-5.0%, due to the increase in aluminum consumption. Nonetheless, life cycle GHG emissions are reduced by 0.7-1.9%, due to the larger reductions in use phase.

ME cascade 4: +Reduced material content could achieve an additional 0.7-10% reduction in life cycle GHG emissions contributed by both lower material demand (2.4-16% reductions for material manufacturing alone) and reduced fuel uses (i.e., higher fuel economy of smaller size vehicles). The benefit of adopting this strategy is highly country-specific, depending upon the domestic vehicle market (e.g., minicars and passenger cars dominate the Japanese vehicle market), the choice of alternatives (e.g., from light trucks to passenger cars in the USA) and the corresponding material-saving potentials. The higher reduction potentials are usually achieved through shifting from minivans to microcars (e.g., France in LED scenario), while the lower reduction potentials are typically due to the already significant share of smaller size vehicles in the market (e.g., Japan in all scenarios).

ME cascade 5&6: +More intensive use indicates the largest reduction potential (11-20%) due to both reduced demand on new vehicle production

and lower use phase emissions. From both material manufacturing and life cycle perspectives, ridesharing account for roughly 2/3 of the total reductions by implementing MIU in all countries.

Overall, the full potential (i.e., ME cascade 6) to reduce cumulative life cycle GHG emissions for vehicles are approximately 0.6 (Italy)-7.5 (USA), 0.5 (Italy)-10 (USA), 0.5 (Canada)-3.9 (USA) Gt CO_2e for SSP1, SSP2 and LED, for G7 countries, respectively. The corresponding ranges of relative reduction are 22 (Japan)-27% (Canada), 15 (Japan)-21% (Canada) and 23(USA)-31% (France), respectively. From material manufacturing perspective (i.e., without use phase emissions), the reductions in cumulative emissions are 54 (Italy)-927 (USA), 39 (Italy)-787 (USA) and 61 (Italy)-616 (USA) Mt CO_2e for SSP1, SSP2 and LED, respectively. The corresponding relative reductions are 42 (UK)-52% (Japan), 30 (UK)-37% (Japan), 49% (UK) and 56% (USA), respectively.

All G7 countries have the potential to reduce cumulative emissions by 15% or more and 25% for material manufacturing alone (Figure S 5). See section S3 for country-specific results.

S3. Country-specific results

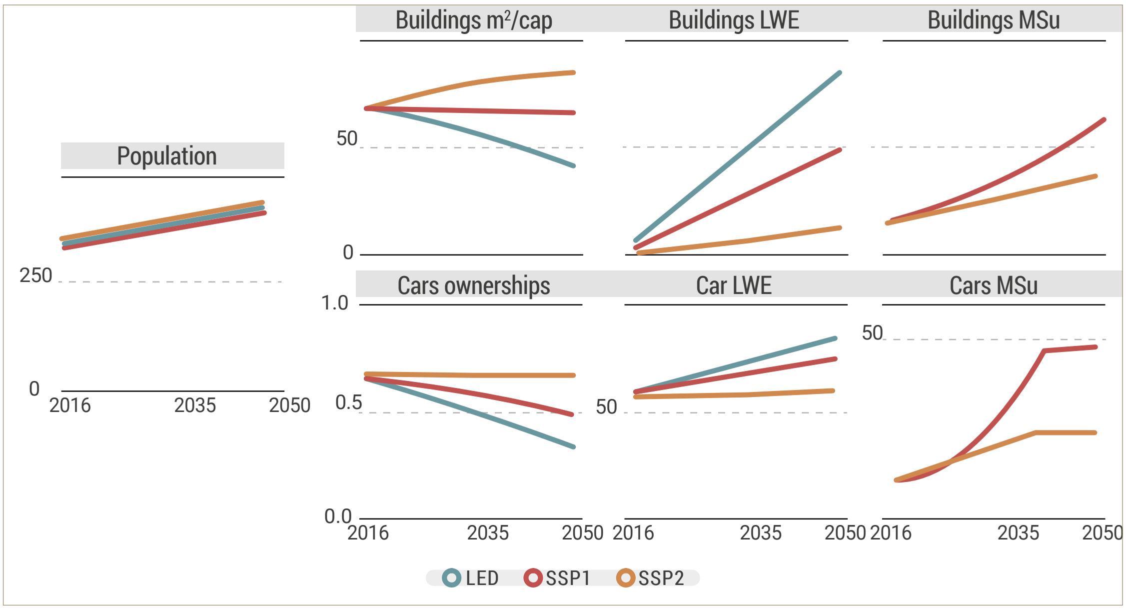
The model results are available for the individual countries. This section gives a short summary of the key assumptions and key results for each G7 country, as well as China and India. Figure S 6 illustrates the panel used to document the assumptions for all three scenarios. From top left the plots have the following meaning and units:

- **Population:** Population in million persons from (Riahi et al., 2017). Population in the LED scenario is identical to the population in SSP2.
- **Buildings m²/cap:** Per capita floor area in square meter per person
- **Buildings ULD:** Share of the light-weighted (ULD) building archetype for new constructions in percent
- **Buildings MSu:** Share of the material substitution (MSu) building archetype for new constructions in percent
- **Car ownership:** Number of cars per person in #/cap
- **Cars ULD:** Share of the smaller (ULD) vehicle archetype for new cars in percent
- **Cars MSu:** Share of the aluminum material light-weighted (MSu) vehicle archetype for new cars in percent

S3.1. Canada

Based on our results, Canada contributes ca. 5% of the GHG emissions related to residential buildings and vehicles in the G7. Among G7 countries, residential and vehicle emissions per capita are

Figure S 6. Example panel with key assumptions that is used for every country.



ULD: using less materials by design, MSu: material substitution

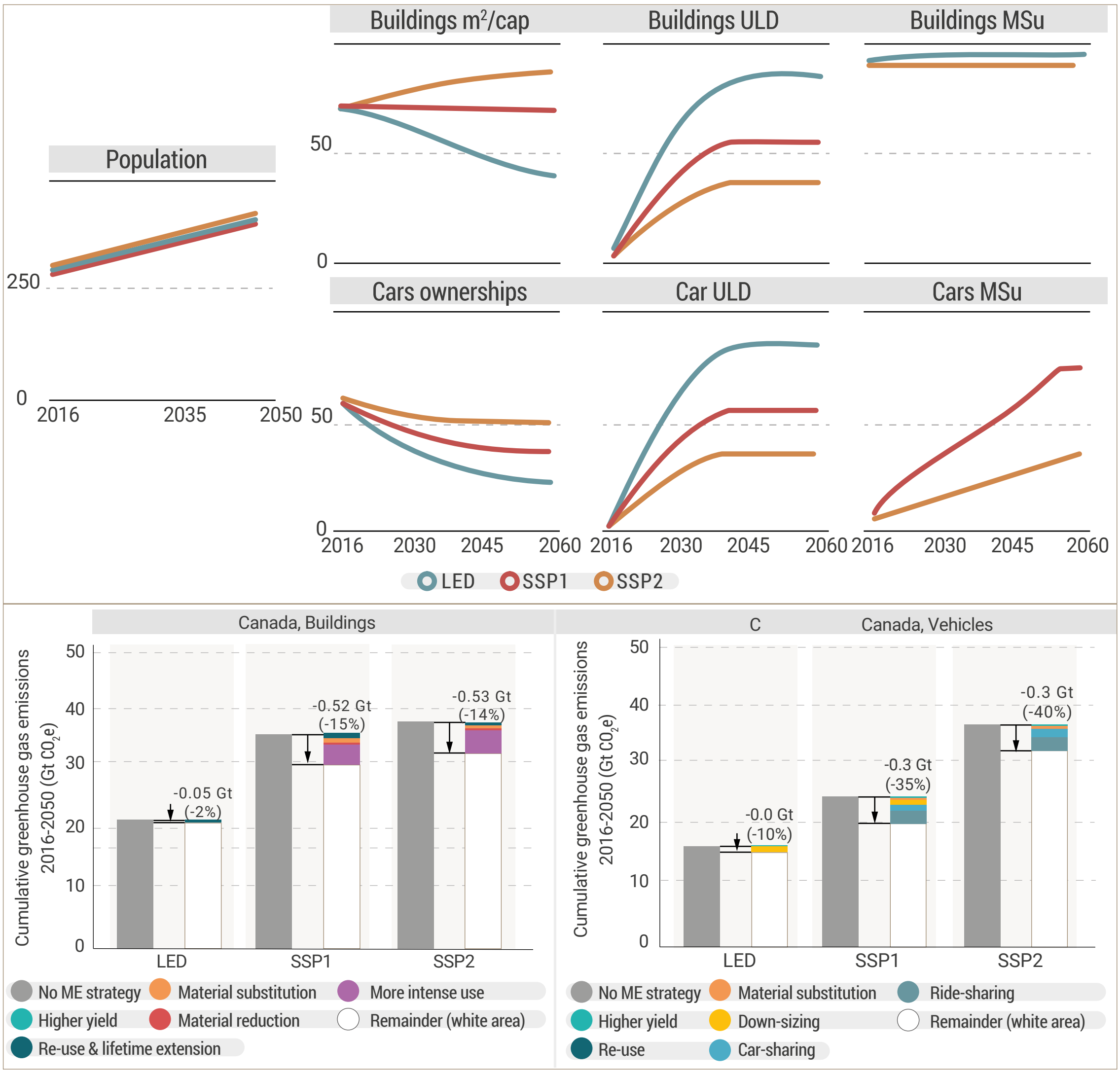
second only to the USA. Canada is expected to have the highest population growth rate between 2016-2060 of all G7 countries, driving growth in the stocks of buildings and vehicles(Kc and Lutz, 2017).

Residential buildings

Material efficiency strategies can contribute notably to a reduction of residential GHG emissions in Canada. The investigated ME strategies would reduce cumulative emissions by around 22-23% in the SSP1 and SSP2 scenarios (Figure S 7).

Most emission reductions arise from more intensive use, modelled through a reduction of the floor space per capita by 20% compared to the respective SSP1 and SSP2 baselines. This would reduce cumulative emissions also by 20% both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. One way in which use is likely to intensify is through the move from single-family to multi-family structures, most likely connected to a transition to living in more urban residential areas. More intensive use also incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. By 2060, baseline floor area per capita

Figure S 7. Cumulated greenhouse gas emissions 2016–2060 for Canada by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

remains at 61 m^2/cap in SSP1, increases to 73 m^2/cap in SSP2, and decreases aggressively to 35 m^2/cap in LED. Among other material efficiency strategies, higher recycling yields, incorporating higher material recovery rates in waste streams and improvements in fabrication yields, has the highest potential, reducing GHG emissions by 1-2% in each scenario. Because of the already relatively high portion of wood frame buildings in Canada, potential cumulative emission reductions from material substitution are low.

Even with the high demand growth SSP2 and before any ME strategies, annual emissions from residential buildings would decline to 70% of current levels by 2060 due to the assumed transition in the energy system. Steady growth in population in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, increased use of electricity and fuelwood in the fuel mix for heating, and a 99% reduction in the GHG intensity of electricity supply in 2060 with respect to 2016. In SSP1, electricity GHG intensity decreases by 97%.

Passenger vehicles

Canada contributes 4% to total passenger vehicle GHG emission in the G7. Relative to a scenario without ME strategies, ME strategies can provide reductions of cumulative emissions by 11-26%. A modest reduction of cumulative emissions by 1.3-2.1% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction is due to a light-weighting of vehicles, i.e. a shift from steel to lighter materials, aluminium, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.9-1.7% through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of light trucks and sport utility vehicles in the fleet, could reduce cumulative emissions by up to 8%. More intensive use, through the introduction of car sharing and ride sharing, would reduce cumulative emissions from private vehicles by 13-18% in SSP2 and SSP1, whereas these measures are already implemented in LEDs. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

S3.2. France

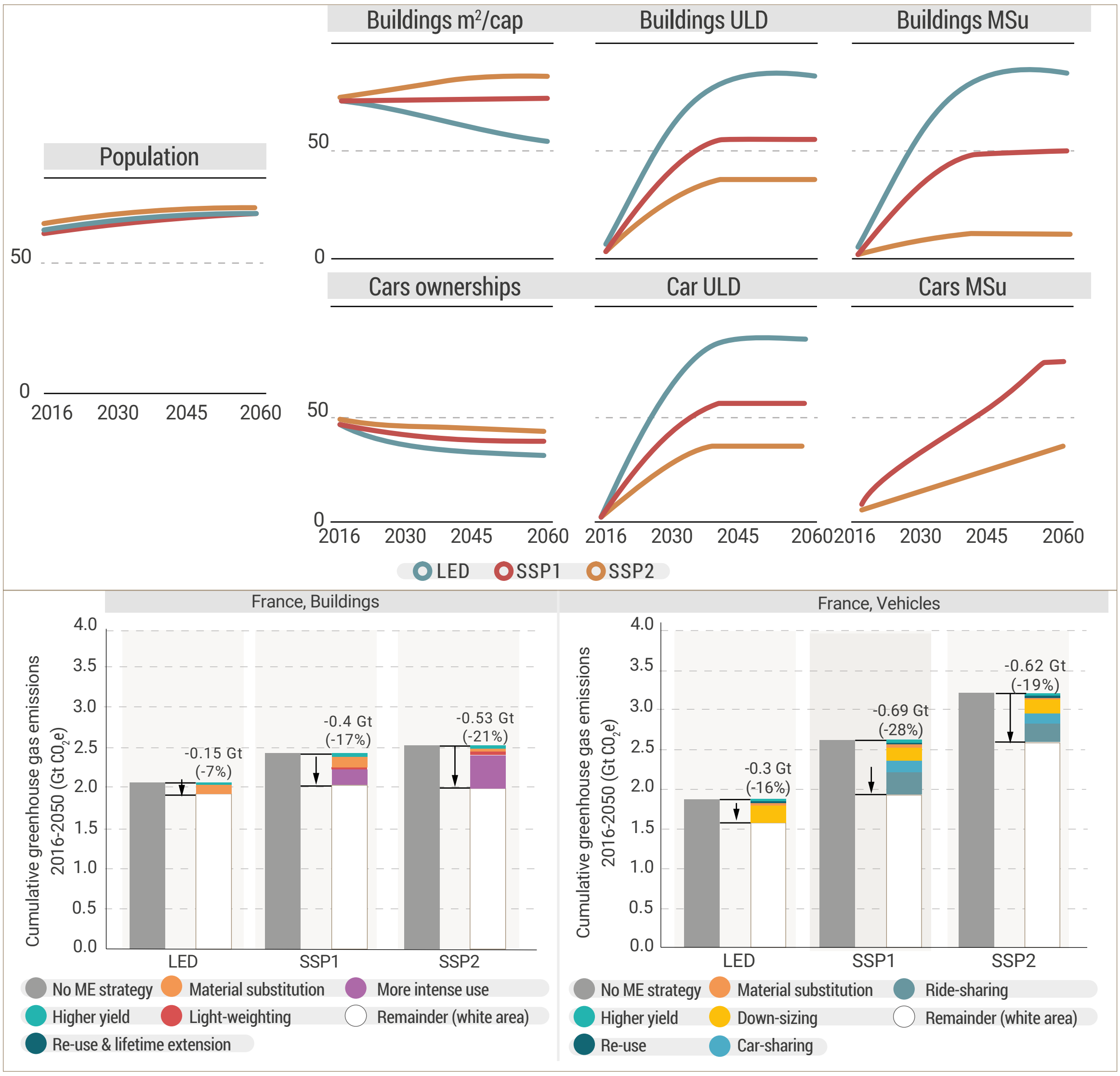
France contributes ca. 4% of the GHG emissions related to residential buildings and vehicles in the G7. It currently has by far the lowest GHG intensity of electricity among all G7 countries. Population in 2060 is expected to increase by 10% relative to 2016.

Residential buildings

Material efficiency strategies can contribute notably to a reduction of residential GHG emissions in France. The investigated ME strategies would reduce cumulative emissions by 7-21%, depending on the SSP scenario (Figure S 8).

The largest emissions reductions would arise from more intensive use in SSP1 and SSP2, modelled here through a reduction of the scenario baseline floor space per capita by 20%. This would reduce cumulative emissions by 9% in SSP1 and 16% in SSP2%, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. More intensive use incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. By 2060, baseline floor area per capita remains at 41 m^2/cap in SSP1, increases to 47 m^2/cap in SSP2, and decreases to 30 m^2/cap inLED. In SSP1 and LED, the material substitution strategy of increased use of wood in construction could reduce life-cycle emissions from buildings by 5%. In SSP2, higher recycling yields, material substitution, and lightweighting of new buildings all reduce cumulative GHG emissions by between 1-2%.

Figure S 8. Cumulated greenhouse gas emissions 2016–2060 for France by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

Even within the high demand growth in SSP2 and before any ME strategies, annual emissions from residential buildings would decline to 51% of current levels by 2060 due to the assumed transition in the energy system. Modest growth in population and floor area per capita in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, increased use of electricity and fuelwood in the fuel mix for heating, and a reduction of 75%, from a very low starting point, in the GHG intensity of electricity supply.

Passenger vehicles

France contributes 4% to total passenger vehicle GHG emission in the G7. ME strategies can provide reduction of cumulative emissions on the order of 13-26%. A modest reduction by 1.7-2.2% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminum, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.7-1.4% through operational fuel savings. A shift

of the composition of the vehicle fleet, modeled here yields a reduction of the share of passenger cars and sport utility vehicles in the fleet , could reduce cumulative emissions by up to 10%. More intensive use, through the introduction of car sharing and ride sharing, would reduce emissions from private vehicles by 12-16% in SSP2 and SSP1, whereas these measures are already implemented in LED and hence do not lead to further savings. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

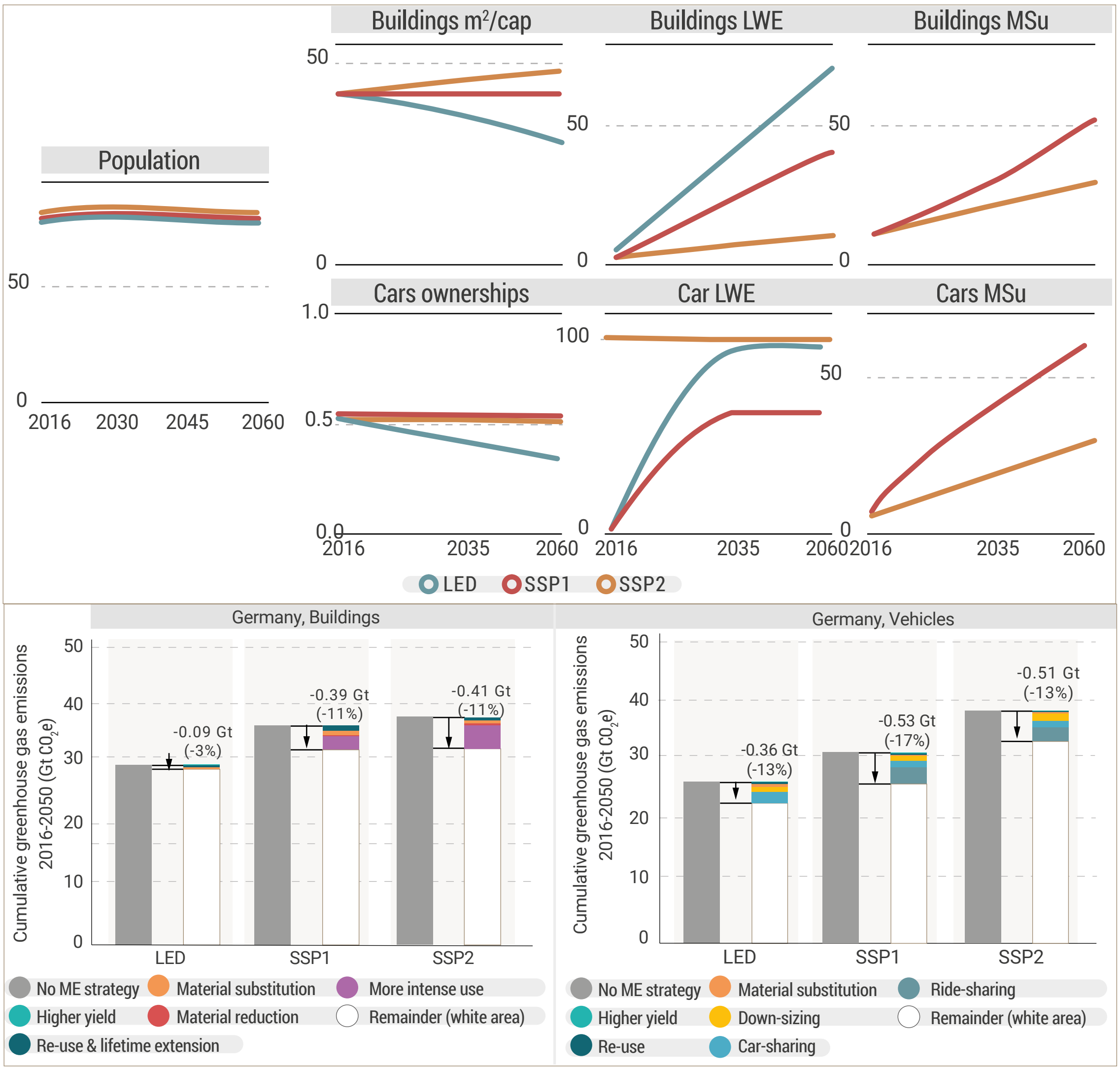
S3.3. Germany

Germany contributes ca. 8% of the GHG emissions related to residential buildings and vehicles in the G7, the highest of the European G7 countries. Germany's population in 2060 is expected to decrease by 6% relative to 2016.

Residential buildings

Material efficiency strategies can contribute notably to a reduction of residential GHG emissions in Germany. The investigated ME strategies would

Figure S 9. Cumulated greenhouse gas emissions 2016–2060 for Germany by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

reduce cumulative emissions by 5-19%, depending on the SSP scenario (Figure S 9).

The largest emissions reductions would arise from more intensive use in SSP1 and SSP2, modelled here through a reduction of the scenario floor space per capita by 20% compared to baseline scenario development. This would reduce cumulative emissions by 8% in SSP1 and 15% in SSP2, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. One way in which use is likely to intensify is through the move from single-family to multi-family structures, most likely connected to a transition to living in more urban residential areas. More intensive use incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. By 2060, baseline floor area per capita remains at 42 m^2/cap in SSP1, increases to 49 m^2/cap in SSP2, and decreases to 30 m^2/cap in LED. In SSP1 and LED, the material substitution strategy of increased use of wood in construction could reduce life-cycle emissions from buildings by 3%. In SSP2, higher recycling yields, material substitution, and lightweighting of new buildings each reduce cumulative GHG emissions by around 1%.

Even in the most intensive scenario (SSP2) and before any ME strategies, annual emissions from residential buildings are projected to decline to 33% of current levels by 2060 due to the energy transition required to meet a 2 degree target. Modest growth in floor area per capita in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, a population decline beginning in 2022, increased use of electricity and fuelwood in the fuel mix for heating, and a 97% reduction in the GHG intensity of electricity supply.

Passenger vehicles

Germany contributes 8% to total passenger vehicle GHG emission in the G7. ME strategies can provide reduction of cumulative emissions on the order of 10-25%. A modest reduction by 1.5-2.1% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminium, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.7-1.4% through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of passenger cars and sport utility vehicles in the fleet, could reduce cumulative emissions by up to 7%, with greatest reductions in LED. More intensive use, modeled through an introduction of car sharing and ride sharing, would reduce emissions from private vehicles by 12-17% in SSP2 and SSP1, whereas these measures are already implemented in LED and hence do not lead to further savings. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

S3.4. Italy

Italy contributes ca. 4% of the GHG emissions related to residential buildings and vehicles in the G7. It has the lowest travel demand in terms of passenger kilometers of all G7 countries, despite having higher per capita car ownership than any other European G7 country. Along with Germany and Japan, it is one of the few countries where the population is expected to decline, with a reduction of 11% compared to 2016 by 2060.

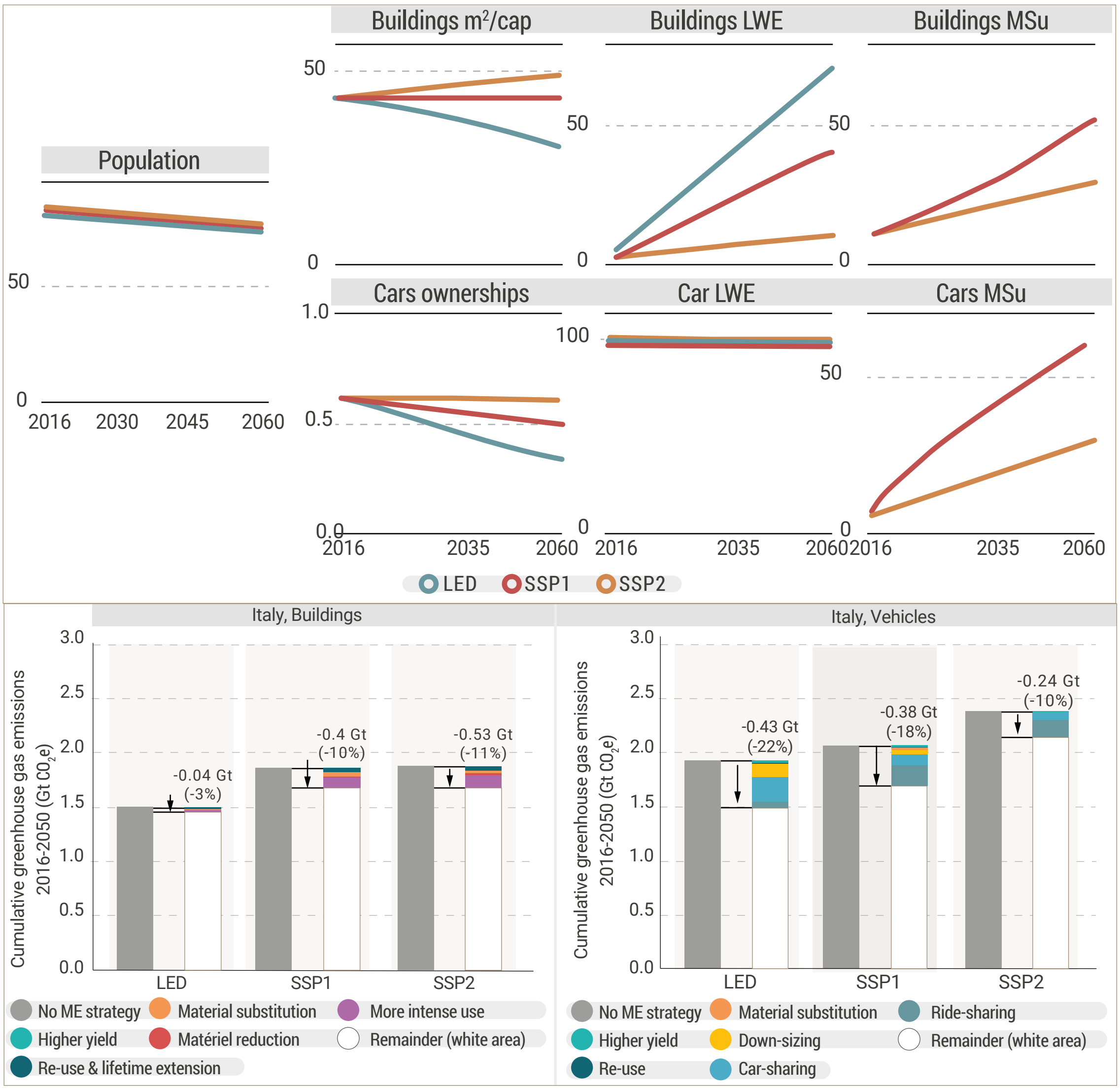
Residential buildings

Material efficiency strategies can contribute notably to a reduction of residential GHG emissions in Italy. The investigated ME strategies would reduce cumulative emissions by 4-18%, depending on the SSP scenario (Figure S 10).

The largest emissions reductions would arise from more intensive use, modelled here through a reduction of the required floor space per capita by 20%. This would reduce cumulative emissions by 8% in SSP1 and 14% in SSP2, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. One way in which use is likely to intensify is through the move from single-family to multi-family structures, most likely connected to a transition to living in more urban residential areas. More intensive use incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. By 2060, baseline floor area per capita remains at 43 m^2/cap in SSP1, increases to 50 m^2/cap in SSP2, and decreases to 30 m^2/cap in LED. In SSP1 and LED, the material substitution strategy of increased use of wood in construction could reduce life-cycle emissions from buildings by 3.5% and 2.5% respectively. In SSP2, higher recycling yields, material substitution, and lightweighting of new buildings each reduce cumulative GHG emissions by around 1%.

A rise in floor space and a shift to cleaner

Figure S 10. Cumulated greenhouse gas emissions 2016–2060 for Italy by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

energy sources would combine to reduce annual emissions from residential buildings to only 36% of current levels by 2060, a substantial reduction but too little to meet Paris targets. Modest growth in floor area per capita in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, an overall population decline, increased use of electricity and fuelwood in the fuel mix for heating, and a 95% reduction in the GHG intensity of electricity supply.

Passenger vehicles

Italy contributes 4% to total passenger vehicle GHG emission in the G7. ME strategies can provide reduction of cumulative emissions on the order of 11-25%. A modest reduction by 1.3-1.5% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminium, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.7-1.6% through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of passenger cars and sport utility vehicles in the fleet , could reduce cumulative emissions by up to 8%, with greatest reductions in LED. More intensive use, modeled through an introduction of car sharing and ride sharing, would reduce emissions from private vehicles by 12-17% in SSP2 and SSP1, whereas these measures are already implemented in LED and hence do not lead to further savings. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

S3.5. Japan

Japan contributes ca. 7% of the GHG emissions related to residential buildings and vehicles in the G7. It is the only G7 country that has much lower emissions from buildings than from vehicles, and residential emissions for Japan are well below the G7 average.

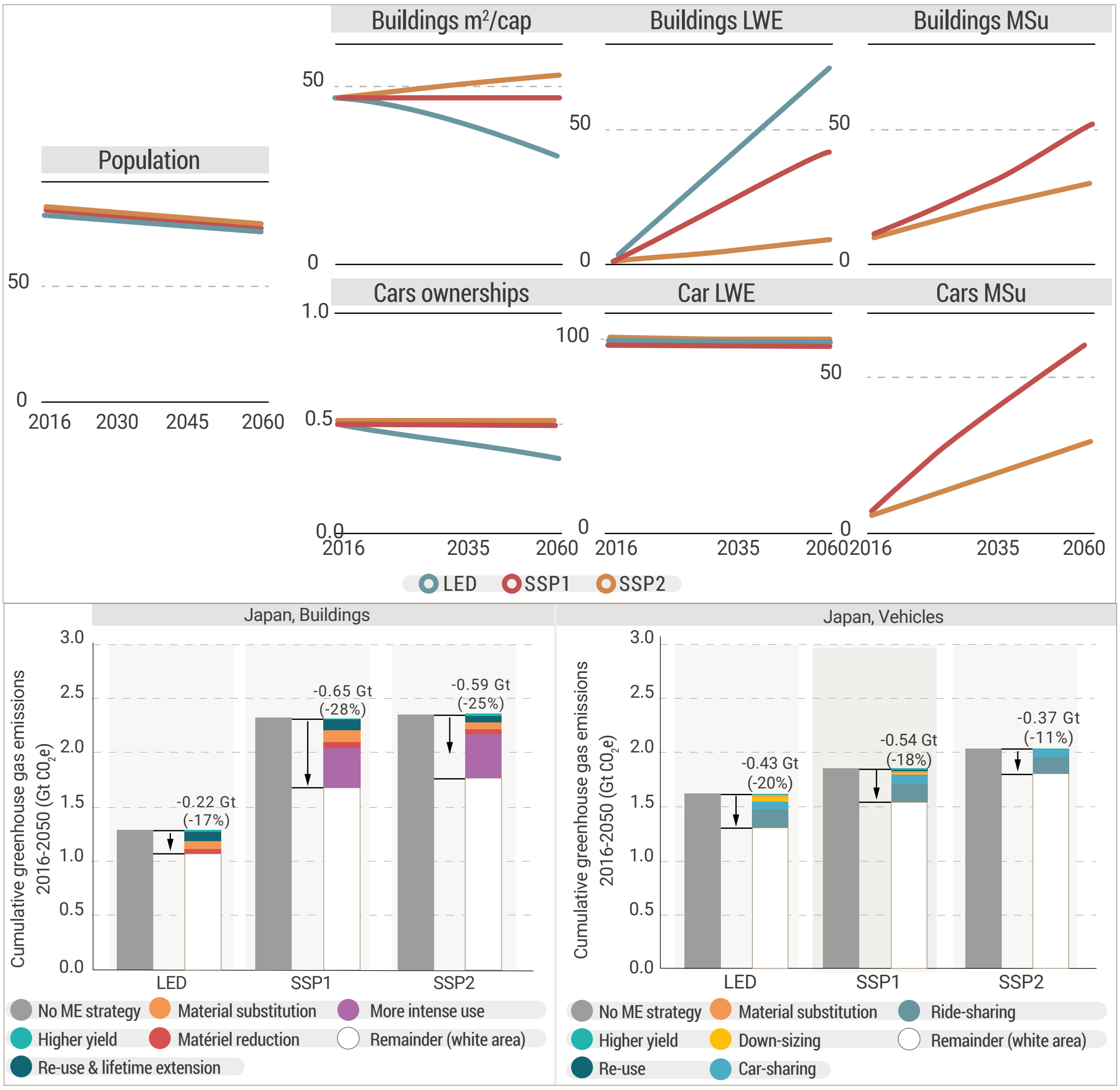
Residential buildings

Material efficiency strategies can contribute substantially to a reduction of residential GHG emissions in Japan. The investigated ME strategies would reduce cumulative emissions by 11-29%, depending on the SSP scenario (Figure S 11). This is one of the largest reduction ranges observed among G7 countries.

The largest emissions reductions would arise from more intensive use, modelled here through a reduction of the required floor space per capita of up to 20% by 2060. This would reduce cumulative emissions by 12% in SSP1 and 22% in SSP2, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. One way in which use is likely to intensify is through the move from single-family to multi-family structures, most likely connected to a transition to living in more urban residential areas. More intensive use incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. By 2060, baseline floor area per capita remains at 39 m^2/cap in SSP1, increases to 46 m^2/cap in SSP2, and decreases to 30 m^2/cap in LED. Higher recycling yields, incorporating higher material recovery rates in waste streams and improvements in fabrication yields show high potential in Japan, reducing GHG emissions by 7% in LED and 5% in SSP1 and SSP2. In SSP1 and LED, the material substitution strategy of increased use of wood in construction could reduce life-cycle emissions from buildings by 1% and 2% respectively. The strategies of component re-use and building lifetime extension, and lightweighting in new construction each reduce cumulative emissions by about 1% in each scenario.

Even in the most intensive scenario (SSP2) and before any ME strategies, annual emissions from

Figure S 11. Cumulated greenhouse gas emissions 2016–2060 for Japan by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

residential buildings are projected to decline to 45% of current levels by 2060. Growth in floor area per capita in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, an overall population decline, increased use of electricity in the fuel mix for heating, and a 99% reduction in the GHG intensity of electricity supply.

Passenger vehicles

Japan contributes 10% to total passenger vehicle GHG emission in the G7. ME strategies can provide reduction of cumulative emissions on the order of 5-22%. A modest reduction by 1.3-1.6% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminium, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.7-1.5% through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of vans and passenger cars in the fleet, could reduce cumulative emissions by up to 2%, with greatest reductions in LED. More intensive use, modeled through an introduction of car sharing and ride sharing, would reduce emissions from private vehicles by 12-18% in SSP2 and SSP1, whereas these measures are already implemented in LED

and hence do not lead to further savings. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

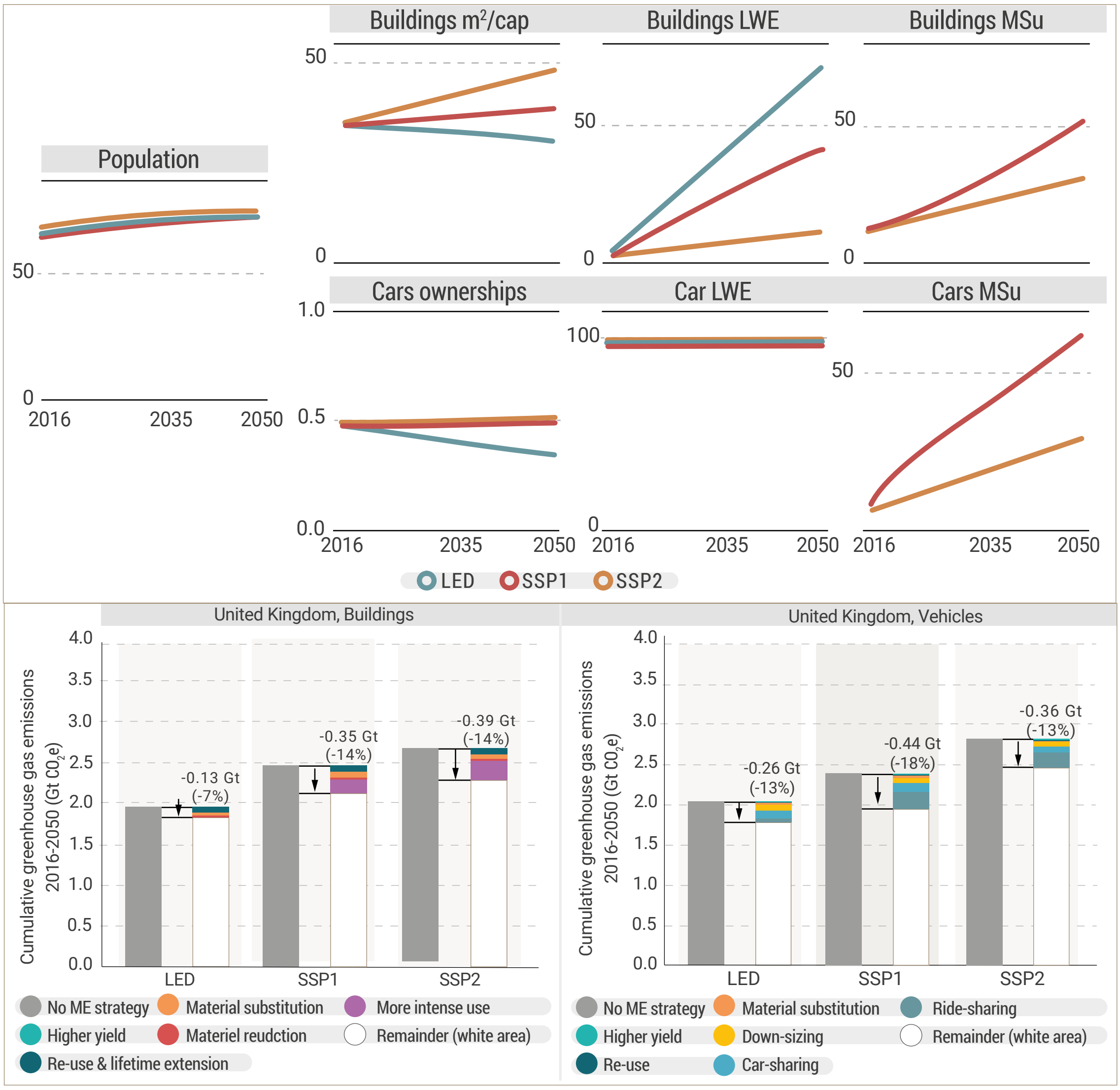
S3.6. United Kingdom

The United Kingdom contributes ca. 5% of the GHG emissions related to residential buildings and vehicles in the G7. It currently has the lowest floor space per capita and one of the lowest cars per capita in the G7.

Residential buildings

Material efficiency strategies can contribute notably to a reduction of residential GHG emissions in the UK. The investigated ME strategies would reduce cumulative emissions by 9-22%, depending on the SSP scenario (Figure S 12). Despite having the lowest residential floor space per person in the G7, there is still considerable potential for GHG reduction through more intensive use, modelled here through a reduction of the required floor space

Figure S 12. Cumulated greenhouse gas emissions 2016–2060 for the United Kingdom by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

per capita by 20%. This would reduce cumulative emissions by 11% in SSP1 and 18% in SSP2, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. One way in which use is likely to intensify is through the move from single-family to multi-family structures, most likely connected to a transition to living in more urban residential areas. More intensive use incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. By 2060, baseline floor area per capita increases to 40 m^2/cap in SSP1, increases to 50 m^2/cap in SSP2, and decreases to 30 m^2/cap in LED. In SSP1 and LED, the material substitution strategy of increased use of wood in construction could reduce life-cycle emissions from buildings by 5% and 7% respectively. Improving material recycling yields reduces emissions by about 1%, while lightweighting in new construction reduces cumulative emissions by 1-2% in each scenario.

Even in the most intensive scenario (SSP2) and before any ME strategies, annual emissions from residential buildings are projected to decline to 49% of current levels by 2060. Modest growth in population and floor area per capita in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, increased use of electricity and fuelwood in the fuel mix for heating, and a 95% reduction in the GHG intensity of electricity supply.

Passenger vehicles

The United Kingdom contributes 5% to total passenger vehicle GHG emission in the G7. ME strategies can provide reduction of cumulative emissions on the order of 10-25%. A modest reduction by 1.6-2.2% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminium, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.8-1.5% through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of passenger cars and sport utility vehicles in the fleet , could reduce cumulative emissions by up to 6%, with greatest reductions in LED. More intensive use, modeled through an introduction of car sharing and ride sharing, would reduce emissions from private vehicles by 12-17% in SSP2 and SSP1, whereas these measures are already implemented in LED and hence do not lead to further savings. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

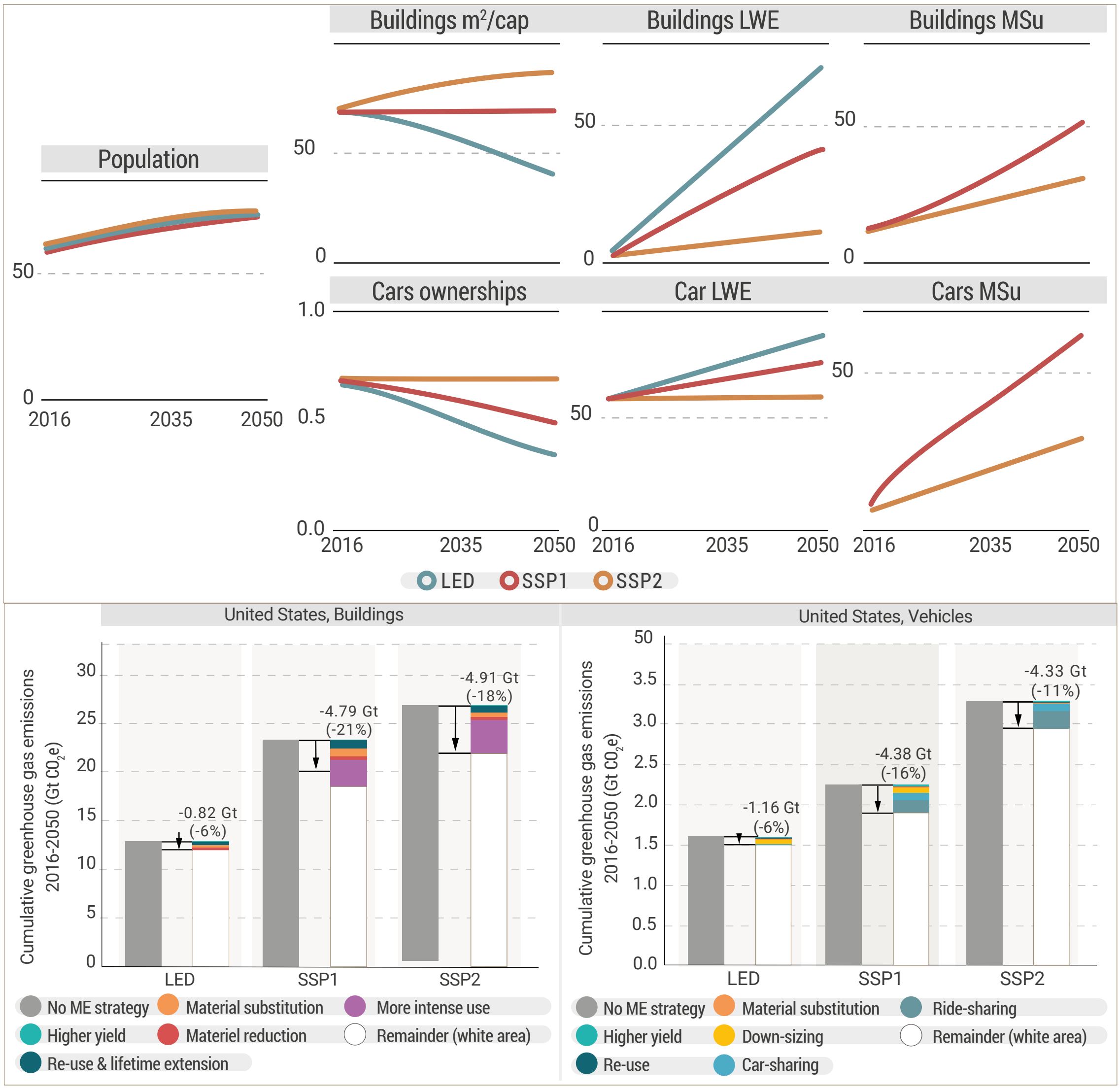
S3.7. United States of America

The United States has the highest contribution to GHG emissions of all G7 member states. It contributes ca. 60% of the GHG emissions related to residential buildings and vehicles in the G7. Compared to other countries, it has very high emissions related to the operations of buildings and vehicles, caused by larger residences, vehicles, lower efficiencies, and longer driving distances per capita. It has the second highest expected population growth in the G7 after Canada, which combined with its current high emissions, large living space and high car ownership per capita, make more intense use an essential strategy which is crucial to reducing national and global emissions.

Residential buildings

The United States contributes to more than half of residential GHG emissions in the G7. Staying within the bounds of a two degree scenario would require a dramatic lowering of those emissions. Material efficiency strategies can contribute substantially to a reduction of emissions. The investigated ME strategies would reduce cumulative emissions by 3-22%, depending on the SSP scenario and ambition level (Figure S 13).

Figure S 13. Cumulated greenhouse gas emissions 2016–2060 for the United States by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

The largest emissions reductions would arise from more intensive use, modelled here through a reduction of the required floor space per capita by 20%. This would reduce cumulative emissions by 19% in SSP1 and 20% SSP2, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. One way in which use is likely to intensify is through the move from single-family to multi-family structures, connected to the current trend towards living in more urban residential areas, as well as a change in planning rules with currently favor single-family housing. More intensive use incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. By 2060, baseline floor area per capita remains at 68 m^2/cap in SSP1, increases to 88 m^2/cap in SSP2, and decreases to 38 m^2/cap in LED. Unlike other G7 countries except Canada, material substitution has almost no effect on US houses, because of the already high prevalence of wood frame housing. Higher recycling yields, incorporating higher material recovery rates in waste streams and improvements in fabrication yields, reduces cumulative GHG emissions by 3% in LED and 2% in SSP1 and SSP2.

Without material efficiency, a growth in residential building space and a decarbonization of the energy supply in a 2 degree scenario would combine to yield annual emissions from residential buildings to 63% of current levels by 2060, not meeting even modest climate targets. Steady growth in population and floor area per capita in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, increased use of electricity and fuelwood in the fuel mix for heating, and a 98% reduction in the GHG intensity of electricity supply. To make meaningful and necessary reductions to residential emissions, it is imperative that floor area per capita declines from current levels.

Passenger vehicles

The US contributes 61% to total passenger vehicle GHG emission in the G7. In the US, emissions from material production and vehicle manufacturing as a share of total emissions is less than in other countries because of the higher number of vehicle kilometers travelled and the fuel consumption of the current fleet. In any 2°C scenario, most of the vehicle-related emission reductions must be from a shift away from gasoline towards electric vehicles, combined with a decarbonization of the electricity supply. ME strategies can provide further reduction of cumulative emissions on the order of 8-24%. A modest reduction by about 1.2-1.7% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminium, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.8-1.5% through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of light trucks and sport utility vehicles in the fleet, could reduce cumulative emissions by up to 6%, with greatest reductions in LED. More intensive use, modeled through an introduction of car sharing and ride sharing, would reduce emissions from private vehicles by 12-16% in SSP2 and SSP1, whereas these measures are already implemented in LED and hence no further savings occur. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

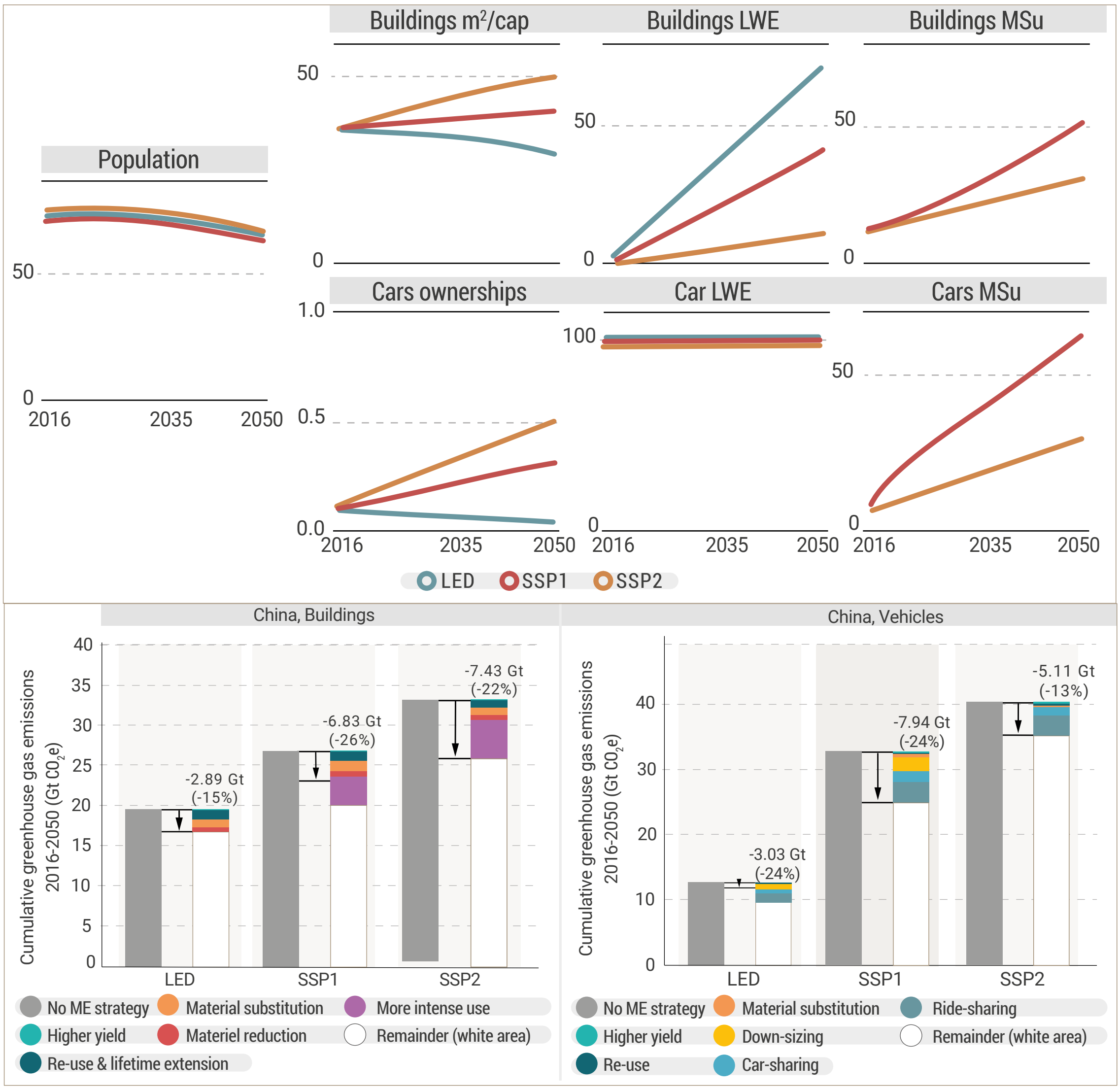
S3.8. China

Residential buildings

China currently has larger residential GHG emissions than any country in the world, although per capita emissions are lower than any country in the G7. Material efficiency strategies can contribute substantially to a reduction of residential GHG emissions in China. The investigated ME strategies would reduce cumulative emissions by 25-38%, depending on the SSP scenario (Figure S 14).

The largest emissions reductions would arise from more intensive use, modelled here through a reduction of the required floor space per capita by 20%. This would reduce cumulative emissions by 16% in SSP1 and 25% in SSP2, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. More intensive use incurs a trade-off, as it reduces the need for new construction and hence the speed with which newer more energy efficient building designs come online. Efficiency gains are also expected to be achieved through retrofits of existing buildings, but this mechanism is not incorporated into our model. Large-scale retrofits are however less likely to have a major effect in China due to the much shorter lifetimes of residential buildings. By 2060, baseline floor area per capita increases to 41 m^2/cap in SSP1, increases to 54 m^2/cap in SSP2, and decreases to 30 m^2/cap in LED. After MIU, the largest potential for emission reduction in SSP1 and LED comes from the material substitution strategy of increased use of wood in construction, which could reduce life-cycle emissions from buildings by 8% and 13% respectively. Higher recycling yields, incorporating higher material recovery rates in waste streams and improvements in fabrication yields, also

Figure S 14. Cumulated greenhouse gas emissions 2016–2060 for China by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

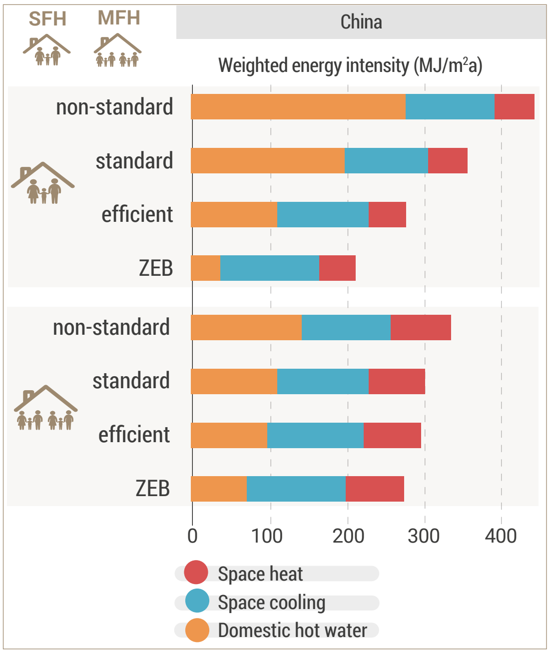
shows considerable potential, reducing cumulative GHG emissions by 8% in LED, 7% in SSP1, and 6% SSP2. Component re-use and longer building lifetimes could reduce cumulative emissions by 1-2% (highest in LED) while lightweighting in new construction could reduce cumulative emissions by 2-4% (highest in SSP2).

With a combination or growing floor space and a decarbonization of the energy system, annual emissions from residential buildings are projected to decline to 50% of current levels by 2060, not meeting climate targets. Growth in floor area per capita in SSP2 is tempered by shifts of population to live in more energy efficient homes, more population living in multifamily homes, an overall population decline starting from the mid 2020s, increased use of electricity and fuelwood in the fuel mix for heating, and a reduction in the GHG intensity of electricity supply to almost zero in 2060.

Passenger vehicles

ME strategies can provide reduction of cumulative emissions on the order of 11-26% for China. A modest reduction by 1.8-2.7% would be achieved through improved yields, recycling, and the use of

Figure S 15. Climate-weighted average energy intensity for the archetype buildings (no ME strategy applied) in China.



These numbers represent full implementation of cooling equipment. However, the final national demand also depends on the implementation level. For instance, not all houses are equipped with air-conditioning systems and the effective cooling demand will therefore be lower. ZEB = Zero Energy Building

remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminium, which is assumed to occur slowly in our scenarios, and would reach a reduction by 0.9-1.8% through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of vans and passenger cars in the fleet, could reduce cumulative emissions by up to 7%, with greatest reductions in LED. More intensive use, modeled through an introduction of car sharing and ride sharing, would reduce emissions from private vehicles by 14-20% in SSP2 and SSP1, whereas these measures are already implemented in LED and hence do not lead to further savings. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

S3.9. India

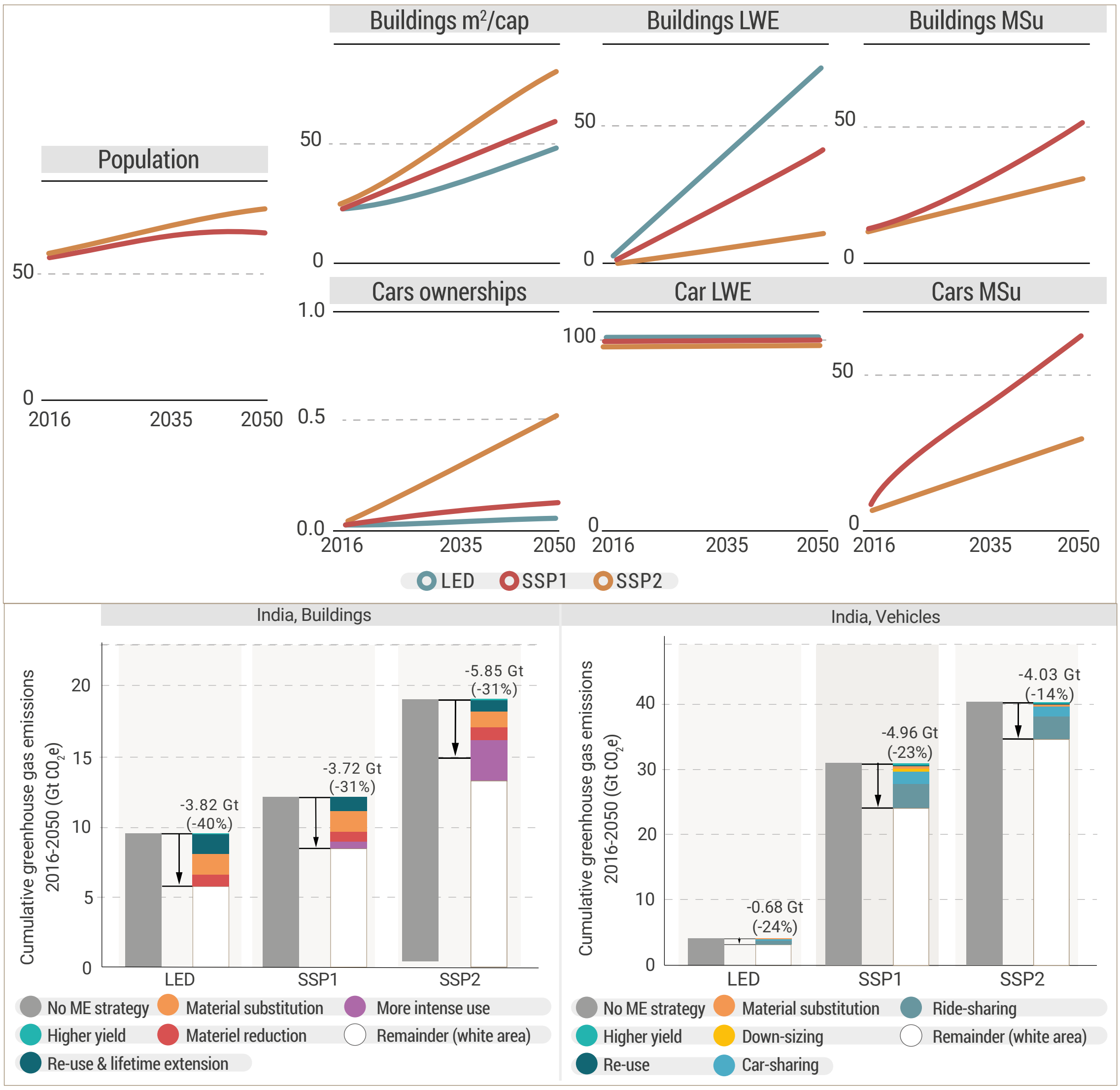
Compared to the other countries in this study, India is expected to see significant population growth over the next few years. At the same time India has service intensity levels that are far below the levels of the G7 countries. Per capita floor area is even below the LED scenario level of 30 m^2/cap. Therefore, it is assumed that per capita floor area and car ownership will continue to grow in all scenario baselines.

Residential buildings

Material efficiency strategies can contribute greatly to a reduction of residential GHG emissions in India. The investigated ME strategies would reduce cumulative emissions by 31-40%, depending on the SSP scenario, a larger percentage reduction than any other country in this study (Figure S 16). This unique position shows that ME is most relevant in emerging economies.

In SSP2 only, the largest emissions reductions would arise from more intensive use, modelled here through a reduction of the required floor space per capita by 20%. This would reduce emissions by 28%, both because it reduces the need for new construction and because it reduces the area that needs space conditioning, thus providing an important synergy between material and energy use reduction. Contrary to other countries, India has already a very intensive use of its limited floor space, and the assumption of a more intensive use scenario means only that floor space would grow more modestly than otherwise assumed. Baseline floor area per capita increases from 12 to 32 m^2/cap by 2050 in SSP1, 43 m^2/cap by 2060 in SSP2, and 28 m^2/cap by 2060 in LED. In SSP1 and LED, the material substitution strategy of increased use of wood in construction could reduce life-cycle emissions from buildings by 18% and 21% respectively. In SSP2 on the other hand, material substitution reduces emissions by just 4%. the most impactful material efficiency strategy after MIU is material reduction with a reduction of 7%.

Figure S 16. Cumulated greenhouse gas emissions 2016–2060 for India by scenarios and ME strategy cascade.



Left: life-cycle GHG emissions from residential buildings; Right: fleet-wide life-cycle GHG emissions from passenger vehicles. Colored areas illustrate the reduction potential compared to a situation without the implementation of any ME strategy (gray bar).

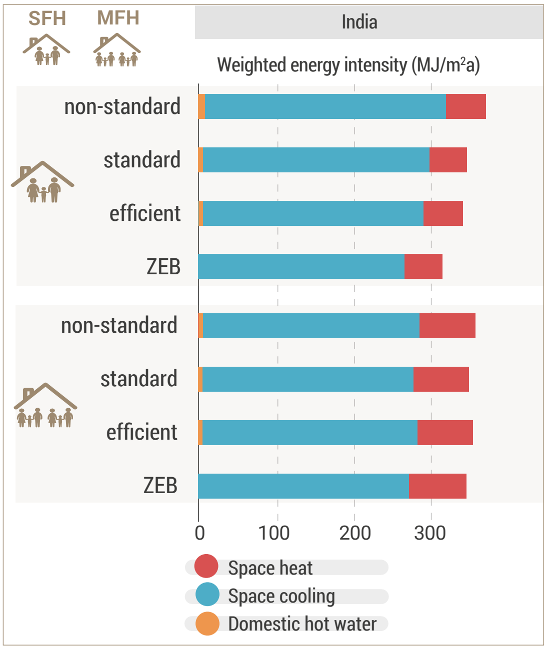
Lightweighting in new construction could reduce cumulative emissions by 8% in LED, 6% in SSP1, and 7% in SSP2.

In all scenarios, baseline annual emissions from residential buildings are projected to increase from current levels by 2060, largely driven by increasing population and floor space per person. Indian electricity currently has one of the highest GHG intensities globally, and will need to halve in SSP1, or become zero in SSP2.

Passenger vehicles

ME strategies can provide reduction of cumulative emissions on the order of 7-27%% for India. A modest reduction by 1.8-2.9% would be achieved through improved yields, recycling, and the use of remanufactured parts in automobile production. A similar reduction would be achieved by a light-weighting of vehicles through a shift from steel to lighter materials, here aluminium, which is assumed to occur slowly in our scenarios, and would reach a cumulative reduction by 1.0-1.9% by 2060 through operational fuel savings. A shift of the composition of the vehicle fleet, modeled here yields a reduction of the share of vans and passenger cars in the fleet, could reduce cumulative emissions by up to 2%, with greatest reductions in LED. More intensive use, modeled through an introduction of car sharing and ride sharing, would reduce emissions

Figure S 17. Climate-weighted average energy intensity for the archetype buildings (no ME strategy applied) in India.



These numbers represent full implementation of cooling equipment. However, the final national demand also depends on the implementation level. For instance, not all houses are equipped with air-conditioning systems and the effective cooling demand will therefore be lower. ZEB = Zero Energy Building

from private vehicles by 15-22% in SSP2 and SSP1, whereas these measures are already implemented in LED and hence do not lead to further savings. Higher reductions are possible if these measures are phased in more quickly. The measures are largely complementary to the electrification of the fleet and achieve additional emission reductions. Research indicates that more intensive use and a shift of the vehicle fleet composition towards smaller vehicles can both be achieved through a move towards car sharing, whereas ride sharing would only increase the use intensity.

S4. References for Appendix A

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