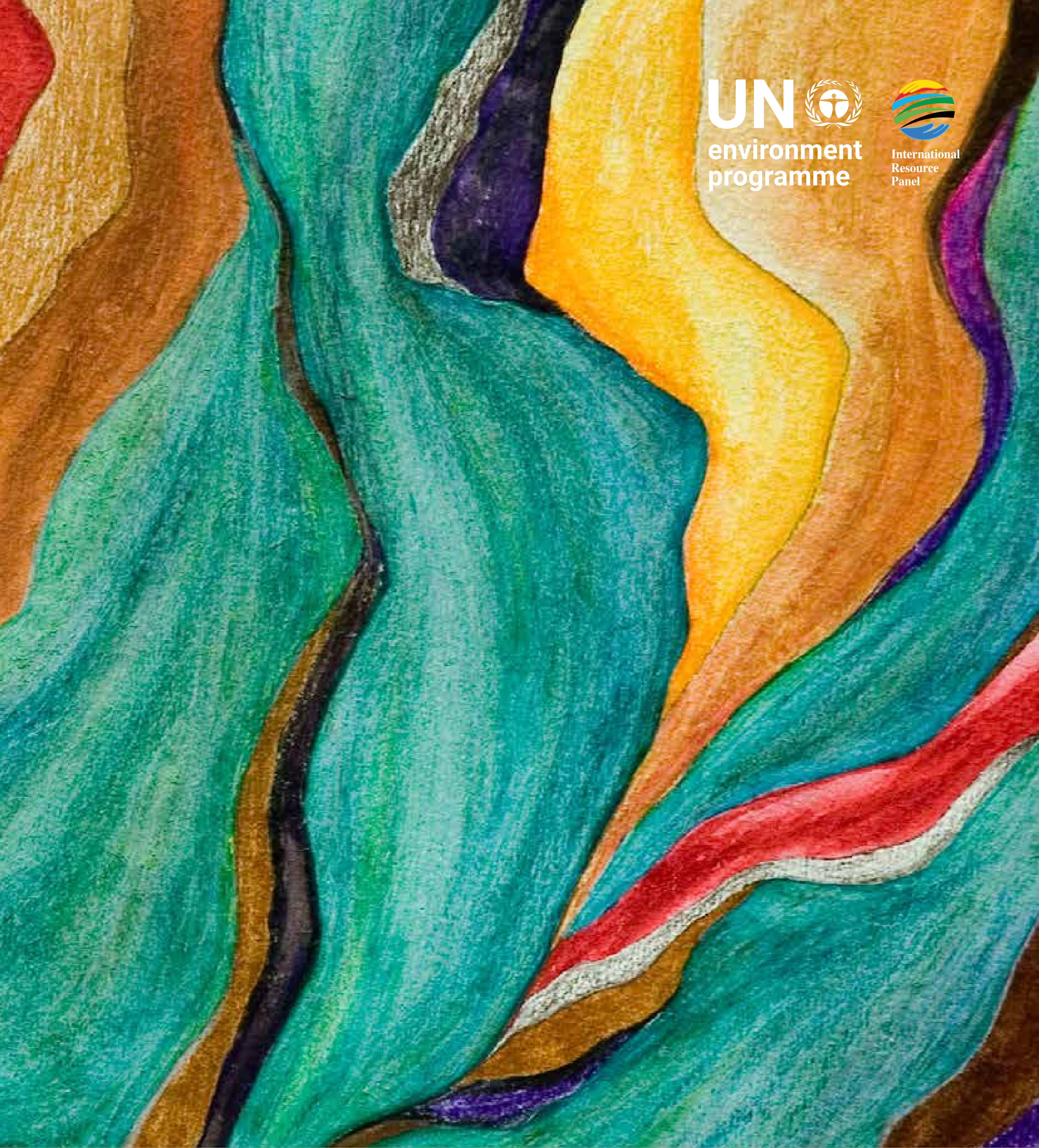

RESOURCE EFFICIENCY AND CLIMATE CHANGE

Material Efficiency Strategies for a Low-Carbon Future

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UN environment programme

International Resource Panel

Resource Efficiency and Climate Change

Material Efficiency Strategies for a Low-Carbon Future

Credit: Ricardo Gomez Angel/Unsplash

Foreword

In 2019, the UN Environment Programme (UNEP) published the tenth edition of its Emissions Gap Report, which revealed that the world must immediately begin delivering deeper and faster greenhouse gas emission cuts to keep global temperature rise to 1.5°C. To achieve this goal, we will need to use the full range of emission reduction options, including the implementation of material efficiency strategies.

The International Resource Panel (IRP) has been providing insights into how humanity can better manage its resources since 2007. Its research shows that natural resource extraction and processing account for more than 90 per cent of global biodiversity loss and water stress and approximately half of global greenhouse gas emissions. This new IRP report, Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future, commissioned by the Group of 7, points to exciting new opportunities to reduce these impacts through material efficiencies in homes and cars.

Climate mitigation efforts have traditionally focused on enhancing energy efficiency and accelerating the transition to renewables. While this is still key, this report shows that material efficiency can also deliver big gains. According to IRP modelling, emissions from the material cycle of residential buildings in the G7 and China could be reduced by at least 80 per cent in 2050 through a series of material efficiency strategies. A more intensive use of homes, design with less material, and improved recycling of construction materials are among the most promising strategies.

Likewise, material efficiency could deliver significant emission reductions in the production, use and disposal of cars. Specifically, material efficiency strategies could reduce emissions from the material cycle of passenger cars in 2050 by up to 70 per cent in G7 countries and 50 to 60 per cent in China and India. The largest savings would come from a change in patterns of vehicle use (ride-sharing and car-sharing) and a shift towards more intensive use and trip-appropriate smaller cars.

This report makes it clear that natural resources are vital for our well-being, our housing, and our transportation. Their efficient use is central to a future with universal access to sustainable and affordable energy sources, emissions-neutral infrastructure and buildings, zero- emission transport systems, energy-efficient industries and low-waste societies. The strategies highlighted in this report can play a big part in making this future a reality.

Inger Andersen
Executive Director
United Nations
Environment Programme

Preface

We are living in a crisis of global heating, which poses a great threat to the wellbeing of the global population that will exceed 9 billion people by mid-century. At the same time, there is a great opportunity to reshape our production and consumption systems in ways that respect planetary boundaries and support societal wellbeing. Material- efficiency strategies will play an essential role in this endeavor, for example, by providing low-carbon housing and mobility services.

The International Resource Panel (IRP) was launched in 2007 to provide independent, authoritative and policy relevant scientific assessments on the status, trends and future state of natural resources. In 28 reports, the Panel has advanced knowledge as to how society can decouple economic development and well-being from environmental degradation and resource use.

The attention of policymaking to natural resources has increased in the last decade under frameworks such as the Circular Economy, Sustainable Materials Management and a Sound Materials-Cycle Society. Yet, as shown by this report, policies related to material use still largely focus on waste management rather than reduction of greenhouse gas emissions. Policies and research on natural resources must be better aligned to the urgent need of mitigating and adapting to climate change.

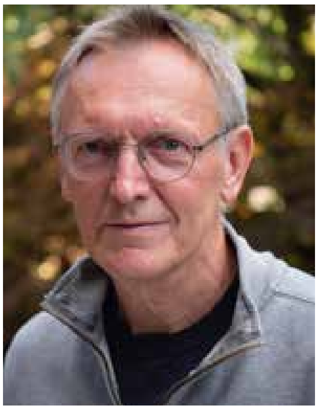
The IRP is a proud knowledge provider to the Group of 7 on sustainable resource management. Back in 2017, the IRP published a report commissioned by the G7 entitled "Resource Efficiency: Potential and Economic Implications". This report provided scientific evidence showing that increased resource efficiency is not only practically attainable but also contributes to economic growth, job creation and climate change strategies. As a follow-up to this work, the G7 asked the IRP to zoom into the contributions of resource efficiency to greenhouse gas emission reductions.

Consequently, this new report, Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future, examines the mitigation opportunities presented by higher material efficiency in the production and use of residential buildings and light-duty vehicles.

The unprecedented integrated bottom-up modeling of the report shows, for example, that in 2060, these strategies could reduce a significant amount of GHG emissions associated with the material cycle of residential buildings. More concretely, the modelling tells us that within this sector, we would have 350 million tons less of GHG emissions in China; a 270 million tons less in India, and 170 million tons less in G7 countries, between 2016 and 2060. Opportunities are as significant for material efficiency strategies applied to cars. Even better news, material- efficiency strategies are based on proven technologies available today and therefore provide tangible options for moving towards a 1.5°C target.

The report finds that policy intervention from different angles is required to achieve these savings. Policies can influence how people live, which materials they use and how they use them. Instruments such as taxation, zoning and land use regulation play a role, but so do consumer preferences and behavior.

We are grateful to Edgar Hertwich and his team for their dedicated efforts to produce new insights into the material-climate nexus. Material efficiency is an important piece in the climate puzzle, particularly at a moment when more ambitious, fast-paced and impact-driven action is so urgently needed to ensure a prosperous future for all.



Janez Potočnik
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Izabella Teixeira
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Credit: MarioGuti/iStock/Getty Images Plus

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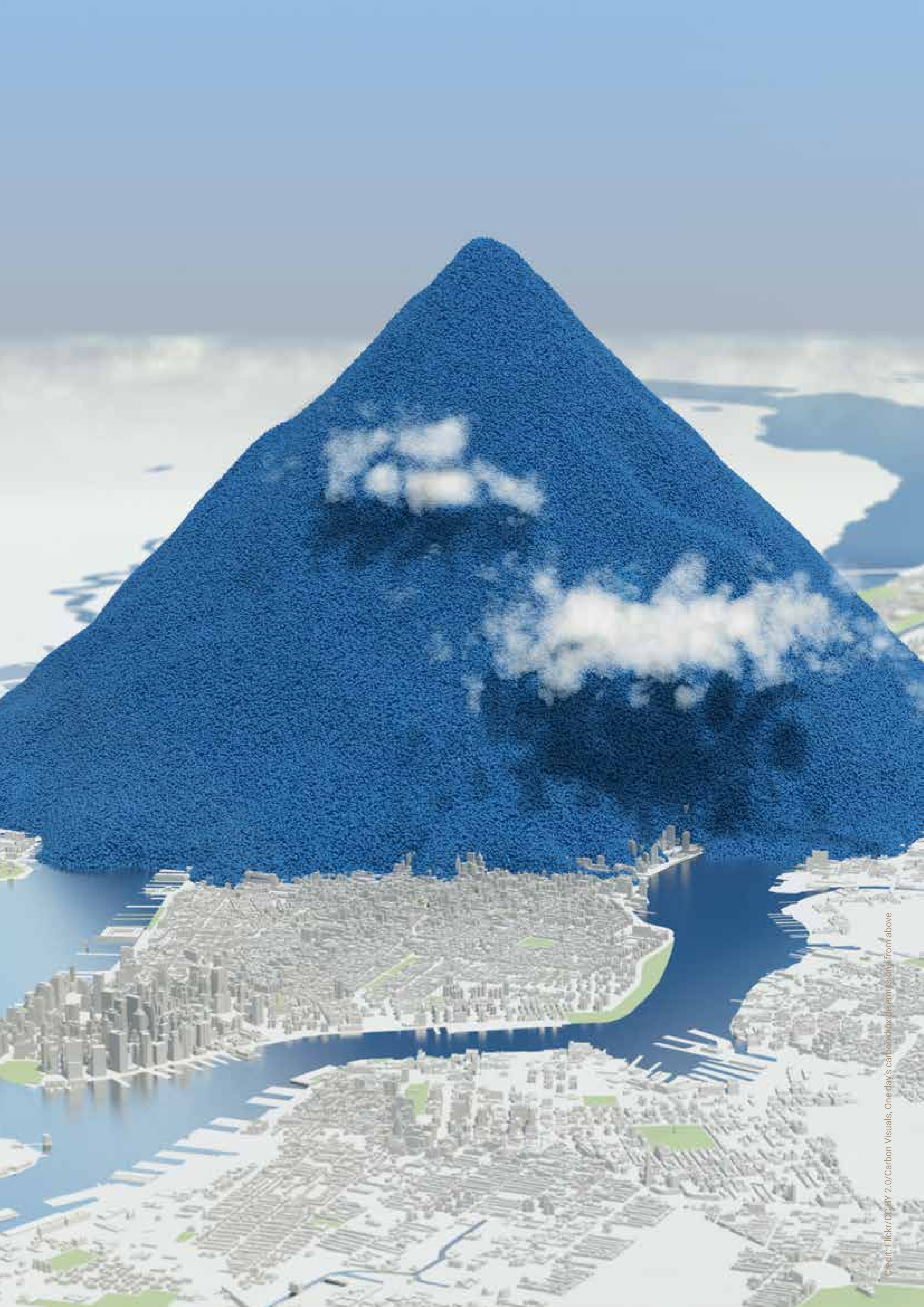
Glossary

Term	Acronym, units	Description
Battery electric vehicle	BEV	Vehicle that runs solely on battery power and electric motors, thus lacking an internal combustion engine or fuel cell.
Building Information Modelling	BIM	Modelling a building project in a three-dimensional environment through collaboration with architects, engineers, contractors and suppliers.
Car-sharing		Vehicles owned by a company or individuals that are shared through an online platform and rented for short periods, either from a fixed location or free-floating.
Circular economy	CE	An economy where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimized.
Construction & demolition waste	C&DW	Waste generated during the construction, renovation, or demolition of a building or infrastructure.
Energy intensity	EI, MJ/m^2a or MJ/km	Energy demand per unit (and year).
End-of-life recovery rate improvement	EoL	ME strategy investigated in this report concerned with improving the recovery and recycling of materials from products no longer in use and discarded, to increase the amount of secondary materials available.
Fabrication yield improvement	FYI	ME strategy investigated in this report which reduces the amount of material scrap in the fabrication process, thereby lessening the demand for primary materials.
Greenhouse gas emissions	GHG, kg or Gt CO_2e	Emissions of gases that cause the greenhouse effect. Reported in units of potency equivalent to that of a kilogram, ton, or gigaton of carbon dioxide.
Hybrid electric vehicle, plug-in hybrid electric vehicle	HEV, PHEV	A type of automobile that switches between an electric driving system and an internal combustion engine system, with a plug-in having the additional capability to charge its battery at a charge station.
Hydrogen fuel cell electric vehicle	HFCEV	A type of electric vehicle that uses compressed hydrogen and oxygen in air to generate electricity and power its electric motor. This vehicle could carry a battery.
International Code Council	ICC	An association responsible for setting the standards that govern the design and construction of buildings
Internal combustion engine vehicle- gasoline/ diesel	ICEV-g, ICEV-d	Automobile that runs on internal combustion engine technology using gasoline or diesel as fuel.
International Energy Agency	IEA	A Paris-based intergovernmental organization that acts as an energy policy advisor to its 29 member countries, the European Commission and other nations.
International Institute for Applied Systems Analysis	IIASA	An international research institute that conducts studies on global environmental, economic, technological and social change. Based in Austria.
Life-cycle emissions		The emissions associated with the entire life cycle of a product, including material production, construction, operations and disposal. Includes credit for replacing primary materials when recycling at the end-of-life of a product, and for the storage of carbon in wood. Also labelled as 'systems-wide' emissions. Here, they refer to the system-wide emissions associated with the production, operations, and disposal of the entire modelled product stock.
Low Energy Demand (scenario)	LED	A scenario aiming to limit global average temperature rise to 1.5°C through the implementation of radical energy demand reduction efforts and with renewable energy, without using CO_2 capture and storage. One of three scenarios investigated in this report.
Light truck	LT	According to the United States EPA, a light truck is an automobile that is not a car or a work truck. Both, passenger cars and light trucks, are grouped together under the category light-duty vehicle, i.e., a vehicle up to a gross weight of 8,500 lbs (3,856 kg).
Lifetime extension	LTE	ME strategy investigated in this report to increase the lifetime of products through better design, increased repair and enhanced secondary markets.
Per capita floor area	m^2/cap	The average residential floor area available per person.
Material-cycle emissions		Emissions associated with producing and processing materials, including credit for replacing primary materials when recycling at the end-of-life of a product, and for the storage of carbon in wood (Guest et al., 2013).

Term	Acronym, units	Description
Material Efficiency	ME	The pursuit of technical strategies, business models, consumer preferences and policy instruments that would lead to a substantial reduction in the production of high-volume, energy-intensive materials required to deliver human well-being; expressed as a ratio of the amount of product or service obtained by unit of material use.
Material Efficiency cascade	ME cascade	The ME strategies investigated here were applied as bundles according to their life-cycle and in a specific order.
Material Efficiency strategy	ME strategy	A unique approach to improve material efficiency. In this report, a range of strategies is modelled and their implementation through policy is investigated, as listed in Table 1.
Multi-family home	MFH	A type of housing where multiple housing units are contained within one or several buildings within a complex (e.g., apartments).
Material intensity	MI, kg/m^2 and kg/car	Amount of material content per unit or product.
More intensive use	MIU	ME strategy investigated in this report entailing the use of less product to provide the same service. MIU of vehicles increases the occupancy of vehicles, which could be achieved by ride-sharing (car pooling), or the utilization rate of the vehicle, which can be achieved through car-sharing. For buildings, MIU could consist of peer-to-peer lodging, increasing household size/cohabitation, reduction of floor space per person, and the reduction of second homes.
Material substitution	MSu	ME strategy investigated in this report in which materials in products are replaced by other materials (e.g., wood replacing cement and steel in buildings and aluminium replacing steel in cars).
Open dynamic material systems model	ODYM	An open model for Material Flow Analysis developed by Pauliuk and Heeren (2019).
Open dynamic material systems model for the resource efficiency and climate change mitigation project	ODYM-RECC	A modular depiction of product stocks in major end-use sectors and the associated material cycles of climate-relevant bulk materials.
Passenger car or light-duty vehicle	PC or LDV	A motor vehicle designed or adapted for the primary purpose of transporting people.
Passenger kilometre travelled	PKT	A km of distance traveled by a passenger. Related to vehicle kilometres travelled (VKT) through the occupancy factor (number of passengers per vehicle).
Percentage point	pp	Arithmetic difference between two percentages. For example, the difference between 20% and 22% is two percentage points, but 22% is 10% larger than 20%.
Resource Efficiency	RE	Efficient use resources including materials, water, energy, biodiversity, land and, in the context of climate change, financial resources.
Reduce, reuse, recycle	3Rs	Indicates an order of priority for strategies to reduce and manage waste.
Reuse	ReU	ME strategy investigated in this report consisting of recovery, remanufacturing, and reuse of components or products displacing the production of spare parts or primary products.
Ride-hailing		Digital platforms that connect drivers using their personal vehicles as de facto taxis with passengers.
Ride-sharing		Digital applications that match drivers and passengers with similar origin-destination pairings.
Section	Sec	Abbreviation used to refer to sections, especially in legal texts.
Single-family home	SFH	A housing unit with a stand-alone structure and its own lot intended for one family.
Shared Socioeconomic Pathway	SSP	Narratives and socioeconomic scenarios used by modellers to develop global energy and GHG emissions scenarios.
Sound Material-Cycle Society	SMCS	According to the Japanese Basic Act for Establishing a Sound Material-Cycle Society "a society in which the consumption of natural resources is conserved and the environmental load is reduced to the greatest extent possible, by preventing or reducing the generation of wastes and by promoting proper cyclical use and disposal of products and materials".
Sustainable consumption and production	SCP	A framework encompassing any and all issues that seek to improve the way that products and materials are sourced, manufactured and marketed and the way that products are purchased, used, and disposed of at the end of their useful lives.
Using Less Material by Design	ULD	ME strategy investigated in this report regarding reducing the size or solid mass of products, which reduces the amount of materials in the product and potentially also the energy required for operation (e.g. using less steel in the bearing structure of buildings and shifting from light trucks to passenger cars or microcars).
Vehicle-kilometres of travel	VKT	A measurement of the total distance traveled by vehicles in a given area over a specified period.
Zero Energy Building	ZEB	A building with a very low energy demand. When equipped with photovoltaics, such buildings produce as much energy as they consume throughout the year.



Executive Summary

The Need for Material Efficiency

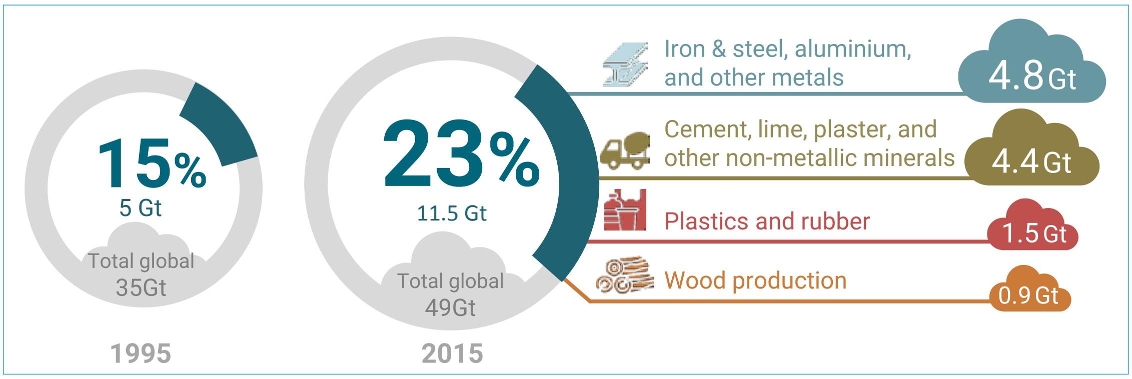
Increasing material efficiency (ME) is a key opportunity for moving towards the 1.5° C target in the Paris Agreement. Materials are vital to modern society, but their production is an important source of greenhouse gases (GHGs). Emissions from the production of materials increased from 5 gigatons (Gt) of CO_2-equivalent in 1995 to 11 Gt in 2015, with their share of global emissions rising from 15 per cent to 23 per cent. This corresponds to the share of GHG emissions from agriculture, forestry and land-use change, yet these have received much less attention. Here, materials are understood as solid materials including metals, wood, construction minerals and plastics. Fuel, food or reagents are not included. Most of the material-related emissions stem from the production of bulk materials: iron and steel (32 per cent), cement, lime and plaster (25 per cent), as well as plastics and rubber (13 per cent).

Construction and manufactured goods each account for 40 per cent of the GHG emissions from global materials production in terms of material use with a climate impact. Residential buildings are the most important "product" in the construction sector, while light-duty vehicles are the most important product in manufacturing. Most materials are used in long-lived products that become part of the capital stock.

GHG emissions from material production can be reduced through both supply and demand-side measures. On the supply side, increased efficiency of production processes, a shift towards low-carbon fuels and feedstocks and CO_2 capture and storage are the prominent strategies. On the demand side, a more efficient use of materials through strategies including products that use less material by design, lifetime extension, service efficiency, reuse and recycling can help reduce material use and associated GHG emissions. Material efficiency may be deployable more quickly than some of the supply-side strategies that depend on either substantial technical breakthroughs or large-scale investments. Furthermore, supply-side material efficiency strategies may compete for access to technologies and resources also required for decarbonizing emissions in electricity, transport and heating fuels.

This report (a) assesses the reduction potential of GHG emissions from material efficiency strategies applied to residential buildings and light-duty vehicles; and (b) reviews policies that address these strategies. The life cycles of homes and cars are studied in detail to understand the functional interconnections between materials and energy use in the production, operation and disposal of these products over time and to determine the

Figure 1. Emissions caused by material production as a share of total global emissions 1995 vs. 2015



availability of secondary materials from discarded products. Modelling quantifies GHG emissions from energy supply and primary materials production, as well as the storage of carbon in wood products and the ability of recycled materials to replace virgin materials. Alternative ways of providing the services of these product systems (such as public transport) are outside the scope of this study.

The impact of material efficiency strategies is quantified on the basis of scenarios for the demand for building space and car transport, population and economic projections, as well as storylines consistent with the Shared Socioeconomic Pathways (SSP) 1 or 2 – which are widely used in climate scenario modelling. Both scenarios consider decarbonization of the energy mix and a shift towards electric vehicles compatible with the target of limiting global warming to 2°C. A third scenario relies extensively on more efficient use of and reduced demand for energy and materials to keep global temperature rise to 1.5°C.

Additional emission reductions arising from material efficiency are estimated by comparing scenarios with and without the implementation of various material efficiency strategies. The reduction of GHG emissions quantified in this report is therefore in addition to reductions achieved through the assumed decarbonization of the energy supply and the shift towards electric vehicles.

More details on the assumptions of the model can be found in section 2.2.3.

Emission Savings from Material Efficiency in Homes

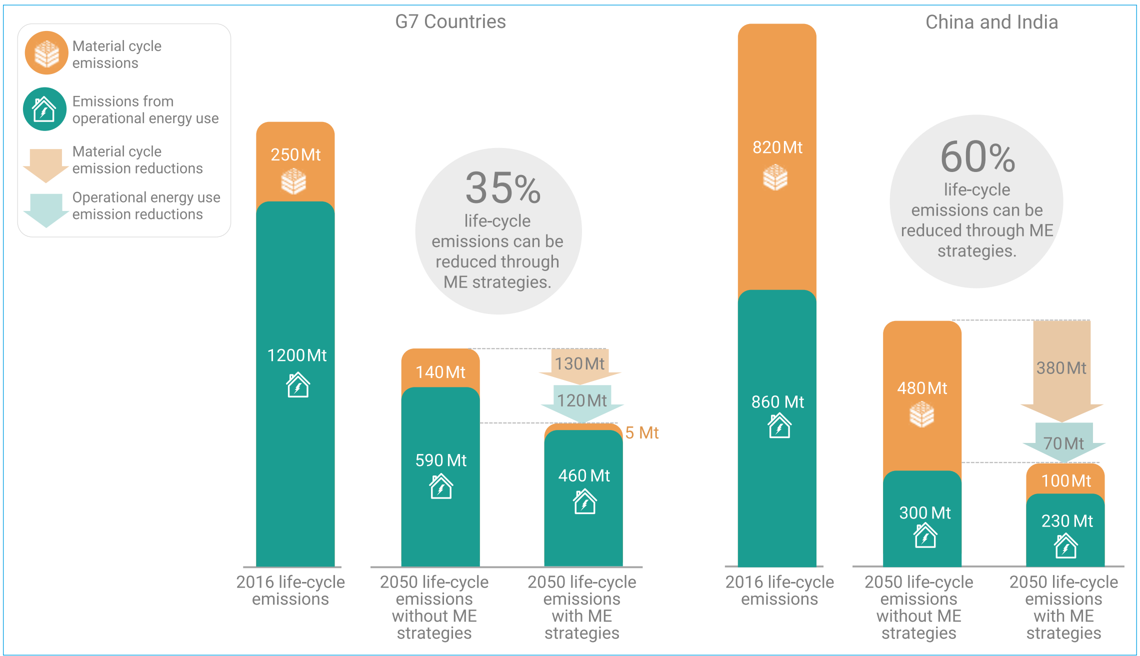
Changes in the design, construction, maintenance and demolition of buildings can: reduce the amount or carbon intensity of construction materials required, decrease the energy used during a building's operation, extend a building's lifetime and make materials and components available for reuse or recycling (thereby removing the need for virgin materials or new components).

To capture the effect of material efficiency strategies on emissions throughout the life cycle of buildings, life-cycle assessment was combined with energy demand modelling of building archetypes – illustrative representations of building types – while tracking the construction, use and demolition of building cohorts over time. Archetypes used in the modelling represent single family and multi-family houses of different energy-efficiency standards and varying construction methods including reinforced concrete and wood-frame construction. The modelling incorporates the effect of material efficiency measures on both material and energy use.

The modelling shows that the use of material efficiency strategies can result in substantial reductions in the demand for virgin materials and associated GHG emissions. More intensive use of homes (for instance, less floor area per person) also reduces GHG emissions from the heating and cooling of buildings. These savings are discussed below.

- **Lighter buildings:** Prevailing building methods and design result in higher carbon footprints than necessary due to the overuse of carbon-intensive materials such as steel, cement and glass. Buildings that are lighter and designed closer to technical specifications use less material and can lower associated emissions across the G7 nations by between 8 and 10 per cent by 2050.
- **Using wood instead of reinforced concrete and masonry:** Emission reductions of 1 to 8 per cent are possible in the G7 with even greater potential in China and India, where larger volumes of new construction are expected, and timber currently is not widely used. As suggested by modelling land-use competition, however, timber supply is potentially limited in many climate change mitigation scenarios, and climate benefits only apply to sustainably sourced wood products.
- **Reducing demand** for floor space by up to 20 per cent compared to the reference scenario could lower material related GHG emissions from the construction of residential buildings by up to 73 per cent by 2050 when emissions savings from recycled building materials used elsewhere in the economy are credited. More intensive use can be achieved when individuals choose to live in smaller units in multi-family residences rather

Figure 2. Life-cycle emissions from homes with and without material efficiency strategies in 2050 in G7 countries, China and India



than single-family homes – a change that is becoming increasingly popular in urban areas. Furthermore, individuals can be encouraged to share homes and related residential facilities (as in co-housing) and to move to smaller residences when families downsize (for example when children move out). More intensive use may also be attractive when associated with urban lifestyles and easier access to job markets and public amenities.

- **Improved recycling:** In 2016, the recycling of building materials saved 15 to 20 per cent of the emissions in the primary production of materials for residential buildings in the G7. Under optimistic assumptions, improved recycling could save an additional 14 to 18 per cent.

Emission reductions from reduced energy use for heating and cooling (resulting from more intensive use of homes) can be as large as the reductions associated with reduced use of construction material. Among the G7 countries, the residential building sector in the United States of America has the largest potential emission reductions.

If applied at their full technical potential, the assessed material efficiency strategies could combine to reduce annual GHG emissions associated with the material cycle of the construction of residential housing in G7 countries and China by 80 to 100 per cent in 2050, compared to a scenario without material efficiency. Savings in India would be 50 to 70 per cent. In 2050, this translates to annual GHG savings of 130-170 million tons in the G7, 270-350 million tons in China and 110-270 Mt in India. Reduced floor space also reduces the need for heating and cooling, resulting in estimated emissions savings of 120-130 million tons in the G7 by 2050.

Looking at the whole building life cycle, in 2050 the material efficiency strategies researched could reduce emissions from the construction, operation and deconstruction (dismantling) of homes by 35 to 40 per cent in the G7. Analogous savings could be up to 50 to 70 per cent in China and India, where building energy use is lower and the importance of carbon storage in wood-based construction would play a larger role.

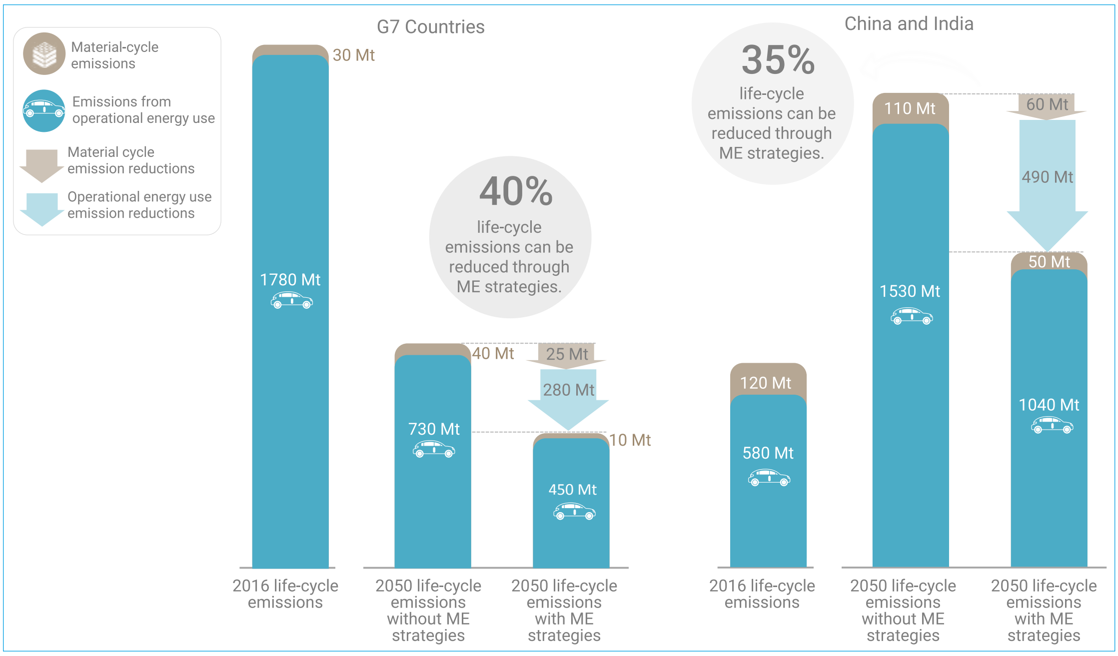
Emission Savings from Material Efficiency in Cars

Similar to the analysis of strategies for buildings, the modelling of light-duty vehicles assesses the effect of material efficiency measures on: material and energy use in vehicle manufacturing; energy use in vehicle operations; and the availability of recycled materials. It incorporates changes in the vehicle fleet and the timing of the availability of end-of-life vehicles for recycling. Material from end-of-life vehicles that is not used to manufacture new vehicles is mostly downcycled to construction and credit is given for the displacement of primary material.

Compared to a scenario where no new material efficiency strategies are implemented, the modelled material efficiency strategies in the G7 can save up to 25 Mt CO_2e per year from the material cycle of vehicle production and disposal in 2050. Similar savings of 25-30 Mt per country can be attained in China and India. Synergistic emission reductions associated with reduced operational energy use are 280-430 MtCO_2e per year in the G7 and 240-270 Mt per country in China and India.

- Materials recovered from end-of-life vehicles are widely recycled in G7 countries. The use of recycled materials can offset half of the GHG emissions associated with the production of materials used in cars. However, secondary steel obtained from car recycling using current technology is contaminated with copper, thereby potentially limiting scrap use as market conditions evolve. Innovative scrap recovery could enable closed-loop recycling and increase GHGs savings by up to one third.
- Improvements in manufacturing yields, fabrication scrap reuse and end-of-life recovery can reduce annual material cycle GHG emissions by up to 38 per cent by 2050. Lifetime extension of vehicles is a double-edged sword, as it may cause prolonged use of inefficient vehicles. Lifetime extension for electric vehicles and increased reuse of parts leads to additional savings of 5 to 13 per cent in the G7, 14 per cent in China and 9 per cent in India.
- Reducing vehicle weight through material substitution leads to fuel savings during vehicle operations. A shift from steel to aluminium in vehicle material composition shows an increase of materials-cycle GHG emissions, while the total emissions throughout the vehicle life cycle are reduced. Other light-weighting strategies, such as the use of high-strength steel and carbon fibre, exhibit similar trade-offs.
- Ride-sharing, car-sharing and a shift towards smaller vehicles imply a change in the patterns of vehicle use. Both ride- and car-sharing have the potential to reduce the total vehicle stock required for meeting travel demand, leading to a lower material demand for vehicle manufacturing. If 25 per cent of the trips in the G7 were conducted as shared rides, emissions would be reduced by 13 to 20 per cent. Reductions would be similar in China and India. A partial shift towards smaller vehicles would reduce material-cycle emissions

Figure 3. Life-cycle emissions from cars with and without material effciency strategies in 2050 in G7 countries, China and India



by 14 to 19 per cent in the G7, 4 per cent in China and 3 per cent in India.

Taken together, in 2050 the improvements in material efficiency can reduce annual material-cycle emissions in vehicle manufacturing and disposal by 57 to 70 per cent in the G7, 29 to 62 per cent in China and 39 to 53 per cent in India. Material-cycle strategies such as the reuse of components and changes in use patterns (e.g. ride-sharing, smaller vehicles) both play important roles.

Several of the material efficiency strategies researched simultaneously reduce energy use for the manufacturing and operations of vehicles. The emission savings from operational energy use reductions would be several times larger than those from material production, including reductions in scenarios that reflect a gradual shift towards battery-electric and fuel cell vehicles. The material efficiency strategies researched could reduce total G7 GHG emissions for the manufacturing, operations and end-of-life management of cars by 30 to 40 per cent (the equivalent of 300-450 million tons CO_2) in 2050. Savings in China and India would be 20 to 35 per cent. The most important strategies for the reduction in overall life-cycle emissions are ride-sharing, car-sharing and a shift towards smaller vehicle sizes.

Material Efficiency Policy

Climate change policies have focused on energy efficiency rather than materials efficiency as a central strategy for GHG emissions reduction. Material efficiency policies typically emerged through efforts to improve the environmental and resource dimensions of waste management (as exemplified by attention to the 3Rs) with limited linkages to climate change mitigation.

Clarity of purpose and intentional policy change are crucial for linking material efficiency and climate change mitigation. The sharing economy, both for lodging and transportation, has generated considerable enthusiasm in environmental circles as an impetus for resource efficiency. The research on sharing reviewed in this report, however, shows that the sharing economy can lead to increased emissions. This serves as a reminder that sustainability must be “designed in.” Without policy steering and regulation, other societal benefits may result from these new developments, but emissions may increase further. Policies can be specific to a sector or even to a particular material efficiency strategy. They can also cut across sectors and strategies.

The policies identified in this rapid assessment do not yet align well with the results from the modelling. Policies related to material efficiency have traditionally focused on recycling, while other equally or more promising strategies have typically not been the focus of either resource- or climate-oriented policies. In other cases, material efficiency strategies have either been the subject of limited policy development (as with the use of mass timber in construction), or such strategies have not been a policy focus at all (as with shared housing or mobility). Rigorous quantitative ex-post policy evaluation is uncommon. Thus, in many cases, knowledge of policy efficacy is simply very limited, making judgments difficult as to how best use policy to realize the benefits indicated by the modelling.

Policies for Material Efficiency in Homes

For many material efficiency strategies for building and construction, design is a crucial point of intervention. Design is indirectly shaped by policy — primarily through building codes. Decisions at the design stage affect material choice, construction techniques, opportunities for increased building lifetimes and end-of-life strategies including deconstruction, component reuse and construction and demolition recycling. This suggests the need for careful attention to the content of building standards and codes, as well as to their dissemination and adoption by public authorities. In particular, performance standards rather than prescriptive standards can play a key role in removing barriers to innovative material efficiency practices.

Increasing use of building information management (BIM) software and prefabrication can facilitate the adoption of practices and technologies that reduce material use. In some jurisdictions like the United Kingdom, Denmark, and the state of Wisconsin in the United States, they are mandated for use in the construction primarily of larger buildings. Policies for end-of-life management (namely the reuse and recycling of construction and demolition waste) are widespread, but are often focused on landfill diversion. If material efficiency is to lead to climate change mitigation, policy targets need to shift to, or at least include, GHG emission reduction goals.

Increased intensity of use of residential buildings through shared and smaller housing is shaped by building codes but also zoning and land use regulation; property, carbon and other taxes; urbanization; demographic trends; and consumer preferences. Shared and smaller housing can be encouraged through changes in regulation and taxation but will also require changes in behaviour and lifestyle.

Policies for Material Efficiency in Cars

Material efficiency policies related to cars largely revolve around material choice and end-of-life management. A reduction in materials consumption through light-weight design has been a side-effect of policies aimed at reducing fuel consumption and GHG emissions in vehicle operation. In many countries, however, policies have been too weak to counter the trend towards larger, heavier vehicles. Some forms of light-weighting can present trade-offs between increased carbon emissions in production and lessening of emissions during use.

Current policy towards shared mobility in the form of car-sharing and ride-hailing is appropriately focusing on issues of company and driver behaviour, impacts on public transit use and congestion. While emissions from vehicle travel are part of policy discourse, discussions of material use are much less common. Two especially important imperatives for material efficiency-related policy are: ongoing, systematic access to data; and incentives for ride-splitting and other practices that encourage the use of under-utilized capacity rather than purchase and use of additional vehicles.

End-of-life management for cars has focused on de-pollution and, because metal from cars is readily recycled, increasing recycling and recovery rates of non-metallic residues from car shredding. Policy has been less focused on the GHG implications of ELV management targets. Adjustment of ELV policy to increase closed-loop recycling and attendant opportunities to reduce GHGs warrants attention.

Cross-cutting Policies for Material Efficiency

Policies that cut across sectors or that are cross-cutting by nature may have more impact than those focusing specifically on one sector (such as homes or cars) or that are one dimensional. These include building certification, green public procurement (GPP), virgin material taxes, recycled content mandates and removal of virgin material subsidies. Building certification provides potential leverage to increase uptake of many material efficiency strategies related to building design and end-of-life management. GPP is used widely throughout the G7 at many levels of government. The material and GHG benefits of GPP are not routinely assessed but should be if this policy instrument is to be used effectively. Requirements for recycled content are relatively rare but are increasingly discussed in the context of plastics waste management. Virgin materials taxes, as distinct from royalty payments associated with resource extraction, are not widely used with the exception of modest levies on construction minerals. While politically challenging, reduction of subsidies for virgin resources is likely to provide dual benefits — increased material efficiency and government revenues.

Advancing Material Efficiency Policy

Material efficiency policies must address key challenges if they are to be effective. Although reductions in GHG emissions can be countered by rebound effects (where savings from increased efficiency are spent on additional consumption), this impact can be mitigated by economic instruments such as taxes and cap-and-trade systems to directly or indirectly raise the cost of production or consumption.

Very limited comprehensive research on the efficacy of material efficiency policy was found.

Ex post evaluations, experimental studies and counterfactual analysis can help policymakers evaluate the efficacy of material efficiency policy. The monitoring of outcomes (which is common in G7 countries) indicates whether targets have been achieved but does not reveal if the outcome is the result of the policy of interest.

Assessment of outcomes — both reductions in material use and in GHG emissions — provides a better basis for evaluating policy tracking than the number of programmes or participants arising from a policy. The assessment of emission reduction strategies on a life-cycle basis allows decision makers to consider synergies across different sectors (as in the production and use of vehicles for ride-sharing), as well as trade-offs (such as the increase in material-related emissions through the use of light-weight materials). Identification of synergies and trade-offs needs to be more prominent in policy guidance. Increasing building lifetimes, for example, is an intriguing strategy but, in many cases, brings emission reductions only when accompanied by a deep-energy retrofit of the buildings in question.

Contributions from material efficiency could help countries stay within their carbon budget. There is only a finite amount of CO_2 that can be emitted before the atmosphere reaches a concentration at which the global average temperature will rise by 1.5°C above pre-industrial level, a benchmark set by the Paris accord. At the end of 2019, this carbon budget was estimated to be 500 billion tons. Emissions of 1400 billion tons would result in a warming of 2°C. Current modelling of emissions pathways indicates that it is very challenging to stay within the 1.5° budget, even with a radical transformation of the energy system, but that meeting the 2° target might be possible. Distributed in proportion to population across the world, the G7's shares would be 50 and 140 billion tons, respectively. By comparison, the modelled material efficiency strategies could reduce emissions from residential building life cycles by 8-10 billion tons and those from vehicles by 7-13 billion tons. Material efficiency can therefore make a substantial contribution to bridging the gap between the 1.5° and the 2°C targets. If extended to other sectors and product systems, its potential may be even larger.

Policies related to material efficiency are summarized in the following tables (1 and 2). Material efficiency strategies, relevant policy instruments and examples of relevant policies are shown for housing in table 1 and for cars in table 2. The section of the report where the examples are discussed is indicated adjacent to the relevant example. Policies that are likely to affect multiple strategies, sectors or life cycles are summarized in table 3.


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Table 1. Material efficiency strategies and policy options for housing

Material Efficiency Strategy	Policy Instruments[1]	Description / Notes	Regional / Country / local level examples[2]
Using less material by design	No policy instruments directly focused on lightweighting identified		
	Mandated prefabrication and modular construction	• Mandating prefabrication and modular construction can facilitate lightweighting	
	Mandated use of building information modeling (BIM)	• Use of BIM during design can help to locate areas of medium and low structural loads allowing light-weighting	
Enhanced end-of-life recovery and recycling of materials	Mandated sorting and processing of construction and demolition waste (C&D)	• Increased sorting allows for better processing and separation of wastes facilitating recycling and the substitution for primary materials	• Norway Planning and Building Act rules (Sec. 3.3.4)[3]
		• Mandated sorting helps maintain value of materials and increases likelihood of recycling	• Japan Construction Material Recycling Law (Sec. 3.3.4)
	Landfill bans	• Landfill bans are often coupled with supporting policies	• Vermont Agency of Natural Resources Acts 148 and 175 (Sec. 3.3.4) • Massachusetts Waste Disposal Bans (Sec. 3.3.4)
Reuse of Materials and Components	• Mandated prefabrication and modular construction	• Prefabricated elements and modular construction facilitate design for disassembly and component reuse	• China, 30% of new builds prefab, 13th 5-year plan (Sec. 3.3.2)
	• Building codes allowing use of salvaged components	• Allowing the use of salvaged wood without regrading facilitates reuse	• State of Washington Building Code (sec. 3.3.4)
	• Mandated reuse	• Obligating contractors to not only recycle but also reuse materials and components from building demolition increases component supply and stimulates salvage businesses	• Cook County, Illinois, US Demolition Debris Ordinance (Sec.3.3.4)
Product Lifetime Extension	• No policies for durable construction identified		
	• Heritage listings	• Policies to preserve historic buildings that restrict demolition or alteration can limit building energy efficiency	• US National Historic Preservation Act (Sec.3.3.1) • New York City Local Law 97 (Sec.3.3.1)

Table 2. Material efficiency strategies and policy options for cars

Material Efficiency Strategy	Policy Instruments[1]	Description / Notes	Regional / Country / local level examples[2]
Reduction of material content	• By product of fuel economy measures • Tax on CO_2 intensity	• Fuel economy is widely regulated throughout the G7 resulting in reduced material weight to meet targets. No instances of policy directly focused on light-weighting were identified. • "One-off registration tax" in Norway based on CO_2 intensity encourages the choice of higher fuel economy and lighter vehicles	• U.S. Corporate Average Fuel Economy Standards (Sec. 3.4.1)[3] • EU regulations on emission performance standards for light duty vehicles (Sec. 3.4.1) • Norwegian vehicle registration tax (Sec. 3.4.1)
Material substitution	By product of fuel economy policy	• Fuel economy is widely regulated throughout the G7 resulting in increased use of aluminum, plastics, and novel materials. No policies directly focused on material composition identified	• U.S. Corporate Average Fuel Economy Standards (Sec. 3.4.1) • EU regulations on emission performance standards for light duty vehicles (Sec. 3.4.1)
More Intensive Use[4]			
Ride-sharing[5]	High occupancy vehicle (HOV) lanes	• Ride-sharing is a practice long encouraged by governments to reduce congestion, energy use and pollution. As with other forms of shared mobility, digital platforms have enhanced its use	• Bay Area Toll Authority, San Francisco region, US (Sec. 3.4.2) • City of Portland, Oregon car sharing parkingpolicy (Sec. 3.4.2)
Car-sharing[6]	Favourable treatment in parking, zoning and building codes. No policy identified that focuses on material efficiency	• Policies generally encourage car-sharing through relaxation of regulations relating to parking, real estate development and urban planning	• San Francisco On-Street Shared Vehicle Permit Program (Sec. 3.4.2) • Vancouver On-Street Car Sharing Parking Policy (Sec. 3.4.2)

Material Efficiency Strategy	Policy Instruments[1]	Description / Notes	Regional / Country / local level examples[2]
Enhanced end-of-life recovery and recycling of materials	Extended producer responsibility with recycling & recovery targets	• Policy toward end-of-life vehicles (ELVs) focuses on auto shredder residue (non-metallic materials remaining after shredding of car hulks). Material efficiency could be enhanced if a life-cycle approach were employed with greater attention to the end use of recycled metals	• EU End-of-Life Vehicle Directive (Sec. 3.4.4)
	Regulation of pollution arising from auto recycling	• ELV policy in the US and Canada focuses on reduction of risk/pollution arising from ELV management practices without explicit attention to material efficiency	• US Clean Air Act, for refrigerants (Sec 3.4.4) • US Clean Water Act, for stormwater management (Sec 3.4.4)
Reuse and Remanufacturing of Components	Mandating reuse and recycling fee and targets	• Prevention and management of pollution from dismantling and recycling processes • Remanufacturing of engines and tires extends the life of vehicles and components but is largely limited to heavy-duty vehicles	• Japanese Automotive Recycling Law (Box 4)
	Standards and definitions for reuse and remanufacturing	• Differing standards and definitions of used and remanufactured goods across industries and countries inhibits trade	• Basel Convention, EU Waste Framework Directive, US Federal Trade Commission (Sec. 3.4.3)
Product Lifetime Extension	Regulations mandating access to or quality of repair	• Consumer protection, rather than product lifetime extension, is a common focus of policy on auto repair. Repair may extend product life increasing material efficiency but can keep less fuel-efficient vehicles in service	• EU regulation (EC) No 715/2007 (Sec 3.4.4) • U.S. Federal Vehicle Repair Cost Savings Act of 2015 (Sec. 3.4.3)

Table 3. Cross-cutting policies for material efficiency

Policy Instrument[1]	Description / Notes	Relevant Material Efficiency Strategies	Regional / Country /local level examples[2]
Green Public Procurement (GPP)	Preferential purchasing by public entities of products and materials designed for material efficiency, more intensive use or containing low embodied carbon or recycled materials	• More intensive use	• Use of local car sharing by Bremen municipality (Sec. 3.5.1)[3]
		• Increased end of life recycling	• Dutch system for roads and buildings (Box 5)
		• Recycled content	• Japanese Law of Green Purchasing (Sec. 3.5.1)
Virgin material taxation (VMTs)/subsidy removal	While resource royalties have a long history, VMTs are not common	Change in cost can support all material efficiency strategies	• European taxes and levies on minerals (Sec.3.5.2)
Recycled Content Mandates	Not widely used but increasingly proposed for plastics	Increased recycled content	• Japanese Law of Green Purchasing (Sec. 3.5.1)
Revised building standards and codes	Building codes can inhibit or facilitate material efficiency strategies	• Change in material composition	• International Code Council (ICC) Ad Hoc Committee on Tall Wood Buildings (Sec.3.3.3)
		• Light-weighting	• American Cement Institute standard on Minimum Cementitious Materials Content (Sec. 3.3.1)
		• Reuse of materials and components	• Oregon Chapter 639 (US) (Sec.3.3.4)
Use of building certification systems by government	Certification systems can encourage the choice of low-carbon, recycled, or less material by providing points for more material-efficient choices	• Increased end of life recycling • Recycled content • Change in material composition • Re-use of materials and components	• Adoption, support or promotion of LEED by state and local governments in the US (Sec. 3.3.1)

1 Policy instruments for or related to material efficiency. Some policies which are not intended to encourage material efficiency are included because they have important impacts on material efficiency. The list of policy instruments and examples in this table are meant indicate the relevance of the instrument to the given material efficiency strategy, but not to imply that the instruments are sufficient to achieve the quantitative outcomes obtained in the modeling results in this report.
2 Laws, regulations and other forms of policy in this column are provided as examples, but not necessarily as instances of effective policy. Some are examples of policies that constitute barriers.
3 Sec. refers to the section of the main text where the example is discussed.
4 Research suggests that ride-hailing does not currently improve material efficiency and was not modeled
5 Sometimes called car-pooling, ride-sharing refers to driving arrangements where people with same or similar driving destinations share a ride. This differs from ride-hailing (e.g., Uber and Lyft), which is a modified taxi service.
6 Car sharing includes both companies with centralized digital platforms which own vehicles that are rented to members (e.g., Zip Car and Car2Go) and platforms for direct peer-topeer rental of a vehicle owned by another person or entity.

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1. Introduction

Authors
Edgar Hertwich, Reid Lifset and Niko Heeren

1.1. Chapter highlights

1. **Materials matter for climate strategies.** The share of global greenhouse gas emissions from the production of materials increased from 15 per cent (5 Gt CO_2e) in 1995 to 23 per cent (11 Gt) in 2015. The most important material groups by emissions are metals (4.8 Gt), non-metallic minerals (4.4 Gt), as well as plastics and rubber (1.5 Gt).

2. **There are significant opportunities to reduce GHG emissions in the supply and demand of materials.** This could occur through (a) increased efficiency of the materials used (for example replacing high-carbon with low-carbon and recycled materials); and (b) reduced emissions in the production of materials by using more efficient production processes; shifting to low-carbon technologies, raw materials, and energy carriers; and employing CO_2 capture and storage.

3. **Houses and cars are key sectors to further reduce GHG emissions.** Construction and manufactured goods each account for 40 per cent of the GHG emissions associated with global materials use. The most important product from the construction sector is residential buildings, while the most important manufactured product is vehicles. This report assesses options to reduce GHG emissions associated with the material cycle of homes and cars while considering trade-offs with energy use during building and vehicle operation.

4. **Designing low-carbon cars and houses can help further reduce GHG emissions.** The design of products such as houses and vehicles determines how much material they contain, the energy requirement for manufacturing and operations, durability and ease of reuse and recycling. Assessments of different emissions reduction strategies need to consider potential trade-offs and synergies in GHG emissions across the life-cycle stages of a product.

5. **The material efficiency angle.** Existing policy frameworks such as sustainable materials management, the circular economy, a sound material-cycle society, resource efficiency, material efficiency and reduce-reuse-recycle (3Rs) are widely used in G7 countries. They all focus on reducing the demand for primary materials and increasing the use of secondary materials through reuse and recycling. This report focuses on material efficiency, in particular the contribution of the life cycle of materials to global greenhouse gas emissions.

1.2. The rationale for material efficiency

In the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC), countries committed to avoid dangerous human interference with the climate by limiting average global temperature rise to well below 2 degrees Celsius. This would be achieved through reductions of GHG emissions specified in nationally determined contributions (NDCs). According to the UNEP Emissions Gap Report, reductions of 25 per cent and 55 per cent of greenhouse gas emissions are required by 2030 to limit global warming to 2°C and 1.5 °C, respectively (UNEP, 2019). Current NDCs, however, are unlikely to prevent continued increases in emissions. Policymakers must make new, more ambitious commitments to reduce emissions if they are to achieve the Paris target. There is only a finite amount of CO_2 that can be emitted before the atmosphere reaches a concentration at which the global average temperature will rise by 1.5°C above pre-industrial levels. Emissions need to be reduced on a gigaton-scale to stay within the carbon budget proposed by the IPCC: 500 Gt at the end of 2019 (or 1400 Gt to stay at or below 2°C) (IPCC, 2018).

Emissions from the production of materials – including the mining, energy, transport and industrial processes required to produce them – constituted 23 per cent of global greenhouse gas (GHG) emissions or 11 Gt CO_2e in 2015 (Hertwich, 2019). These emissions are as large as those of agriculture and land-use change combined (IPCC, 2019). There is an emerging body of research on options to reduce emissions from materials through increased efficiency and decarbonization of the production of materials; substitution to low-carbon materials; and material efficiency (IPCC, 2018). However, compared to the attention given to agriculture and land use as indicated by the recent special report by the Intergovernmental Panel on Climate Change (IPCC, 2019), assessments of emissions mitigation through improved materials cycles are at an early stage of development. Material efficiency is not systematically included in most mitigation scenarios or climate policies. As this report shows, studies of material-related policies often focus on waste management rather than GHG emissions. Detailed assessment models, such as those integrating food demand, land use, agriculture, forestry and the biogenic carbon cycle, do not yet exist for materials (Pauliuk et al., 2017). There is limited understanding of future material demand for particular products and the availability of materials from secondary sources.

Emissions from the material cycle of products can be reduced in a variety of ways: by reducing or shifting the demand for primary materials; by increasing the demand for less carbon-intensive materials; by increasing the efficiency of the production of materials; and by decarbonizing the production of materials through low-carbon energy and reductants, as well as CO_2 capture and storage (CCS) (International Energy Agency, 2019a). A combination of these strategies is likely to yield the fastest reduction at the lowest cost. By reducing GHG emissions from the production of materials, policymakers can build synergies between the objectives of GHG abatement, resource conservation and waste management.

This study seeks to gain an understanding of the impact of material efficiency on GHG emissions. Chapter 2 presents an evaluation of the life-cycle GHG emissions of specific material efficiency strategies for residential buildings and light-duty vehicles based on product-oriented bottom-up modelling. It scales up results to the national level for the Group of Seven (United States, Japan, Canada, the United Kingdom, Germany, France and Italy), China and India. The modelling focuses on the reduction of emissions that are additional to those arising from a transition to clean electricity and electric transport, thus evaluating whether material efficiency can help limit global warming 'well below 2°C' – the goal of the Paris Agreement. The modelling is complemented by a review of policies for and related to material efficiency in various industrialized countries (Chapter 3). The present bottom-up approach offers more granularity and specific implementation-oriented insights than top-down economic modelling, thereby complementing work by the OECD (OECD, 2019), the International Energy Agency (International Energy Agency, 2019) and previous work by the International Resource Panel (Ekins et al., 2017; Oberle et al., 2019).

This introduction provides background information, explains the scope of this report, describes the role of materials and the historical development of material production, and explains the climate change – material nexus. It concludes with a description of the material efficiency strategies assessed in this report.

1.3. A request from the Group of 7

Since the 2007 Kobe meeting, the G7 countries have focused on reducing waste through a set of related frameworks including *sustainable materials management*, a *sound material-cycle society*, the waste hierarchy (with its prioritization of waste reduction), reuse and material recycling (the 3Rs), and, more recently, the *circular economy* (Box 1). All of these frameworks highlight the importance of waste reduction and reuse throughout the life cycle of products. Such improvements can be achieved by designing products that are durable, reusable, repairable and recyclable; developing strategies to increase manufacturing yields; choosing the most appropriate materials per function; recycling materials; and applying lifetime extension strategies such as increased durability and repair, as well as remanufacturing. These frameworks also look at the design and use phases of a product, as the demand for physical products depends not only on the expected service but also on the degree of capacity utilization. Unused capacity can be made accessible through certain strategies (such as sharing) or reduced through appropriate business models.

In the Communiqué of the G7 Environment Ministers' Meeting in Bologna, the IRP was asked to assess the potential GHG reductions of resource efficiency policies with the aim of pursuing co-benefits by identifying the most promising resource efficient measures in terms of their GHG abatement potential. After acknowledging the contribution of the IRP report "Resource Efficiency: Potential and Economic Implications" (Ekins et al., 2017), and in particular the contribution of the IRP to the development of resource efficiency indicators, the communiqué asked the IRP to:

> *Further assess the potential GHG reductions of resource efficiency policies with the aim of pursuing co-benefits by identifying the most promising resource efficient measures in regard to their GHG abatement potential. To this end, we invite the IRP to conduct a study on the above, including providing emissions scenarios connected to the implementation of RE/CE/3R/SMM[7] policies and comparing these with the implementation of conventional policies. An assessment of the deployment of low carbon technologies relevant for the implementation of RE/CE/3R/SMM should also be provided.*

In response to this request, emissions scenarios were developed to quantify the potential reductions of GHG emissions from increased material efficiency in homes and cars of the G7, with results also shown for China and India. Policies that encourage or mandate material efficiency strategies in those sectors were reviewed. Homes and cars were chosen as the focus because construction and manufacturing each account for 40 per cent of global GHG emissions related to the use of materials. The specificity and somewhat homogenous nature of these two product categories were necessary in order to develop a solid bottom-up model.

As the co-chairs of the OECD-UNEP 2008 Resource Efficiency Conference stated, "the different concepts and approaches are converging: 3Rs, sound material-cycle society, circular economy, integrated or sustainable waste management, sustainable consumption & production, lifecycle management and sustainable materials or resource management, all aim at similar objectives and require similar action by the various stakeholders" (Mwandosya, M. and Namiki, M., 2008).

While not necessarily interchangeable, the different policy frameworks have considerable overlap in terms of their objectives and strategies. Most frameworks address materials (the solids that make up products based on their structural and functional properties), but some frameworks have a wider scope and include fuels, chemicals, food, water, land, labour and financial resources. Considering that materials are the primary point of intersection between these different approaches, this report focused on materials using the term "material efficiency" (Allwood et al., 2011; Fischedick et al., 2014; International Energy Agency, 2019a; Worrell et al., 1995). Material efficiency is more specific than resource efficiency and it is encompassed in the other concepts. It is a term of art that emphasizes the relationship of material resources to climate change. For a broader view of resource efficiency and GHG emissions mitigation, see Oberle et al. (2019).

To reduce emissions through material efficiency, policy must reduce the use of materials or substitute energy-intensive primary materials with less energy-intensive materials, whether they are yet unused secondary or low-carbon primary materials. This must occur with only smaller concomitant emission increases elsewhere in the system.

7 Resource efficiency; circular economy; reduce, reuse and recycle; sustainable materials management.

The request calls for the development of emissions scenarios that provide a counterfactual analysis of what would happen to GHG emissions with and without the implementation of material efficiency.

Material efficiency strategies such as light-weight design, product lifetime extension and recycling are at the heart of this assessment and will be explained at the end of this chapter. Policy could encourage, steer or mandate the use of such strategies and set objectives to reduce both total material use and GHG emissions.

In this study, the goal was to respond to the following policy relevant questions:

1. Can material efficiency strategies, if implemented successfully, reduce material use and GHG emissions (considering co-benefits and trade-offs) in the production, operations and end-of-life of targeted products and the associated primary and secondary material flows?
2. What policies affect material use and do these policies lead to the successful implementation of material efficiency strategies?

To respond to the first question, the function and life cycle of products were modelled to understand how some performance characteristics (such as operational energy use) change when the mass or material composition of the product is altered. In quantifying the level of greenhouse gas emissions, a model must therefore target products that require significant amounts of materials, the energy use and emissions associated with their production and operations, as well as the materials or components that become available at their end-of-life stage, including some form of credit for secondary use.

Regarding the second question, there are many policies that could affect the use of materials, ranging from technical standards, building codes and land-use planning to vehicle registration fees. One could wish for a model that can simulate the effects of such policies and determine relevant outcomes, but models commonly capture only one or two policy instruments, and they may not reflect what happens in reality. The authors therefore decided to assess the literature searching first and foremost for empirical studies of implemented policies and their outcomes. The authors also reviewed modelling studies, policy descriptions, discussions and reviews that address outcomes that are or can be classified as material efficiency.

The G7 request also asked the IRP to consider low-carbon technologies relevant to the implementation of several resource-related frameworks (Resource Efficiency; Circular Economy; Reduce, Reuse, Recycle; Sustainable Materials Management; and Sound Material-Cycle Society). In the scenario modelling developed for this report, changes in the background energy mix and associated GHG emissions were considered, as well as the increasing penetration of low-carbon technologies (e.g. passive houses, electric vehicles) in the two selected sectors.

The *Toyama Framework on Material Cycles* (Ministry of the Environment, Japan and Institute for Global Environmental Strategies, 2016), adopted by the meeting of G7 Environment Ministers in July 2016, underlines the importance of "reducing the consumption of natural resources and promoting recycled materials so as to remain within the boundaries of the planet". This commitment was confirmed by both the 5-year Bologna Roadmap on resource efficiency (G7, 2017) and a G7 progress report published in 2019 (Aoki-Suzuki et al., 2019). However, as the findings of the report suggest, GHG emissions reductions from many of the resource efficiency policies put forward need to be monitored (Aoki-Suzuki et al., 2019).

The modelling presented in this report suggests that areas of high impact in carbon mitigation are often not included as priorities for policy intervention. This is the case of the construction and building sector, an area with great potential for GHG emissions reductions from materials as shown by this report. This sector was not included as part of the focus areas of the Bologna Roadmap and the 2019 G7 progress report (Ibid, 2019).

Box 1. A note on the terminology and scope of this report

There are multiple terms and labels in the framework of this report. They include resource efficiency, materials efficiency, sustainable materials management, the circular economy, the 3Rs, the Sound Material-Cycle Society and sustainable production and consumption. To varying degrees, they all refer to the way in which resources can or should be used in environmentally preferable and resource conserving ways by society.

- **Material Efficiency** (ME) is the focus of this report. The authors follow the conceptual approach of the Royal Society (UK) after a consultative meeting with experts in 2012, in which material efficiency was defined as "the pursuit of technical strategies, business models, consumer preferences, and policy instruments that would lead to a substantial reduction in the production of high-volume, energy-intensive materials required to deliver human well-being" (Allwood et al., 2013). Materials include biomass, cement, fossil fuels, metals, non-metallic minerals, plastics and wood. As a metric, ME is expressed as a ratio of the amount of product or service obtained by unit of material use. In the context of the present analysis, material substitutions are also included when they reduce GHG emissions.
- **Resource efficiency** (RE) encompasses material efficiency, but is a broader term that may include other resources such as water, energy, biodiversity, land and, in the context of climate change, financial resources. The International Resource Panel (Ekins et al., 2017, p. 43) notes that resource efficiency can be used "to refer generically to all these different ideas: the technical efficiency of resource use; resource productivity, or the extent to which economic value is added to a given quantity of resources; and the extent to which resource extraction or use has negative impacts on the environment (increased resource efficiency implies reducing the environmental pressures that cause such impacts)". This report addresses the narrower scope of material efficiency.
- As defined by the Oslo Symposium in 1994, **sustainable consumption and production** (SCP) is "the use of services and related products which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations" (United Nations, 2019).
- **Sustainable materials management** (SMM) is, according to the United States EPA, "an approach to serving human needs by using/reusing resources most productively and sustainably throughout their life cycles, generally minimizing the amount of materials involved and all the associated impacts" (US EPA, 2015).
- The **circular economy** refers to an economy where "the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste minimised" (EU, 2015).
- The **3Rs** (reduce, reuse, recycle) originated in waste management and policy. They indicate an order of priority for strategies to reduce and manage waste. The 3Rs encompass many strategies included in the other frameworks because all of the "Rs" affect and are affected by what happens upstream in life-cycle stages of production and use.
- The **Sound Material-Cycle Society** (SMCS) is very similar to the 3Rs and SMM concepts. According to the Japanese Basic Act for Establishing a Sound Material-Cycle Society "a society in which the consumption of natural resources is conserved and the environmental load is reduced to the greatest extent possible, by preventing or reducing the generation of wastes and by promoting proper cyclical use and disposal of products and materials" (Ministry of the Environment, Government of Japan, 2010). SMM is primarily a term used in the United States and by the OECD, while SMCS is used in Japan.

The focus here is not on canonical definitions but clarity about the scope and usage in this report. We use material efficiency in this report because it avoids implying that the report encompasses energy, water, biodiversity or land resources. The specific focus on material resources is not meant to imply that such resources are more important to climate change mitigation than other types of resources. Rather, it reflects an effort to bring further attention to the relationship between materials management and climate change. More detail on the differences in scope and focus of the terms and the underlying concepts can be found in discussions, for example, by the UNEP (2017) and Blomsma and Brennan (2017).

1.3.1. Scope of the assessment

This report addresses the opportunities for material efficiency in homes and cars of the G7, with results also shown for China and India. We chose to focus the assessment on specific, widely used products because only a product-level assessment is able to (a) track materials to estimate recycling potential and (b) model the functioning of the products and thus the potential trade-off between material efficiency and energy efficiency. The choice of residential buildings and light-duty vehicles is based on their overarching importance and somewhat homogeneous nature. This makes it feasible to develop a model that captures the impacts of specific material efficiency strategies (such as the light-weighting of buildings) on material and energy use. Such engineering-based models require general strategies to be represented in terms of granular measures with identifiable technical features (such as lighter framing in houses closer to required specifications), or to rely on more generalized relationships derived from empirical models (like the ones between vehicle weight and fuel consumption). Without this level of specificity and granularity, additional steps (and assumptions) would be required to extrapolate from specific examples to broader product groups. The carbon footprint of materials used in construction was nearly 5 Gt CO_2e, or 10 per cent of global emissions in 2015. The production of motor vehicles for final consumption required materials with a carbon footprint of 0.6 Gt CO_2e in 2015 (Hertwich et al., 2019). In both cases, materials contribute approximately 55 per cent to the cradle-to-gate emissions of the final product (Hertwich, 2019). For a consistent discussion, the policy review also focused on these two products.

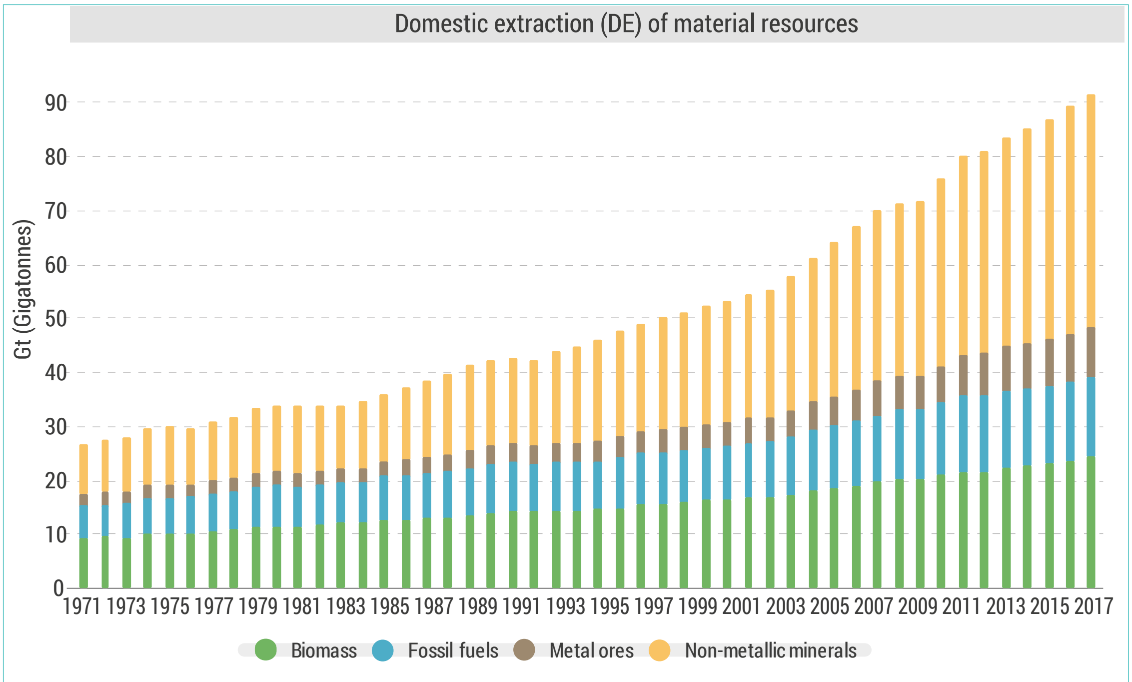
The focus of the study is on the two product systems and the services they provide. It captures changes in patterns of use and provisioning systems, such as a potential move towards shared, car-based mobility systems instead of individually owned vehicles but does not address larger, societal changes (such as the replacement of cars by public transport or autonomous vehicles). The two product systems are studies in isolation, although the findings point to important interactions. For example, denser, more urban living encourages smaller, more efficient apartments in multi-unit buildings, and promotes shared and public mobility. Such systemic interactions, while not explicitly modelled in this study, have been addressed in previous work of the International Resource Panel, in particular the Weight of Cities report (Swilling et al., 2018).

1.4. A growing demand for materials

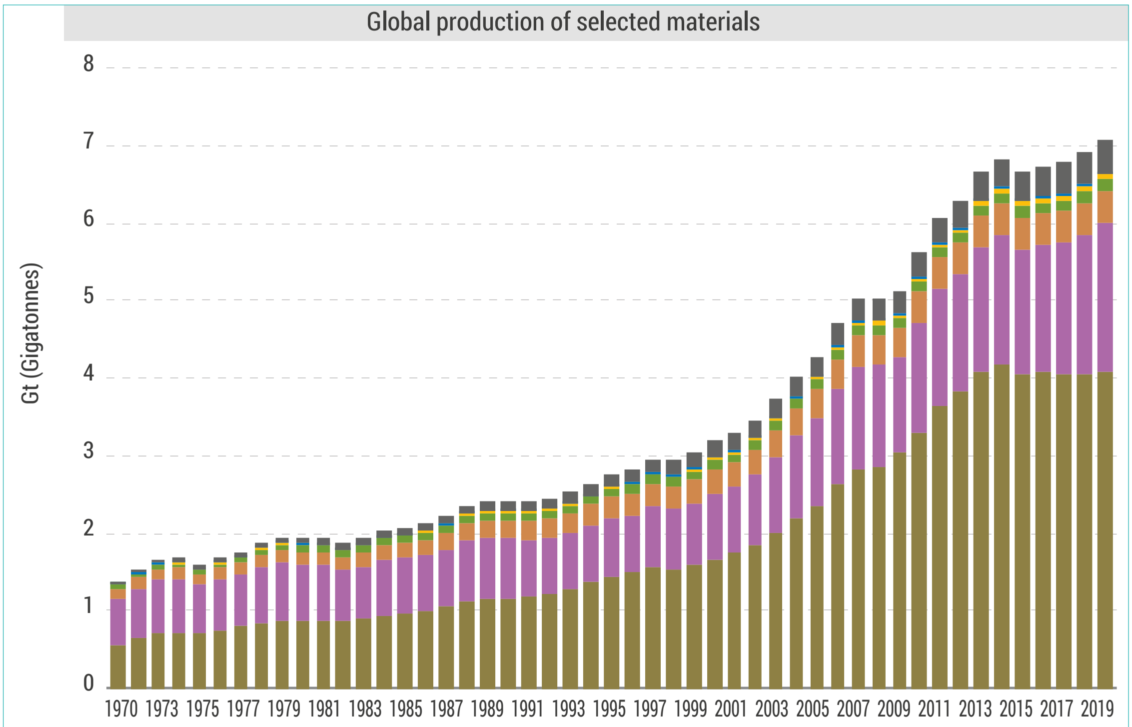
Historians classify pre-historical societies by the materials produced and used. No single material adequately represents the technological advances of today; rather, our technically sophisticated economies are characterized by utilizing an ever increasing range of the mechanical, electrical, catalytic and other properties of materials, as well as customizing these through alloys, compounds and composites that take advantage of almost the entire periodic table (Graedel et al., 2015). Advances in material science and engineering are the basis for technical progress from advanced medical imaging, progress in computational power and speed of microchips, to nanotechnologies enabling improved batteries and PV solar cells. Increased access to and reduced costs of materials, together with our expanding ability to control and use their functional properties, are an important component of economic and technological development. Material use has grown with population and GDP (see Figure 4).

Credit: Kerkez/iStock/Getty Images Plus

Figure 4.
A. Extraction of material resources from nature



B. Historical growth in the use of selected materials



Source: Oberle et al., 2019, Fig. 2.7 (A.); USGS (2020) for minerals, FAO (2020) for paper, Geyer et al. (2017) for polymers. Data for paper and polymers extrapolated to 2019 (B.).
Note: Numbers are for the whole world.

The primary production of materials is resource and energy intensive and polluting (Oberle et al., 2019; van der Voet et al., 2013). The IRP's Global Resources Outlook (Oberle et al., 2019) found that resource extraction and processing (including biomass, fossil fuels, metals and non-metallic minerals) caused over 50 per cent of global GHG emissions and a wide range of other impacts such as toxic emissions, land use, water use and biodiversity impacts. Moreover, 10 per cent of GHG emissions were from metals and 10 per cent from non-metallic minerals, in line with the findings of this report.

Aggregate global material resource demand as measured by the Domestic Material Consumption (DMC) indicator (measuring the aggregate mass of resources extracted from earth or harvested from nature) has grown steadily, outpacing population growth. While resource productivity (the unit of value added per kg of DMC) improved up until the turn of the century, it has declined since then, as reported by the IRP in its Global Resources Outlook (Oberle et al., 2019). That means that, in 2000-2015, resource use growth rates outpaced economic growth (Schandl et al., 2018). The main reason for this unexpected reversal of a historical trend was that economic growth was stronger in low- and middle-income countries that have lower resource productivity than higher income countries. In most countries, the improvement of resource productivity continued during this period (Schandl et al., 2018). The OECD and the IRP have both published scenarios for the development of future resource demand through 2060. In the historical trend scenario of the IRP, global resource use more than doubles, with resource productivity increasing very slowly. In contrast, in the IRP's Towards Sustainability scenario, resource productivity increases substantially, leading to a growth of resource use of only 75 per cent (Oberle et al., 2019). The improvement in resource productivity is achieved through increased material efficiency of individual industries, a shift in diets and a shift in value added to industries with lower material requirements. The OECD paints a similar picture (OECD, 2019). The increasing resource use poses a challenge to climate change mitigation, given the high GHG emissions of material production, fossil fuel extraction/processing and farming. Therefore, it is critical to search for further improvements of resource productivity through resource efficiency strategies and changes in consumption patterns.

The reports by the IRP and the OECD indicate that there are potential synergies between resource efficiency and greenhouse gas emission reductions (Oberle et al., 2019; OECD, 2019a). In the economic models developed by each, these synergies emerge because the same economic sectors that extract and process large quantities of resources also require large amounts of energy. A resource tax is likely to also reduce carbon emissions: a reduction of material processing also reduces energy use. Climate change mitigation research has extensively focused on energy, agriculture and land-use change. This report focuses only on materials. It unpacks aggregate sectors and investigates potential synergies between material efficiency and GHG mitigation using engineering-based models of two specific products (homes and cars) at a finer level of granularity than the macro-level models used in the IRP's Global Resource Outlook and the OECD's Global Material Resources Outlook. Such bottom-up modelling can reveal the mechanisms behind material efficiency gains, thus identifying policy intervention points. It may also help to identify additional mechanisms and opportunities, as well as providing a deeper, more grounded understanding of material efficiency. It can also confirm or refute relationships that are assumed in more macro-level models.

Several earlier IRP studies also relate to materials and climate change, including a set of studies on metals (**Box 2**), resource efficiency and decoupling and climate change mitigation (see the following section). This work will be cited where appropriate.

Box 2. Key insights from the IRP's work on metals

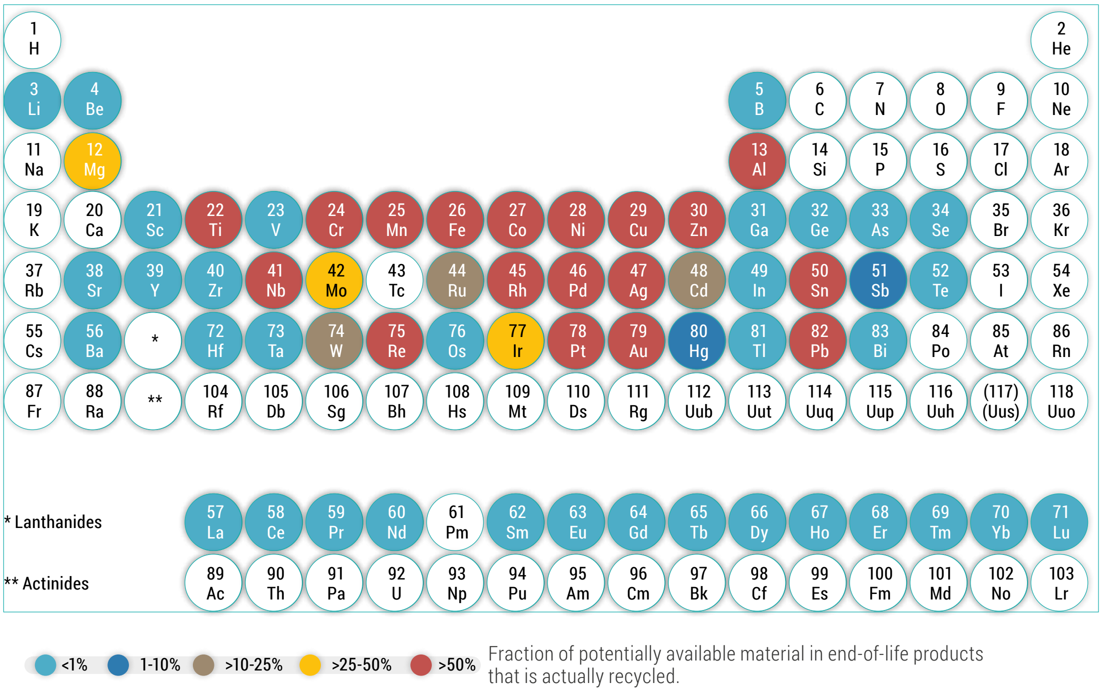
Metal Stocks in Society

This report presents the concepts of material flow analysis and shows that the amount of metals in different countries and cities increases with wealth and accumulates over time. Potential saturation has only been identified for steel (Graedel, 2010).

Recycling Rates of Metals

Metals are regarded as having excellent properties for recycling. Some metals such as steel, aluminium and copper have long traditions of being recycled. For these, recycling infrastructure and technologies exist in many countries. However, this is not the case for many of the metals used in small amounts and in more complex technologies such as the modern automobile and smartphone. The IRP's report on recycling rates was produced by a group of experts convened by the IRP. It estimated the recycling rates of each metal, as shown in the diagram below. While estimated end-of-life recycling rates were greater than 50 per cent for the metals shown in red (although not much greater), for many more elements the estimated recycling rate was less than 1 per cent (see Figure 5).

Figure 5. Periodic table of elements indicating the recycling rates for individual elements



Source: Graedel et al., 2011.

Metal recycling: opportunities, limits, infrastructure

The second IRP recycling report presented the technical and economic challenges and opportunities of metal recycling (Reuter, 2013). These aspects are shaped by the fundamental properties of metals, such as the affinity of different metals to each other. Mixing metals in products can be irreversible. Therefore, recycling alloy mixtures can be of little metallurgical and economic value. Collection and sorting are important prerequisites for improving metal recycling rates.

Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles

The IRP report on the environmental impacts of metal flows (van der Voet et al., 2013) found that the production of primary metals was responsible for 7 to 8 per cent of global energy use and an even larger share of toxic impacts. The local impacts of mining and metal refining were substantial. Ore grade degradation could lead to further increases, while environmental regulation and technological progress could reduce these impacts.

1.5. The climate change-materials nexus

Climate change and the production/use of materials interact in several ways. The production of materials causes greenhouse gas emissions, which are the cause of anthropogenic climate change. The mitigation of GHG emissions and adaptation to climate change, in turn, affect the demand for materials. Climate change may impact material production positively or negatively through longer growing seasons for trees or extreme weather events impacting mining areas.

1.5.1. Materials for climate change mitigation

Low-carbon electricity generation technologies (photovoltaics, wind power, nuclear power and fossil fuel combustion with carbon dioxide capture and storage) use larger amounts of materials or more uncommon ones than conventional fossil power generation. The same is true for other technologies, such as battery-electric and fuel cell vehicles and low-emissivity windows. The IRP has published two reports that investigate the trade-offs and synergies of GHG mitigation with other resource and environmental issues from power generation and selected energy demand strategies.

Electricity generation: The IRP report *Green Energy Choices* (Hertwich et al., 2016) investigated the potential co-benefits and adverse environmental impacts of moving from the current electricity supply (relying largely on fossil fuel power plants) to a low-carbon mix of renewable power and fossil fuelled power plants with CO_2 capture and storage. In this context, the report quantified the impact on materials use, in addition to emissions, land and water use. The report found that renewable power has substantially lower pollution impacts than fossil power on ecosystems and human health, but required more iron and steel, copper and cement. Looking at a clean energy scenario, cement use in the electricity system almost doubles, while iron and copper consumption would increase by approximately 10 per cent until 2050.

Energy efficiency: The IRP report *Green Technology Choices* (Suh et al., 2017) investigated a range of technologies that would reduce energy use or enable the shift to greener energy sources. For all strategies, it found significant synergies between GHG reduction and the reduction of particulate matter emissions and freshwater consumption. For many strategies, such as the improvement of building shells, efficient lighting, improved copper production and building demand-side management, it found synergies across the board, including a reduction in an aggregate metal use indicator. GHG emission reductions from the electrification of passenger transport would result in a significant increase of metal use. The increased use of metal for passenger transport would be much larger than the reductions for other technologies that were investigated in the report. Please note that, in the present report, we also assume a shift towards electric vehicles and consider a wide range of materials, while addressing only their GHG emissions and not their criticality or geological availability.

1.5.2. Materials for climate change adaptation

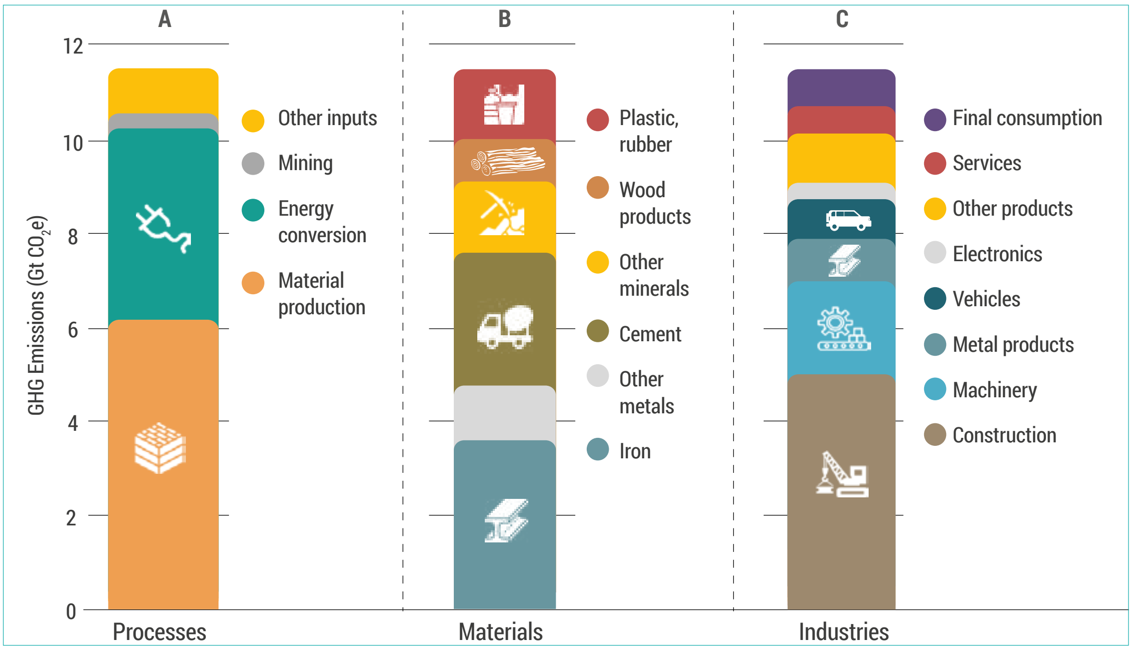
Both climate mitigation and adaptation will lead to an increase in the use of materials. Adapting to a changed and more capricious climate, plus the repair of damage from extreme weather events, will instigate additional material use. Adaptation options include: construction efforts along coastal areas such as seawalls and coastal protection structures, flood levees and culverts, and floating houses; civil infrastructure modification including sewage works, improved drainage, flood and cyclone shelters, transport and road infrastructure adaptation, robust power plants and electricity grids, and food storage and preservation facilities; as well as resilience in the built environment including building insulation and cooling (Noble et al., 2014). Each of these options places demand on high volume materials. Disaster-resilient buildings are discussed in section 3.3.1.4.

Climate change adaptation strategies that lead to higher demand for materials fall into at least three categories: (1) rebuilding and increased frequency of repair efforts after natural disasters, which are expected to increase in response to a changing climate; (2) increasing robustness of coastal structures to cope with sea level rise; and (3) evolving construction practices and standards in response to a changing climate. While there is a paucity of studies quantifying the total materials demand resulting from these adaptations, a few case studies provide some indication of the approach one might take to estimate this. For the first category, future materials estimates can be based on the historic demand in response to events such as hurricanes and flooding (Symmes et al., 2019). An example of the third category can be found in pavement design practices where temperature is a primary driver for materials selection and design in roadways. Current practice, however, uses climate data from 1964-1995 (Underwood et al., 2017). Quantitative assessments of materials demand for climate adaptation are few and far between, and no large-scale analyses have yet been carried out other than those describing national planning activities (Araos et al., 2016).

1.5.3. The carbon footprint of materials

The primary material production of some materials produced in high volumes, such as cement and metals, is both energy intensive and associated with process-based emissions. As a result, materials have been identified as contributing to more than half of GHG emissions from industry or one sixth of global emissions (Allwood et al., 2010; Nuss and Eckelman, 2014). In many cases, the secondary production of materials (recycling) can lead to substantial reductions of GHG emissions.

Figure 6. Global carbon footprint of materials in 2015: (A) by emitting process, (B) by material produced, (C) by first use of materials by downstream production processes



Source: Hertwich et al., 2019.

A recent analysis conducted in preparation for this report offers a comprehensive picture of cradle-to-gate GHG emissions associated with material production and an analysis of the use of materials by downstream industries and final consumption (Hertwich, 2019). It indicates that, in 2015, over half of the carbon footprints of materials are direct emissions from material production processes. Energy supply for the materials production process accounted for 35 per cent of emissions, mining for 2 per cent and other economic processes for 9 per cent (see Figure 6A). The most important materials in terms of GHG emissions were iron and steel (32 per cent), cement, lime and plaster (25 per cent), rubber and plastics (13 per cent) and other non-metallic minerals (13 per cent) (see Figure 6B). In terms of the carbon footprint of materials, construction and manufacturing each constitute slightly more than 40 per cent of the first use of materials. While construction is not broken down further, a breakdown of the manufacturing sector shows that the most important manufacturing processes are the production of machinery and (mechanical and electrical) equipment, metal parts and vehicles (see Figure 6C).

Two thirds of the materials are used to produce capital goods such as roads, buildings and machinery, while only one third is used to produce consumer goods such as refrigerators, privately owned vehicles and furniture. Contrary to most energy use, which serves consumption either directly or through the production of short-lived consumer goods and instantaneous services, most materials are used to produce long-lived goods. The dynamics of material use are thus driven by build-up of capital, such as buildings and infrastructure, which happens mostly in emerging economies. Emerging economies therefore contribute more to global material use than to global energy use. The material-related GHG emissions in G7 countries have remained fairly stable at around 2 Gt CO_2 equivalent since 1995, while China's footprint has grown from 1.2 to 5 Gt (Hertwich, 2019).

Residential buildings are the most important product of the construction industry, both in terms of revenue and emissions, while private cars are the most important manufactured product sold to consumers. Machinery serves manufacturing and construction. Metal parts include building components and car parts.

1.6. Mitigation of GHG emissions from materials

Historically, decarbonization efforts related to materials have focused primarily on reducing process-level energy use and GHG emissions in material production. These production-oriented strategies include energy efficiency, fuel and feedstock switching, process-related CO_2 emissions reductions and carbon capture and storage (CCS). They are an important complement to the consumption-oriented strategies that are the focus of the current report.

Previous industrial sector mitigation assessments in select industries have often included the production of secondary materials (such as electric arc furnaces for scrap-based steel) and plant-level material substitution (e.g. the use of additives to reduce the clinker content of cement) as additional mitigation strategies. These two broad strategies are included in the materials efficiency scope of this report. Additionally, there is a growing body of literature exploring the potential of emerging process technologies such as renewable hydrogen-based direct reduced iron (DRI), electrolysis using renewable electricity to produce chemicals, carbon capture and utilization (CCU) and large-scale process electrification as future production-oriented mitigation measures.

1.6.1. Mitigation opportunities from efficient material production

In many production-oriented mitigation studies, improving energy efficiency in production processes has been identified as the greatest mitigation opportunity. For example, in its Beyond 2 Degrees Scenario, the IEA estimates cumulative emissions savings of around 40 per cent in the global industrial sector by mid-century if plants were to adopt best practice energy-efficient technologies (International Energy Agency and Cement Sustainability Initiative, 2018). Significant efficiency-related savings in materials production are attributable to shifts to best available process heating technologies (such as preheater/precalciner kilns in the cement industry, improved catalytic processes in the petro-chemicals industry and process intensification). Improvements of cross-cutting systems (such as machine drives, compressors and steam systems) play important supporting roles (International Energy Agency, 2018; International Energy Agency and Cement Sustainability Initiative, 2018). These technologies are well-proven, but adoption is often impaired by financial, knowledge and operational barriers, as well as the slow stock turnover rates associated with core process equipment (such as kilns, furnaces and crackers) in the materials industries, where equipment lifespans are often measured in decades (International Energy Agency, 2017; Sorrell et al., 2011; U.S. Department of Energy, n.d.). These barriers explain the large remaining mitigation potential of energy efficiency in many industrial mitigation studies.

Factory-level material efficiency measures in material production processes (such as improved yields, reduced process waste and diversion of fabrication scrap) are not frequently investigated from the perspective of GHG emission reductions, but may provide similar savings (Gonzalez Hernandez et al., 2018).

1.6.2. Mitigation opportunities from low-carbon energy

Switching to low-carbon sources of direct fuels and electricity is another key strategy with widely varying opportunities according to industrial subsectors. For example, in the cement industry, a shift from coal to natural gas and the use of biomass and waste energy sources to replace fossil fuels can yield substantial emissions reductions (International Energy Agency and Cement Sustainability Initiative, 2018). Across the industrial sector, the substitution of direct fuels with lower-carbon materials can technically deliver cumulative emissions savings of 10 to 15 per cent beyond energy efficiency alone by mid-century (International Energy Agency, 2017).

Substantial additional emissions savings may be achievable through emerging process electrification technologies coupled with renewable electricity sources. Some key examples include process heating via heat pumps (Chua et al., 2010; U.S. Department of Energy, 2009), induction heating (Rudnev et al., 2017) and radio frequency drying (Lung et al., 2006). Emerging electrified manufacturing innovations, such as additive manufacturing of metal products (Huang et al., 2018), may provide additional opportunities for process electrification (Huang et al., 2017). Furthermore, alternative heat technologies (primarily solar concentrating and geothermal heat) hold significant potential for supplementing or offsetting fossil fuels in many low- to mid-temperature processing heating applications, including the steam-intensive petrochemicals and pulp and paper industries (McMillan and Ruth, 2019). For example, in the United States, up to 30 per cent of industrial fossil fuels use may technically be replaceable by alternative process heating technology options (McMillan and Ruth, 2019). While many of these technologies are proven, their uptake is often limited by prohibitive capital investment requirements, perceived risk, lack of policy incentives and knowledge gaps.

1.6.3. Mitigation opportunities from alternative feedstocks

Beyond energy efficiency and low-carbon fuel utilization, additional emissions reductions are achievable through alternative feedstocks in primary material production. Key examples include the use of biofeedstocks in chemicals production to reduce fossil inputs (Rogers et al., 2017) and the use of electrolysis-based hydrogen from renewable electricity in a number of emerging process technologies, including hydrogen-based DRI for steel and for ammonia and methanol manufacturing (Philibert, 2017). While these renewable hydrogen pathways hold significant emissions reduction potential, the current cost of electrolyzers can make investments unattractive and sunk costs in existing steel mills and chemical plants coupled with long incumbent technology lifespans limits the transition pace.

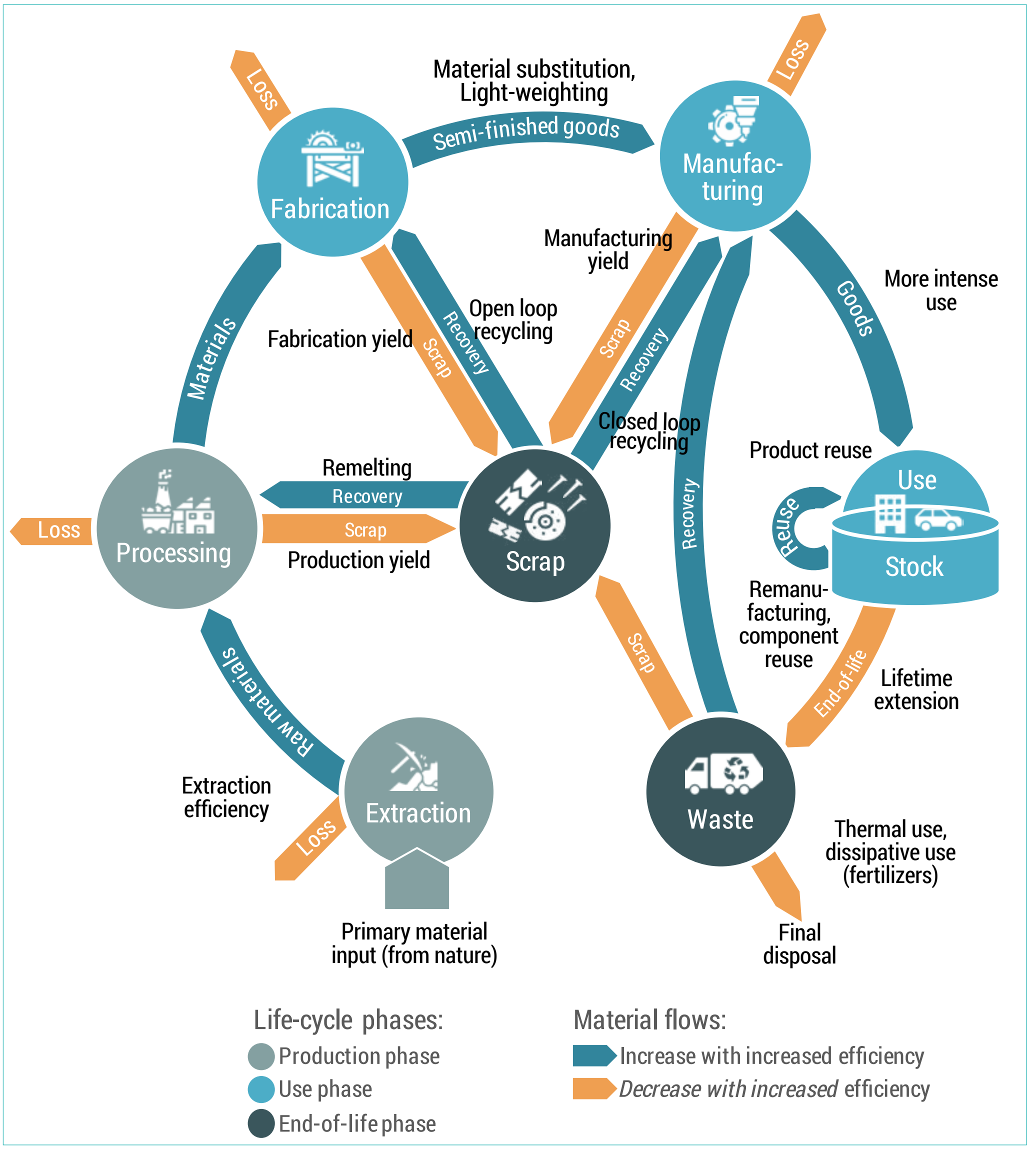
1.6.4. Mitigation opportunities from low-carbon processes

The major emerging technologies for process-related CO_2 emissions reductions include lower-carbon cement chemistries, some of which are commercially-available (International Energy Agency and Cement Sustainability Initiative, 2018), and inert anodes in aluminium smelting (International Energy Agency, 2017). For low-carbon cement chemistries, market barriers include overly prescriptive materials specifications, institutional inertia and building practices that favour ordinary Portland cement, as well as perceived performance risk (Section 3.3.1.3.1). Lastly, Carbon Capture and Utilization (CCU) is gaining attention as a production-oriented mitigation strategy, with potential for significant emissions reductions when applied to the manufacture of chemicals and building materials, but current activities are largely limited to pilot-scale projects and niche applications (International Energy Agency, 2019b).

Given the historically slow pace of adoption of, and the barriers faced by, the above decarbonization options, many industrial mitigation scenarios rely heavily on the use of carbon capture and storage (CCS) for deep decarbonization. For example, in the IEA's Beyond 2 Degree Scenario (B2DS), by 2060, more than 80 per cent of the remaining direct emissions by the world's steel, cement and chemicals plants must be captured and sequestered (International Energy Agency et al., 2017). While there are encouraging signs that industrial-sector CCS is moving forward (by 2018, there were large CCS projects in the chemicals, hydrogen and steel industries (Global CCS Institute, 2018), deployment is woefully behind the pace needed to keep track with the goals of the Paris Agreement (International Energy Agency, 2019a). Moreover, the capture efficiency of carbon capture technologies is less than 100 per cent, meaning CCS will not fully abate fossil-fuel CO_2 emissions. Material efficiency should, therefore, be accelerated to further reduce GHG emissions from materials production.

The demand for virgin materials cannot be brought to zero. Strategies to reduce and eliminate GHG emissions per unit of material produced are thus necessary for achieving zero emissions, but the early-stage development and high costs of some of these strategies suggest that they are not sufficient by themselves. Reducing the demand for primary materials through material efficiency can reduce the overall financial and environmental costs associated with decarbonizing industrial production and increase the speed with which decarbonization is attained.

Figure 7. Material efficiency strategies in the product life cycle



Source: Inspired by Reck et al. (2008) and Allwood et al. (2011).

1.7. Material efficiency strategies

As noted earlier, reducing the demand for primary materials has been recognized as a potential route to reduce energy use and greenhouse gas emissions (Allwood et al., 2011; Worrell et al., 1995). Efficiency increases can be obtained at each stage of the material life cycle displayed in Figure 7. Such reductions can be achieved through various approaches to reduce the demand for services, develop more efficient solutions to provide the same or an equivalent service, reduce waste, recover materials or extend the use of a product to increase the amount of service it provides. Recent reviews of material efficiency provide an assessment of the literature in the field (Hertwich et al., 2019; Worrell et al., 2016). In this report, the following material efficiency strategies were considered: using less material by design; material substitution; fabrication yield improvements; more intensive use; enhanced end-of-life recovery and recycling of materials; recovery, remanufacturing and reuse of components; and product lifetime extension. A description is included in the box below.

These strategies may not always result in totally equivalent services, as the experience with the service may be different or the perception of the quality may be influenced, positively or negatively. When a smaller car is used, for example, kilometres travelled may remain unchanged, but other aspects of the driving experience or ease of finding a parking space may not. In this report, more intensive use and the downsizing of vehicles are considered as changes in the provisioning system or use pattern that change user experience and may require changes in consumer preferences, whereas the other strategies are more technical in nature and considered as changes in the material cycle. In addition, there is a concern about the degree to which certain strategies result in a behavioural response that deviates from a 1:1 replacement. An important concern is the rebound effect (Makov and Font Vivanco, 2018; Zink and Geyer, 2017). An example discussed in the policy chapter is peer-to-peer lodging through services such as Airbnb, which can lead to a better utilization of spare residential dwelling space and thus reduce GHG emissions, but it may also result in an expansion of tourist accommodations and travel, thus potentially increasing GHG emissions.

1.8. Material efficiency and climate change mitigation

There is an emerging body of literature on the linkages between material efficiency and climate change mitigation. We provide a short overview in this sub-section. Chapter 2 discusses the modelling work and compares the results of the current model with those of previous research. Chapter 3 provides a review of the literature on material efficiency policies and their effectiveness. For additional reviews of the literature see (Allwood et al., 2011; Hertwich et al., 2019; Worrell et al., 2016). There is a long history of research on the use of materials, material cycle management and material efficiency upon which this literature builds. See, for example, research by (Kneese et al., 1970; Larson et al., 1986; Opschoor, 1994; Worrell et al., 1995).

1.8.1. Modelling of material efficiency

Allwood et al. (2010) showed that just five materials (iron and steel, aluminium, paper, cement and plastics) were the source of 56 per cent of CO_2 emissions from the industry sector, one of five sectors addressed in the IPCC assessment reports on climate change mitigation. The other sectors are energy, transport, buildings, agriculture, forestry and other land-use change. In a book-length treatment, Allwood et al. (2012) provided a comprehensive analysis of the use of these materials in different applications, an identification and description of a wide range of material efficiency opportunities and a framework for how to think about, analyse and quantify material efficiency. Much of the research of this group of scientists has since focused on specific material efficiency options, associated business models and policies (Allwood et al., 2017; Olivetti and Cullen, 2018; Worrell et al., 2016).

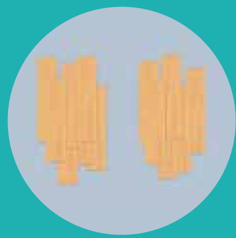
Milford et al. (2013) showed that material efficiency could reduce GHG emissions from future steel production by 50 per cent and that, if steel stocks converge to current rich-world levels, steel production would then peak in 2020. The quantification of the effect of different material

Box 3. Material efficiency strategies for climate action

The following material efficiency strategies were considered in the report:

Using less material by design

Designing lighter and smaller products that deliver the same service, reduces the amount of materials incorporated in the product and often the energy required to operate the product as well. In this report, we address both the construction of lighter structures (less steel and concrete in the bearing structure of multifamily buildings) and the downsizing of vehicles, i.e., the shift from large vehicles (light trucks, sports utility vehicles) to smaller ones (passenger cars, minicars).



Material substitution

Replacing cement and steel with wood in buildings and steel with aluminium in cars can reduce life cycle emissions. The mechanisms of emission reductions vary. While wooden structures require less carbon in the construction and even store carbon, aluminium in cars causes an increase in material-related emissions but reduces operational energy use, resulting in a reduction of life cycle emissions.

Fabrication yield improvements

Reducing material scrap used in the fabrication and manufacturing process can decrease the demand for material input. For example, reduction of trimmings or amount of machining needed in car manufacturing.

efficiency strategies from this study has been used in much subsequent research, including the work of the IEA, Material Economics and the current analysis.

In the industry chapter of its Fifth Assessment Report, the IPCC noted that emissions in the industry sector were largely driven by the demand of either new or replacement products. Strategies such as product life extension, more intensive use and demand reduction affect the demand of one or both of these categories. Material efficiency, product-service efficiency, waste reduction, reuse and recycling were identified as effective mitigation options. Reviewing the evidence, the IPCC stated that, to date, 'few policies specifically pursued material or product service efficiency.' A lack of experience with the implementation of mitigation measures related to material efficiency prevented the IPCC from assessing barriers and evaluating policies (Fischedick et al., 2014).

These GHG mitigation opportunities, however, were not considered in the scenario analysis that shaped the core message of the entire report, due to a lack of modelling capabilities (Pauliuk et al., 2017).

The IEA investigated selected material efficiency strategies as a special topic in the World Energy Outlook 2015 and the Energy Technology Perspectives 2017 (International Energy Agency, 2017). Without considering the upstream or downstream effects of material efficiency (such as reduced transport of materials in the former and reduced fuel consumption of lighter vehicles in the latter), the IEA estimated that the material efficiency strategies investigated would reduce industry emissions by about 5 per cent. In a more recent analysis, the IEA's modelling suggests that

More intensive use

It implies that less product is required to provide the same service. In the case of vehicles, ride sharing (car-pooling) and car sharing imply that fewer vehicles are used more intensively to provide transport services to a given population. For buildings, both higher utilization rates, e.g., through peer-to-peer lodging, smaller, more efficiently designed residential units, and increased household size/cohabitation can achieve a reduction of building space required.

Enhanced end-of-life recovery and recycling of materials

This increases the amount or quality of secondary materials available, which can reduce the amount of primary materials used to produce the same or another product. More of the materials in homes and cars can be recycled but it may require more dismantling/deconstruction to avoid contamination of the different material flows.

Recovery, remanufacturing, and reuse of components

Replacing production of spare parts or even primary products. For example, I-beams of buildings can be reused.

Product lifetime extension

Through better design, increasing repair, and enhancing secondary markets. For example, the lifetime of buildings can be enhanced through flexible design which makes it easier to modify interior walls, thus accommodating changing use patterns.

material efficiency could reduce the demand of selected materials by 15 to 25 per cent, contributing to about 30 per cent of the emissions reductions in the industry sector.

The Swedish think tank Material Economics (2018) investigated emission reductions following the Circular Economy framework. It found that 56 per cent of emissions from the production of steel, cement, aluminium and plastics could be reduced through increased recycling, improved yields, lighter designs, product sharing and more intensive use. In a new study, Material Economics (2019) investigates how emissions in the production of steel, chemicals and cement can be brought to zero using a combination of material efficiency strategies including circular material flows with process innovations (such as using renewably produced hydrogen in the production of steel and reducing the content of cement in concrete fillers and other binders). They estimated that such measures would require investment rates to increase by 25 per cent to 60 per cent but only an additional 1 per cent cost to the consumer. These findings are also reflected in a new report by the Ellen MacArthur Foundation (2019).

1.8.2. Material efficiency policies for climate mitigation

Several recent studies investigate policy aspects of material efficiency. In addition to the studies using the term 'material efficiency', research related to policy for material efficiency also appears under the rubric of frameworks described in Box 1. Five cross-cutting studies are of particular relevance to this report. A table listing additional studies is available in Supplementary Material B.

The OECD developed a framework for material efficiency policy focusing on guidance relevant to policies across all sectors (OECD, 2016). The guidance includes a characterization of policies by life-cycle stages that is broader than what is discussed in the present report. The OECD emphasizes the need for policy coherence and coordination to target the entire life cycles of products. The policy review in Chapter 3 of the present study has a more specific focus on the effectiveness of policy in meeting material efficiency goals as they relate to climate change.

More recently, the OECD (2019a) projected trends in materials use and assessed the likely environmental consequences. It argues that "Policy priorities should be determined considering the links between the use of a specific material and its economic drivers, as well as its impacts on the environment, and the criticality of its supply" and that "A granular approach is needed to understand which policy interventions may improve resource efficiency at the sectoral level, and how major environmental consequences can be avoided" (OECD, 2019a, p. 26). It is that need for granularity that motivates the focus on specific policies related to material efficiency in the present report.

A mapping exercise conducted for the United Nations Environment Programme in 2018 as part of the 10 Year Framework Plan provides an indication of the policies pursued by United Nations Member States (10YFP for the Sustainable Development Goal on Resource Production and Consumption, SDG 12). The report highlights the large variation across regions in terms of targeting particular sectors for policy intervention. Policies directed at the building/construction sector and the transportation sector are noticeably scant as a proportion of overall reported policies, despite the sectors' major impact in terms of GHG emissions in terms of material use (as indicated in the present report).

The above-mentioned IEA study on material efficiency provides guidance regarding policy strategies on material efficiency for homes and cars but does not address policy efficacy. The research by Material Economics (Material Economics, 2018, 2019) includes discussions of policy, circular economy business models and institutional responses; the studies do not seek to evaluate existing policies.

Hernandez et al., (2018) examine why material efficiency has been overlooked as a strategy for reducing energy and GHG emissions from heavy industry in the European Union (EU). They find that several factors play a role, including difficulties in reframing the prevailing rationale for climate mitigation to include ME; the inadequacy of monitored indicators that track energy embodied in materials; the lack of high-level political buy-in from key directorates in the European Commission and uncoordinated policy management across the directorates; the dominance of the EU emissions trading scheme (ETS) in EU climate policy and the difficulty in changing the ETS; and the absence of an industry lobby advocating for ME. While arguing that short-term policy change is unlikely, the authors provide a set of policy proposals to advance ME in the EU and Member States.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2. Emission Savings from Material Efficiency in Homes and Cars – An Industrial Ecology Assessment

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2.1. Chapter highlights

2.1.1. Residential buildings

- As population growth slows and reverses in some countries and the building stock becomes saturated, the demand for new construction materials and associated GHG emissions decline over time.
- There are significant opportunities to achieve greater reductions of emissions in residential buildings if material efficiency strategies are put in place. According to scenarios developed for this report, in 2050, a reduced demand for floor area arising from the more intensive use of homes in the G7 could reduce annual, system-wide greenhouse gas emissions associated with the material and energy requirements of homes by 35 to 40 per cent (250-300 million tons per year, Mt/a), compared to a scenario without these strategies.
- Cumulative, system-wide emissions of residential buildings in the G7 can be reduced by approximately 8–10 gigatons (Gt) CO_2e for the shared socioeconomic pathway (SSP) 1 and 2 scenarios in the period 2016-2060, using all relevant material efficiency strategies (end-of-life recovery rate improvement, fabrication yield improvement and scrap diversion, reuse, lifetime extension, material substitution, using less material by design/lighter structures and more intensive use of floor space). For reference, according to the total carbon budget proposed by the IPCC, the G7 would need to limit their remaining CO_2 emissions to 50 Gt for temperature increases to be confined to 1.5° C (if emissions are distributed evenly across the global population).
- The residential floor area occupied per person is one of the most important drivers of residential GHG emissions. A reduction of residential per capita floor area by 20 per cent compared to baseline development through more intensive use could reduce cumulative emissions by 7–9 Gt CO_2e for SSP1 and SSP2, delivering a large share of the savings identified above.
- Today's recycling practices provide secondary

raw materials, saving 1.5-2 Gt CO_2e in the period 2016-2060 compared to production from virgin resources. Improved recycling could increase these cumulative savings by another 0.7-0.8 Gt.

- The potential reduction of cumulative emissions in economies with growing stocks of materials such as China and India are comparable to those in the G7 countries. The reduction potential differs from country to country.
- There is significant potential to reduce emissions through substitution of materials such as reinforced concrete and masonry with wood. Plant-based materials tend to cause less CO_2 in their production and store carbon during their use. In the G7, the use of sustainably sourced wood could reduce cumulative emissions by 100-500 Mt in the period 2016-2060, or 1 to 2 per cent of expected building life-cycle emissions.
- Using less material for construction would save 300-500 Mt in the period of 2016-2060.

2.1.2. Light-duty vehicles

- Material efficiency strategies offer significant opportunities to achieve reductions of greenhouse gas emissions in light-duty vehicles. According to scenarios developed for this report, emissions from the production of materials for the manufacture of cars can be reduced by 30 to 70 per cent in 2050, depending on scenario assumptions and extent of implementation of the strategies.
- In all scenarios (Low Energy Demand, SSP1 and SSP2), material efficiency could deliver significant reductions of GHG emissions in addition to those reductions expected from a shift towards clean energy and the gradual adoption of battery-electric and hydrogen-fuelled vehicles. Under the SSP1 scenario, for example, material efficiency strategies could reduce emissions from the manufacturing, operation and disposal of light-duty vehicles in G7 countries by 24 per cent in the period 2016-2060. Similar relative savings could be attained in China and India.
- Cumulative emissions in G7 in the period 2016-2060 can be reduced by 1.6 Gt CO_2e for SSP1 and SSP2 by following material cycle improvements: increased fabrication yields and fabrication scrap diversion, light-weighting of vehicles through a shift from steel to aluminium, lifetime extension and increasing the reuse of parts and recycling of materials from end-of-life vehicles. Savings from the same strategies in China and India would be 1.6 and 1.3 Gt, respectively.
- A continuation of today's end-of-life vehicle recycling practices in the G7 is estimated to save 1.6-1.9 $GtCO_2e$ in the period 2016-2060. That is assuming impacts on scrap markets from the contamination of the metal recycling stream with copper and other tramp elements are avoided. A further improvement of recycling can deliver emission reductions of up to 0.4 $GtCO_2e$.
- Using less material could be achieved by switching to smaller, trip-appropriate vehicles. A modest shift, for example reducing the share of light trucks and SUVs in the United States light-duty fleet from half to one third, could save about 5 per cent in cumulative emissions.
- The number of vehicles per capita is one of the most important drivers of GHG emissions for vehicles. The largest reductions of life-cycle emissions could be attained through car- and ride-sharing. Collectively-shared vehicle fleets allow customers to consider alternative means of transport and to choose trip-appropriate vehicle sizes; shared rides increase the occupancy of vehicles and reduce the number of vehicles on the road. Assuming that up to 25 per cent of rides are shared and 25 per cent of all vehicles are part of car-sharing pools, reductions in cumulative emissions from the manufacturing, operations and disposal of vehicles in the SSP1 scenario would be 8 $GtCO_2e$ (or 17 per cent) in the period 2016-2060.
- Overall reduction potential differs from country to country, but the differences are relatively small.

2.2. Assessing the climate benefits of material efficiency

2.2.1. Modelling approaches to material efficiency

Research on material efficiency has significantly progressed through several interrelated strands starting from engineering fundamentals applied to individual case studies and considerations of specific products and technologies. These include conceptual developments, small-scale case study quantifications, sectoral analysis and large-scale country- and global-level prospective modelling. More specifically:

- Research on material efficiency has its origin in the engineering community, identifying specific strategies and measures that can result in reductions in specific material applications, namely products (Allwood et al., 2012; Worrell et al., 2016). This research contains descriptions of technologies and addresses empirical aspects, such as the magnitude of the use of structural steel in buildings beyond what engineering standards require (Moynihan and Allwood, 2014). It also quantifies potential savings of materials, energy and emissions from shifting current practices to, for instance, lighter designs (Carruth et al., 2011) or closed-loop recycling (Nakamura et al., 2012). Many such individual material and emissions savings have been documented.
- There have been several quantifications of savings in materials and emissions from the economy-wide implementation of several material efficiency strategies (in parallel or incrementally). One example addressed the global demand for iron, steel and aluminium (Liu et al., 2013; Milford et al., 2013).
- Recycling of materials and reuse of products or components are important strategies. Quantifying the future availability of used products or secondary materials requires a modelling of the stock of buildings and cars in use. Many materials are downcycled because the recovered material qualities are not good enough for closed loop recycling. Ideally, models would be able to keep track of material quality, such as the composition of alloys, and find optimal recycling solutions across different product or material categories. To our knowledge, such models exist for some specific cases (Løvik et al., 2014; Ohno et al., 2017), but not in general.
- Decisions regarding the use of materials in the production process can affect the energy use in the operation of the product itself, as is the case for buildings, vehicles and machinery (Heeren et al., 2015; Hertwich et al., 2019). Engineering models at the product level have been devised to assess environmental impacts and analyse the trade-off between energy and material efficiency. For example, extending the lifetime of buildings or cars, while saving materials, slows down the penetration of more energy efficient technologies, thereby increasing operational energy demand (Serrenho et al., 2017). Cohort models of product stocks, covering both production and use, are required to properly understand the trade-offs (Pauliuk et al., 2013). At present, such models only exist at the national level and for individual products.
- To study the economy-wide implications of applying material efficiency on emissions, employment, domestic value added and resource use, input-output models have been used, either at the level of individual economies (Scott et al., 2019), or for the global economy (Donati et al., 2020; Wiebe et al., 2019). Current models are comparative static ones that do not represent the cohort effects discussed above. Also, current studies approximate the trade-offs mentioned. Such comparative static input-output models can be used to examine the interaction between different strategies, including material efficiency, energy efficiency and a decarbonization of the energy supply.
- Another approach to studying the economy-wide implications of material efficiency, including the impact on product prices and demand, is through economic general equilibrium models (Oberle et al., 2019; OECD, 2019a). Its strength is that prices and quantities adjust following an economic logic. It also allows modelling of economic policy instruments such as a resource tax. However, it is difficult to implement a trade-off analysis between material savings and operational energy use resulting from the implementation of specific resource efficiency strategies, or trace product composition and hence recycling material availability (Pauliuk et al., 2017).
- There are ways to represent material efficiency strategies in a simplified manner, through implementation curves and resulting reductions in materials demand within scenario models, such as those used in climate change mitigation research (International Energy Agency, 2019a). However, such approaches are ad hoc and often miss crucial interactions, such as those between the use of materials and operational energy use. Hence, there are several nascent efforts to develop

integrated models that allow the tracking of materials and product cohorts in the economy and include energy/climate scenario models.

Product-level models addressing the implementation of material efficiency strategies and their impact on the composition, material content and operational energy use of product cohorts over time have not been developed or have had not been applied for the countries in question and a decarbonizing energy mix. This assessment therefore included a suitable model (Pauliuk and Heeren, 2019) and collected data on the existing product stock and composition in the countries of interest.

This chapter outlines current GHG emissions, assumptions about future demand, modelled material efficiency strategies and results. The next subsection describes the goal and scope of the chapter and defines the storylines used in the scenario formulation, both for input data and assumptions about the implementation of material efficiency. In the following subsection, the modelling approach is outlined, material efficiency strategies are identified and the sequence of implementation for the different material efficiency strategies in the model is described. In sections 2.3 and 2.4, the material efficiency of homes and cars, respectively, is explored. Section 2.5 provides a discussion of the results. Additional descriptions of scenario assumptions, intermediate results on the floor space and building materials, as well as country-level results are provided in Supplementary Material A. Further, Pauliuk et al. (Pauliuk et al., 2020) describe the methods, data collection and model characteristics; Fishman et al. (Fishman et al., 2020) describe the scenario assumptions, and Wolfram et al.(2020) describe the vehicle model. Detailed documentation on the ODYM-RECC model (Pauliuk, 2019; Wolfram et al., 2020), input data (Pauliuk et al., 2019a), and model output (Pauliuk et al., 2019b) is available online.

2.2.2. Goal and scope

This chapter assesses potential reductions in the life cycle GHG emissions of residential buildings and light-duty vehicles in G7 countries that can be obtained through a set of identified material efficiency strategies. The analytical concept used in this assessment is a scenario-based modelling approach. Unlike forecasting models, which describe a future path together with assessments of its likelihood or probabilities, the scenario-based approach is a what-if counterfactual framework. The assessment consists of several scenarios, each describing an internally consistent potential future with its own development trends, pathways and assumptions, which determine the resulting GHG emissions, reductions potentials and related material cycles to 2060. There is no estimation of the likelihood of any scenario over another. The assessment seeks to quantify GHG emissions reductions expected from material efficiency strategies in a potential future development where climate change mitigation is broadly in line with the Paris Agreement. Potential futures are represented by three scenarios with various levels of transformation, congruent with two of the five storylines of the Shared Socioeconomic Pathway (SSP) family used in the climate research.

- The SSP1 storyline reflects a very optimistic view of the future in which conditions are good for climate change mitigation and adaptation, with good international cooperation, low population growth and strong economic growth.
- The SSP2 storyline reflects an improvement of conditions for climate change mitigation and adaptation but a continued growth in driving forces such as population and the economy. Many scenarios have been based on the SSP2 storyline. We chose a 2-degree climate policy scenario for the energy mix and penetration of electric vehicle drive technologies to evaluate how much material efficiency could move the development to well below 2 degrees.
- The Low Energy Demand (LED) scenario reflects a socioeconomic development following the SSP2 pathway and very aggressive efforts to reduce energy demand, including through changes in consumer behaviour and production- and consumption patterns. It was developed specifically to explore whether it was possible to limit the global average temperature rise to 1.5°C above pre-industrial temperature levels without using extensive carbon-removal technologies and nuclear power (Supplementary Material A).

In this report, we do not show results for other scenarios or SSPs, as aggressive material efficiency only makes sense if implemented together with other climate change mitigation policies, and an achievement of the Paris targets in other scenarios is highly unlikely.

The time horizon of the scenario modelling is 2016-2060. The year 2015 is the last one for which complete empirical data on product stocks and emissions were available at the time this report was prepared.

The benefit of a material efficiency strategy is calculated as the difference in GHG emissions between scenarios with and without the adoption of this strategy. In our case, the total life-cycle emissions associated with the services delivered by the vehicle fleet/building stock with the adoption of material efficiency strategies are compared to the same service delivered without material efficiency strategies.

The material efficiency strategies included in the analysis are listed in the introduction and in Table 4. Implementation of these strategies within each sector (residential buildings and vehicles) is further specified in the corresponding section.

The scenario modelling addresses the production and use of primary materials and use of secondary materials, the material content of products, the manufacturing and use of products and their waste management. A vintage-stock model traces both material in- and outflows and the energy demand of the operation of the vehicle and building stocks explicitly. For each of these life cycle steps, the material balance (including product yield and waste generation), energy use and emissions are considered based on data derived from empirical observations or engineering calculations.

2.2.3. The Open Dynamic Material System Model for Resource Efficiency and Climate Change

Modelling was conducted with the Open Dynamic Material System Model for Resource Efficiency and Climate Change (ODYM-RECC model), further described in Supplementary Material A and by Pauliuk et al., (2020). ODYM-RECC combines a dynamic material stock and flow model with life-cycle assessment and engineering calculations (Pauliuk and Heeren, 2019).

We developed a description of archetypes, that is, illustrative representations, of future cars and residential buildings, modelling different drive technologies, material choices and energy standards. Using engineering-based models, we determined the material requirements and operational energy use of each of the archetypes, reflecting changing energy mixes, adoption of technology such as electric and fuel-cell vehicles, regional climates and regional product use patterns. Starting from these archetypes, we then modelled the implementation of material efficiency strategies such as higher yields, lighter components and different materials. Table 4 provides an overview of the strategies. The engineering models were complemented by data from life-cycle assessments on the energy and emissions associated with materials processing and product manufacturing.

Based on scenarios for floor space demand and transportation services provided by automobiles (Fishman et al., 2020), as well as information on the stock of homes and vehicles available in 2015, we calculated both the need for new floor space and vehicles and the retirement of existing buildings and vehicles given typical product life spans. Thus, energy use along the supply chain of new houses and vehicles, material input and secondary material availability and process emissions were calculated based on the newly manufactured, used and dis-used products in each year, keeping track of the cohort-specific performance of these products.

The importance of each individual strategy was investigated through a sensitivity analysis, where only that ME strategy is applied and the resulting emissions are compared with the base case of no material efficiency. In addition, we implemented a cascade of material efficiency strategies, where the least intrusive strategies such as yield improvement and enhanced recycling are implemented initially, followed by strategies that require more systemic changes and may be seen as more disruptive (see Table 5). As some emission reductions have already been achieved by the earlier steps, the absolute reductions of the later steps will be smaller. Most of the emissions reductions reported in this chapter are based on the cascade shown in Table 5.

Table 4. Material efficiency strategies and modelling assumptions per sector

Strategy	Residential buildings	Light duty-vehicles
Using less material by design – light-weighting	Lighter buildings: Using less material by optimized design and engineering without loss in functionality.	Smaller vehicles: Segment shift from large vehicles (light trucks, sports utility vehicles) to smaller ones (passenger cars).
Material Substitution	Construction materials with lower life-cycle emissions are used. Wooden buildings have fewer life-cycle emissions than concrete or brick buildings. While other material options exist, wood is particularly effective because of its carbon sequestration capacity.	Material is substituted to achieve less operational energy demand. Replacing steel with aluminium (considered here), carbon fibre, magnesium or high-strength steel reduces life-cycle emissions, because lower vehicle weight saves fuel in the use phase.
Improvement of fabrication yield	Fabrication yield improvements (FYI) reduce the amount of material scrap used in the fabrication and manufacturing process, thereby lessening the demand for material input from the manufacturing sector.	
Improvement of End-of-Life (EoL) recovery rate	The improvement of the EoL recovery rate increases the share of materials salvaged as scrap from discarded products. This increased recycling eventually leads to a displacement of primary materials by secondary materials.	
Diversion of scrap	Manufacturing scrap, like trimmings or cuttings, is diverted into other manufacturing units to make smaller components. This avoids re-melting and may reduce costs.	
More intensive use (fewer products are required to provide the same basic service)	Peer-to-peer lodging, increased household size/ cohabitation and shift from single to multi-family houses.	Car-sharing (shift from the personal car to cars from a shared fleet) and ride-sharing (driving patterns where people with same or similar driving destinations share a ride) are considered.
Product lifetime extension	Better design (facilitating repurposing of a product), increased repair and enhanced secondary markets.	
Recovery, remanufacturing and reuse of components	Replacement of the production of spare parts or even primary products.	

Given the potential interactions among different strategies, reductions that are ascribed to any one strategy depend on the sequence in which these strategies are implemented through model runs. The model is run first without any strategies, then with those identified as step 1, and the resulting difference in emissions is identified as emissions reductions ascribed to the strategies constituting step 1. Then, the model is run with the strategies identified as step 2, and the difference in emissions between step 2 and step 1 is ascribed to the strategies added in step 2 and so forth.

Table 5. Implementation cascade of material efficiency strategies

	Implementation cascade of material efficiency (ME) strategies						
	Steps						
	0 (Current ME levels)	1	2	3	4	5 (buildings only)	6 (cars only)
End-of-life recovery rate improvement		x	x	x	x	x	x
Fabrication yield improvement		x	x	x	x	x	x
Fabrication scrap diversion		x	x	x	x	x	x
Reuse			x	x	x	x	x
Lifetime extension			x	x	x	x	x
Material substitution				x	x	x	x
Using less material by design / lighter structures and smaller vehicles					x	x	x
More intensive use of floor space						x	
Car-sharing							x
Ride-sharing for cars							x

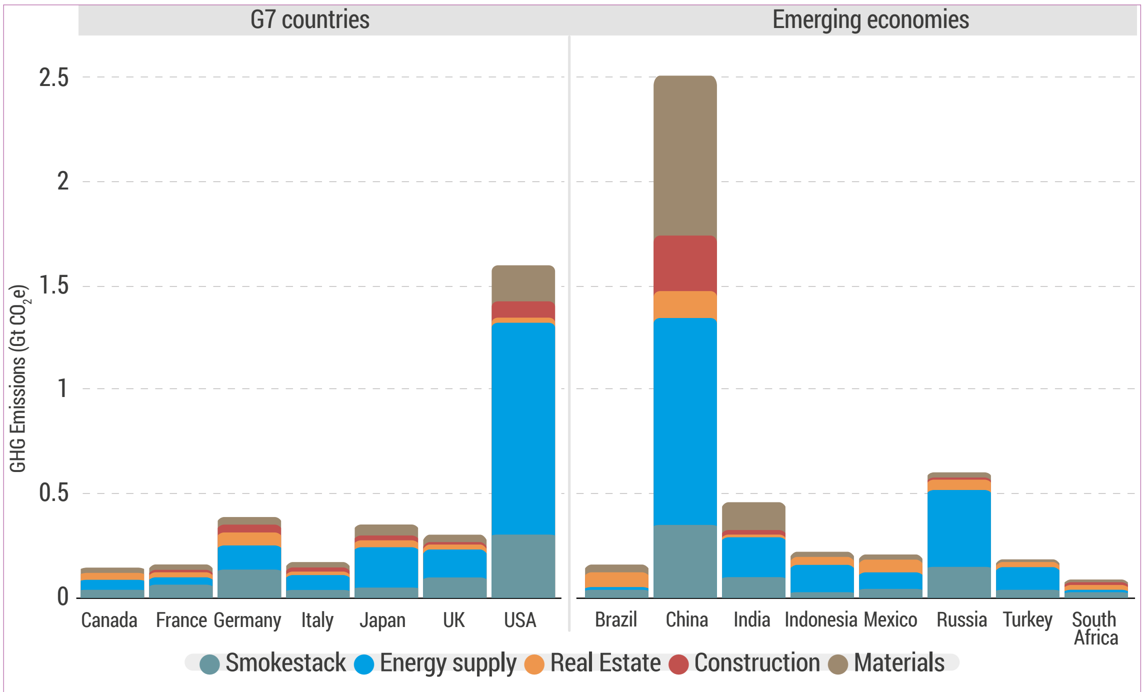
2.3. Material efficient homes

2.3.1. Introduction

Residential buildings are an essential part of a country's infrastructure and fulfil the basic function of providing shelter and comfort to people. However, resource demand is driven not only by population growth, but also by continuous increases in floor space per capita (Moura et al., 2015), and higher thermal comfort requirements (Shove, 2003), particularly for space cooling (Isaac and van Vuuren, 2009). Buildings are responsible for about a quarter of energy-related GHG emissions globally (Lucon et al., 2014). In 2015, fuel combustion in residential buildings worldwide contributed about 2 Gt CO_2 emissions, while the production of electricity consumed by households caused 4

Gt CO_2 emissions (International Energy Agency, 2019c). Emissions related to the construction of residential buildings are not identified in emission statistics. We estimated, conservatively, that the construction-related emissions of residential buildings in 2015 were 4 Gt CO_2e, with more than 60 per cent attributable to materials (see Figure 8). About half of those emissions were associated with an expansion of floor space, while the other half served to maintain or replace existing floor space.

Figure 8. Emissions from housing in the G7 countries and selected emerging economies in 2015



Source: Based on EXIOBASE 3.6 (Hertwich, 2019; Stadler et al., 2018).
Note: The operational emissions comprise direct emissions from the combustion of fuels purchased by households (smokestack), energy supply emissions associated with the production of fuels and electricity purchased by households (apart from motor gasoline), and real estate emissions from the real estate services, including energy paid as part of the rent, Construction emissions are past emissions associated with construction of currently occupied homes. Materials indicates emissions from the production of materials used in the construction of currently occupied homes and for their maintenance and repairs.

Building energy efficiency has been an important focus of policy over the past decades. Energy consumption and related GHG emissions from the building sector in industrialized countries have remained stable or even decreased since 2000. Tighter building standards in many industrialized regions ensure much lower heating-related energy demand in new and refurbished buildings, reflecting recent advances in technology. At the same time, there is a rise in cooling loads caused by a warming climate, southward migration, urbanization and changing comfort expectations. Mitigation scenarios include a further reduction of building-energy use. Assessments often ignore material and construction-related emissions. When these emissions are included, they are treated as functionally separate – thereby ignoring interactions (International Energy Agency, 2019c). By deriving both material composition and operational energy use from the same archetype model, the present report addresses the implications of changes in construction and use patterns on both materials and energy use. The present model traces the replacement of the existing building stock with new, more efficient building designs, but does not consider refurbishment of existing buildings in its current version. In Supplementary Material A, we provide a more detailed explanation of the scenario assumptions, modelling results for material demand, and country-level results.

2.3.2. Future floor-space demand

Scenarios for future floor space were based on the value in 2015, past dynamics and the climate-friendliness of the underlying scenario (see Table 6). While there is a large difference in per capita living space in countries at a similar stage of development, there has been a general trend of increasing floor space with growing GDP, but a recent flattening of demand. We assumed that this trend continues for SSP2, that floor space demand in SSP1 does not change and that it converges towards 30 m^2 per capita in the LED scenario (see Supplementary Material A).

Table 6. Floor area per capita in 2015 and their target value in 2060 for each scenario, before implementing more intensive use

		Floor space [m^2/cap]								
Country		USA	Japan	Canada	UK	France	Germany	Italy	China	India
2015		68	39	61	34	41	42	43	36	12
2060	LED	38	30	35	30	30	30	30	30	28
	SSP 1	68	39	61	40	41	42	43	41	32
	SSP 2	88	46	75	50	47	49	50	54	43

The building model uses two basic archetypes: one for single-family homes (SFH) and one for multi-family homes (MFH). The share of MFH differs widely across countries from 20 per cent in North America to as high as 88 per cent in Italy. We used the share of MFH as an indicator for a country's future urbanization. As MFH are typically more space efficient and require less energy for space heating, we assumed that in scenarios with low per capita floor area their share in new construction rises to around 80 per cent in the LED scenario.

The building archetypes have four subtypes to describe their energy efficiency standard: 'non-standard' describes buildings that do not comply with today's typical energy efficiency standards, 'standard' complies with typical energy standards, 'efficient' is a building that has significantly reduced energy demand compared to the standard, and zero-energy building 'ZEB' is a standard that allows zero net-energy demand (with the help of renewable energy). The latter has been adopted by several governments, as well as the EU, as a political target. We assumed that, in SSP2, about half of the new buildings will meet either a high efficiency or zero energy building standard. This roughly corresponds to an extrapolation of building energy codes to 2050, as implemented in the United States of America from 1980 onwards (Amann, 2014).

2.3.3. Material efficiency strategies for buildings

The building archetype model captures the following material efficiency strategies for representative single and multi-family buildings in each climate region, evaluates the impact of the strategies on material composition and energy use and provides material and energy intensity as weighted national average to the dynamic stock model (ODYM-RECC). Table 5 indicates the degree of adoption of the various strategies. In Section 3.3, these strategies are discussed from a policy perspective and existing policies and tools are identified.

Material substitution leads to reductions in emissions if materials with lower life-cycle emissions are used (Heeren and Hellweg, 2019). Compared to reinforced concrete and masonry, sustainably harvested timber as a building material can generate fewer emissions in its extraction and processing and can store carbon in the building. Its use, however, can lead to increased heating and cooling demand compared to a more massive building, especially in the shoulder season, due to reduced heat storage (Heeren et al., 2015). We assumed that brick or concrete walls and elements are replaced with timber construction, with identical thermal resistance. The insulation layer is applied between wood beams instead of the exterior, as done with concrete. Furthermore, wood beams are employed as load-bearing structures instead of steel. For instance, the base exterior wall in the single-family home archetype has 15 cm of reinforced concrete, which is replaced with wood beams with 15 cm x 7.5 cm every 80cm. It is assumed that market penetration of new construction employing this material substitution will be 85 per cent, 50 per cent and 10 per cent for the LED, SSP1, and SSP2 scenarios in the European G7 countries, respectively. In North America and Japan, it would rise slightly from an already high level (see Figure 9).

Light-weighting of structures is often possible without loss in functionality or service through optimized and purpose-specific design (Dunant et al., 2018; Milford et al., 2013; Moynihan and Allwood, 2014). It is assumed that the amount of reinforced concrete in walls and slabs and the volume of steel in beams can be reduced by 20 per cent and 15 per cent, respectively, which is somewhat lower than the assumption by Milford et al. (2013b). In the LED and SSP1 scenarios, it is assumed that 85 per cent and 55 per cent of new buildings can be light-weighted by 2050 and 35 per cent for SSP2, respectively (see Figure 9).

More intensive use of buildings involves strategies that reduce the demand for floor area per person compared to an expected increase. Decreasing family size and the continued use of a large residence by a shrinking family are important drivers for rising floor areas. Measures to achieve more intensive use and thus less floor space per capita include buildings with smart and adaptable floor plans, peer-to-peer lodging, trendy smaller homes and replacing single family homes with multi-family homes, which are normally smaller per capita and are the residence of choice in urban areas that offer amenities. See Section 3.3.3 for a more in-depth discussion of potential mechanisms that could lead to more intensive use.

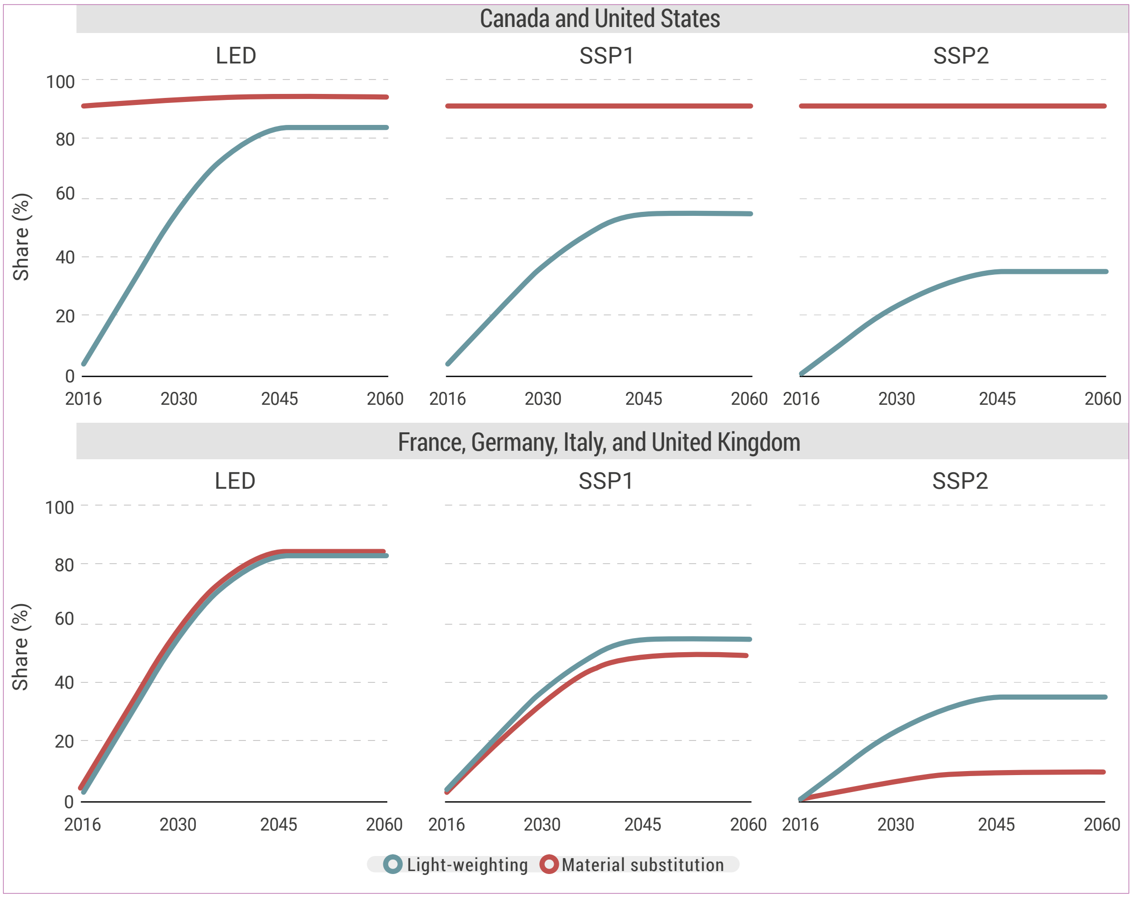
Section 2.3.2 summarizes assumptions on per capita floor area in 2060. For the SSP1 and SSP2 scenarios including more intense use, a reduction of up to 20 per cent from scenario average per capita floor space in Table 6 is assumed.

Lifetime extension can reduce life-cycle material demand as a building remains in use for longer. Based on case studies, we assumed that building lifetime can increase by up to 90 per cent of the base value (Milford et al., 2013). In the case of the United States of America, that corresponds to 68 years in addition to the 75 years average lifetime. One way to achieve longer building lifetime is to increase the durability of components. Lifetime extension makes sense for well-designed, energy-efficient homes or houses of cultural heritage value rather than those of poor quality and high operational energy requirements. Refurbishment was not considered here, but existing homes were modelled as shifting to cleaner energy supply in accordance with the respective energy scenarios.

Reuse of building components is a strategy that avoids the impacts of production of primary materials. Based on case studies, we assumed that up to 29 per cent of the steel components (Milford et al., 2013) and up to 27 per cent of the concrete (Shanks et al., 2019) can be reused. Building design is an important factor for ensuring component reuse. Such design includes ensuring easy disassembly of components and standardization of joints.

Recycling steel from structures with recovery rates of more than 90 per cent were used in the modelling (Pauliuk et al., 2013). Concrete recycling is not considered in the model, though bricks and concrete from building demolition are sometimes crushed and used as filling material (in road construction, for instance). Crushed concrete can also be used as aggregates when recycling concrete, but life-cycle GHG benefits of concrete aggregate recycling depend strongly on transport distance and the amount of additional cement needed. This often generates little or no reduction of carbon emissions. Recovery rates for aluminium, copper, plastics and timber are set at 87 per cent, 78 per cent, 18 per cent and 30 per cent, respectively, with additional improvement of 8pp, 15pp, 52pp, and 0pp possible in the resource efficiency scenarios (pp = percentage points).

Figure 9. Share of newly built residential buildings subject to light-weighting and material substitution



Note: North American and Japanese residential buildings are predominantly made from wood. For individual countries, see Supplementary Material A. Definitions of abbreviations can be found in the glossary.

Table 7. Modelling assumptions of target values for material efficiency strategies in residential buildings per scenario in 2060

Strategy	LED	SSP1	SSP2
Timber structures	85% of new builds	50% of new builds	10% of new builds
Light-weighting	85% of new builds	55% of new builds	35% of new builds
More Intensive Use	No change	-20% from reference	-20% from reference
Lifetime Extension	90% extension	90% extension	90% extension
Reuse			
Steel	29% of components	29% of components	29% of components
Concrete	27% of components	27% of components	27% of components
Recycling Recovery Rate			
Aluminium	95% (currently 87%)	95% (currently 87%)	95% (currently 87%)
Copper	93% (currently 78%)	93% (currently 78%)	93% (currently 78%)
Plastic	70% (currently 18%)	70% (currently 18%)	70% (currently 18%)
Timber	30% (no change)	30% (no change)	30% (no change)

Note: Figures are representative and may differ in some cases for individual countries.

2.3.4. Results

2.3.4.1. Main results

Material efficiency can reduce GHG emissions from residential buildings. The assessed strategies could reduce annual GHG emissions associated with the material cycle of residential buildings in G7 countries and China by 80 to 100 per cent by 2050, compared to a scenario without material efficiency (including the benefits of use of recycled material). Savings in India would be 50 to 70 per cent by 2050. At the same time, the investigated material efficiency strategies can reduce operational emissions by up to 20 per cent. The reduction in system-wide GHG emissions associated with construction, operation and disposal of residential buildings in 2050 would be 35 to 40 per cent across the G7 (see Figure 10) and 40 to 70 per cent in China and India. These reductions are on top of reductions that are assumed to be achieved through the shift towards low-carbon energy supply. The reduction of emissions could be achieved quickly and do not depend on the development of new technologies.

While material efficiency primarily aims to reduce emissions associated with the material cycle of construction materials, some strategies also affect the energy use during the construction process and the heating and cooling of buildings. Especially in existing buildings in G7 countries, the operational energy use causes more emissions than construction (see Figure 10). The percentages we report comprise either the emissions associated with producing and processing materials (including credit for recycling and the storage of carbon in wood, labelled as 'material cycle emissions') or the system-wide emissions associated with the entire building life-cycle (including material production, construction, operations, and disposal of residential buildings, labelled as 'life-cycle' or 'systems-wide' emissions).

The recycling of building materials offsets or saves 15 to 20 per cent of the emissions in the primary production of materials for residential buildings in the G7 in 2016. Improved recycling could increase the GHG savings from recycling by 14 to 18 per cent in 2050, while the reduced material demand through other material efficiency strategies could increase the share of recycled materials in the overall supply of building materials because secondary materials would be able to meet a larger share of a reduced demand.

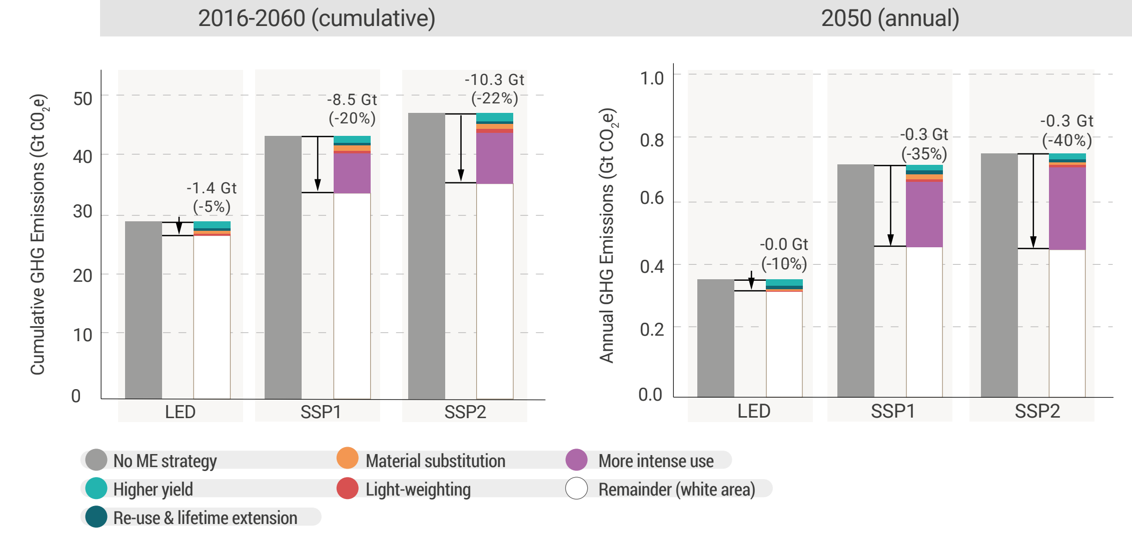
One can distinguish more intensive use, a material efficiency strategy that may require a change in behaviour or preference, from strategies that require technical changes, such as lighter structures or increased recycling.

The results indicate that material cycle improvements – primarily recycling rate improvements, lighter structures and increased use of timber – could reduce GHG emissions from the material cycle of G7 residential buildings in 2050 by 25 to 37 per cent. This would translate to 6 to 7 per cent of system-wide emissions. Cumulative savings would be in the order of 1-2 Gt CO_2 equivalent. By comparison, the remaining amount of CO_2 that can be emitted before the 1.5 °C temperature increase is reached is estimated to be 500 Gt by the end of 2019 (IPCC, 2018). If 1400 Gt CO_2 are added, the Earth's surface would warm by 2°C. If these carbon budgets were distributed evenly across the global population, the G7's share would be 50 Gt for 1.5°C and 140 Gt for 2°C. Cumulative savings are thus substantial compared to the emissions budget.

The use of up to 20 per cent less living space compared to the baseline development through more intensive use of existing space could result in more substantial savings and offsets in the GHG emissions from the production of building materials by 56 to 58 per cent, or 4–6 billion tons CO_2 equivalent cumulatively. This large reduction of primary material demand results from the ability of recycling and reuse to provide the required building materials. Heating and cooling smaller spaces also reduces energy demand, resulting in additional savings of 3-3.5 billion tons, or 9 to 10 per cent of the cumulative energy requirements for heating and cooling.

The deployment of all material efficiency strategies could reduce GHG emissions from the construction, operations and disposal of residential buildings by 20 to 22 per cent cumulatively in the SSP1 and SSP2 scenarios, rising to 35 to 40 per cent in 2050 (see Figure 10).

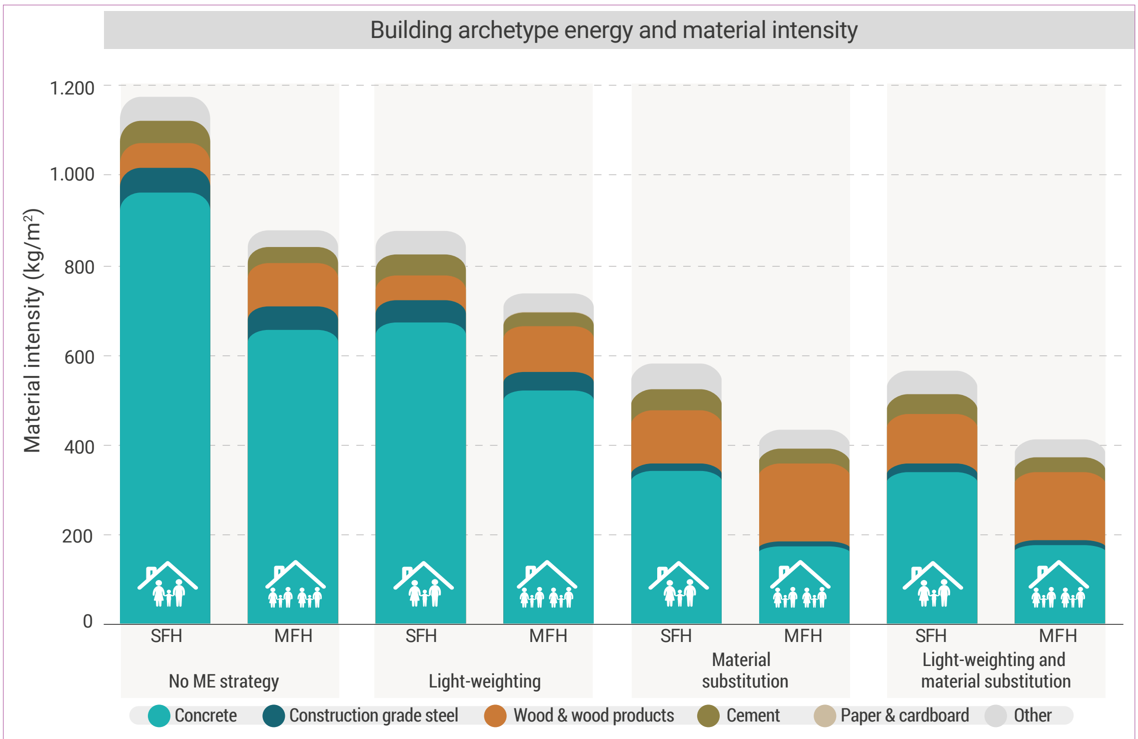
Figure 10. Cumulative savings in greenhouse gas emissions in 2016–2060 (left) and in 2050 (right) by scenario and ME strategy cascade for residential buildings, G7 total



The colored areas illustrate the reduction potential compared to a situation without any ME strategy (grey bar).

2.3.4.2. Building archetype energy and material intensity

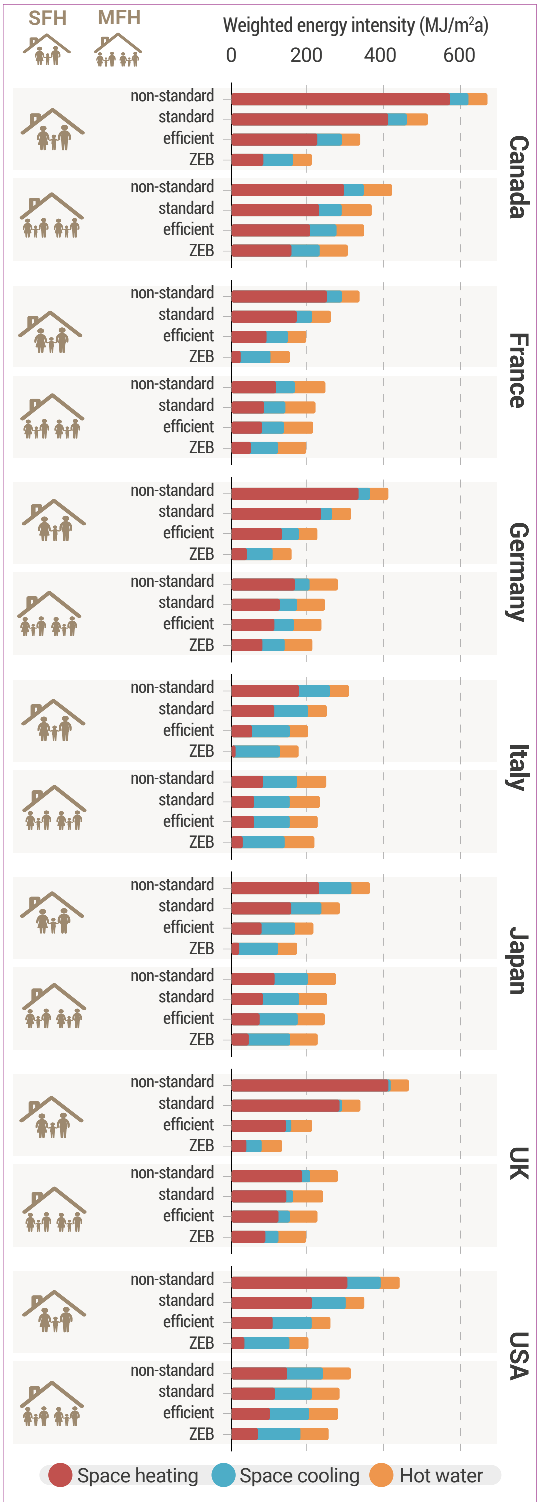
Figure 11. Building material intensity for each material efficiency strategy



Notes:

- SFH: single-family home; MFH: multi-family home.
- Occupation archetype with a standard energy efficiency. The concrete fraction includes 13% cement which is additional to the cement fraction (green olive). MFHs in tower developments tend to have higher material demand (Marinova et al., 2020), while the low-rise buildings assumed here have lower specific material demand and are in line with recommendations of earlier IRP reports (Swilling et al., 2018).

Figure 12. Average energy intensity for the archetype buildings in G7 countries



Notes:

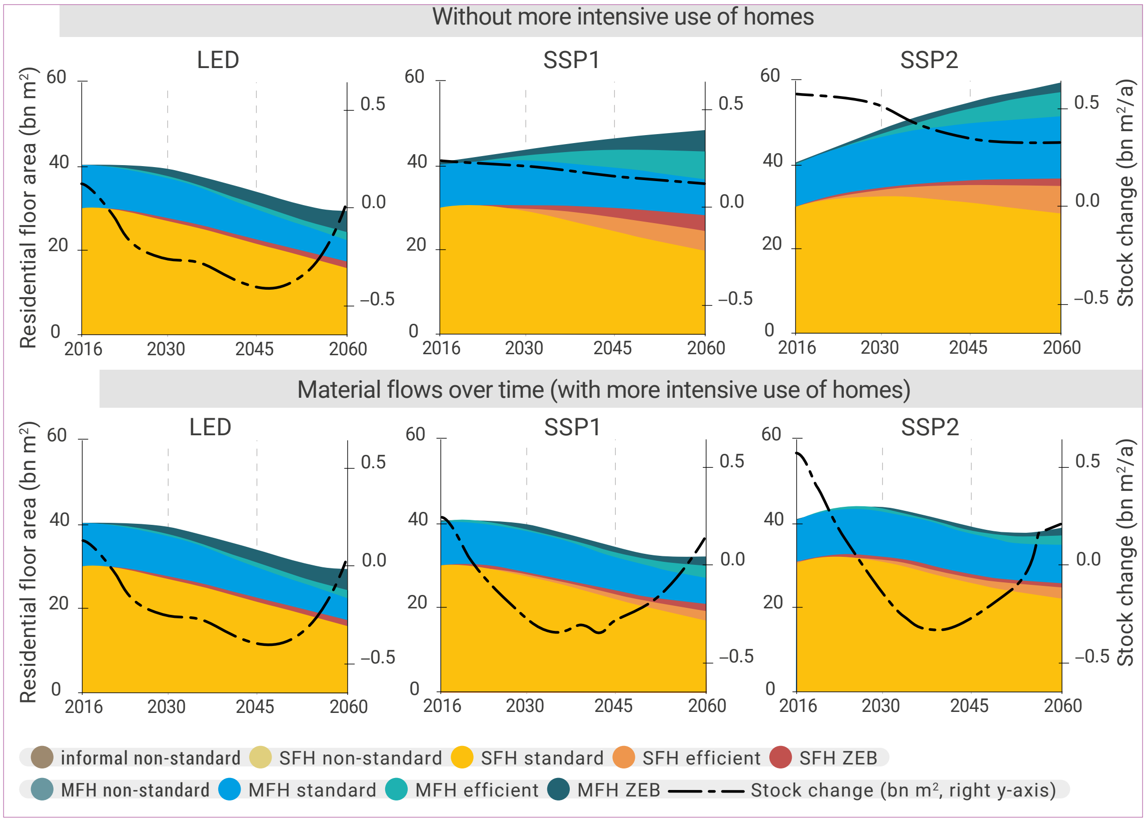
- SFH: single-family home; MFH: multi-family home; ZEB: Zero Energy Building.
- Simulation result, weighted by floor area distribution in regional climate zones and assuming no material efficiency strategies applied.

The material intensity of archetypes depends on the selected material efficiency strategy (see Figure 11). Only the strategies of light-weighting and material substitution were applied to the archetype model, while other strategies are implemented at the stock level. Furthermore, material intensity depends on the type of building. Larger multi-family houses require less building envelope per floor area. The energy efficiency standard also influences total material content. Archetypes with a higher energy efficiency (omitted in Figure 11) have a larger "other" material fraction, because more insulation material is considered. The single-family home (SFH) type has a total material intensity of 1180 kg/m², with concrete representing by far the largest share of materials (960 kg/m²). Considering per capita material intensity, the multi-family home (MFH) type building is much more efficient. In the United States of America for example, individuals living in a SFH occupy on average of 72.9 m², while those living in a MFH occupy 46.2 m² per person. This corresponds to material intensities of 86.0 and 44.3 metric tons per capita for SFH and MFH, respectively. Therefore, the MFH archetype is approximately 20 per cent more material efficient per square metre and almost 50 per cent more material efficient per person sheltered. Light-weighting assumes optimized building design and saves approximately 20 per cent of materials. A timber building has half the material content by weight of the variant without any material efficiency strategy. In this archetype, the concrete content is replaced with wood, which has less GHG-intensity. The light-weighted timber archetype has another 2 to 3 per cent less material content than the timber archetype.

Building energy demand depends on the climate and the relevant energy standard (see Figure 12). The applied material efficiency strategies also influence space heating and cooling demand. The two archetypes with material substitution replace much of the concrete content with timber (see Figure 11). Space heating and cooling energy demand is 2 to 5 per cent higher for wooden buildings due to reduced thermal energy storage in the building envelope, which is in line with existing literature (Heeren et al., 2015). This effect is not illustrated in the figure but considered in the calculations. The energy simulation results in Figure 12 are a hypothetical demand to indicate, for instance, the demand for space cooling if air conditioning equipment is installed. Final national demand, however, also depends on the national implementation level (in other words, the share of buildings that are equipped with heating and cooling devices). This value increases over time in the modelling. Changes in energy demand due to climate change are not considered. Other factors that influence energy demand are user behaviour, building design and window size (Haldi and Robinson, 2011; Heeren et al., 2015).

2.3.4.3. Material flows over time

Figure 13. Total floor area in G7 countries by building type, energy efficiency standard, and scenarios with (bottom) and without (top) more intensive use



Notes:

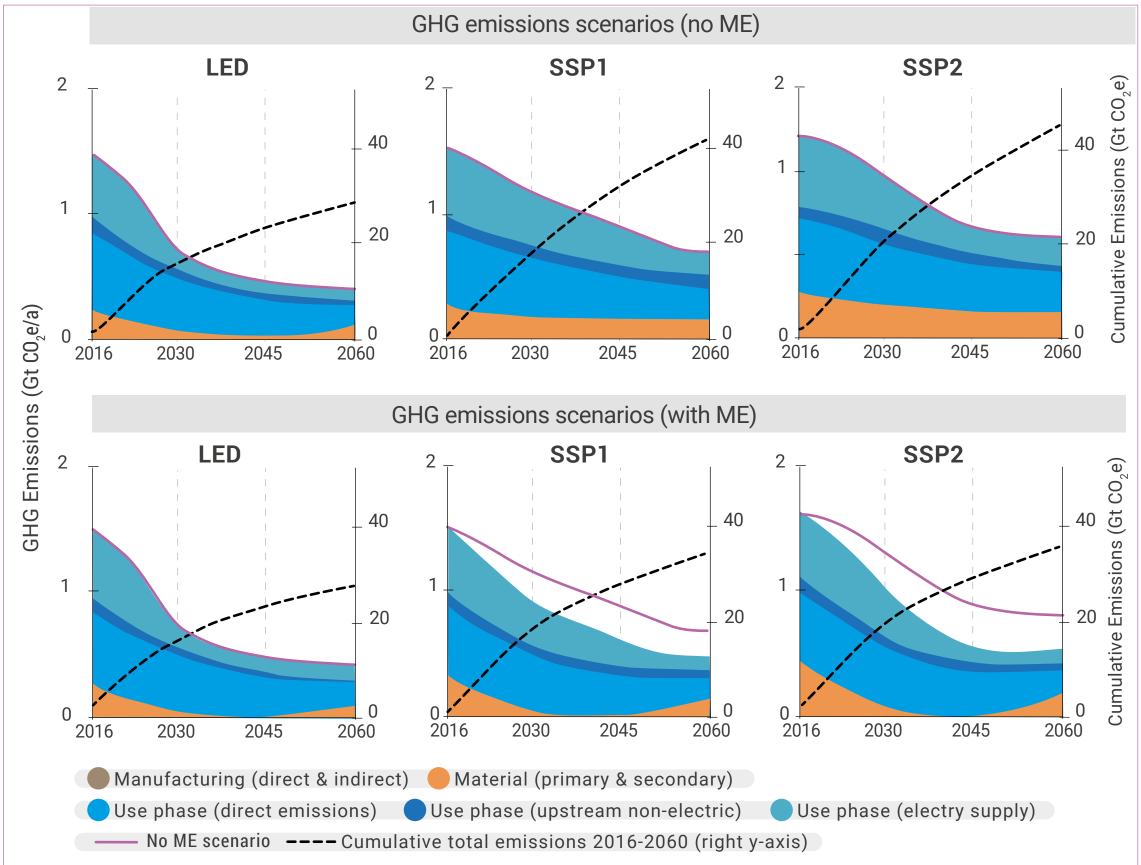
- SFH: single-family home; MFH: multi-family home; ZEB: Zero Energy Building.
- The dotted line illustrates the net stock change in each year and is plotted against the right y-axis.
- For the LED scenario, no additional intensive use occurs.

Floor area demand is calculated from the SSP population forecast and the assumed building use intensity. Population growth in the G7 averages 14 per cent in SSP1 and 12 per cent in SSP2 and LED. The assumptions on per capita floor area are explained in section 2.3.2. Total floor area in the SSP2 scenario grows by 47 per cent until 2060 (see Figure 13), because it is assumed that per capita floor area continues to increase (see Table 4). As the LED scenario assumes radical reductions in personal floor area demand, population growth can be offset and total floor area decreases by 27 per cent until 2060. Average floor area in 2060 is 34, 55, and 70 m²/cap for LED, SSP1 and SSP2, respectively. The propagation of the nine different archetypes is illustrated in Figure 13. Over time, the share of MFH and energy efficiency standards change as a function of stock, building lifetime, and the country, as well as the scenario and material efficiency strategy.

The annual addition to building stock declines as population growth slows or reverses and the building stock is saturated. This translates into reduced demand for construction materials across all scenarios (see Supplementary Material A). The implementation of material efficiency leads to additional reductions. As discussed in section 1.2.3, the implementation of different material efficiency strategies is done step-wise. Cascades 1 to 5 reduce cumulative total material demand in 2016–2060 in SSP1 by 0 per cent, 1 per cent, 3 per cent, 9 per cent and 53 per cent, respectively. In the LED-scenario with the highest service intensity, it is possible that, by 2045, no more primary material will be required.

2.3.4.4. GHG emissions scenarios with material efficiency

Figure 14. System-wide GHG emissions associated with the lifecycle of residential buildings in the G7



Note: These estimates assume a transformation of the energy system towards zero emissions. The top row is the baseline scenario, the bottom row with all material efficiency strategies implemented (cascade 5). The areas illustrate annual emissions by scope (colors), scenario (columns in figure grid), and ME strategy cascade (rows in figure grid). The dashed line represents cumulative emissions from 2015 to 2060 and is plotted against the right y-axis.

Material-related GHG emissions (orange areas in Figure 14) constitute around 10 per cent of total emissions in the residential building sector in 2016 and around 25 per cent in 2060 (SSP2). Following the trend of material flows (see Supplementary Material A), emissions reduce across all scenarios. Even without applying additional material efficiency strategies, material-related impacts reduce over time, which is a result of declining construction activity as discussed above. With material efficiency, material-related emissions drop to almost zero by 2040 because recycling credits for demolished buildings and carbon-storage in timber offset the relatively small amount of emissions.

The demand for construction materials for residential buildings in the model shows substantial reductions and shifts to less carbon-intensive alternatives, like timber. With more intensive use, the importance of homes as a source of secondary materials would increase in a transition phase. Overall, GHG emissions from the materials cycle could decrease by 70 to 80 per cent in the SSP1 and SSP2 scenarios. In the LED scenario, building materials would turn from a source of GHG emissions to a sink, given the use of timber and credit for the recycling of metals and minerals. Cumulative savings of emissions from material cycles would be of 5 to 7 billion tons of CO_2 equivalent over the time period of 2016-2060 in the G7, 6 to 13 billion tons in China and 4 to 9 billion tons in India (depending on the scenario).

The United States, being the largest G7 country, has the largest cumulative reduction potential of 0.5, 5.3 and 6.0 Gt CO_2e for the LED, SSP1 and SSP2 scenarios, respectively. All countries have the potential to reduce building sector emissions by 10 per cent or more (SSP1). See Supplementary Material A for country-specific results.

Emission reduction opportunities vary across countries, as Supplementary Material A shows. In North America and Japan, timber is already a widely used construction material, limiting the scope of material substitution. In Europe, there is substantial scope for this material efficiency strategy. In North America and Germany, residences tend to be larger than in other G7 countries, providing greater opportunity for more intensive use. In Japan, building lifetimes are shorter than in other G7 countries, providing more opportunity for lifetime extension.

In emerging countries such as India, material cycle strategies would have a larger impact due to the quantity of buildings that still need to be built, while the savings due to more intensive use are largest in the SSP2 scenario where a greater expansion of floor space would otherwise be expected. Relative reductions would be larger in India due to the low operational energy use and thus the larger proportional influence of construction.

Reduction in cumulative emissions by strategy

Higher yield includes the strategies of fabrication yield improvement and fabrication scrap diversion. Together they reduce cumulative greenhouse gas emissions by approximately 0.8 Gt CO_2e in all scenarios. As recycling rates are already very high, increasing recycling (EoL) has limited additional benefit. In a sensitivity calculation, the hypothetical case of no recycling was also considered (see Table 8). Without recycling, cumulative GHG emissions 2016–2060 would be 1.3, 1.4, and 1.5 Gt higher in scenarios LED, SSP1 and SSP2, compared to the baseline. In other words, recycling avoids or offsets 15 to 40 percentage points (pp) of the GHG emissions that would be generated if all buildings were produced using virgin materials.

Reuse and lifetime extension can allow additional savings of approx. 0.1 Gt CO_2e in cumulative emissions, mainly thanks to reuse. While lifetime extension reduces material consumption, it prolongs the use of older and less efficient buildings. The degree to which a deep-energy retrofit could increase the contribution of this strategy was not evaluated.

Material substitution yields some important reductions. In SSP1, a total of 2.1 Gt of concrete are replaced by 0.3 Gt of wood. This leads to reductions in cumulative GHG emissions of about 0.5 Gt CO_2e or 2 per cent of system-wide emissions in SSP1. Less use of timber is assumed in SSP2, arriving at savings of 0.1 Gt (1%). Around one third of the savings are due to carbon storage and the rest is due to lower emissions from replacing cement with wood. Like the light-weight design strategy, most of the benefits come from the reduction of cement use. As timber buildings already have a high market share in Canada, Japan and the United States of America the impact of this replacement in the G7 is limited. However, higher impacts could be attained in emerging economies where there is currently less timber used in construction.

Light-weighting can reduce emissions by 0.3 Gt CO_2e in SSP1 if applied after the above listed strategies. If considered as an isolated strategy (see Table 8), material reduction results in cumulative benefits of 0.4 Gt CO_2e (1%).

More intensive use has the highest reduction potential for SSP1 and SSP2, compared to the other strategies. It is assumed that more intensive use is already implemented in the LED scenario.

Between 2016 and 2060, savings could amount to 6.8 Gt CO_2e (16 per cent) in SSP1 and 8.8 Gt (20 per cent) in SSP2. The assumed gradual reduction in per capita floor area by 20 per cent is partially achieved by the increased use of a more energy and material efficient multi-family home building type. Reduced floor area in industrialized countries with low population growth and high stocks means (a) less need for new buildings and (b) demolition of old buildings with high operational energy-use. In regions with high urban growth and relatively low stock, more intensive use mainly means a reduced need for new buildings.

Table 8. Changes in cumulative greenhouse gas emissions in 2016–2060 (left) and in 2050 (right) per material efficiency strategy

[Mt CO_2e]	2016-2060			2050		
	LED	SSP1	SSP2	LED	SSP1	SSP2
Fabrication yield improvement	-9	-28	-38	0	-1	-1
Fabrication scrap diversion	0	0	0	0	0	0
End-of-life recovery rate improvement	-758	-769	-785	-24	-25	-25
Material substitution	-523	-546	-126	-12	-14	-4
Using less material by design/down-sizing	-186	-382	-470	-4	-11	-13
Reuse	-61	-66	-65	-2	-2	-2
Lifetime extension	-18	-29	-23	-1	-1	-1
More intense use	0	-7251	-9202	0	-218	-268
No recycling	1675	1771	1852	34	37	38

Note: Negative and positive values are savings and increases, compared to the baseline. Compared to Figure 10 these are the reductions from applying each strategy alone at a time, i.e. not the cascade. Savings and increases in emissions are colour-coded in green and purple, respectively, per column..

2.3.5. Discussion

The results are influenced mostly by the degree to which the material efficiency strategies can be implemented, namely the market penetration of the light-weighted and timber archetypes – as well as per capita floor area more intensively used. The assumptions for those values are, especially in the LED and SSP1 scenario, very ambitious and will require significant efforts to implement. Moreover, they may also come with additional challenges, such as the availability of timber or skilled workforce to build light-weighted, zero-energy buildings.

The resolution of the archetype model that was used to determine the energy and material intensities of the national building stocks is relatively coarse and may not adequately reflect the entire range of residential buildings. Currently, there is little research providing representative regional archetypes for building modelling. The approach for this report is not a complete assessment of the major mitigation strategies in the building sector. It is focused on strategies tightly linked to bulk materials. The use of an engineering bottom-up archetype approach proved effective to represent the physical characteristics of buildings and test the influence of material efficiency strategies on energy and material demand. Furthermore, the model has national relevance as it was simulated for the most important climate regions of each country.

With building lifetimes of 50-120 years, many of the material-related strategies cannot develop their full potential within the relatively short modelling period of 45 years. On the one hand, this illustrates the urgency of implementing effective measures to reduce GHG emissions in the building sector. On the other hand, it highlights the danger of lock-in effects (Lucon et al., 2014; Seto et al., 2016), as investments in buildings have long-term implications. The modelling developed for this report does not address refurbishment or retrofits because these do not affect the structure of buildings, where the climate-relevant bulk materials are located. The deep-energy-retrofit of existing buildings is an important element of any climate change mitigation policy package in the building sector and should be a precondition for the lifetime extension of less efficient buildings (International Energy Agency, 2019c). Lifetime extension only makes sense in this context if it is accompanied by deep building retrofits to bring down energy consumption in the use phase. Even when considering the potential of retrofits, it is an open question whether lifetime extension with retrofits or demolition and replacement by zero-net-energy buildings deliver the highest emissions reductions (Itard and Klunder, 2007; Meijer et al., 2009).

The "more intensive use" material efficiency strategy shows much higher benefits than more technical material cycle improvements. Higher service levels are applied to the entire building stock and not only to new constructions. Hence, this strategy shows considerable GHG reductions despite the low growth in floor area and material demand. The strategy presupposes that per capita floor area demand is stabilized (SSP2) or decreases (SSP1). The LED scenario assumes 30 m^2 per capita, which is half of what is common in North America and well below the average in most European countries. As discussed in the following chapter (sec. 3.3.3.2), such a scenario would certainly involve inhabitants embracing a norm of sufficiency. Therefore, additional insights on social acceptance, community lifestyles and neighbourhood planning are required, which reaches beyond the scope of this study. In reality, the intensification of use of existing buildings is likely to require refurbishment, for example to more flexible floor plans that can adapt to changing resident numbers and constellations. These processes would use materials and energy but also present an opportunity to upgrade the energy efficiency of buildings. Up-front investment of materials to achieve an intensification of use is not included in the current model.

As a result of construction and demolition waste policies described in Chapter 3, current recycling rates already save significant amounts of material related GHG emissions (see the last row in Table 8). We estimate that additional, more modest improvements in recycling are possible. In certain cases, however, more recycling can be counterproductive. As construction materials are normally bulky and heavy, their transport implies considerable environmental impacts. Furthermore, recycling aggregates may require larger amounts of cement, which is responsible for most of the impacts of concrete (Gao et al., 2017; Knoeri et al., 2013).

The use of wood as a construction material comes with a double benefit: carbon storage in the use phase of buildings and the replacement of concrete and steel. The climate benefit of the former is accounted for by using the global warming potential indicators for biomaterials calculated by Guest et al. (2013). The substitution effect and its impacts on energy use and emissions are determined by the ODYM-RECC model. The material substitution scenario relies on the availability of wood. While our assessment is not directly linked to any land-use model, we did check the resulting regional timber demand, compared it to recent supply estimates (Johnston and Radeloff, 2019) and reduced the share of wooden buildings in the new construction where timber flows were deemed too high, taking into account that the residential building sector is only one of several major users of wood. With this adjustment, we ensured that the wood flows determined by the RECC model can be sourced from sustainable forestry and hence no land-use change emissions were included. The global warming potential factors for the wood storage in buildings include the carbon sequestration from regrowing forests and plantations.

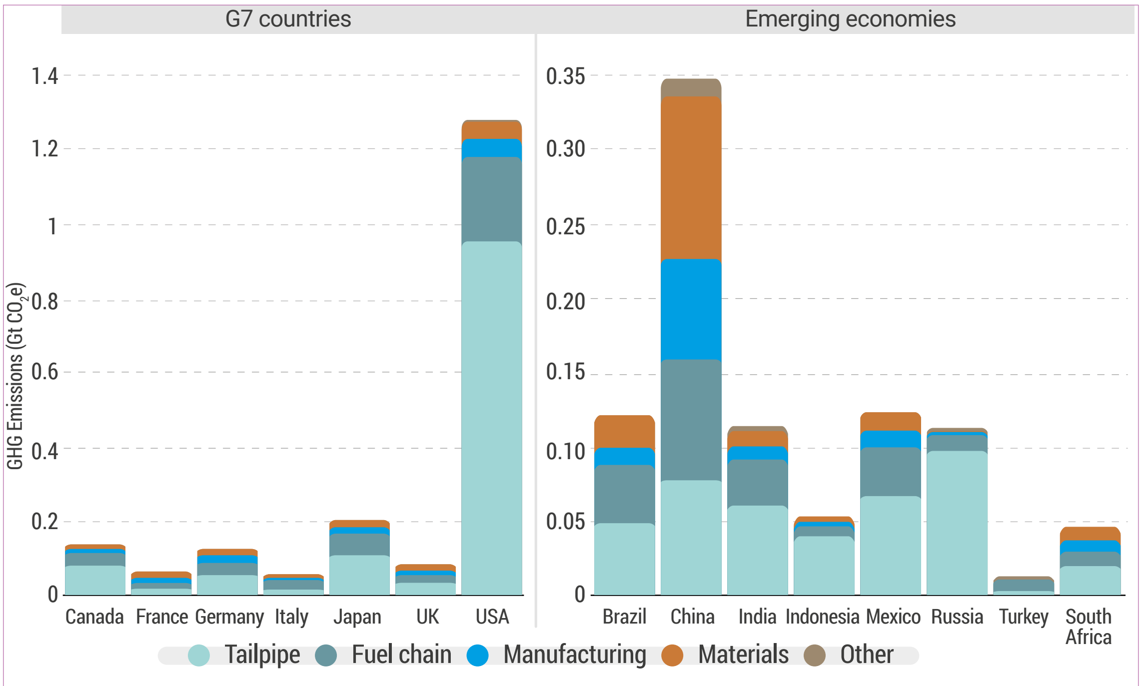
Wood demand in the G7 stays relatively constant in SSP1 and SSP2 over the entire time period at around 82 Mt per annum and 112 Mt/a on average. The LED scenario starts off at around 73 Mt/a, but decreases due to the low floor area demand to approximately 12 Mt/a in 2040 and finally increases again to 74 Mt/a in 2060. For China and India, we see a similar development with fluctuations of around 20 Mt/a. These demands are well below the projections calculated for timber and wood panel production by Johnston and Radeloff for 2065 of 147 Mt/a and 142 Mt/a in SSP1 and SSP2 for the G7 (Johnston and Radeloff, 2019). According to FAOSTAT, in 2016 around 400 Mt of timber and wood panels were produced (Food and Agriculture Organization of the United Nations, 2016). Oliver et al. (2014) estimate that 6500 Mt/a of timber could potentially be produced globally. That means wood construction could be scaled up further with the assumption that it can be traded internationally. However, it is not clear from the literature how quickly this could occur.

2.4. Material efficient cars

2.4.1. Introduction

In 2015, light-duty vehicles (LDVs)[8] accounted for around 14 per cent of global GHG emissions, 7.5 Gt CO_2e. A total of 4.7 Gt of these emissions occurred during the operation of light-duty vehicles (International Transport Forum, 2019), 1.4 Gt were associated with the production of fuels and 1.4 Gt were associated with the production of vehicles. Materials produce 55 per cent of the emissions associated with vehicle production (Hertwich, 2019). Only about half of the vehicles produced replaced retired vehicles, while the remainder reflected the growth in vehicle stock (Hertwich and Wood, 2018). Especially noticeable is a shift towards bigger and heavier cars, such as sports utility vehicles (SUVs), vans and light trucks, which has substantially contributed to the global rise in GHG emissions, according to the IEA (Cozzi and Petropoulos, 2019). G7 countries were responsible for about 40 per cent of global GHG emissions from light-duty vehicles, with the United States of America alone representing 24 per cent (see Figure 15). The relative importance of vehicle production varied across countries, which can be partly explained by substantial differences in the emissions associated with the production of a vehicle. Elements such as the energy mix, production technology, vehicle characteristics and distance driven determine the amount of emissions. The United States and Canada have the longest annual driving distances of the G7.

Figure 15. Emissions attributed to light-duty vehicles in G7 countries and emerging economies in 2015



Source: Based on EXIOBASE 3.6 (Hertwich, 2019; Stadler et al., 2018).
Notes: Tailpipe are direct emissions during driving, fuel chain are the emissions associated with purchasing vehicle fuels, materials are the material-related emissions associated with manufacturing the cars purchased in 2015, and manufacturing indicates the non-material-related emissions associated with car purchases.

Environmental policy related to cars has traditionally focused on reducing fuel consumption and air pollution, to the extent that other life-cycle stages have been ignored. With the introduction of biofuels and electric vehicles, analysts extended the perspective to the entire fuel chain, leading to the realization that GHG emissions vary a lot and can be quite substantial for gasoline as well (Masnadi et al., 2018). Only recently has it been recognized that vehicle production and road construction contribute in significant ways to global GHG emissions (Chester and Horvath, 2009; Hawkins et

8 A light-duty vehicle is any motor vehicle with a gross vehicle weight rating of 10,000 pounds (4,500 kg) or less, typically used for passenger transport.

al., 2013). As a result, the GHG reduction potential connected to the manufacturing of vehicles and transport infrastructure has only been investigated in studies addressing individual material efficiency strategies (Suh et al., 2017). However, the potential savings are normally not included in integrated climate change mitigation assessments (Pauliuk et al., 2017), and interactions between energy and material use have not yet been captured (Hertwich et al., 2019; Wolfram and Hertwich, 2019).

In this section, we show that many of the material efficiency strategies can substantially reduce the demand for virgin materials for the production of LDVs. As with buildings, the most significant savings of GHG emissions come from a set of interrelated strategies that also reduce operational energy use. The most common material efficiency policies for vehicles are end-of-life-vehicle (ELV) regulations, as Section 3.3 shows. There are also numerous policies that affect material use, such as those relating to fuel economy, congestion, parking, ride-hailing and land-use planning. In this section, we provide a short introduction to our analysis and the main results. In Supplementary Material A, we provide a detailed explanation of the modelling, more in-depth investigation of some material efficiency strategies and some supplementary results addressing the changing material composition of vehicles.

2.4.2. Future vehicle demand

Currently, there is a wide variation in distances driven annually using passenger vehicles across the investigated countries. The 2015 figures are 322 person-km per capita in India; 6350 km per capita in Japan; 10,450 km per capita in Germany; and 22,500 km per capita in the United States. The assumption of the LED scenario is that, by 2050, due to shifts in transportation modes (from personal vehicles to public transportation) and changes in the urban landscape, passenger vehicle transport demand in developed countries will reduce to 8434 person-km per capita and year on average (Grubler et al., 2018). The authors assume that all G7 countries converge on this value by 2050. It is also assumed that China grows to half of this value. For India, the LED developing country value of 1350 person-km per year is used. In industrialized countries, it is assumed that 2050 passenger vehicle transport demand in SSP2 remains at the 2015 level or converges to the LED scenario target (whichever value is higher). The SSP1 scenario value was chosen to be between the LED scenario and the SSP2 scenario. For China and India, in the SSP1 and SSP2 scenarios, a continued, uninterrupted growth of per capita person-km in passenger vehicles is assumed. Rates grow to intermediate levels of what is currently observed in the G7 and other high-income countries, which is about 10,000 km per person and year. The impacts of the modal shift on other transport modes are not part of the current assessment.

Future baseline vehicle ownership (see Table 9) is endogenously determined by the assumed annual service demand for passenger vehicle transport and a group of parameters including vehicle occupancy rate and annual vehicle kilometrage. Car-sharing and ride-sharing, as implemented in the developed scenario, reduce car ownership rates.

Table 9. Number of vehicles per capita in G7 countries, China and India (without car-sharing and ride-sharing)

Scenario	# of vehicles per capita								
	USA	Japan	Canada	UK	France	Germany	Italy	China	India
2016	0.67	0.48	0.61	0.47	0.44	0.52	0.61	0.10	0.02
2050 (LED)*	0.26	0.28	0.35	0.41	0.43	0.42	0.3	0.19	0.07
2050 (SSP 1)*	0.51	0.28	0.51	0.50	0.50	0.50	0.3	0.47	0.47
2050 (SSP 2)*	0.67	0.28	0.61	0.50	0.50	0.52	0.3	0.47	0.47

*LED: Low Energy Demand; SSP: Shared Socioeconomic Pathways

2.4.3. Material efficiency strategies for cars

Higher yields in manufacturing, reuse and recycling: Previous analysis of higher yields in metal use in the broader economy suggest substantial emission reductions, but it is unclear how important those are for the vehicle sector (Milford et al., 2013). While yields in manufacturing are already high and scope for savings is limited, a sizable number of vehicles in industrialized countries are unaccounted for and may be abandoned, stored unused or exported illegally – leading to lower vehicle recovery rates than one would expect (Melhart et al., 2018). Reusing vehicle parts, in particular engines and tyres, often involves remanufacturing that restores functionality to like-new condition. This can reduce emissions by 70 to 90 per cent compared to new components (Nasr et al., 2018) and saves about twice as much as recycling (Sato et al., 2019). See section 3.4 for experience with recycling and reuse programmes. Remanufacturing mainly applies to heavy-duty vehicles and is therefore not explicitly modelled in this study. Given the low utilization rate and long lifetime of privately-owned passenger vehicles, the question is whether improvements in efficiency and the introduction of low-emissions technology over time yield larger emissions savings than the avoided manufacturing and the recycling of components. Assessments of the 'cash-for-clunkers' programme of early vehicle retirement in the United States find GHG benefits, as do investigations of potential vehicle lifetime extension schemes in Japan (Lenski et al., 2013; Nakamoto, 2017). These contradictory results indicate that the benefit of life-cycle extension is small and depends on the typical age and performance of retired vehicles.

In our modelling, we do not account for the export or disappearance of vehicles but assume that a specific fraction of end-of-life vehicles are recovered and that improvements in the recovery rates of individual material fractions are possible. Reuse of specific parts, such as engines, batteries and tires, may reduce the energy needed to produce a vehicle because the energy consumption associated with reuse of material (contained in the parts) is significantly smaller compared to virgin material production or material recycling. We represent the increased reuse strategy as increasing the reused portion of a material (such as automotive steel) that is aggregated from reusing different parts in a vehicle (including engine, transmission and alternators). We adapted a list of reuse rate factors for vehicle parts in Japan (Nakamura et al., 2012), and converted these to material reuse factors in vehicles for each country based on the assumption that reuse rates of a vehicle part are inversely proportional to the lifetime vehicle kilometres of travel (in other words, the more distance travelled, the less likely a part can be reused). According to this estimate, in the G7 (not including Japan) up to 27 per cent of automotive steel (38 per cent for Japan), 35 per cent of wrought aluminium (up to 55 per cent for Japan), 42 per cent of cast aluminium (62 per cent for Japan), and 38 per cent for cast iron/steel components (57 per cent for Japan) are reused. Baseline end-of-life recovery rates for steel, aluminium, copper and plastics are 69 per cent, 87 per cent, 78 per cent and 18%, respectively with improvement potentials of up to 26pp, 8pp, 15pp, and 52pp for the resource efficiency scenarios (pp = percentage points).

Smaller, lighter vehicles: The vehicle size segment (passenger vehicles and light trucks) is an important predictor of both material and energy use (Ellingsen et al., 2016), as it has a strong correlation with total mass and fuel economy. Reducing material demand for vehicle production through shifting from a larger sized vehicle to a smaller one lowers embodied and use phase energy requirements (Serrenho et al., 2017), without necessarily impacting the service delivered (as most trips do not require the higher transport capacity). We define four global vehicle segments: microcars, passenger cars, minivans/SUVs and light trucks. Downsizing is thus implemented as an increasing share of smaller vehicles as a fraction of total vehicle stock. In the United States of America, the share of passenger cars fell from over 80 per cent in 1975 to around 50 per cent in 2005. The share of pickup trucks, vans and sports utility vehicles (SUVs) has risen correspondingly (US Environmental Protection Agency, 2018a). Light-weighting of vehicles has often occurred in periods and jurisdictions when fuel-economy regulations have been stringent or fuel prices increased (see section 3.4).

Material substitution: Substituting steel with lighter materials for certain vehicle parts (such as aluminium, carbon fibre, magnesium or high-strength steel) could lead to overall weight reduction ("light-weighting") and hence improve the fuel economy of vehicles. These lighter materials often cause more emissions during their production but lead to attractive reductions in operational energy use. Advanced high-strength steel (AHSS) is also used for vehicle light-weighting via material substitution, but calculations show that aluminium-based archetypes have a larger overall mass and emissions reduction potential and were therefore chosen for this analysis (Milovanoff et al., 2019; Modaresi et al., 2014). Carbon fibre can lead to a larger weight reduction, but recycling technologies are not well established. In practice, a variety of options are used because material choice depends on several factors including cost, available machinery and safety.

We defined one conventional vehicle and one where steel components have been replaced by aluminium, largely based on best available data based on the 2017 version of the GREET vehicle cycle model for each vehicle powertrain archetype (Burnham et al., 2006; Wang et al., 2017). We then assumed a gradual increase in the market share for new light vehicles from the 2015 value (13 per cent for passenger cars in the United States) to 75 per cent in 2060 for SSP1 and LED and 40 per cent for SSP2. The representative material composition for each powertrain for a given year is determined as the weighted-average material composition, based on the number of conventional and lightweight-designed vehicles. This representative material composition is used for quantifying material efficiency and associated environmental impacts (such as production of aluminium). Based on vehicle masses and powertrain characteristics, the energy consumption of all vehicle archetypes was simulated using FASTSim.

More intensive use: Emerging patterns of vehicle use decouple ownership and use of vehicles through car-sharing (cars are owned collectively but used individually through hourly rental, for instance), ride-sharing (you join someone else on part of a trip) and ride-hailing (you are the passenger in a taxi-like service). The evidence evaluated in section 3.4 shows that ride-hailing does not reduce emissions, but both ride-sharing and car-sharing tend to lead to more intensive vehicle use in the form of higher vehicle occupancy and/or a higher utilization rate. Ride-hailing is therefore not modelled in this study. Both ride-sharing and car-sharing reduce the vehicle stock needed to satisfy transport demands, yet these two strategies are modelled separately and the respective impacts are aggregated when evaluating the overall impact of more intensive use. Specifically, the modelling approach categorizes transport demands (person-km) in four shares that are fulfilled by no sharing, ride-sharing only, car-sharing only and ride-sharing plus car-sharing, respectively. The corresponding vehicle km of travel and vehicle stock size per share are calculated based on the respective vehicle occupancy rates and ownership rates. For instance, it is assumed that ride-sharing increases occupancy rates by 40 per cent for SSP1 and SSP2 (Bhat, 2016; Yin et al., 2018). A 30 per cent reduction in person km travelled when a person shifts to car-sharing is also considered (Martin and Shaheen, 2016; Sperling and Shaheen, 1999). The same level of car- and ride-sharing is assumed, as well as the same effect on vehicle km of travel in all regions. In populated areas and intercity traffic where public transport achieves high load factors, buses and railways tend to achieve substantially higher energy efficiencies and probably also material efficiencies than private cars (Chester and Horvath, 2009; Sims et al., 2014). The authors were not able to evaluate a modal shift since the model does not yet capture those transport modes.

Table 10. Penetration of material efficiency strategies for vehicles, per scenario, in 2060

Strategy	LED	SSP1	SSP2
Less material use by design (Smaller vehicles)			
• Microcar	20% (0% in 2015)	10% (0% in 2015)	8% (0% in 2015)
• Passenger car	70% (47% in 2015)	59% (47% in 2015)	57% (47% in 2015)
• Minivan/SUV	4.6% (14% in 2015)	9.4% (14% in 2015)	10% (14% in 2015)
• Light truck	5.4% (39% in 2015)	22% (39% in 2015)	25% (39% in 2015)
Light-weighting through material substitution	61-62% (4-14% in 2015) of new vehicles	61-62% (4-14% in 2015) of new vehicles	28-35% (4-14% in 2015) of new builds
More Intensive Use			
• Car-sharing	30% service demand by car-sharing (0% in 2015)	25% service demand by car-sharing (0% in 2015)	15% service demand by car-sharing (0% in 2015)
• Ride-sharing	40% of trips are ride-shared	25% of trips are ride-shared	15% of trips are ride-shared
Lifetime Extension	20% extension (PHEV, BEV, FCV), no extension (ICEVg, ICEVd, HEV)	20% extension (PHEV, BEV, FCV), no extension (ICEVg, ICEVd, HEV)	20% extension (PHEV, BEV, FCV), no extension (ICEVg, ICEVd, HEV)
Reuse			
• Steel	21-26% (7-9% in 2015)	21-26% (7-9% in 2015)	12-14% (7-9% in 2015)
• Cast iron	17-38% (6-12% in 2015)	17-38% (6-12% in 2015)	9-21% (6-12% in 2015)
• Cast Al	23-42% (7-13% in 2015)	23-42% (7-13% in 2015)	12-23% (7-13% in 2015)
• Wrought Al	35-38% (11-12% in 2015)	35-38% (11-12% in 2015)	19-21% (11-12% in 2015)
• Copper	30-36% (10-12% in 2015)	30-36% (10-12% in 2015)	16-20% (10-12% in 2015)
• Plastics	21-27% (7-9%, 2015)	21-27% (7-9%, 2015)	12-14% (7-9%, 2015)
Recycling Recovery			
• Steel	95% (currently 69%)	95% (69% in 2015)	95% (69% in 2015)
• Cast iron	95% (93% in 2015)	95% (93% in 2015)	95% (93% in 2015)
• Cast Al	95.5% (87.5% in 2015)	95.5% (87.5% in 2015)	95.5% (87.5% in 2015)
• Wrought Al	95.5% (87.5% in 2015)	95.5% (87.5% in 2015)	95.5% (87.5% in 2015)
• Copper	82% (67% in 2015)	82% (67% in 2015)	82% (67% in 2015)
• Plastics	70% (18% in 2015)	70% (18% in 2015)	70% (18% in 2015)

Note: Figures are representative and may differ in some cases for individual countries.

2.4.4. Results

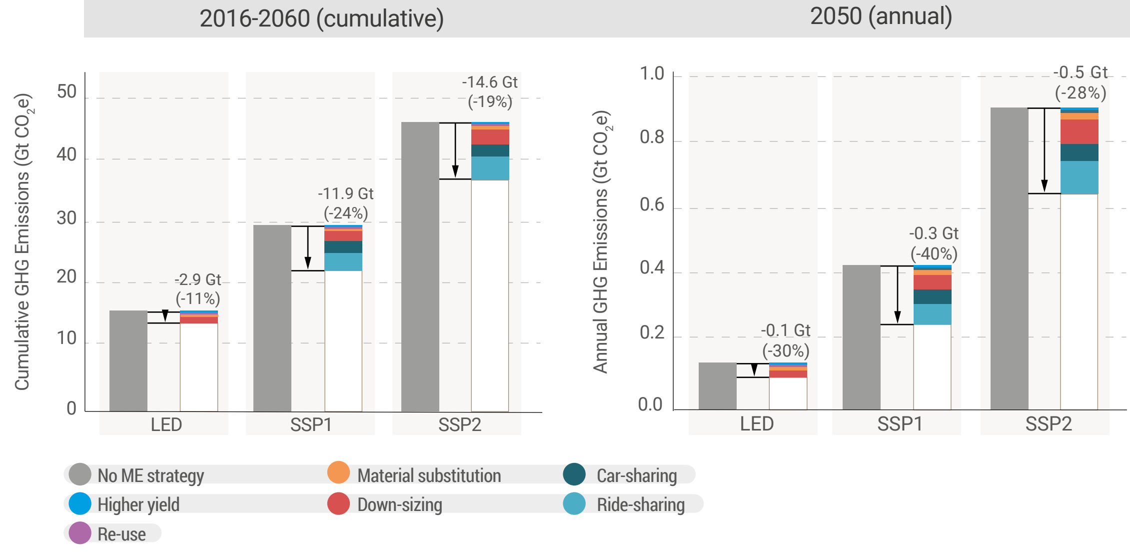
2.4.4.1. Main results

We find that improvements in material efficiency can reduce the carbon footprint of materials used in vehicle production for the G7 by 2050 by 30 per cent to 70 per cent, depending on scenario assumptions. Both improvements in the material cycle (such as the reuse of components) and changes in patterns of use (such as increased ride-sharing and trip-appropriate vehicle sizes) play important roles.

Several investigated material efficiency strategies also reduce energy use for the manufacturing and operation of vehicles. Emission savings from reductions of operational energy use would be several times larger than those from material production, even assuming a gradual shift towards battery-electric and fuel cell vehicles. The investigated material efficiency strategies could reduce total GHG emissions for the manufacturing, operations and disposal of cars by 30 to 40 per cent, or 300-450 million tons CO_2 equivalent by 2050 (see Figure 16). The most important strategies for the reduction in life-cycle emissions are ride-sharing, car-sharing and a shift towards smaller vehicle sizes. Similar savings can be attained from implementing the same strategies in China and India.

Vehicles are widely recycled in G7 countries, as long as they are not exported as used vehicles (to have a second life in a less affluent country). The recycled materials can offset about 50 per cent of GHG emissions associated with the production of materials used in cars. However, this benefit is threatened because of potential contamination of secondary steel from car recycling with copper (Daehn et al., 2017; Liu et al., 2013; Nakamura et al., 2012).

Figure 16. Reduction of cumulative fleet-wide life-cycle emissions in the G7 through material efficiency strategies per scenario in 2016–2060 (left) and in 2050 (right)



Notes:

- Material efficiency strategies are implemented in a cascade, with the more technical measures implemented first, and car- and ride-sharing implemented last. Arrows indicate the potential reductions as a result of material efficiency.
- Gt: gigatons, LED: Low Energy Demand scenario, SSP: Shared Socioeconomic Pathways.

Material cycle improvements. Several strategies significantly contribute to the reduction of emissions. Improvements in yields, fabrication scrap collection and end-of-life recovery can lead to savings of 38 to 45 per cent of the GHG emissions from materials production by 2050 (when the gains from the second use of materials recovered at the end-of-life of the vehicle are accounted for). Increased reuse of parts and lifetime extension of vehicles can lead to additional savings of 5 to 15 per cent. Although a shift from steel to aluminium (which saves fuel during operations) is initially connected with an increase of materials-related GHG emissions, a shift towards a cleaner electricity mix and improved recycling may see the use of aluminium resulting in lower material-cycle emissions than that of steel by 2050 – unless steel production is decarbonized as well. In terms of saving materials, these strategies are of comparable importance to those associated with more fundamental changes in the provisioning system that would lead to fewer and smaller cars. Cumulative savings of such material cycle improvements of vehicles in the G7 up to 2060 are 0.9-1.6 billion tons of CO_2 equivalent, compared to a remaining carbon budget for the G7 of 50 billion tons CO_2 (IPCC, 2018). Savings in China are 0.6-1.6, while those in India are 0.2-1.4 billion tons across the range of scenarios.

Changes in patterns of use and provisioning systems. Other scenarios could yield fewer and smaller cars. Shared fleets of vehicles of different sizes have been imagined in connection with ride-sharing, car-sharing, ride-hailing and autonomous vehicles. More compact settlements with good public transportation systems and a shift towards paid parking would make individual car ownership less attractive and at the same time focus car use on the last mile between a rail or subway station and the origin/destination, utility trips and vacation travel. For the G7, the largest reductions in emissions would result from ride-sharing. If 25 per cent of the trips were conducted as shared rides, there would be a 33 per cent increase in vehicle occupancy. This would reduce system-wide GHG emissions from cars in 2050 by 13 to 20 per cent (see Figure 16). If 15 to 25 per cent of cars were shared in 2050, this would reduce emissions by 6 to 10 per cent. A shift towards smaller vehicles would reduce emissions in 2050 by 9 per cent. **Together, these three strategies could reduce cumulative GHG emissions by 10-13 billion tons in the period of 2016 – 2060**, in addition to savings that come from the anticipated shift towards electric and fuel cell vehicles and a decarbonization of the electricity mix. Given the higher population density, shorter driving distances and predicted smaller average car size, the expected **savings in cumulative emissions in China and India are somewhat smaller at 7 to 8 billion tons each.**

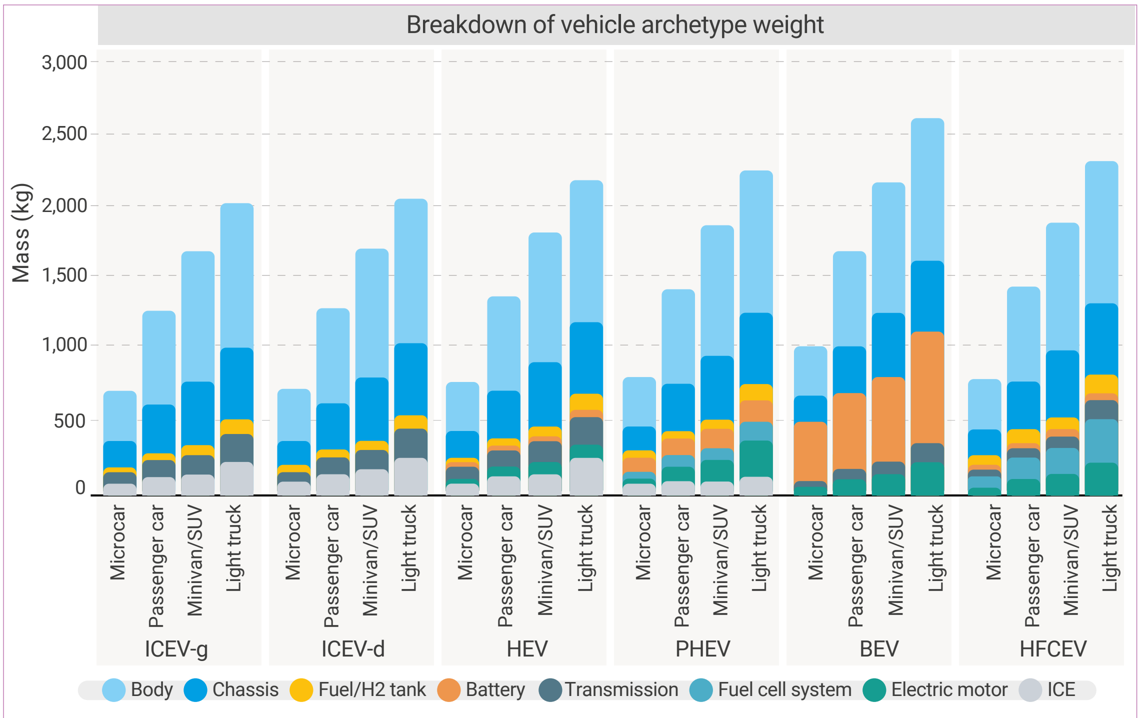
Car- and ride-sharing assumed in SSP1 and SSP2 is consistent with the SSP narrative. However, higher intensification can be imagined, as illustrated by the LED scenario in Table 10. In the following section, we present the modelling results in more detail.

2.4.4.2. Material composition and energy intensity of vehicle archetypes

Figure 17 shows the kerb weights of the archetypical passenger cars (PC), light trucks (LT), minivans/SUVs and microcars by technology and broken down by main components. Passenger cars are modelled after the Toyota Camry with a mass of 1.3 tons (on average – varies by power, drive and extras). The gasoline light truck is modelled after a Ford F-150, with a mass of about 2.0 tons. The microcar is modelled on the Maruti Suzuki Alto, the-highest selling car in India between 2004 and 2018 (PTI, 2018). The Alto has been sold 35 million times, which is comparable to the popular Volkswagen Golf (GCC, 2013). The minivan/SUV has been modelled on the Wuling Hongguang, which is the most popular vehicle in China (Goodwood, 2018). Chinese sales of the Hongguang are exceeding European sales of the Golf since 2013 ("Wuling Hongguang China auto sales figures," n.d.).

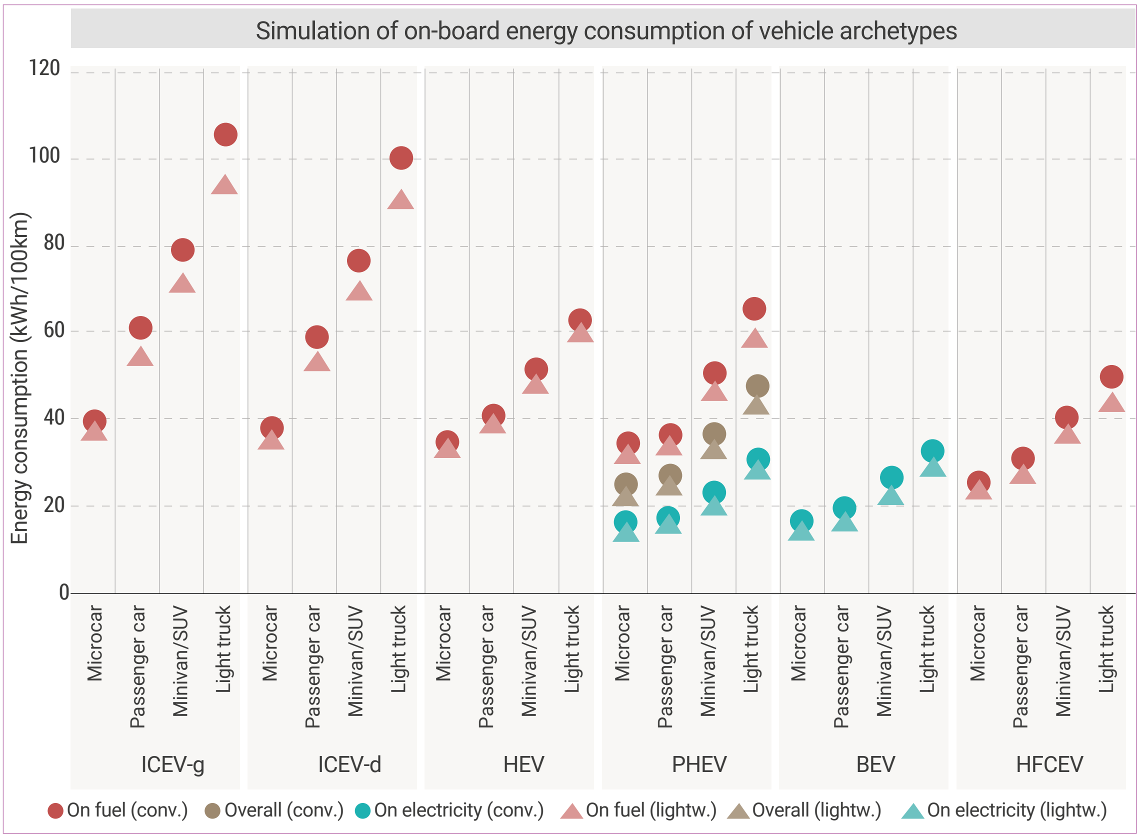
The overall mass is then broken down by components adopting the assumptions from Bauer et al. (2015) and GREET (Burnham et al., 2006; Wang et al., 2017). The gasoline-powered archetypes are the foundation to modelling the other technologies. For alternative powertrains, components are added, removed or scaled based on the ICEV archetypes. For instance, for a battery electric vehicle (BEV), engine, fuel tank and conventional transmission are removed from the ICEV, while a battery, an electric motor and an EV-specific transmission are added (Wolfram and Wiedmann, 2017), see Figure 17. The weight ratio between light trucks and corresponding passenger cars across power trains (HEV, PHEV, BEV and HFCEV) is approximately 1.6 on average. Alternative powertrains are heavier than those of internal combustion engine vehicles, due to the inclusion of batteries or a fuel cell system.

Figure 17. Components and total vehicle mass of vehicle archetypes



Note: ICEV-g: internal combustion engine vehicle powered by gasoline; ICEV-d:internal combustion engine vehicle powered by diesel; HEV: hybrid electric vehicle; PHEV: plug-in hybrid electric vehicle; BEV: battery electric vehicle; HFCEV: hydrogen fuel cell vehicle.

Figure 18. Simulation of on-board energy consumption of vehicle archetypes using FASTSim



Notes:

- Use phase only, based on 'real-world' driving conditions.
- The utility factor (fraction of electric driving) is assumed to be 0.5. BEV and PHEV energy consumption includes charging losses (conv.= conventional design; lightw.= light-weight design).

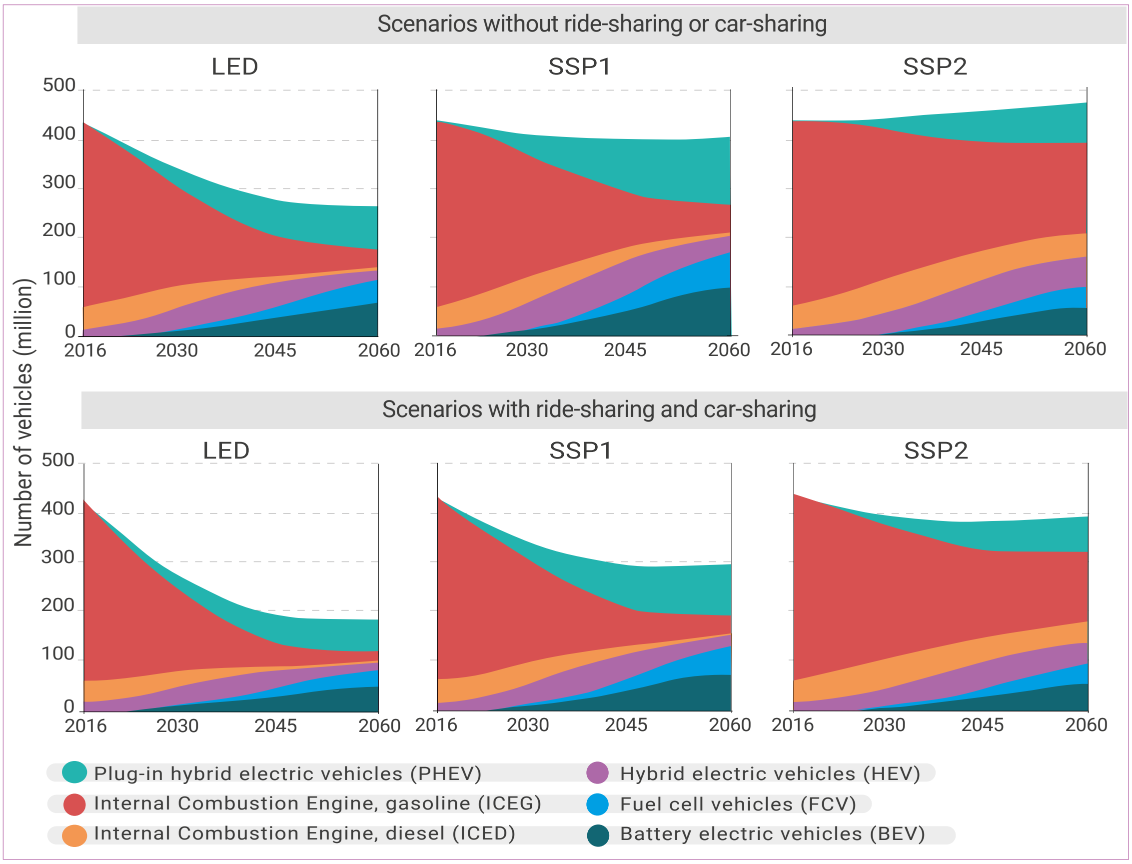
Generally, heavier and more powerful vehicles have higher fuel consumption. Material substitution can reduce vehicle weights by 18 per cent to 24 per cent and use-phase energy use by 6 per cent to 15 per cent (see Figure 18). The largest mass reduction is achieved for the BEV light truck (about 590 kg), which has the largest base mass, followed by the HFCEV and PHEV light trucks (about 520 kg reduction). The largest use-phase energy reduction is achieved for conventional light truck (about 10 kWh per 100 km reduction). The ratio of percentage energy reduction to percentage mass reduction achieved varies from 0.30 (hybrid passenger cars) to 0.58 (diesel light truck).

2.4.4.3. Material flows and GHG emissions over time

The evolution of market shares in the G7 for six vehicle power trains (conventional and light-weight designs combined) is shown in Figure 19. The vehicle stocks decrease by 39 per cent in LED in 2050, given the assumed increase in use intensity. The vehicle stocks decrease by 10 per cent and increase by 5 per cent in SSP1 and SSP2, respectively. In SSP2, the internal combustion engine vehicles (ICEG and ICED) account for 55 per cent of the market in 2050, followed by PHEV (16 per cent), HEV (14 per cent), BEV (9 per cent) and HFCEV (6 per cent). The market share of internal combustion engine vehicles decreases to around 24 per cent and PHEVs account for the largest market share (31 per cent) in both SSP1 and LED.

When both car-sharing and ride-sharing are implemented, the vehicle stocks decrease due to the lower demand for new vehicles (three graphs at the bottom of Figure 19). For the entire G7, vehicle stocks are reduced by 13 per cent to 57 per cent in 2050. As in the base case, internal combustion engine vehicles continue to dominate the market

Figure 19. Development of the G7 vehicle fleet by 2060 per scenario with (bottom) and without (top) more intensive use



Note: ride- and car-sharing are combined.

in 2050 in SSP2 with a combined market share of 55 per cent. PHEVs account for the largest market share (32 per cent) in both LED and SSP1.

GHG emissions from cars in the G7 decrease in all scenarios from 2016 to 2060, even without material efficiency due to a shift towards cleaner power trains (see Supplementary Material A). The largest additional reductions from material efficiency are achieved by reducing direct emissions from fuel consumption due to a decrease in vehicle stock (SSP1 and LED) and a shift to smaller vehicles. Although vehicle stock increases in SSP2 when car- and ride-sharing do not increase (Figure 19), the reduction in tailpipe emissions can be explained by the increased market share of alternative powertrains (such as HEV, PHEV and BEV). The reduction of GHG emissions from material production and manufacturing of vehicles is lower when vehicle light-weighting is implemented than otherwise, which is due to the increased production of aluminium.

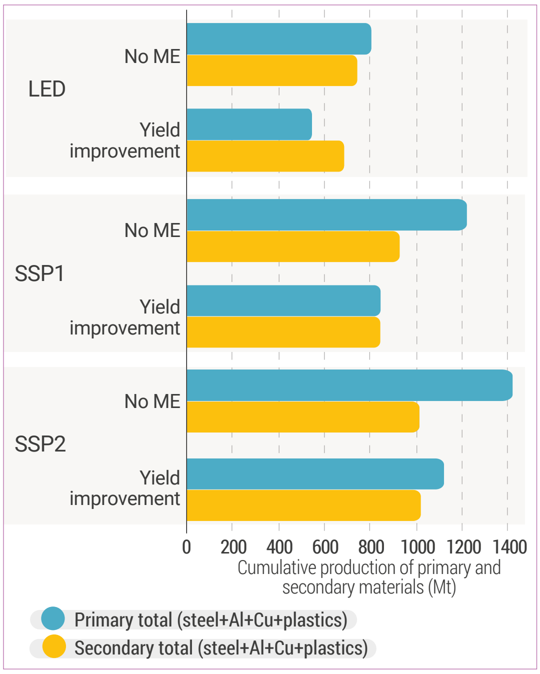
2.4.4.4. Scenarios of GHG emission savings from specific material efficiency strategies

Higher yields and reuse

Implementation of "Fabrication yield improvement" alone leads to a reduction of approximately 33 per cent in fabrication scraps of steel, aluminium and copper (cumulative 2016-2060) for all scenarios (see Supplementary Material A). The corresponding cumulative reduction in GHG emissions associated with the materials cycle manufacturing is 3 to 4 per cent (including benefits from closed-loop recycling of plastics). Nonetheless, the system-wide reduction in cumulative GHG emissions (2016-2060) from improving fabrication yield is small (<1%). System-wide emission reductions from strategies not affecting the operational energy use of cars appear small because materials have a much smaller share in system-wide emissions than for buildings.

The combination of "fabrication yield improvement", "end-of-life recovery rate improvement" and "material reuse" leads to a significant use of secondary materials (see Figure 20). Accordingly, the three strategies reduce or offset 49 per cent, 28 per cent, and 26 per cent of the cumulative GHG emissions (2016-2060) of material-cycle emissions of cars in the LED, SSP1 and SSP2 scenarios, respectively. Reductions of the total emissions associated with the production, operations and disposal of cars in all three scenarios are around 1 per cent.

Figure 20. Primary and secondary materials production for LDV in G7 countries, with and without yield improvements and increased recycling and reuse (2016–2060)



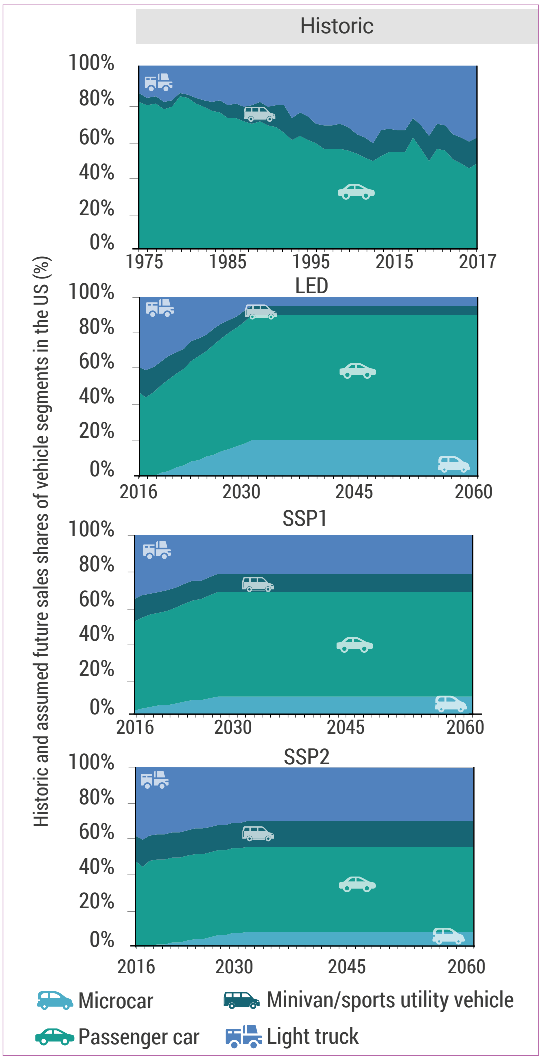
Material substitution (light-weighting with aluminium)

The market shares of light-weight vehicles within each power train varied from 8.9 per cent (PHEV) to 14 per cent (HFCEV) in 2015. Material substitution increases the market share of light-weight vehicle archetypes to 48 per cent (PHEV) and 50 per cent (HFCEV) in both LED and SSP1, and to 24 per cent (BEV) and 28 per cent (ICEV) in SSP2. The implementation of this strategy reduces the use of total (primary and secondary) steel and therefore increases of use of aluminium over time (See Supplementary Material A). In LED and SSP1, for example, the cumulative flows of steel (2016-2060) are 23 per cent and 25 per cent lower when light-weighting is implemented. Accordingly, the cumulative increase in total aluminium flows are 115 per cent and 121 per cent, compared to the case without increased light-weighting. The change in the use of steel (10 per cent decrease) and aluminium (53 per cent increase) is lower in SSP2, which reflects the assumption of lower ambition for climate change mitigation. The reduction in cumulative GHG emissions related to fuel consumption 2016-2060 is small (1.3 per cent, 1.7 per cent and 0.9 per cent for LED, SSP1 and SSP2, respectively), due to a relatively minor reduction in vehicle weight. On the other hand, GHG emissions from vehicle manufacturing and materials production increase slightly in all scenarios when light-weighting is implemented, due to the higher energy use for aluminium manufacturing. Overall, implementing vehicle light-weighting in addition to yield improvement, recycling and reuse reduces cumulative (2016-2060) total GHG emissions by an additional 0.8 to 1.5 per cent for all three scenarios.

Shifting the size distribution to smaller vehicles

A shift towards more trip-appropriate vehicle sizes would result in a gradual shift from light trucks and SUVs to passenger cars and microcars. For example, the United States sales share of microcars is assumed to grow from zero to 8 to 20 per cent, depending on the scenario. Meanwhile the sales share of passenger cars is assumed to grow from 47 per cent in 2017 to up to 70 per cent in 2060 (see Figure 21). In Japan and India, where microcars are already common , their sales share grows by up to 56 per cent and 70 per cent, respectively, while the EU and China achieve values that are half of that in the most optimistic scenario (31 per cent and 35 per cent). The reduced weight of smaller vehicles lowers the energy used in manufacturing and the energy used in the operation of the vehicle. Lower fuel requirements also reduce the emissions associated with fuel production. Taken together, downsizing achieves a reduction in cumulative GHG emissions, in addition to those achieved by implementing the more technical strategies listed above, of 1 to 10 per cent compared to the cumulative (2016-2050) emissions without any material efficiency strategies across the various G7 countries. In the United States, the reduction is 5 to 6 per cent, depending on the scenario. The lowest reductions are achieved in Japan and India (0.7 to 2.4 per cent), since the shares of micro and passenger cars are already high.

Figure 21. Historic and assumed share of future sales of vehicle segments in the United States



The share of passenger cars fell by 0.54 per cent per year on average in the observed period (United States Environmental Protection Agency 2018). The scenarios of this report assume that this downward trend is reversed.

More intensive use

More intensive use leads to the reduction of vehicle stocks (in 2050 compared to 2016) by 33 per cent in the SSP2 scenario and 13 per cent in the SSP1 scenario. The LED scenario must be understood as one where demand reductions have already been fully accounted for; without these, the vehicle stock would be 57 per cent higher. In 2050, car-sharing would reduce emissions by 5 to 6 per cent in the SSP2 scenario and 9 to 11 per cent in SSP1, with the largest reductions achievable in Italy and the United States. Ride-sharing would reduce emissions by 13 per cent in SSP2 and 20 per cent in SSP1, compared to what they would be without these reductions. Cumulative savings (2016-2060) could be in the range of 6.3-10 Gt CO_2e. Large reductions are also achieved outside the G7, with 2.8 (LED) and 7.5 (SSP1) Gt CO_2 in China and 1.0 (LED) and 6.8 (SSP1) Gt CO_2 in India.

2.4.5. Country-level results

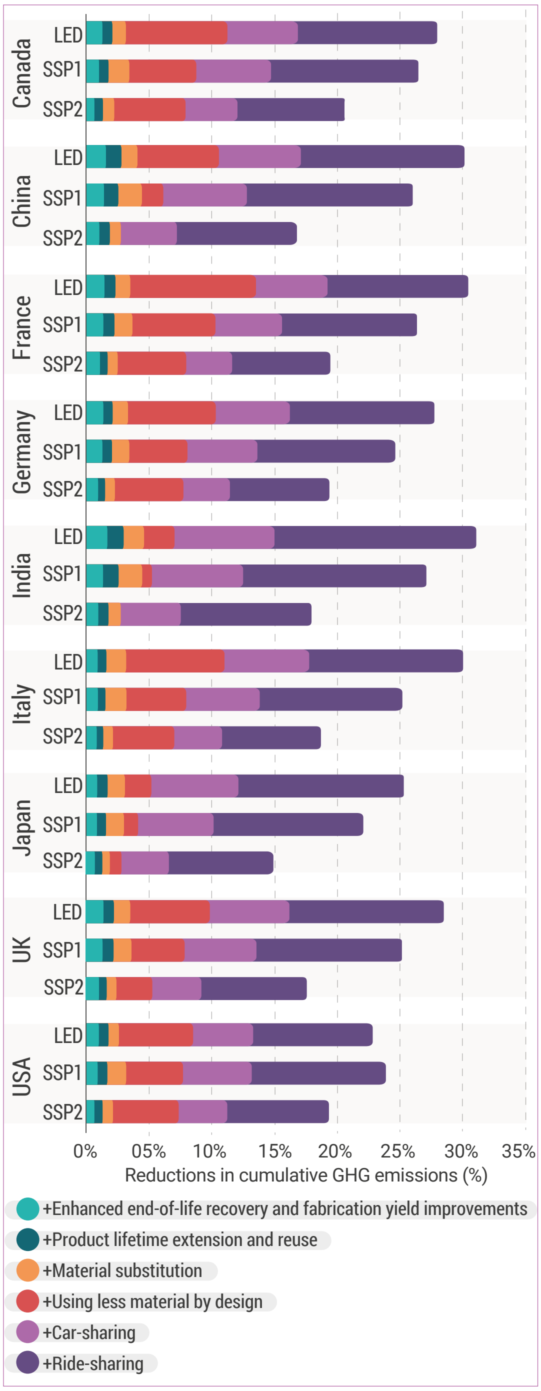
The overall reductions in cumulative GHG emissions (2016-2060) from the implementation of all material efficiency strategies range from 23 per cent (United States) to 31 per cent (India) for LED, 22 per cent (Japan) to 27 per cent (India) for SSP1, and 15 per cent (Japan) to 21 per cent (Canada) for SSP2, respectively (see **Fig. 22**). "More intensive use" makes the highest contribution to the overall reduction for most countries under SSP1 and SSP2. Downsizing varies between 0.7 per cent (India, SSP1) and 10 per cent (France, LED). In general, reductions are largest in countries that currently have large vehicles (Canada, Germany and the United States) and are more modest in countries where average vehicle sizes are smaller (Japan and India). GHG reductions from material substitution are 0.7-1.9 per cent across all countries but would increase to above 3 per cent in 2050 due to reduced emissions from aluminium production given the decarbonization of energy supply. A combination of "end-of-life recovery improvement", "fabrication yield improvement" and "material reuse" reduces GHG emissions by between 1.1 per cent and 2.6 per cent. Please note that the implementation of all strategies is assumed to be gradual to allow time for policy introduction, re-tooling and building-up capacity. The impact of strategies at the end of the time period could be substantially larger. For example, light-weighting reduces emissions at the end of the time period by 5 per cent, in line with other studies.

2.4.6. Discussion

2.4.6.1. Synergies and trade-offs among resource efficiency strategies

There could be synergies between the improvement of end-of-life recovery and material substitution. An increase in the number of light-weight vehicles could lead to a higher availability of light-weight metal scraps, which could increase the benefit of improving the end-of-life recovery rates (Løvik et al., 2014). Similar synergies could occur between

Figure 22. Contribution of different material efficiency strategies to the reduction in cumulative GHG emissions (2016-2060)



For SSP2, emission reductions are smaller in relative terms due to the assumed lower ambition level, reflecting the scenario storyline. As absolute emissions are higher, total reductions are often comparable to those attained for SSP1. For LED, car and ride sharing are assumed to be implemented as part of the baseline LED, and so the given shares are to be understood as how much higher emissions would be without these strategies.

material reuse and material substitution. For instance, the reuse of parts containing aluminium could potentially reduce energy consumption and therefore the GHG emissions from light-weight vehicle manufacturing. The increased availability of parts containing aluminium from retired light-weight vehicles could further enhance the advantage of reuse.

Competition occurs when improvement from one material efficiency strategy limits the potential improvement from another strategy. For example, yield improvements, improved recycling and increased reuse address the same material stream and hence compete with each other. When implemented at the same time, the emissions reductions are lower than the sum of those attained from implementing each strategy individually.

2.4.6.2. Important assumptions and future research needs

Like with buildings, modelling results depend on assumptions about the implementation of different material efficiency strategies. As changes of use patterns offer the largest emission savings in all scenarios, the assumptions of its implementation may need to be scrutinized. Currently, the implementation of more intensive use is modelled through a gradual increase in car-sharing and ride-sharing to up to 30 per cent over the 2020-2050 period, compared to the respective scenario baselines (Fishman et al., 2020; Wolfram et al., 2020). Both uptake rates and levels depend on social change, policy and business models. The potential has not yet been fully understood.

The material composition of different vehicle archetypes (both conventional and light-weight) and market shares of LDV segments are based on United States data and are assumed to be identical among all countries, due to the lack of country-specific data with the required resolution. Similarly, the reuse rates of different materials in vehicles for other countries are determined based on the data of Japan, although they are not completely identical. Future efforts should focus on creating country-specific data to characterize material efficiency strategies (such as material composition for lightweight vehicles).

2.5. Discussion of modelling results

2.5.1. Comparisons to other studies

There is a small but growing body of literature that has estimated potential emissions reductions of material efficiency strategies. Previous studies have varied considerably in scope. Some estimate emission reductions from specific material efficiency strategies such as more intensive vehicle use (Greenblatt and Saxena, 2015), vehicle light-weighting (Kim, 2010; Modaresi et al., 2014) or building lifetime extension (Cai et al., 2015). Others estimate emissions reductions for material efficiency strategies aimed at specific materials like steel (Milford et al., 2013a; Moynihan and Allwood, 2014) or cement and concrete (Shanks et al., 2019). There are also studies that consider combinations of resource efficiency strategies for multiple materials rolled out within long-term scenario assessments (Deloitte, 2017; IEA, 2019, 2015; Material Economics, 2018).

In addition to differences in scope, previous studies have also exhibited major differences in geographical and temporal boundaries; baseline and scenario assumptions; and levels of reporting transparency and granularity. Unfortunately, such differences preclude any direct comparisons of results between the published studies and the results of this study.

However, a review of the approximate scale and relative contributions of different material efficiency strategies to overall emissions savings can provide a first-order sense of how the results from this report compare to previous results.

Table 11 presents emissions reductions estimates available in the literature for the material efficiency strategies and materials considered herein, as summarized by Hertwich et al. (2019). However, it must be noted that Table 11 presents reductions as a percentage of materials-related emissions only (a common reporting benchmark in the literature), whereas the present study reports emissions reductions as a percentage of total baseline life-cycle emissions, including those associated with the use phase. Given the assumed continuous decrease of emissions from the production of materials, the estimates of this report are smaller. However, some similarities can be observed for vehicles and buildings.

Table 11. Reported reductions of material-related GHG emissions of homes and cars due to the implementation of specific material efficiency strategies

		Reductions of Material-related GHG emissions		
Sector/technology	**Material efficiency strategy**	**This study**	**Literature**	**Source**
Buildings	More intensive use	70%	40% for steel	Milford et al. (2013)
	Lifetime extension	1%	47% for steel	Milford et al. (2013)
			40% in China	Cai et al. (2015)
	Light-weight design	5-6%	19%-50%	Milford et al. (2013); Moynihan and Allwood (2014)
	Reuse	1-2%	15% (metals)	Milford et al. (2013)
			0%-5% (minerals)	Hertwich et al. (2019)
	Recycling	6-9%	10%-20%	Hertwich et al. (2019)
Passenger vehicles	More intensive use	30-60%	39% (steel fleet)	Milford et al. (2013)
			93%-96% (vehicles)	Greenblatt and Saxena (2015)
	Lifetime extension	3-4%	13% (steel fleet)	Milford et al. (2013)
	Light-weight design	11-14%	5%-45% (steel)	Milford et al. (2013); Kim et al. (2011)
			50% (metals)	Modaresi et al. (2014); Lovik et al. (2014)
	Increased reuse	5-14%	30% (steel fleet)	Milford et al. (2013)
			2.8%-5.1% (fleet)	McKenna et al. (2013)
	Improved recycling	21-32%	10%-38% (vehicle)	Dhingra and Das (2014); Nakamura (2012)
			50% (Al in fleet)	Modaresi et al. (2014); Lovik et al. (2014)

Note: Ranges in the numbers for this study reflect different scenarios.

Table 12 and Table 13 summarize the results of two recent studies by the International Energy Agency (2019a) and Material Economics (2018). These two studies are highlighted because they examined similar material efficiency options to decarbonize buildings and passenger vehicles, as well as using long-term scenario analysis approaches.

However, these two studies considered emission savings from the production cycle of materials only, whereas the present report looked at savings from the entire life cycle of cars and residential buildings. As such, the percentage emission savings stated in the present study are smaller than those in the IEA and Material Economics studies due to the use of the much larger life-cycle emissions as a denominator. The absolute emissions reductions identified by the present study are higher, given that emissions savings during manufacturing and use are also quantified.

For buildings (Table 12), both the IEA and Material Economics considered building lifetime extension, material waste reduction, increased recycling and buildings designed with lower materials intensities, which bear similarities to the material efficiency strategies considered in this study. Among these options, both studies concluded that building lifetime extension represented the greatest emission reduction opportunity. While the current assessment also finds benefits from lifetime extension, the model results show two findings. First, more intensive use has potentially larger benefits. Second, a shift to timber as a construction material has comparable impacts. In the IEA analysis, all lifespan extensions are coupled with deep energy retrofits to simultaneously reduce operational energy use. In the current study, we did not model such a deep energy retrofit, only upgrades in the heating systems and a shift towards cleaner energy sources. As a result, we find benefits from lifetime extension only in climates with low heating requirements and for modern, well-insulated buildings.

The material efficiency strategy with the largest savings in this study (more intensive use) was only reported explicitly in the Material Economics study (as "sharing") and represented a smaller relative share of overall emissions savings. These differences emerge from the scenario assumptions of each report: Material Economics assumed a 5 per cent reduction in overall floor area in Europe due to sharing, whereas the present study assumed far greater reductions in floor area as discussed in Section 2.3.4.

Table 12. Reported reductions of material-related GHG emissions of buildings due to the implementation of material efficiency strategies

Study	Geographical focus	Reporting basis	ME improvement categories	Reduction compared to baseline		
				Cement	Steel	Other mat'ls
Material Efficiency in Clean Energy Transitions (International Energy Agency, 2019)	Global	• 14 Gt CO_2e cumulative 2017-2060 for material production (Fig. 38)	Building design (e.g., structural optimization, composite frames)	7%	4%	
			Material properties (e.g., reduced cement in concrete)	14%	2%	
			Precast and prefabrication	4%	4%	
			Lifetime extension	43%	18%	
			Waste reduction and reuse	2%	2%	
The Circular Economy: A Powerful Force for Climate Mitigation(Material Economics, 2018)	European Union	• 123 $MtCO_2e$ in 2050 for material production (Exhibit 6.7)	Cement recycling	10%		
			Waste reduction	3%	3%	2%
			Reuse of building components	6%	6%	4%
			ME (less waste, less overspecification, high-strength materials)	6%	6%	5%
			Sharing	4%	4%	2%
			Prolonged lifetime		43%	

Note: totals may not equal 100% due to rounding

With respect to passenger vehicles, only the Material Economics study reported results for multiple material efficiency strategies, which are summarized in Table 12. The most promising material efficiency strategy identified by Material Economics was increased vehicle lifespan.

The authors of the present report found that lifetime extension for fossil-fuel powered vehicles slows down the introduction of electric vehicles and, hence, results in increased emissions. Considering this, the current study considered a moderate lifetime extension of 20 per cent for electric vehicles only, which results in savings of cumulative life-cycle emissions in the 2016-2060 period of 0.25 per cent, increasing to annual savings of 1.5 per cent in 2050. Furthermore, Materials Economics identified sharing and light-weighting to be significant sources of emission reductions. These are similar in nature and relative importance to the results from more intensive use and vehicle downsizing/light-weighting according to the authors of this report.

Table 13. Reported reductions of material-related GHG emissions of passenger vehicles due to the implementation of material efficiency strategies

Study	Geographical focus	Reporting basis	ME improvement categories	Reduction compared to baseline
The Circular Economy: A Powerful Force for Climate Mitigation (Material Economics, 2018)	European Union	• 42 $MtCO_2e$ in 2050 for material production (Exhibit 5.9)	Reuse and remanufacturing	10%
			Light-weighting	20%
			Longer lifetime	50%
			Sharing	20%

2.5.2. The ODYM-RECC assessment: context, data and model limitations

2.5.2.1. Model development context

The ODYM-RECC scenario model framework applied here is a dynamic material flow analysis model. It contains a consistent description of the product, material, chemical element and energy layers for the passenger vehicle and residential building end-use sectors. The rationale for developing and deploying ODYM-RECC in the context of this study is that a mass-balanced description of material stocks and flows must be at the core of any assessment intended to quantify the system-wide impacts of material efficiency on GHG emissions.

The set-up of ODYM-RECC optimally fits its purpose: (i) to estimate the maximum technical potential of material and resource efficiency at all material cycle stages; and (ii) to study how the strategies interact and how their mitigation potential varies under changing technology, use patterns and the transformation of the energy system.

The ODYM-RECC model, including the link to the different product archetype descriptions, represents a major advancement in prospective modelling of the economy, as it consistently integrates the service, product and material perspectives down to the individual chemical element; works in a multi-regional setting at full sectoral scale; and combines a large variety of data in a consistent manner. Consistent data on the energy consumption and material composition of the product archetypes for buildings and vehicles used were obtained from widely used high-resolution model platforms for buildings and vehicles (accurate down to the individual component).

The framework has an intermediate level of resolution and covers the relevant time frame. The representation of products, processes and materials is at a level of detail that clearly depicts the differences between individual drive technologies; primary and secondary production; and standard and light-weight construction. Synergies and trade-offs between energy and material efficiency can be quantified. Its resolution is much more detailed in terms of products, processes and materials than economy-wide models. It is similar to the resolution of energy system and energy end-use partial equilibrium models (where the two overlap), but it is coarser than the resolution of some specific case studies (including ones on the comparative assessment of different material substitution options for vehicles and buildings or the specific challenges arising from imperfect sorting of metal scrap into different alloy groups). That means, that the technology pathways and product archetypes studied here represent of a larger set of options, rather than the only candidates. For example, although we studied the impacts of light-weighting passenger vehicles by replacing steel components in the body-in-white with aluminium, there are other viable options with similar weight reduction potential (such as advanced high-strength steel).

The resolution was chosen so that ODYM-RECC scenarios can provide quantified sector-wide impacts of resource efficiency with a manageable level of detail and the available technological options, many of which had not been scaled up in a scenario assessment before.

2.5.2.2. Model and data limitations

On the resource and engineering side, the following gaps remain due to the limited workforce available to collect relevant data, add them to the project database and implement the relevant model features:

- Depiction of non-residential buildings, infra-structure and transport other than automotive transport
- Detailed scenario analysis of primary material production, including potential breakthrough technologies
- Consideration of advanced scrap-recovery and recycling technologies such as car dismantling
- More systematic consideration of other biogenic construction materials, and of supply constraints, such as those relating to wood/timber.

ODYM-RECC is currently a purely physical-engineering model. The economic layers, in the form of costs at the (micro-economic) process level and cross-sector interference at the (macro-economic) sectoral level are not included. It stands in the tradition of prospective material cycle modelling and extends this tradition by linking material stocks to the product and service layers and material flows to the energy and emissions layer. Options for more systematic coupling between economic and physical prospective models are currently being explored in the industrial ecology community. This link is crucial to (a) determine the magnitude of rebound effects, and (b) study the impact of economic and tax incentives (such as an ecological tax reform on the uptake of the different resource efficiency strategies).

Lastly, although ODYM-RECC is built on a well-defined system and a consistent database, much of the data collected were derived from models that were run with local input parameters and numerous assumptions. Even though the different models strive for consistency with the SSP storylines, there can be underlying inconsistencies due to the omissions of certain system linkages in the assessment. The use of such data in ODYM-RECC thus assumes that consistency across input data is maintained, and future model integration work can help test for consistency of input parameters and subsequently generate refined input data. The following assumptions were made during the compilation of the ODYM-RECC database:

- The independent description of the different end-use services, product type allocations and intensity-of-use parameters can all be achieved together in a single (urban) setting. For the future, the different sectoral descriptions need to be linked to a consistent depiction of the urban and rural lifestyles in the various regions.
- The different building archetypes are static and do not change over time due to variations in local climate, for instance.
- The impact of material efficiency on energy consumption, the energy mix and related GHG emissions is implicitly accounted for already in the macroeconomic and energy system model used to generate the energy supply GHG intensities used. Work to test the validity of this assumption is ongoing. The lack of system linkages is part of a wider problem: that natural resources and material-related processes are not well depicted in most energy-climate models, despite the substantial contribution of materials to the total GHG emissions budget.
- The GHG emission factors of primary production account for a change in the GHG intensity of the energy mix that is supplied. However, the emission factors do not yet account for potential process changes such as a partial replacement of cement clinker by calcinated clay in cement.
- The massive change in the transport and building sectors implied by the introduction of the more intense use, car-sharing and ride-sharing strategies hinges on the transformation

of transport patterns and lifestyles in response to price signals and attitude change in a world with substantial efforts dedicated to climate change mitigation. Steps to initiate such a transformation are assumed here. Challenges, experiences and potential policy levers are discussed in the policy review in chapter 3.

2.5.3. Outlook

2.5.3.1. Resource efficient cities

Ensuring that homes and transportation support the 1.5°C target requires a systemic change in the way we meet the social needs for housing and mobility. Modest changes in the current system will not reduce emissions sufficiently, as shown by the scenario modelling in this report. The IRP report 'The Weight of Cities' shows the important role that city planning can play as a nexus of the two systems. In addition to smaller, more efficient apartments in multi-unit buildings, we need integrated neighbourhood planning in 'strategic densification', including aspects of functional diversity (Swilling et al., 2018). These neighbourhoods form strategic high-density nodes that will facilitate efficient public transit routes between nodes and new mobility, including walking, cycling and shared rides within nodes. Integrated neighbourhood or 'node' planning will not only be based on buildings of higher utilization as a key element, but the nodes-approach will also ideally encourage a shift to more efficient buildings. Integrated neighbourhood planning (with functional performance in mind) can provide new societal benefits such as shortened transit routes, improved access to services and easier access to green spaces or communal spaces surrounding hubs to support social cohesion. Such features increase the attractiveness of the more efficient homes in such nodes.

While the broader systemic change in the nexus place of cities is described in the IRP *Cities* report, this report provides the detailed evidence base of two key elements of that system: efficient buildings and efficient private transportation in light-duty vehicles. In this report, the two product systems are studied in isolation. This limited scope enables a deep analysis of the potential of material efficiency strategies in the respective sectors. For decision makers, this analysis provides unprecedented high confidence on the potential of certain material-efficiency interventions, such as the promotion of ride-sharing, vehicle remanufacturing and multi-unit buildings of extended, high utilization. These findings can therefore be taken as one important element in the systemic planning of housing and mobility within a city or national context. They can also feed into further research that will estimate the potential of combining these strategies for systemic change, for example car-sharing in combination with strengthened bus and rail services or bicycle lanes. Such future research could integrate the modelling of product systems, as presented in this chapter, with the modelling of activity patterns and an evaluation of different urban forms and lifestyles. It also needs to consider cultural preferences and current spatial organization, as well as governance capacities and access to resources. It will need to be undertaken at a local scale, informing urban planners, while the modelling approaches and tools can be generic.

In summary, while the modelling and policy review in this report cannot describe the complete future system of housing and transportation, it gives unprecedented insight into the potential of two core elements in the system. To implement the strategies and to go beyond the modelled reductions (which are mainly falling short of 1.5°C consistency), these material-efficiency strategies will probably need to be combined in a policy mix that includes low-carbon material production and a shift from private to public transport for a fundamental decarbonization of the housing and mobility systems.

2.5.3.2. Understanding the global scope of material efficiency

Changes in production methods and product systems provide numerous options through material efficiency, circular strategies and technological advances that are not consistently represented in the integrated assessment models (IAMs) used to inform decision makers on climate change mitigation (Pauliuk et al., 2017). In current IAMs, changes in the way buildings are constructed do not have a direct impact on the quantity of materials produced by the corresponding industry. The approach developed for this assessment may enable this to happen. However, further developments are needed to integrate this approach in integrated assessments of climate change mitigation:

1. The geographical coverage needs to be extended to capture all relevant world regions in terms of historical and future demand for the products of interest, as well as to reflect product composition and function. More bottom-up empirical data will be needed. There should be an open, community-driven process to collect, share and validate this data, using as much empirical input as possible. The authors of this report are publishing the input data and assumptions used (Pauliuk et al., 2019a) to provide an avenue for critical examination, validation and improvement.
2. The product coverage needs to be extended. The current work relates to the building and transport sectors as they are characterized in respective modules of integrated assessment models. However, the modelling in this report covers only residential buildings and cars. The many types of commercial buildings and various means of transport, including their infrastructure, need to be incorporated as well. Substantial work is required for that.
3. An important share of materials is used in machinery and equipment. Some of that will be used by the energy sector, and much of it by the industry sector. There is a dearth of information on the types of machinery and equipment produced, on their use in different applications and on their life-cycle impacts.
4. The current model is physically based and ignores costs. Integrated assessment models choose among mitigation options using costs as a decision criterion. In order to consider material efficiency and circular strategies as options in mitigation research, cost estimates will be required.
5. Adaptation to climate change will require changes in building codes and the construction of infrastructure. The current framework provides an avenue to consider such changes and the associated emissions.

The advancement of material efficiency analysis using the ODYM-RECC framework can provide substantial insights for policy analysis. For example, it can identify new mitigation opportunities (with analysis of synergies and trade-offs) including the use of material, land and water resources and the emissions of pollutants other than greenhouse gases. The ODYM-RECC framework can also provide a more granular understanding of mitigation strategies with respect to changes in product systems, production methods and lifestyles that are opaque in more macro-level assessments.

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3. Review of Material Efficiency Policies for Climate Change Mitigation

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3.1. Chapter highlights

Measuring the material efficiency gains from policy requires the use of life-cycle assessment and related life-cycle approaches to reveal synergies and trade-offs across the product life cycle. Policies for end-of-life management would benefit from a more direct focus on the reduction of GHG emissions. Monitoring and indicator systems alone will not reveal whether a policy is effective. More widespread use of ex post evaluations, experimental studies and counterfactual analyses are needed.

To reduce greenhouse gases, a series of steps is needed: policies must stimulate the adoption of material efficiency policies; those policies must reduce material use; and the reduction of the use of materials must, in turn, lead to lowered emissions.

3.1.1. Residential buildings

Opportunities for material efficiency in residential construction and buildings are significantly shaped by design decisions. Building codes and standards are an important vehicle for policy intervention. Shifting from prescriptive to performance-based standards is key to increasing material efficiency.

Voluntary building certification systems, such as LEED and BREEAM, are being incorporated into government policy in many jurisdictions. Certification systems can encourage material efficiency. As with all rating schemes, the details of the certification systems will shape the outcomes.

Light-weighting and material substitution are important levers for material efficiency, but are not typically a focus of policy. Policies to encourage, promote or incentivize material efficiency in cement and concrete are largely absent. Many existing building codes and standards for concrete lead to the overuse of cement because they are prescriptive rather than performance-based.

Many building codes have limitations on mass timber construction for historical fire-safety reasons. Building codes in some countries have been updated to reflect changes in mass timber technology.

Prefabrication of buildings and modular building components provide multiple opportunities for material efficiency. Some countries in Asia have mandated prefabrication as part of their sustainability agenda.

Peer-to-peer lodging (P2P), such as Airbnb, takes advantage of underutilized space in dwellings. Policies restricting shared lodging to owner-occupied premises and related regulations could limit it to underutilized space with associated material efficiency benefits.

Policies on dwelling size have historically sought to ensure sufficient floor space for decent living conditions. Policies to reduce dwelling size include changes in taxation, removal of zoning requirements blocking multi-unit and/or smaller housing and removal of barriers for those seeking to downsize as a result of transitions in life stages.

Deconstruction – the disassembly of a building to improve reuse and recycling of materials – increases material efficiency, but the overall energy and GHG benefits are sensitive to how the recovered components and materials are used. Policy typically takes the form of information provision and financial support.

Recycling of construction and demolition debris is widely practiced, with an emphasis on recovery of metals. Policy is widespread and diverse, ranging from environmental permitting, recycling targets, landfill bans and taxes, to informational and business assistance programmes. While monitoring of outcomes is common, in-depth policy evaluation is not.

3.1.2. Light-duty vehicles

Reduction of the quantity of material used in a vehicle is not the focus of public policy, but fuel-economy policies can encourage smaller and lighter cars.

Public policies toward shared mobility currently focus on regulating the behaviours of drivers and companies to ensure passenger safety and reduce congestion and on the impact on public transit. Policies that discourage low-occupancy shared vehicles or penalize increased congestion can improve environmental performance and material efficiency. Data availability is a challenge for policymaking. No studies of policy effectiveness were found.

Policies on the management of end-of-life vehicles are common and typically focus on prevention and management of pollution from dismantling and recycling processes and on recovery of resources from automobile shredder residue. End-of-life vehicle recycling targets typically employ mass rather than GHG-based targets.

3.1.3. Cross-sectoral policies and challenges

More evaluation of the impact of cross-sectoral material efficiency policies on a sectoral and life-cycle basis is needed.

Green public procurement (GPP) is widely practiced around the world. Monitoring of programme implementation and goods purchased is common, but rigorous ex post evaluation of market or environmental and resource impacts is not. Subsidies for primary resource industries are common, but are more widely studied for energy production than material production. Such subsidies are significant and likely to reduce the extent of recycling.

Mandatory requirements for the use of recycled content have the potential to make recycling more financially viable. There are challenges in terms of perceptions of product quality, applications of mandates to complex products and verification of recycled content.

Rebound effects threaten the efficacy of material efficiency as a GHG-mitigation strategy. Policy instruments that directly or indirectly raise the cost of production or consumption, such as taxes and cap-and-trade systems, can reduce rebound.

Nationally determined contributions (NDCs) represent a potentially important vehicle for the mitigation of climate change through the use of material efficiency strategies, but currently only include limited commitments to material efficiency. Waste-management commitments are common but not focused on material efficiency. Building energy efficiency commitments (which are important for material efficiency if increased building lifetimes are pursued) are more common and can be instructive for the incorporation of material efficiency commitments.

3.2. Motivation, scope and summary of current policy review

In a recent report on resource efficiency policies, the Organisation for Economic Co-operation and Development (OECD, 2016, p. 42) notes that "a striking feature of the literature on resource efficiency is the lack of studies evaluating the impact of policy instruments … and ultimately [on] material consumption and extraction." While the OECD study does not comment on the connection between resource efficiency and climate change per se, the gap exists there as well. Despite the wellknown potential to reduce emissions via material efficiency, it is rare to find material efficiency targets that have been formulated to assist in reaching GHG reduction targets.

There is thus a need to generate a clearer and more robust understanding of the relationship between policy related to material efficiency and GHG emissions.[9] Chapter 2 of this report quantifies the potential reductions of GHG emissions from increased material efficiency. This chapter reviews policies aimed at encouraging or mandating material efficiency strategies.

3.2.1. The scope of this review

As part of the 5-year Bologna Roadmap to increase resource efficiency issued in 2017, the G7 invited the International Resource Panel (IRP) to prepare a rapid assessment of the relationship between resource efficiency and climate change (RECC). This chapter on policies for material efficiency is part of that study for the G7.

The IRP has framed much of its policy analytic work around the concept of "decoupling," whereby economic growth can occur without a concomitant increase in environmental harm – both in terms of resource depletion and pollution (Fischer-Kowalski et al., 2011; von Weizsäcker et al., 2014). GHG emissions are a pivotal concern and an important pollution metric. Prior panel work has noted linkages between resource efficiency and climate change on a case-analysis basis. Policies for resource efficiency and GHG emissions reduction have been a focus of previous IRP reports, but mostly at the macro level. The most recent results are from the 2019 Global Resources Outlook, which are provided here as an illustration.

In the 2019 Global Resources Outlook, the IRP assessed a "Towards Sustainability" scenario and a "Historical Trends" scenario. What distinguishes these scenarios is three "Policy Packages" that are implemented in the former but not the latter. Key features of these packages are:

a. Resource efficiency is promoted through an extraction tax and implemented in the same way in all nations, but set 25 per cent higher in high-income countries than in other nations;
b. A carbon policy package implemented through a carbon levy and dividend. For simplicity and transparency, the levy is modelled as applying equally to all countries and to all emissions sources, including emissions from land clearing; and
c. An integrated policy package to protecting landscapes and biodiversity by means of conservation targets, a carbon levy and a phasing out of crop-based biofuels by 2020 (Oberle et al., 2019).

Such a policy package would be able to reduce global material extraction by 25 per cent compared to historical trends, while at the same time reducing GHG emissions to 5 Gt CO_2e per year in 2060, compared to an increase from 47 to 65 Gt under historical trends.

An earlier IRP report for the G7 on Resource Efficiency (Ekins et al., 2017) addressed the connection between several dimensions of resource use (materials, land, water and energy), greenhouse gas emissions and economic development. That report provided key contributions, laying the groundwork for the present study.

- Ekins et al. provided an economic rationale for using resource efficiency as a strategy of climate change mitigation and embedded climate change mitigation in the larger economic policy framework of sustainable development. This framework identifies market and organizational failures, as well as transaction costs, as points of policy intervention.

9 The term material efficiency, rather than resource efficiency, is used throughout this report. The reason for this choice is explained in Box 1 in the introduction to this report.

- It analysed global resource governance, distinguishing between resources that are under the territorial authority of sovereign governments and shared resources (such as high seas, the ocean floor and the atmosphere). Global value chains and markets serve as a way in which resources are distributed around the globe and provide a rationale to ensure effective resource governance through global frameworks and mechanisms that can hold national governments to account. The report identified different governance models, their vulnerability to corruption and the capture of resource rents as key features of the resource curse. Governance models differ with respect to the involvement and power of stakeholders. This influences policy outcomes, which are unfortunately still deficient.
- Sustainable consumption and production can increase resource efficiency through a wide number of strategies, such as public and private procurement of sustainable inputs; the increase in reuse and recycling of products, components and materials; and the choice of urban forms that require less resources to build and operate. Examples from Canada and India illustrated green procurement and an example from Germany illustrated the use of less materials. The report also identified interesting initiatives towards zero waste in Italy and towards industrial symbiosis in Japan.
- In Ekins et al. the IRP first identified the synergies between resource efficiency and climate change mitigation based on resource-economic modelling that was later used in the IRP's Global Resources Outlook. It showed that energy efficiency often but not always reduces the use of resources, and that the increased employment of renewable energy is likely to lead to the use of more metals, rather than less.
- The report contained a description of numerous case studies of resource efficiency policies and measures implemented by local and national governments, as well as corporations.

In an earlier report on decoupling resource use from economic growth (von Weizsäcker et al., 2014), the IRP had identified the need for economic policy instruments to achieve technologically feasible reductions in resource use and emissions.

The present chapter reviews strategies and policies that encourage or mandate material efficiency (ME) at a more detailed level, examining policies related to a range of specific material efficiency strategies on a strategy-by-strategy basis. The sectors of residential building and construction and personal (light-duty) vehicle transportation are the focus of the policy review to complement the modelling presented in this report.[10] As discussed in the introduction to this report, homes and cars were chosen to represent construction and manufacturing, as these two sectors each account for significant and growing GHG emissions. Furthermore, policies exist for some aspects of material efficiency in these sectors, especially at end of life, while in other life-cycle stages, such as material-efficiency design and increased intensity of use, policy is less evolved – signalling a need for more policy development.

The review is based on a life-cycle typology on ME set forth by Allwood et al. (2011) and used in the RECC modelling and scenario development work (see section 1.5.3 and Figure 6 in the introduction of this report). The modelling presented in this report assessed seven ME strategies (Section 1.7):

1. Using less material by design
2. Material substitution
3. Fabrication yield improvements
4. Increased intensity of use
5. Product lifetime extension
6. Recovery, remanufacturing and reuse of components
7. Enhanced end-of-life recovery and recycling of materials.

In this chapter, the review of the policies for material efficiency in homes and cars is presented on a life-cycle basis. This enables discussion of the role of design in material efficiency and mitigation of GHG emissions.

As shown in **Figure 7** of the introduction, points of intervention for material efficiency strategies can occur throughout the product life cycle: in the choice or processing of materials, the production

10 A study conducted in preparation for this report presents a review of the existing research literature on the GHG-related impacts of material efficiency strategies (Hertwich et al., 2019)

of products and buildings, in their use and management or at end of life. Equally important, the net effect of policies cannot be adequately judged without taking into account what happens up and down the product life cycle.

It is vital to understand that the motivation for material efficiency in the context of this study is not landfill diversion, but rather the reduction of materials use as a means of lowering GHG emissions that are caused primarily by the extraction and processing of primary materials (Worrell et al., 2016). While landfilling of waste generates methane emissions,[11] waste from the building and construction or transportation sectors (which is the focus of the RECC study) is not a significant source of GHG emissions in landfills. A premise of emerging research on material efficiency is that it is a necessary complement to energy efficiency and other energy-focused climate policy if climate change goals are to be achieved (Gutowski et al., 2017). That is, material efficiency is seen as a means of achieving GHG emission reductions in addition to those achieved through energy-efficiency and decarbonization strategies. Thus, this report deliberately does not address energy efficiency strategies, policies or outcomes. Extensive research and policy on energy efficiency already exist (see, inter alia, Gillingham et al., 2018; Solnørdal and Foss, 2018).

It is also very important to recognize that material efficiency strategies may generate benefits and burdens beyond those related to GHG emissions. Ultimately, the environmental value of material efficiency strategies should be judged by their impact on a comprehensive set of environmental concerns including, but not limited to, air and water quality, human and ecological toxicity, soil, land, resource availability and biodiversity. The IRP has previously evaluated other GHG mitigation options for their environmental co-benefits and trade-offs (Hertwich et al., 2016 ; Suh et al., 2017, 2016). The analysis here is limited to the relationship of material efficiency to climate change because of a specific interest in filling the gap in understanding of this topic.

This rapid assessment describes a range of material efficiency strategies and policies with varying degrees of potential for climate mitigation. Because material efficiency is very broad in scope, this assessment cannot be comprehensive. In other words, all conceivable policy instruments applicable to each material efficiency strategy across all national and subnational jurisdictions were not inventoried and reviewed for the existence of policy evaluations. Even as this report goes into publication, the authors continue to find research on policy evaluation, often in the form of consulting reports prepared for governments that are unfortunately not catalogued as extensively as academic research. Instead, literature reviews were conducted and supplemented by information provided by members of the International Resource Panel and government representatives in the IRP steering committee. The goal was to identify significant and/or salient policies associated with material efficiency strategies for homes and cars, and to ensure that the findings and guidance about those policies are as accurate and reliable as possible.

The emphasis in the policy review is on "hard policy" – regulatory and economic instruments focused on material efficiency – rather than "soft policy" employing voluntary and informational approaches. This is in part because, in a rapid assessment, the sheer vastness of soft policy programmes is difficult to encompass and because mandatory instruments, whatever their faults, seem likely to have generated more outcomes and evaluation.

Finally, it should be noted that this policy review is prepared for the G7 countries and thus it examines opportunities for GHG emission reductions through material efficiency in developed countries. While there is discussion of practices and policies in some developing countries, systematic analysis of the opportunities, policies and constraints for such efforts in developing countries would be a welcome complement to this research. The larger context of material efficiency policies that have been proposed by G7 countries individually are described in Supplementary Material B. We also provide specific examples of the limited extent to which the current national determined contributions (NDCs) under

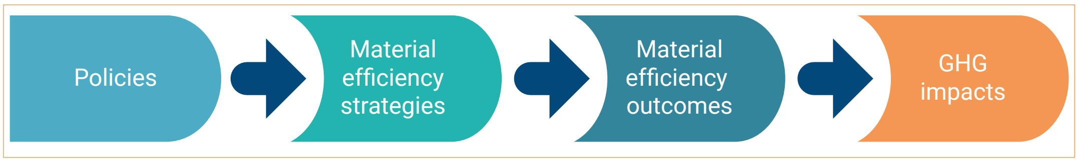
11 Reduction of methane released from landfills is a significant opportunity for climate change benefits through changes in material use, though not from the waste streams examined in this report.

the Paris Agreement include material efficiency components. We note that the NDCs may be an important vehicle for meeting the desired goals of linking material efficiency policies to tangible GHG reductions.

3.2.2. The logic of the analysis

Assessing the GHG mitigation effectiveness of policies for material efficiency has multiple components. In this analysis, we investigate material efficiency policies by examining the causal chain from material efficiency *policies* and *strategies* (actions expected either to reduce production or use of raw materials or to increase material recovery and reuse) through to GHG emission reductions (Figure 23).[12] We follow this approach to identify the weak links in the chain and highlight the areas that require better understanding and opportunities for policy development.

Figure 23. The causal chain used in the policy analysis in this report



The policies reviewed below are those intended to encourage or mandate the adoption of material efficiency strategies related to homes and cars. This review focuses on research and related literature that indicate whether, and to what degree, existing policies succeed in bringing about the adoption of material efficiency strategies (the first arrow in Figure 23) and especially —where the information is available — on the effectiveness of material efficiency strategies in generating material efficiency outcomes (the second arrow in Figure 23). Where identified, information on policies that block or discourage material efficiency is included. As noted above, the relationship between material efficiency outcomes and GHG reductions (the third arrow in Figure 23) is addressed in chapter 2. Where useful, some information is provided in this chapter about the environmental outcomes associated with material efficiency strategies.

For example, in the building and construction sector in some jurisdictions of the United States of America, local agencies receive grants from higher levels of government to promote deconstruction of a building at end of its life (i.e., disassembly rather than demolition) (Northwest Economic Research Center, 2016). In the Framework of this report, the grant programme represents a policy meant to promote the uptake of component reuse (a generic material efficiency strategy) in the sector-specific strategy of selective deconstruction of buildings. There are three points where analysis of effectiveness is relevant to this review: are grant programmes effective in stimulating the use of deconstruction?; how much of a building is typically salvaged through deconstruction activity?; and does deconstruction result in GHG reductions? In most cases, the focus in this chapter is the first of these questions.

While this approach provides a clear focus to the analysis, it involves several important challenges. First, adoption of a policy may not be the most significant driver for the use or effectiveness of a strategy. Deconstruction could, for example, be pursued by builders for many reasons: because it is cost-effective irrespective of the grant programme; in order to investigate the feasibility of deconstruction; or for business reputation purposes. Further, the material efficiency strategies may be sufficiently new such that policies have not been adopted or outcomes of those policies are not yet available. Local governments may not yet have put key deconstruction-friendly policies in place. Perhaps most tellingly, there is also a notable lack of studies assessing the effectiveness of material efficiency strategies more generally. Ideally, such studies would involve quantitative analysis of outcomes

12 The causal chain is actually more elaborate than the figure shows. For material efficiency policies to be effective in reducing GHG emissions, the policies must be effective in stimulating material efficiency strategies, the strategies themselves have to be effective in reducing material use, and they must be used extensively enough to generate significant results. Those results in turn must reduce GHG emissions. For simplicity, the diagram also does not include the impacts of rebound.

after a policy is in place (ex post),[13] with methods that could control for the influence of factors other than the policy. A less optimal but still useful approach is research that simulates the impact of such policies in anticipation of potential adoption (ex-ante). We found both types of studies to be uncommon.

Policies directly targeted at the strategies and practices described in this report, but not intended to influence material efficiency strategies (such as vehicle fuel economy regulations) are discussed, but broader economic or societal policies (such as macroeconomic, fiscal and tax policy) are not. Many other aspects of policy (including wages, employment conditions and interest rates) may play an important role in the adoption of material efficiency (for instance by encouraging employment over increased material use).

3.2.3. Structure of this review

The core of this review is an examination of material efficiency strategies in the residential building/construction and the (light-duty) passenger vehicle sectors. Any policies are identified, alongside their rationale, intended outcomes and policy evaluations. To clarify the connection between policy analysis and modelling of material efficiency strategies, the way of measuring the success of these strategies in quantitative terms is also presented. The policies for material efficiency in the two sectors are presented within a product life-cycle framework:

- Design and material choice
- Production
- Use
- End-of-life management

Several key cross-cutting strategies and challenges are then reviewed:

- Green public procurement
- Virgin material taxation, resource royalties and virgin material subsidies
- Recycled content mandates
- Rebound effect

The incorporation of material efficiency goals into nationally determined contributions (NDCs) for climate mitigation is also reviewed.

The conclusion of this rapid assessment summarizes and assesses the key findings. In the appendices, additional background on building codes, virgin material taxes and recycled content mandates is presented alongside a detailed tabulation of construction and demolition waste and end-of-life vehicle policies, a list of green public purchasing policies in the EU and a list of cross-sectoral reports related to material efficiency.

While our primary goal in this research was to find rigorous ex-post studies that highlight policy effectiveness, these are few and far between. This is partly due to the relatively new salience of material efficiency. Quantitative evaluations of building energy efficiency codes provide a benchmark for the rigour of such analysis. The European Union (EU) has also commissioned effectiveness studies but primarily in sectors other than those studied here (Ardente et al., 2018; Ardente and Mathieux, 2014a; Bobba et al., 2016; Montalvo et al., 2016). We note these towards the end of our evaluation, as the same approach could be applied to the construction and transport sectors.

3.3. Residential building and construction

Opportunities for material efficiency in the building and construction sector exist at the materials, components and whole building level. Points of intervention exist in design; material or component production; construction site activities; building use and maintenance; renovation, rehabilitation and reuse of existing buildings; and end-of-life management. In what follows, material efficiency strategies and associated policies are organized and consolidated into five broad topics based on relevance to building and construction:

- Design: Material choice and light-weighting
- Construction: Framing, prefabrication and modularity[14]
- Use: More intensive use and the sharing economy
- Product life extension: Renovation, refurbishment and reuse
- End of life: Deconstruction and increased recycling

13 Ex-post: research based on observations or data on performance rather than simulations or forecasts from theories or models.
14 Modularity can refer to modular construction, where large components of a building are produced off-site and then assembled into an entire building (see below). The term is also sometimes used to refer to buildings designed for adaptation and repurposing for changing use.

A summary of potential policy instruments encouraging material efficiency in residential building and construction can be found in Table 1 in the Executive Summary.

3.3.1. Design and material choice

Design is a crucial stage in the life cycle of a building, shaping innumerable aspects of its construction, performance and end of life. All material efficiency strategies can be facilitated, or in some cases, can only be achieved through appropriate design. Design can also inhibit material efficiency as when loads are overspecified because the cost of additional material is negligible compared to the risk of component failure, project delays or increased labour costs (Allwood et al., 2012; Carruth et al., 2011).

The opportunities afforded by design for material efficiency are mentioned in the sections below that address individual strategies. The design process, however, is generally not directly subject to policy, but rather is a potential means to enable compliance with policies related to material efficiency. This is most manifest in the role of building codes, standards and certification systems.

3.3.1.1. Building codes and standards

Building codes play an important role in determining building design and construction practices. A building code is a set of requirements indicating the standards that a building or other structure must meet in order to obtain permission for construction and operation from the relevant jurisdiction, such as national or local governments. Building codes are intended to protect public health, safety and related public goals. Building codes have legal status when they are adopted by the relevant governmental entity, thus becoming a form of public policy. Typically they are focused on new construction, but codes increasingly include provisions related to repair and renovation (Ching et al., 2012).

Building codes are both a hindrance and a potential source of leverage for material efficiency. To the extent that codes dictate material-intensive design or make material-efficient design expensive or cumbersome (such as the requirements for minimum cement content in concrete) (Wassermann et al., 2009), they are an impediment. While codes could mandate specific materials, designs or performance criteria with the aim of advancing material efficiency, current efforts focus on alignment of model green building codes (such as the International Green Construction Code with building certification programs such as LEED (see section 3.1.1.) and on integration of the model codes with existing codes (IgCC, 2018).

A key element in this effort is a move away from prescriptive codes towards those that are performance based. A prescriptive code dictates how a goal is achieved, such as when fire safety is achieved through requirements for particular materials or construction techniques, rather than a performance-based outcome such as the number of hours of fire resistance in a component of a building. Performance-based codes, however, can be challenging due to their complex nature and because there can be ambiguity or a missing link between codes and methods to test compliance (Vermande and van der Heijden, 2011).

Improvements in energy efficiency have been a central focus in efforts to incorporate resource considerations, albeit not material efficiency, into building codes.[15] According to the International Energy Agency, "building energy codes have been instrumental in reducing the overall energy consumption of the residential building stock over the last twenty years in IEA member countries" (International Energy Agency and the United Nations Development Programme, 2013, p. 8). Experience with building energy codes provides potential lessons for the use of codes to promote material efficiency.

In its review of building energy codes, the International Energy Agency and the United Nations Development Programme (2013) find that:

- Only mandatory codes are effective
- Performance rather than prescriptive codes avoid lock-in; allowing architects to take an integrated approach avoids optimizing individual building components at the expense of larger gains at the whole building level
- Designing and implementing effective building codes is a challenge because of governance structures, the fragmentation of the buildings

15 Energy codes do not necessarily reduce embodied energy arising from material use as with increased insulation and some framing strategies (Koezjakov et al., 2018).

sector, complexity of the supply chain, weak alignment of energy requirements in different policy instruments and a lack of expertise

According to the Global Alliance for Buildings and Construction, as of 2018, 69 countries have established voluntary or mandatory building energy codes and 8 other countries are still developing their respective codes (International Energy Agency and OECD, 2018). In a related report, the IEA (2019c) argues that "Policy coverage is improving, but not quickly enough. Almost all mandatory building energy codes in place in 2000 have been revised to include requirements that are more ambitious. Overall, the stringency of building energy policies has improved by around 20% at the global level since 2000. Yet, mandatory policies covered globally still less than 40% of energy use and less than half of CO_2 emissions from buildings in 2017. Progress on building energy codes in particular is not keeping up with floor area growth, and more than two-thirds of additions to 2050 are expected in countries without any mandatory policies in place".

Many countries have submitted building-related nationally determined contributions (NDCs) and some countries have enhanced them (section 3.6). The status of building energy-related codes thus provides a mixed message for material efficiency: progress can be made, but will probably be slow.

The European Union employs national-level mandatory building energy codes as part of its energy efficiency strategy. The EU requires that member states include renovation in their national energy efficiency action plans and that renovated central government buildings meet minimum energy requirements as set out in the European Performance of Buildings Directive (EPBD) (International Energy Agency and the United Nations Development Programme, 2013). For instance, under the EPBD all new buildings must be nearly zero-energy by the end of 2020 and all new public buildings are required to be nearly zero-energy by 2018. The definition of nearly zero-energy is up to member states and must be defined in terms of kilowatt-hours per square meter per year (kWh/m^2/year) (European Parliament, 2010). Building energy codes are important to material efficiency, not only as an exemplar, but also insofar as they play a key role in avoiding lock-in of energy-inefficient technologies in the extension of building lifetimes as discussed below in the section on building durability (see section 3.1.1.)

Unlike many of the other strategies reviewed in this chapter, building energy codes as a policy instrument have been the subject of a variety of rigorous quantitative, ex post evaluations (see, inter alia, Jacobsen and Kotchen, 2013; Kotchen, 2017; Levinson, 2016) through the use of "natural experiments"[16] and regression analysis. The evaluations generally find the codes to be effective in reducing energy use (though often less so than predicted by engineering models) and provide a useful benchmark for rigorous policy assessments. We found no ex-post evaluations of building codes with respect to material efficiency.

3.3.1.2. Certification of buildings

Voluntary certification systems can complement and/or facilitate the development of mandatory building codes. Environmental certification systems develop standards and confirm the performance of products, buildings, organizations and other entities seeking to improve upon and/or establish goals. The greening of the construction sector in particular has benefited from a rapid rise in certification standards for energy and material-efficient design emanating from voluntary and voluntary-government initiatives (Vermande and van der Heijden, 2011).

The United States Green Building Council's certification system, "Leadership in Energy and Environmental Design" (LEED), provides an instructive example of the role of certification systems in the development of policy related to material efficiency. LEED has had significant global uptake: some 97,000 commercial buildings received or are awaiting LEED certification in 175 countries (Elizabeth Beardsley, 2019). The percentage of homes certified by LEED in the United States of America is very small (Rakha et al., 2018), but the absolute number of projects is not insignificant. At the end of 2018, there were 171,474 housing units certified under LEED for Homes globally, the vast majority of which are multi-family

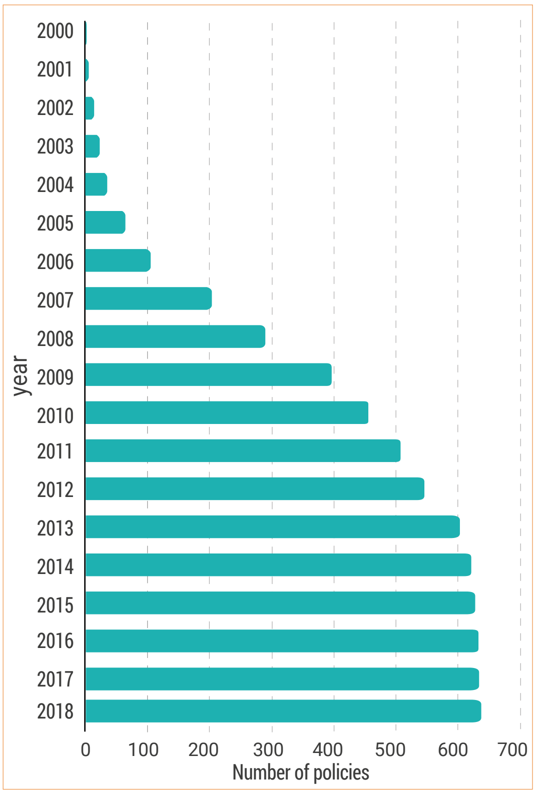
16 Natural experiments are empirical, observational studies that take advantage of conditions outside the researchers control that nonetheless allow rigorous comparisons. They are used when randomized, laboratory experiments are infeasible because of the phenomenon studied or ethical considerations.

low- or mid-rise buildings (United States Green Building Council, 2019).

For the purposes of this policy review, it is important to note that LEED standards have been adopted by various regulatory jurisdictions, as well as serving as a benchmark for sustainable construction. Carbon footprint reduction in 2019 accounts for one-third of the points toward LEED certification, and material efficiency is considered a part of the mitigation strategy considered in such initiatives. In the LEED for Homes rating system, there are 110 possible credits and 10 of those are available in the materials and resources category. The prerequisites in materials and resources, however, do not promote material efficiency (one requires certification of tropical wood and the other requires water/moisture management measures) (United States Green Building Council, 2014).

There is demonstrable evidence to show that government procurement rules that encourage green building certification lead to greater adoption of green building certification more generally, which in turn may lead to more material efficiency and GHG reduction (Simcoe and Toffel, 2014). The adoption of such standards by the private sector also appears to have made it more politically feasible for local and subnational jurisdictions across the United States to adopt policies that are directly linked to such procurement metrics. The United States Green Building Council maintains an online database of policies that facilitate its building

Figure 24. Cumulative number of jurisdictions in the United States of America integrating elements of LEED into policies



Source: Based on United States Green Building Council Public Policy Library, 2019.

standards. As of January 2019, there are 415 cities, town and village level policies and 198 state-level policies that have been recorded.[17] Figure 24 shows the number of jurisdictions in the United States of America that have integrated LEED standards into construction-related policy in some fashion.

Box 4. Green building certification as a path to material efficiency?

Green building certification systems provide an intriguing path to increased material efficiency in construction. As noted, uptake of building certification such as LEED and BREEAM is growing, as is the adoption of elements of their standards into building codes by governments. The material efficiency strategies in LEED that earn points include: (1) using “environmentally preferable products,” which includes recycled or reclaimed materials (but can also be met by using certified wood products, bio-based materials or locally sourced products); (2) reducing construction waste or diverting it from landfills/incinerators; and (3) implementing advanced framing techniques (such as placing window and door headers in rim joist or sizing headers for actual loads).

At the same time, the nature of many certification systems is a double-edged sword. The rating systems provide flexibility in how certification can be met. This flexibility is a key element in the growth of such systems, but such flexibility means certification can be received without meeting some specific requirements. Thus, it is entirely possible for a LEED Platinum home (which requires 80 credits) to merely meet the materials and resources prerequisites without pursuing material efficiency strategies (United States Green Building Council, 2014).

17 The specific elements of LEED and the integration of those elements into policy vary widely. See LEED Online Policy Library https://public-policies.usgbc.org/ for more detail (United States Green Building Council Public Policy Library, 2019).

Carbon metrics in such standards have been emphasized in recent years. A study commissioned by the California Air Resources Board evaluates the non-energy related GHG reduction benefits of LEED-certified buildings (Mozingo and Arens, 2014). The study found that buildings certified under LEED for Existing Buildings: Operations & Maintenance (LEED-EBOM) were associated with 50 per cent fewer GHGs from water use, 48 per cent fewer GHGs from solid waste[18] and 5 per cent fewer GHGs from transportation. At the same time, it is important to know that there can be a gap between the green building standards and actual operational building performance, especially with respect to energy consumption. That gap is the subject of ongoing research and debate (De Wilde, 2014; Menezes et al., 2012; Scofield and Doane, 2018). For new construction certifications, there is an inherent time lag between updates to certification systems, construction of buildings using the updated system, buildings becoming operational and then research to evaluate operations.

The original LEED rating system has been enhanced over the past 20 years and, partly to address recent criticism from industry and other groups, a decade-long consultative process led to the 2018 adoption of the "International Green Building Code'' (IgCC, 2018), which has involved a broad coalition of stakeholders within the construction industry. This code has also been embraced by the American Institute of Architects as a means of meeting their 2030 carbon neutrality challenge (Architecture 2030, 2019). The International Codes Council, which has adopted this standard, has over 65,000 member businesses and 337 global chapters at national and subnational levels. The impact potential of this code is thus significant, and policymakers may consider tracking the adoption of this code and its impact in meeting the GHG reduction targets. As of May 2019, however, several United States jurisdictions continue to use prior versions of the IgCC (notably the 2012 edition), while the 2018 IgCC has not yet been adopted as a mandatory code by any jurisdictions (Building Codes Assistance Project, 2019).

The IgCC applies to residential and commercial buildings five storeys and above, but allows local jurisdictions the option to also include all other residential buildings (Home Innovation Research Labs, 2019). In the United States of America, building code systems applicable to the majority of residential buildings are the International Residential Code (International Code Council, 2019a) and the International Energy Conservation Code (International Code Council, 2019b). They do not include standards for material efficiency at this time.

Other than LEED in the United States of America, other building performance evaluation methods include the Building Research Establishment Assessment Method (BREEAM) in the United Kingdom, the Green Star in Australia, the Evaluation Standard for Green Building (ESGB) in China, the Eco-Management and Auditing Scheme (EMAS) in the European Union and CASBEE in Japan. BREEAM, established and operated by the Building Research Establishment (BRE), provides manuals for stakeholders such as planners, local authorities, developers and investors. These manuals provide guidelines on infrastructure, new construction, refurbishment/fit out, in-use and communities. BREEAM has issued over 560,000 certifications as of 2017 (Doan et al., 2017).

3.3.1.3. Material substitution and light-weighting[19]

Material choice is a prominent strategy for improvements in material efficiency and reductions in greenhouse gas emissions. It can take the form of choosing materials lower in embodied carbon[20] or material resource, better in-use performance,[21] easier end-of-life management or simply reduction in mass. Analysis of the benefits of material choice, in the form of material switching/substitution, is often very complicated, clearly extending well beyond matters of mass, where a life cycle assessment is crucial (Lifset and Eckelman, 2013). There are many alternatives to the most common materials used in construction today, some of which have been used for centuries (King, 2017).

18 The solid waste refers to that which is generated by building occupants, not during the construction process.
19 The term light-weighting is often used to indicate a strategy for the reduction of mass either without change in the type of material (as described in the section on cement and concrete below) or through switching to lighter materials capable of providing similar levels of functionality. While the term is used in the context of automobiles and packaging, it is not commonly used with respect to building materials. It is used here to maintain consistency in the chapter.
20 Embodied carbon is the totality of all greenhouse gas emissions that result from the manufacture and supply of construction products and materials, as well as the construction process itself. It does not include GHG emissions during building use (Pasanen et al., 2018).
21 Other than mass timber, use of materials with lower embodied carbon or greater energy efficiency during use is beyond the scope of this chapter.

The challenge lies in scaling up options that are not currently widely used or institutionalized.

Policies toward material reduction or substitution are often constrained but sometimes encouraged by building and construction standards or codes. The Supplementary Material B contains a list of examples of standards that allow or inhibit material substitution. Concerns about insufficient information or evidence to allay safety or performance concerns often prevent development of standards friendly to material efficiency.

In determining the material to be used in constructing buildings, the GHG emissions associated with a material are often much lower down the list of priority attributes, below others such as ease of construction and cost. A carbon tax could help incentivize such material substitution toward materials with low embodied carbon. No research has been identified on construction material choice arising from the limited number of jurisdictions using carbon taxes.

3.3.1.3.1. Cement and concrete

Reducing the mass of cement and concrete used in the construction of buildings is one relatively straightforward strategy for improving material efficiency and reducing GHG emissions. Manufacturing of Portland cement is a carbon-intensive activity due to the emissions released during calcination of limestone at ~1450°C to produce cement clinker, the major ingredient in cement. Concrete is produced by mixing cement with fine and coarse aggregates along with water as well as admixtures such as gypsum and polymer solutions (such as superplasticizers) (Oss and Padovani, 2002; Schivner and Vanderley, 2017).

Favier et al. (2018) identify several, predominantly technical, strategies for the reduction of CO_2 along the value chain of cement and concrete materials (reducing the embodied carbon). These include:[22]

- Reducing CO_2 emissions from *clinker production* by improving energy efficiency of cement plants through strategies such as improved thermal efficiency of the kilns and increased use of alternative fuels
- Reducing CO_2 emissions from cement by *reducing clinker content.* This strategy primarily relies on partial substitution of clinker with supplementary cementitious materials such as fly ash at the cement production level and the use of alternative materials such as calcium sulfoaluminate cement entirely.
- Reducing CO_2 emissions from concrete by *reducing the cement content*. The strategy includes analysing the design mixture of concrete, binder phase and the quality and quantity of aggregates including recycled materials.

Standardization of cement types, as has been done in Europe (see BS EN ISO 197-1:2011) and elsewhere (as in ASTM) can be viewed as a form of policy. Under this approach, cement types are standardized according to class, whereby each class refers to permitted combinations of clinker and other materials (such as fly ash). Establishing different classes of cement helps assure purchasers of the quality and performance of the cement they are buying. These standards can also create markets for cements with lower clinker ratios (Energy Innovations LLC, 2019).

Other policies promoting clinker substitution focus on facilitating the use of recycled materials or creating incentives for co-locating cement kilns with other industrial facilities that produce clinker substitutes as by-products (Domenech et al., 2018; Schivner and Vanderley, 2017; Vigon, 2002).

Marin County in California, United States of America, adopted a building code in 2019 to limit embodied carbon in concrete. The code applies to both residential and commercial construction and contains requirements for concrete composition. The code contains provisions for optimum strength and durability for intended applications that also reduce greenhouse gas emissions. The code consists of compliance guidelines via reduced cement levels or lower emission supplementary cementitious materials" (King, 2018; "Low Carbon Concrete Project – County of Marin," 2020).

Analysis conducted by Shanks et al. (2019) identified four material efficiency techniques to reduce the use of cement and concrete in buildings: (1) post-tensioning floor slabs, (2) using more

22 See also section 1.6.

precast frame elements, (3) reducing the cement content of concrete, and (4) reducing over-design.

Post-tensioning concrete floor slabs allows for not only lighter and thinner floors but also lighter and thinner supporting foundations, beams and columns. This results in material savings of both concrete and steel in primarily multi-story buildings. In the modelling chapter of this report (section 2.3.3), it is assumed that reinforced concrete in walls and slabs and steel in beams can be reduced by 20 per cent and 10 per cent, respectively, in the light-weighting strategy. This strategy alone could yield a cumulative reduction of 0.4 Gt CO_2e (1 per cent) in SSP1 in the G7. Similarly, precast concrete frame elements (such as floors, beams and columns) can reduce the amount of material used in comparison to in-situ concrete. However, this technique would require a massive scale-up of the precast concrete manufacturing industry globally, and the net effect on emissions can vary depending on factors such as transportation distances and cementitious content (Shanks et al., 2019).

The concrete mix used for buildings generally contains more cement than is necessary for the required strength, either as a consequence of conventional practice or minimum specifications (American Concrete Institute, 2018; Shanks et al., 2019). Reducing cementitious content to match these requirements (such as compressive strength) has a significant potential to reduce carbon emissions. This potential is even larger when paired with changes in design to reduce over-specification or overengineering of buildings. Nevertheless, barriers to such changes include labour cost trade-offs; misalignment of incentives; cultural changes in construction; and fragmentation and variability along the value chain.

Policy instruments to encourage, promote or incentivize these four material efficiency techniques are largely absent. In fact, the vast majority of existing building codes and standards for concrete lead to the overuse of cement because they are prescriptive rather than performance based (American Concrete Institute, 2018; Shanks et al., 2019). Correcting this material inefficiency has been the focus of much industry discussion, but has resulted in little policy action thus far.

3.3.1.3.2. Mass timber buildings

Timber structures have lower cradle-to-gate GHG emissions than those produced from masonry or reinforced concrete. As with low-carbon cement and concrete, timber buildings differ somewhat from the other strategies discussed in this chapter in that their material efficiency benefits do not necessarily arise from less mass, longer lifespan or enhanced reusability. In addition, the carbon storage arising from timber use is notable (see section 2.3.3). Mass timber is a type of engineered wood framing characterized by the use of large wood panels for walls, floors and roofs. It is often load-bearing and includes cross-laminated timber (CLT), nail-laminated timber (NLT), glue-laminated timber (glulam), dowel-laminated timber (DLT), structural composite lumber (SCL) and wood-concrete composites.

Extensive use of timber in building has a long history, but large city fires in the late nineteenth century led to legislation prohibiting the use of wood frames in many communities, which helped masonry and concrete dominate the building market in Europe (Mahapatra et al., 2012). All the while, however, timber framing has remained the dominant framing technique for residential construction in North America and Japan. Interest in timber framing, and wood construction more generally, is gaining more traction, partly due to the potential climate benefits. This renewed interest is facilitated by new technologies, especially CLT, which improve structural properties of wood and allow its use in high-rise buildings. The increased interest in mass timber is also due to higher productivity in construction arising from the opportunity to use prefabricated wooden building components (Mahapatra et al., 2012).

Use of sustainably produced timber can reduce net CO_2 emissions (Gustavsson and Sathre, 2006; Hartman, 2010; Wijnants et al., 2018), but the GHG benefits are especially sensitive to the source forestry practices. In a comprehensive analysis of material choice and building operational energy consumption, Heeren et al. (2015) show that, in 95% of cases, timber buildings in certain climates can perform better than a concrete equivalent building in terms of life-cycle GHG emissions. The study also shows that wooden buildings may consume more energy during use, because the wood stores less thermal energy in its mass than competing materials with higher heat capacity. Similar results are also found in our own energy simulations in the modelling section of the report (see sections 2.3.5 and 2.3.4.1). The trade-off between lower thermal energy storage in wood and its other advantages highlights the need for life-cycle assessment to adequately assess material efficiency and GHG impacts.

A variety of factors including perceived costs, lack of knowledge and standards in the construction industry have hindered the adoption of mass timber buildings in some countries (Riala and Ilola, 2014; Schmidt and Griffin, 2013; Xia et al., 2014). Regulations for multi-storey wooden buildings, however, are evolving. German federal regulations, for example, allow construction of wood-framed buildings up to five storeys. Wood products procured in accordance with this regulation must also come from legal and sustainable forest management (Mahapatra et al., 2012). Similar regulations exist in Sweden, where a performance-based building code was introduced in 1994. The code specified that, irrespective of the material, the building must fulfill certain requirements including fire resistance. There is, however, no restriction on the height of a wooden building (Mahapatra et al., 2012). Moreover, in 1991, the United Kingdom lifted its Building Regulations restrictions on the use of wood frames for multi-storey construction of more than three floors. Under current regulations, such construction can be as high as 18 metres and the fire safety standards are the same for all types of frame materials (Mahapatra et al., 2012). National industry organizations such as the United Kingdom Timber Frame Association and American Wood Council are promoting mass timber as a part of mainstream construction practices. In the United States of America, an Ad-Hoc Committee on Tall Wood Buildings has been established by the International Code Council to research and address changes to the future code for the purpose of allowing mass timber buildings to be constructed above 75 feet (23m) (Barber, 2018). In the modelling chapter of this report, it is assumed that a total of 2.1Gt of concrete could be replaced by 0.3 Gt of wood in SSP1, which leads to a reduction in cumulative GHG emissions in the G7 of about 0.5 Gt CO_2e or 2 per cent of the life-cycle emissions of all buildings.

While there is a growing body of research evaluating the environmental impacts of mass timber construction, we did not find any quantitative evaluations of the effectiveness of changes in regulations regarding construction materials.

While changes in building codes are important to increase construction of timber buildings (and taller timber buildings have been built since the change in codes), policies such as pilot projects, information dissemination and training activities that facilitate market introduction can play a catalytic role. “Market transformation,” a policy and programmatic strategy that emerged in the 1990s to stimulate adoption and diffusion of energy efficiency technology and practices, may provide a model (and lessons) for strategic interventions to overcome market barriers for timber buildings. It is a strategy with particular potential for markets undergoing transformations that are not yet large scale (York et al., 2017).

3.3.1.4. Design for product life extension

Reuse can provide material efficiency benefits in building and construction at both the component and whole building level. With respect to building components, the strategy can involve the design of the component itself or of building, in a way that facilitates the recovery of the component.

3.3.1.4.1. Building material and component reuse

In this approach, the component may be designed or installed in a manner that makes the recovery of the component feasible. Prefabrication of building components can simplify component reuse as described in section 2.3.3. Component reuse avoids the production of new components and the associated embedded materials and energy. From a material efficiency perspective, the benefits would be measured in terms of primary materials production and component fabrication avoided.

Reuse can be facilitated through the development of markets for trading used components. In some countries, online platforms already exist to trade end-of-life construction material and components (such as in Canada: www.sustainabuildcanada.com, and Germany: www.bauteilnetz.de). Building components and materials can also be recovered via deconstruction as an end-of-life strategy without necessarily including upstream planning or design. This is discussed in section 3.3.4.

A broad range of building components are capable of being reused as indicated in Table 14, but actual reuse rates are estimated to be quite low. Allwood and colleagues discuss the opportunities for building component reuse in a series of publications. They focus on structural steel in steel-framed buildings because of the potential for the material, energy and GHG emissions savings. While steel framing is primarily used in commercial and industrial buildings, the authors provide examples and discussions of factors that shape feasibility (organization and incentives in the construction industry, a method of joining steel sections and low-cost testing of salvaged materials) that are instructive for many types of component reuse. In subsequent research, the authors investigated why reuse of structural steel is uncommon in the United Kingdom. Dunant et al. (2017) found that credits from the United Kingdom's Building Research Establishment Environmental Assessment Method (BREEAM) certification system are the main driver for changes in reuse of steel by contractors. However, the authors also found that the credits for steel reuse are marginal and generally not cost effective. For instance, it is much easier to use recycled concrete aggregates than to procure reused steel when seeking to acquire BREEAM credits on material reuse. However, the emissions savings from re-using steel components would be much larger (Dunant et al., 2017). In the modelling chapter of this report, it is assumed that up to 29 per cent of the steel components and up to 27 per cent of the concrete in concrete elements can be reused. Together with lifetime extension, the strategy of reuse generates additional savings of approximately 0.1 Gt CO_2e in cumulative emissions. Reuse is primarily responsible for the savings.

Table 14. Reuse potential rates of a range of construction components

No potential (0%)	Low (<50%)	Medium (~ 50%)	High (>50%)
Clay bricks (cement-based mortar)[a,f]	Mineral wool[b,e]	Steel cladding (buildings)[c]	Clay bricks (lime-based mortar)[a,b,f,o]
Steel rebar (buildings)[c]	Gypsum wallboard[a,b,e,g]	Steel cold formed sections (buildings)[c]	Steel rebar (buildings)[c]
Steel rebar (other infrastructure)[c,i]	Steel rebar in pre-cast concrete (buildings)[c]	Steel pipes (buildings)[c]	Structural steel (buildings)[c,f,j,m]
Steel connections[c,f]	Structural steel (infrastructure)[c,h]	Pre-cast concrete[a,m]	Concrete building blocks (with lime mortar)[a,f]
Structural concrete (buildings)[d,e,f,g,i,l]	Timber trusses[m]	Slate tiles[p]	Concrete paving slabs and crash barriers[j]
Asphalt (other infrastructure)[d,g,i]	Concrete in-situ[a,j,k,l,n]	Timber floorboards[p]	Clay roof tiles[j,l]
Asphalt roof shingles[e,m]	Concrete fencing, cladding, staircases and stair units[f]	Asphalt roof shingles[e,m]	Concrete fencing, cladding, staircases and stair units[f]
Plastic pipes (water and sewage), roof sheets, floor mats, electric-cable insulation, plastic windows[n]	Glass components (e.g. windows)[d]		Stone paving[f,j,p]
Concrete pipes and drainage, water treatment and storage tanks and sea and river defence units[j]			
Non-ferrous metal components (aluminium window frames, curtain walling, cladding, copper pipes, zinc sheets for roof cladding)[a,i,n]			Stone walling[f,j,p]

Source: Iacovidou and Purnell (2016).

* Percentages refer to reuse potential based on mass or number of units depending on studies used to compile the table.

a (WRAP, 2008) (figures based on buildings).

b (Thormark, 2000) (figures based on a residential building).

c (Cooper and Allwood, 2012) (figures based on global steel production).

d (BIO Intelligence Service, 2011) (figures based on European data on potential use of construction materials/components).

e (Gorgolewski and Ergun, 2013) (figures based on an archetype wartime house).

f (Webster et al., 2005) (based on literature).

g (Horvath, 2004) (based on literature).

h (Pongiglione and Calderini, 2014) (figure based on a railway station).

i (Tam and Tam, 2006, 2006) (based on literature).

j (Chini, 2005) (based on literature).

k (Sassi, 2004) (based on literature).

l (Sassi, 2002) (based on literature).

M (Nakajima and Russell, 2014).

n (Nakajima and Russell, 2014) based on management of CDW in Germany).

o (Nakajima and Russell, 2014) (based on figures from Norway).

p (WRAP, 2008) (based on figures from the UK).

Because building component reuse policy is relatively new, evaluations of policy are limited. In a study of management of construction and demolition waste in the European Union, Deloitte (2017) found that measuring performance of construction and demolition reuse across EU member states using the Eurostat or national datasets is not possible as there is no separation of recycling and preparation for reuse in the data. In addition, EU statistics do not include reuse activities, as in when no waste is generated and the materials or components are directly reused. As a result, it is not possible to provide conclusive evidence that reuse promotion initiatives have had a significant effect on the levels of reuse or on levels of waste generation.

3.3.1.4.2. Extended lifetimes and building durability

Building lifetimes can be extended through appropriate design, more durable materials, modularity, and renovation. Lifetimes can be extended by simple design choices (such as using a protective roof, design for repairability) or material engineering. A longer lifespan delays the GHG emissions associated with the production of building materials and associated construction activities. This approach to material efficiency, as with all durability or product life extension strategies, faces the challenge of avoiding carbon lock-in that can prevent exploitation of improved technology and associated GHG reductions (Cooper and Gutowski, 2017; Reyna and Chester, 2015; Seto et al., 2016).[23] The trade-off between avoiding production-related GHGs from new construction through longer building life or reuse and reaping the benefits of improvements in energy efficiency technology in new buildings is a central consideration. This trade-off can be improved through designs that facilitate the upgrading of existing buildings. In particular, deep energy retrofits utilizing improved thermal insulation, reduced infiltration, upgraded heating ventilation and air conditioning (HVAC) systems, low-emissivity double glazing for windows or cool roofs can play a crucial role in bringing buildings up to current standards of energy efficiency and thus sidestepping the trade-off mentioned above (International Energy Agency, 2019a).

There is some indication of overly short building lifespans, suggesting opportunities for this material efficiency strategy. According to Vermande and van der Heijden (2011): after World War II, many countries' construction policies had a strong focus on rebuilding, reconstructing and providing housing for the growing population. As a result, they describe how quantity (volume building) became more important than quality. Regulators responded to the needs in construction, and housing in particular, by implementing regulations that would provide for fast construction – buildings that would last for 30 years. Similarly, building lifetimes in China are estimated to be between 25 and 30 years, partly due to a high rate of demolition (Wang et al., 2018). Housing in Japan also has a short lifespan because of cultural norms against the purchase of second-hand homes (Tango et al., 2011; "Why Japanese houses have such limited lifespans," 2018).

In the modelling chapter of this report, it is assumed that building lifetime can increase by up to 90 per cent of the base value. As noted above, although lifetime extension reduces material consumption, it can prolong the use of older and less energy-efficient buildings. Therefore, the modelling results indicate that lifetime extension often results in an increase of emissions. To address the potential for perverse results, in the final model runs (section 2.3.4.4), longer building lifetimes were assumed only for buildings located in mild climates or with high energy standards; This results in savings relatively late in the 2016-2060 time horizon. This finding assumes high levels of retrofit of existing buildings with respect to energy demand and supply. However, materials used in retrofits are not included in the modelling.

Extension of building lifetimes is not a frequent focus of policy. Policies to preserve historic buildings, such as the United States National Historic Preservation Act, are a notable exception. Such policies restrict demolition or alteration, and

23 Similar findings regarding trade-offs between policies that target material efficiency and GHG emissions reduction (because of the tension between durability and new product technology) have been investigated by the European Union – mainly in relation to consumables and household appliances (see, for instance, Ardente et al., 2018; Ardente and Mathieux, 2014b; Bobba et al., 2016).

this can limit improvements in building energy efficiency (Avrami, 2016). More recent policy has started to subject such buildings to environmental requirements, as is the case with the recent New York City Local Law 97. The New York City law, which sets carbon emissions limits for buildings, includes a provision for exemption for historic buildings. The exemption, however, is a not de facto - as is typically the case.

Policies to extend building lifetimes might include taxing the demolition of buildings and subsidies in the form of rebates or loan-interest rate finance for buildings retrofits (International Energy Agency, 2019a). A 2011 study for the European Union found no evidence of policies specifically targeting building lifespan extension (Vermande and van der Heijden, 2011).

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3.3.1.4.3. Disaster resilience

Building regulations including codes and standards have historically aimed to establish minimum levels of health, safety and welfare for occupants. Concern about resilience to disasters, especially fire and natural disasters that will be exacerbated by climate change as noted in section 1.5.2, has prompted initiatives for resilient construction and development of building codes (Rosowsky, 2011). More resilient and durable buildings that can withstand such damage will ultimately extend the life of buildings, thereby impacting improving material efficiency. In many cases, waste from construction and demolition is the primary component of post-disaster waste, so resilient construction combined with disaster waste planning can both minimize construction and demolition waste and increase its recycling (Brown and Milke, 2016). However, there may be trade-offs between resilient construction and material efficient construction (more durable construction can be more material-intensive), which should be considered by policymakers alongside geographically specific vulnerabilities (Meacham, 2016; Phillips et al., 2017).

3.3.2. Construction

3.3.2.1. Framing

Framing, the fitting together of components of a building to provide a structure with support and shape, is both a matter of design and of construction practice. Framing techniques used in construction can decrease the material intensity of a building by reducing the mass of framing elements and/or other components of buildings. The focus of recent research on material efficiency in construction has been on reducing the use of steel in large buildings as mentioned above, but merits mention because it signals possibilities for increased attention to framing.

3.3.2.1.1. Reinforcing steel optimization techniques

More than half of the steel produced in the world is used in the construction sector. Out of this, about 44 per cent of the steel is used for steel reinforcement-bar, also called rebar, which provides structural reinforcement for concrete buildings and infrastructure (Allwood et al., 2012). Surplus reinforcement contributes a large proportion of construction waste. Globally, there is an excess of between 15 per cent and 30 per cent of rebar used than is required to meet performance and code requirements (Allwood et al., 2012). Allwood et al. (2012) describe two strategies to reduce the use of rebar: the use of Qube's Design and Bamtec rollers systems to reduce overuse of steel inherent in conventional rebars and the use of high-strength rebar, which requires relatively less mass with reduced embodied carbon emission (Moynihan and Allwood, 2014). Currently, standards in the United States of America limit the use of high strength steel rebar (National Academies of Sciences, 2011).

24 An EU working group prepared Guidance Paper F on Durability and the Construction Products Directive in 2004 but it does not contain policy (European Commission, 2004). More recently, however, the basic requirement 7 of EU's Construction Products Regulation, basic requirement states "the construction works must be designed, built and demolished in such as way that the use of natural resources is sustainable and in particular ensure the following: …(b) durability in construction works…". (European Parliament, Council of the European Union, 2011)

3.3.2.1.2. Advanced framing techniques

Perhaps the most prevalent material efficiency strategy in light-frame residential building is advanced framing, which is generally supported by the building codes but often relegated to "alternative" approaches or even footnotes in codes. (Yost, 2019) Advanced framing technique (AFT) is premised on optimizing building materials; thus, reducing redundancies associated with conventional framing approaches (Kosny et al., 2014). AFT employs wider spacing for wall studs; uses single rather than double top plate; and optimizes corner designs, as well as framing in windows and doors using less lumber. Generally, AFT produces wood-framed buildings with relatively lower materials cost and embedded carbon than conventional framing techniques.

3.3.2.2. Building information modelling

Building Information Modelling (BIM) is a virtual process that accurately models a building project in a three-dimensional environment through collaboration with architects, engineers, contractors, suppliers and other stakeholders along the construction supply chain (Azhar, 2011). BIM allows for better collaboration of building planners and a higher degree of digitalization and automation. During design, use of BIM can help locate areas of medium and low structural loads that allow changes in framing and reduction in materials use.

In terms of material efficiency, BIM has potential to achieve light-weighting by reducing material where it is not needed (such as reducing thickness of building components without loss of structural soundness (Basbagill et al., 2013)) and supporting waste prevention through more precise optimization of rebar use (Porwal and Hewage, 2012).

An increasing number of jurisdictions are mandating the use of BIM in public projects including the United Kingdom, Denmark, and the state of Wisconsin in the United States (Danish Building Agency, 2018; United Kingdom Department for Business, 2019; Wisconsin Department of Administration, 2009).

In the United Kingdom, collaborative BIM for all government-funded infrastructure was mandated in 2011 to be effective in April 2016. The British standard, PAS 1192, has helped form the basis for the international standard ISO 19650, which in 2018 replaced PAS 1192 in the UK (Link, 2019). The effects of the BIM mandate in the United Kingdom and creation of an International Standards Organisation (ISO) standard for life-cycle management of buildings using BIM should assist stakeholders in producing more energy and material efficient buildings, but it may be too early to look for evidence of that. Some evaluations of BIM effectiveness have focused on projected cost and time savings (Agustí-Juan et al., 2018; Cavalliere et al., 2019; Volk et al., 2014), but no evaluations of material efficiency arising from mandated use of BIM were identified.

3.3.2.3. Modularity and prefabrication

Prefabrication of buildings and modular building components provide opportunities for material efficiency through standardization and efficiency of off-site production, opportunities for prevention of or increased recovery of production scrap, incorporation of material efficiency-related materials and technologies and the avoidance of scrap generation on construction sites. The level of prefabrication can range from subassembly of a few small-scale components such as windows to complete modular construction (Kamali and Hewage, 2016). In this respect, building components have long been produced off-site in factories; what is new is the size and complexity of the components. According to Quale et al. (2012), modular construction is a form of prefabrication. Buildings are produced in "modules" off-site and transported to a site for assembly into a complete building. Prefabrication is attractive to the construction industry insofar as it can lead to greater productivity in construction relative to traditional methods because of the speed of installation, reduction of transport of building materials to construction sites and decreased waste (Lawson and Ogden, 2010).

In terms of the modelling of material efficiency presented in this report, prefabrication provides opportunities for increasing fabrication yields. Other benefits include reduction in transportation impacts, safer working conditions and improved thermal performances of the buildings because of factors such as tighter joints and seams (Wilson, 2019). Prefabrication can also enhance material efficiency by making repair, renovation and reuse more feasible as described in section 3.3.3.3.

It may also facilitate the use of less or alternative material such as timber and light-steel framing, which can often have lower impacts (Tavares et al., 2018) (see section 3.3.2.1). Studies comparing the environmental impact of modular and conventional construction typically find that modular and prefabricated construction have lower GHG emissions and construction waste (Mao et al., 2013; Quale et al., 2012; Tavares et al., 2018; Teng et al., 2018).

Many countries have regulations to promote off-site construction as part of their sustainability agenda and the International Code Council and modular building industry are developing a model code to accelerate modular and off-site construction (IgCC, 2018). However, the extent to which countries have committed to this approach varies.

Singapore has been using forms of prefabrication since the 1980s, and has been a leader in policy on the use of prefabrication in construction (partly due to a need to address labour shortages and improve productivity) (Ting and Jin, n.d.). In 1993, Singapore's Building and Construction Authority (BCA) introduced the Buildable Design Appraisal System (BDAS), a means of quantifying the ease of construction arising from building design decisions — its "buildability". Within BDAS, prefabrication is expected to improve buildability through simplified construction and lower labour requirements on site (Low, 2011). In 2014, the Urban Redevelopment Authority adopted measures to improve productivity in the construction sector by requiring specified levels of prefabrication in developments on land purchased through government land sales (Urban Redevelopment Authority URA, 2014). Completed projects that were subject to such requirements include university residential dormitories and hotels, but adoption of prefabrication is also becoming more common in the construction of residential, commercial and industrial buildings (Xu et al., 2020).

In the United Kingdom, government interest in offsite manufacturing appears to be increasing – according to a report on smart construction by KPMG UK (2016). In China, the State Council issued a policy circular[25] requiring that prefabricated buildings account for at least 30 per cent of total new construction for 10 years in the period starting in 2016 (State Council of The People's Republic of China, 2016).[26] China has a history of promoting prefabrication in construction. Jiang et al. (2019) investigate the effectiveness of government incentives for prefabrication, but do not explore the relationship of the incentives to practices or environmental outcomes.

In Hong Kong Special Administrative Region, China, a prefabrication strategy has been integrated by the government into the building design and construction of public housing developments (Legislative Council Panel on Housing, 2012). In 2017, the Hong Kong government announced its intent to promote the use of modular integrated construction by supporting non-profit organizations to explore the feasibility of constructing prefabricated modular housing on empty sites (The Hong Kong Chief Executive's Policy Address, 2017). Of particular note is Sweden, which has been acknowledged for its high proportion of prefabricated housing. It was found that 96% of Swedish housing is built using an off-site process (Hedges, Scott and La Vardera, Gregory, 2017).

As shown in the modelling chapter of this report, the strategies of fabrication yield improvement and fabrication scrap diversion could combine to reduce accumulated greenhouse gas emissions by approximately 0.8 Gt CO_2e in all scenarios (Section 2.3.4).

Barriers to moving towards off-site construction in China were studied by Mao et al. (2015). They identified the absence of government regulations and incentives, high initial cost and dependence on traditional construction methods as the main barriers. Unfortunately, with the exception of a

25 The 13th Five-year Plan for Economic and Social Development of the People's Republic of China.
26 Manufactured housing (a completely prefabricated building) is discussed in the section on smaller homes.

scenario analysis by Liu et al. (2015), no analysis of policy effectiveness was found.

3.3.3. Building use

3.3.3.1. More intensive use/sharing

More intensive use of buildings can be achieved in a variety of ways including sharing of space, flexibility in the use of space (leading to better use of built space) and reduction of space without a change in function. An approach to sharing of space in the residential housing sector is peer-to-peer (P2P) lodging, as in the well-known services of companies like Airbnb.[27] Other strategies include co-housing, smaller homes, home offices and increased use of urban and multi-family housing. In all of these approaches, the anticipated ME benefit arises from using less space for residential housing or lodging which, in turn, can lead to a reduction in the quantity of materials used to produce and maintain that space. A reduced need for floor space can thus lead to a reduction in GHGs per person or household served. There are co-benefits in that a smaller space will have reduced heating, cooling, lighting and other energy-consuming requirements. For details on how this is modelled, see section 2.3.2.

3.3.3.1.1. Peer-to-peer lodging

In recent years, technological developments and the widespread adoption of smartphones has led to the rise of the sharing economy. In particular, lower transaction costs and establishment of user trust systems, such as consumer feedback and ratings, have allowed individuals to become producers in multi-sided markets, where they can not only buy, but also rent out, or share their underutilized assets with others (Lüdeke-Freund et al., 2019). As demonstrated by high-profile, commercial platforms such as Uber and Airbnb, mobile Internet platforms are exceptionally effective at conveniently matching demand with supply of underutilized stocks. While sharing underutilized assets is not new (Bakker and Twining-Ward, 2018) (sharing of lodging has long taken the form of homestays), the low transaction costs possible in the digital age have transformed niche markets into mainstream economies of scale. For example, a 2015 survey revealed that 11 per cent of adults in the United States had used online home sharing services (Smith and Page, 2016).

The rise of P2P sharing of accommodations holds the potential for the use of underutilized dwelling space and thus increased use of existing residential material stock. However, it can also lead to tensions with local government over taxation and employment-benefit compliance. Furthermore, the environmental impacts of P2P lodgings and how they affect material efficiency and GHG emissions remain unclear, as does their environmental performance relative to conventional hotel accommodations.

While Airbnb claims that P2P lodging leads to substantial GHG benefits (equivalent to taking 33,000 cars off North American roads (Rubicon, 2015), the company does not provide access to the full study and methodology. In contrast, a recent study comparing the environmental impact of P2P lodging with hotel stays found that P2P lodgings did not always outperform hotel stays (Rademaekers et al., 2018). A report submitted to the Nordic Council of Ministers (Skjelvik et al., 2017) states, "While there is limited (and potentially skewed) evidence in the literature, Airbnb guests could have a lower energy use and associated Carbon Dioxide emissions than hotel guests". Nonetheless, growth in P2P lodging can also increase hotel room vacancies, in which case there will be underutilization of hotel building stock, thereby potentially offsetting the gains from use of residential space (Zervas et al., 2017).

Assessing the actual material efficiency impacts of P2P lodging is challenging for several reasons. First, digital platforms for P2P lodging such as Airbnb and CouchSurfing are very reluctant to share data on the use of their services. As a result, it is difficult to collect sufficient empirical evidence required for a comprehensive evaluation. Furthermore, P2P lodging can lead to rebound effects (Frenken, 2017). For example, savings accruing to the users (guests) of P2P lodging may lead to rebound effects as

27 To our knowledge, a widely accepted label for the industry that includes services such as Airbnb and CouchSurfing has not yet emerged. The World Bank uses "P2P accommodations". The Local Governments and Sharing Economy (LGSE) project argues for "short-term rentals" (STRs) as that term reflects the fact that these are economic activities with wider implications for communities than "home-sharing" (Cooper et al., 2015).

travelers have a larger budget available and spend it to travel more, thereby engendering increased transportation-related emissions. Similarly, the ability to earn additional income through P2P lodging could encourage hosts to travel more frequently, or enable hosts to rent or buy larger dwellings than they could otherwise afford (Frenken, 2017; Rademaekers et al., 2018). Furthermore, some shared lodging services are generating perverse incentives for landlords to prevent long-term tenancy in favour of more lucrative short-term rentals – leading to housing shortages. Higher short-term rental rates through P2P lodging also lead to lower housing vacancy rates and may, in fact, lead to increased demand for construction. More broadly, indirect rebound effects can also occur with both guests and hosts when the sharing creates earnings or savings that are then used to buy other goods or services (such as food or vehicles). Finally, the industry is rapidly growing and evolving, and it is unclear what final form it will take.

Policy on P2P lodging has focused on issues related to housing availability, impacts on neighbourhood character and quality of life, loss of municipal tax revenue and fair competition. No instances of policy focusing on the potential material efficiency benefits or drawbacks have been found.[28] Existing policies tend to be restrictive rather than enabling because of concerns that P2P lodging may:

- Crowd out other users of housing, decreasing the availability of affordable housing in neighbourhoods with low vacancy rates;
- Undercut the economic viability of existing hotels and other lodging businesses because hotels must meet building codes and related requirements/regulations to which residences are not subject; or
- Avoid lodging taxes that cities rely upon for revenue.

Concerns about these impacts have led some communities to ban P2P lodging entirely.

Some of these criticisms (especially lodging capacity created specifically for P2P lodging or using capacity previously occupied by renters) suggest that P2P lodging may not always rely upon underutilized capacity (Wachsmuth and Weisler, 2018).[29] Where this is the case, the expected material efficiency benefits would be unlikely to arise.

Regulations, where they exist, tend to be enacted at the subnational level and often apply to residences providing lodging to ensure compliance with existing building codes and ordinances (Bunte, 2014; Mehmed, 2016). Some cities have regulated the digital platforms or pushed the platforms to collect lodging taxes.

The limited available data and the scarcity of peer-reviewed research, combined with the evolving character of the industry, suggest that first steps in assessing potential material efficiency benefits and the formulation of policy should include:

- Requirements for data accessibility,
- Support for research that examines the energy consumption of residential versus commercial lodging and likely rebound effects, and
- Careful attention to and possible regulation of P2P lodging that does not make use of underutilized capacity.

Policy guidance is beginning to emerge. In a study for the European Union, restrictions on the types and duration of rentals are advocated as a means of focusing usage on underutilized capacity (Rademaekers et al., 2018). A study by Cooper et al. (2015), *Local Governments and the Sharing Economy*, provides guidance for local governments seeking to harness the sharing economy to advance urban sustainability. The study lists elements of local government regulation that are central to the pursuit of sustainable outcomes including statements of purpose and right to regulate, definitions,[30] requirements for operators (hosts), taxation rules and complaint process restrictions intended to limit the impacts of P2P lodging. The report also includes case studies of local government regulation. Unfortunately, the main conclusion to be drawn from the case studies is that enforcement is weak, making it difficult to draw inferences about the effectiveness of the

28 The Local Governments and Sharing Economy project echoes this absence of regulations aimed at environmental sustainability for P2P lodging (Cooper et al., 2015).
29 "This would be consistent with recurring industry claims, in response to complaints of unfair competition by the hotel industry, that STRs do not capture existing demand for hotels but create new demand" (Cooper et al., 2015, p. 101).
30 Statements of purpose, right to regulate and definitions may sound obvious but are worth highlighting because they are especially important in the regulation of new industries and practices.

policy. It is possible that restricting P2P lodging to owner-occupied premises and related regulations could have the effect of limiting this form of shared lodging to underutilized space with associated material efficiency benefits.

3.3.3.1.2. Shared housing

There are many forms of shared housing that have the potential to reduce the amount of space used per person or household and thus increase the intensive use of the building stock. These include cooperative housing, co-housing and co-living. Like P2P lodging, there is a long history of such arrangements under a variety of names that vary by country and philosophical or programmatic orientation. The terms used here are based on North American practice. Cooperative housing, a well-established form of housing, refers to a building or set of buildings — owned by a cooperative — containing multiple self-contained, private units (Cooper et al., 2015). In the United States, such housing differs from rental units in other multi-unit housing primarily in terms of governance and financial arrangements rather than physical characteristics. While there may be shared amenities (common rooms for social events, gardens, laundry rooms or pools) -they are not usually distinctive in their approach to shared space. Co-housing communities, in contrast, have a larger proportion of shared facilities integrated with private, self-contained units or homes. Co-housing communities, which originated in their modern form in Denmark in the 1960s, are intentionally structured in physical design and operation to facilitate social interaction.

Co-living refers to a newer variant of unrelated adults renting an apartment or house together. Shared spaces are more extensive than with co-housing and often include bathrooms, kitchens and living rooms. The term often denotes an intentional social character not included in conventional, shared rentals (Cooper et al. 2015). In all forms of shared housing, the material efficiency benefits arise from the use of shared space and from the possibility of related sustainability practices enabled by economies of scale or intent. The latter could include shared mobility and investment in systems such as passive solar, superior insulation and rainwater harvesting.

3.3.3.1.3. Home offices/telework

More intensive use of existing building stock can also be realized through telework. According to the State of Telecommuting report, 3.9 million United States employees, or 2.9 per cent of the country's total workforce, worked from home in 2017 (a 115 per cent increase since 2005) (Global Workplace Analytics & Flexjob, 2017).

As a work arrangement in which employees do not commute to a central location, telework/telecommuting has obvious, if complex, implications for travel-related GHG emissions. Energy and GHG impacts, as would be expected, have long been a focus of most environmental research on telework and thus bear mention. These include empirical studies carried out to identify the benefits of teleworking and its relationship with traffic and air pollution. This is where the rebound effect is relevant again. For example, James (2004) found that telecommuters' cars could be used for other travel purposes or by other household members when not used for commuting. In addition, the study also showed that activities such as shopping and transporting children previously combined with commuting became special trips once no longer combined with travelling to work. Furthermore, non-commute work travel increased for telecommuters.

From the perspective of material efficiency, teleworking may result in a reduction of commercial or institutional office space and the associated material used in construction and maintenance. Naturally, the potential material efficiency benefits rely on first order trade-offs between the expansion of home office space and the reduction of employer-managed office space. If home offices make use of underutilized space, then such space-based trade-offs may disappear and material efficiency benefits will be more likely. Telework can also affect land use patterns, including sprawl with associated impacts on travel and home size (Larson and Zhao, 2017).

Research on the non-travel impacts of telework is very limited. Larson and Zhao (2017) extend the standard urban model (SUM), a well-known model in urban economics, to include households that telework in four cities in the United States. Focusing on the long-run equilibrium effects, they find that all cities experience increases in land area, housing unit size and dwelling energy consumption (Larson and Zhao, 2017). Matthews and Williams (2005) also examine non-travel impacts of telework. They estimate macro-level energy effects across transportation, commercial and residential building sectors, finding that "elimination of office space due to virtual offices yields energy savings that rival those from reduced commuting" (Matthews and Williams, 2005, p. 21).

As with other forms of shared use, reduction in office space can result in the reduction of heating, cooling and other energy-consuming services.[31] Non-travel GHG emissions will also be a function of the relative efficiency of those services in homes as compared to non-home office space.

According to one study, (Horvath, 2010, p. 2) "The existing peer-reviewed literature is convincing enough to conclude that both in-depth, specific, regional studies (such as telecommuting effect on travel behaviour and traffic) as well as local, regional or even broader system-wide studies, accounting for the interactions of transportation, home and office space and equipment, and information and communication technology, are necessary for improved private and societal decision-making about telework".

Currently, teleworking is recognized and encouraged around the world. For instance, the United States Telework Enhancement Act (2010) (United States Office of Personnel Management, 2020) provides greater flexibility in managing the workforce through the use of telework. The European Union has similar telework laws (European Foundation for the Improvement of Living and Working Conditions, 2010). Tools are available for the analysis of some non-travel aspects of telework. Kitou and Horvath (2008) apply E-COMMUT-Air, a scalable web-based tool created by the authors, designed to quantify the air pollution effects of individual or company telework programmes relative to non-telework employment. The tool includes components for assessment of heating and cooling impacts, and could be used to assess scenarios regarding space use.

Telework overlaps with the related and rapidly emerging practice of co-working. Current co-working spaces are typically office spaces shared by people working on their own independent businesses/projects – usually freelancers who do not have their office. Whether co-working leads to overall reductions in office space, with associated impacts on building stock, is likely to depend on how the evolving use of shared workspace is configured, the intensity of utilization and how usage in homes and in conventional office environments change space in response. As with other forms of shared space, reductions in energy use for heating, cooling and lighting are possible as a result of changes in urban density due to location choices by workers. At this early stage, no research on the environmental or resource performance of co-working policies has been identified (Cooper et al., 2015).

3.3.3.2. Smaller homes

Dwelling stock can also be used more intensively by reducing the size of homes (in the form of fewer square metres per inhabitant). Reduction of floor space involves a diverse set of housing practices, issues and policies, and this includes both shared space and smaller homes.

While homes in many developed countries have been growing in size as average household size has been declining (Moura et al., 2015; Wilson and Boehland, 2005), a discourse and (in some cases) a social movement to downsize to dwellings with fewer square metres per person or per household have emerged. Motivated in part by concerns over planetary boundaries or aggregate levels of resource use in excess of ecological thresholds, interest in strategies for absolute rather than relative levels of consumption and environmental impacts is growing, often under the label of

31 The demand for energy can be inelastic (that is, not sensitive to the presence of someone working in a home or office) if, for instance, central heating, ventilation and cooling (HVAC) systems are used. In contrast, in countries where HVAC is often used on-demand (as in Japan) or actively managed through thermostat settings, then empty space will consume less in terms of energy services.

sufficiency. In the context of housing, sufficiency refers to efforts to define and implement reduction or limits on dwelling size per capita or family.[32] The challenge of meeting targets for the reduction of household energy consumption as part of overall energy and climate goals is a key motivation in this regard (Lorek, 2018).

Sufficiency can entail orienting consumption around low growth in material use, changing attitudes and a shift away from economic growth towards broader well-being. In material terms, this may mean fewer personal possessions and fewer rooms in housing units. This can be achieved by reducing the number of underutilized rooms (such as guest bedrooms and spare bathrooms) in houses, as well as by decreasing storage space and basements that 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 proportions of the population living in some form of assisted living, 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 shared urban living arrangements for longer, supporting trends in urbanization and the shift from single family to multi-family housing. In some cases, however, it may lead to smaller households per dwelling unit when people live alone.

Tiny or micro homes have garnered attention as part of current efforts to develop and promote smaller homes. For example, a tiny home was designed as part of the Ecological Living Module developed by the United Nations Environment Programme (UNEP) and Yale University in collaboration with the United Nations Human Settlements Programme (UN-Habitat). The 22 square metre dwelling uses simple construction techniques, sustainable materials and advanced green technology, as well as being energy-efficient, adaptable and fully off-grid (Abergel et al., 2018).

Smaller homes can be facilitated by local government strategies such as accessory dwelling units (ADUs), which permit additional housing units to be built in open space on plots with low-density or single-family housing. Because of the nature of the space constraints, ADUs tend to be smaller and more energy efficient (StopWaste and Arup, 2018). A related approach, infill development, allows for the use of land within existing built up areas and typically results in smaller dwellings per household. Infill development has been promoted by advocates of smart growth and by the new urbanist movement as a way to reduce sprawl, take advantage of existing infrastructure, reduce regional air pollution and increase investment in neighbourhoods (McConnell and Wiley, 2011). Infill development, however, often faces opposition from residents in surrounding neighbourhoods, who are concerned that it will lead to increased congestion, lost open space, increased demand for city services and reduction of local housing values.

Smart growth policies have been enacted by many states in the United States and supported by the federal government. McConnell and Wiley argue, in a 2011 review, that "new infill development has proved difficult to achieve in practice, for a host of economic, political, and regulatory reasons" and there is not strong evidence that policies to promote infill have been successful. A recent study by EPA (Kramer, 2016) discusses 12 case studies that incorporate various green infrastructure strategies and have been successful in promoting infill development.

Recent policy updates in California, however, have strengthened support for ADUs, with a combination of laws (Assembly Bill (AB) 68, AB

32 A somewhat analogous approach is being developed in the context of energy building codes, where energy sufficiency can reduce energy demand by lowering the energy services to operate and maintain the required comfort level in a building. Energy sufficiency involves non-technological solutions beyond the construction of the building as a stand-alone item and addresses its environmental context – including the building's orientation relative to the sun and its placement with respect to surroundings. It also involves strategies for managing the building's temperature set-point by relying on users to adapt their clothing (International Energy Agency and the United Nations Development Programme, 2013).

881, SB 13) that prohibit minimum lot sizes, set maximum dimensions and eliminate off-street parking requirements for ADUs, as well as removing the condition that permit applicants be 'owner-applicants' and removing impact fees for ADUs under 750 square feet. As both regular ADUs and 'junior-ADUs' (living units of up to 500 square feet created within an existing single-family home) are permissible, these laws will allow most single-family homes to be converted into three separate housing units, with the effect of increasing population density and reducing floor space per person in the areas that implement ADU developments (Maclean et al., 2019; Olmstead, 2020).

Urbanization can also reduce dwelling size and associated residential and transport energy consumption (Timmons et al., 2016). Because urban living is often more expensive and tends to be in attached or multi-family units, residences are often smaller and share walls with neighbours, which leads to reduced heating energy demand. In addition, it is easier to supply urban homes with district heat or natural gas, which have lower emissions than oil-fired heating systems that are still common in some rural regions. Urban residents often have better job opportunities and higher incomes, however, leading to rebound effects (in the form of other consumption with attendant GHG emissions). Evidence from the United States suggests that, in spite of increased weekend and holiday transport, urbanization reduces GHG emissions (Underwood and Fremstad, 2018). Further, transport emissions depend significantly on aspects of urban form other than density, with more complex, multi-centered cities having lower transport needs (Muñiz and Garcia-López, 2019).[33]

Entire factory-built homes (variously called manufactured housing, mobile homes or trailer homes) are another path to smaller homes. Mobile homes, despite the name, are intended to be set up for a long period of time or semi-permanently installed,[34] and have long been produced in many countries as an inexpensive form of housing. Because such housing has been associated with lower-income households, zoning restrictions including limitations on the number and density of homes permitted on any given site, minimum size requirements and foundation construction are not uncommon.

As with shared housing, the material efficiency benefits from smaller homes arise from reductions in material stock. Similar to shared housing, co-benefits include less consumption of energy for heating, cooling and other utilities, as well as congruence with other urban sustainability goals of high density and more compact urban form (Cohen, 2016).

Policies to encourage smaller home size are uncommon as the focus in most countries has historically been the opposite – to set standards for a minimum size to ensure decent living conditions.[35] Many social, political and economic forces run counter to efforts to reduce dwelling size. These include home ownership as investments (especially for financial security in old age); profits for construction, real estate, and financial industries; property tax revenues for local governments; and, of course, myriad social and cultural factors. In countries where tax policies favour capital gains or provide other tax benefits based on the value of the home, larger dwellings are thereby encouraged (Cohen, 2016, 2019). Some policies with the potential to reduce dwelling size include carbon taxes or other measures that raise energy prices: there is some empirical evidence suggesting that homes built during times of high energy prices tend to be smaller (Costa and Kahn, 2011).

33 The net impact of population density, urban form and other factors on greenhouse gas emissions is a matter of ongoing, intense analysis in the research community – with complex implications for material efficiency. In a review of the literature and related policies, Ottelin et al. (2019) find that, everything else being equal, in industrialized countries, higher population density is correlated with a lower per capita carbon footprint, while examples from China and the Philippines point in a different direction. They note a lack of experimental or time series studies that would be needed to establish causality.

34 Mobile homes are not the same as the residential modular buildings described in section 3.3.2.2. Mobile homes have a permanent steel frame built into the floor structure and can be relocated (Quale et al., 2012). In the United States, mobile homes are extensively regulated by the federal government under the HUD (Housing and Urban Development) code, whereas modular homes are treated the same as site-built homes.

35 A prominent example is the work of the International Code Council (ICC), an association responsible for setting the standards that govern the design and construction of buildings (Cohen, 2019).

Box 5. Zoning in the United States

Zoning for single-family homes based on minimum lot sizes plays a significant role in encouraging large dwellings in the United States. Along with other housing and land-use policies such as floor-to-area ratios, it has shaped the form of much of the urban landscape in American cities. Critics argue that "that has done as much as any [policy] to entrench [racial] segregation, high housing costs, and sprawl as the American urban paradigm over the past century" (Grabar, 2018).

In the United States, the city of Minneapolis, Minnesota and the state of Oregon have recently voted to enact policies to remove requirements for single-family zoning. Minneapolis enacted "Minneapolis 2040," a comprehensive plan addressing topics including housing, job access, the design of new buildings and the use of streets (Department of Community Planning and Economic Development, 2019). The plan "upzones" areas near jobs and transit to allow large multi-family apartment buildings designed for small households and modifies zoning that restricts smaller multi-family buildings (duplexes and triplexes) in low density neighbourhoods (Schuetz, 2018). If successful, this will not only will improve opportunities for people to move for employment or schooling and help aging residents to downsize without leaving their neighbourhoods (Grabar, 2018), but also increase housing density, decrease home size and contribute to a reduction of material use.

The Oregon Legislature enacted a law that allows duplexes, triplexes, fourplexes and "cottage clusters" on plots currently reserved for single-family houses in cities with more than 25,000 residents; in cities of least 10,000, duplexes are allowed in single-family zones (Bliss, 2019). The city of Olympia, Washington, has enacted similar policies (Bertolet, D., 2018).

Real-estate transfer taxes (often called "stamp duties", which must be paid when property or land over a specified price is sold) can also discourage shifts to smaller homes by reducing the seller's income from the sale (Fritzsche and Vandrei, 2019; Kopczuk and Munroe, 2015; Ommeren and Leuvensteijn, 2005). Scanlon et al. (2017), for example, argue that, while the United Kingdom's Stamp Land Duty[36] is an important source of revenue for government, it is the second most important factor influencing whether or not to downsize.

Efforts to promote sufficiency must thus be formulated recognizing the complexity and the opposing pressures (Lorek, 2018). Graduated property taxes (GPTs), which have increasing rather than flat taxation rates or which are tied to per-capita dwelling floor space standards rather than market value, are an obvious if politically challenging approach. Such policies are more appropriate in countries that have decentralized systems of local government (Cohen, 2016; Lorek and Spangenberg, 2019). A variety of jurisdictions have attempted but not succeeded in enacting GPTs including Cyprus and the states of Minnesota and Massachusetts. Singapore enacted a GPT applying to the top 1 per cent of owner-occupied dwellings in 2013 (Cohen, 2019). Because houses can be a source of capital gains, there can be a strong financial incentive to stay in a dwelling that has become too large as a result of changes in the household (Røpke and Jensen, 2018). As noted above, taxes that must be paid when property or land over a specified price is purchased can also discourage shifts in housing - making downsizing less likely (Fritzsche and Vandrei, 2019; Kopczuk and Munroe, 2015; Ommeren and Leuvensteijn, 2005). Thus, other policies that remove barriers for those seeking to downsize as a result of the transition in life stages or event (children leaving home, divorce or death of partner) are less politically fraught (Clark and Deurloo, 2006; Lorek and Spangenberg, 2019). Policy interventions may be politically feasible if focused on foregoing growth in dwelling size rather than absolute reduction. Because of the absence of policy encouraging downsizing, little can yet be said about policy effectiveness for this material efficiency strategy. The modelling results, in chapter 2 (section 2.3.4.2), however, clearly highlight the importance of "more intense use" of buildings. This strategy has the highest GHG reduction potential across all scenarios modeled and affects material as well as energy demand.

36 https://www.gov.uk/stamp-duty-land-tax

3.3.3.3. Renovation and reuse of whole buildings

Buildings as a whole can be reused through a variety of strategies including renovation/refurbishment[37] and adaptive reuse. According to the International Energy Agency, on average in residential buildings, the building envelope is renovated every 30 to 40 years and the heating and cooling systems every 10 years to 15 years (International Energy Agency and the United Nations Development Programme, 2013).

A noteworthy policy for extending of the life of buildings is the heritage listing process to preserve historically significant premises. As noted in section 3.3.1, there is a wide range of policies in most countries and local government jurisdictions where registries of historic places and other mechanisms are used to limit redevelopment. Such policies can extend the life of existing material infrastructure and therefore reduce material usage moving forward. As with other approaches to increased building lifespans, heritage policies may engender trade-offs between avoidance of new construction and the opportunity for higher energy efficiency.

There have been many studies conducted to address the choice between replacement of the existing building and extension of life cycle by renovation and refurbishment (see, for instance, Itard and Klunder, 2007; Sunikka and Boon, 2003; Thomsen and van der Flier, 2009). Renovation is more environmentally efficient in terms of material efficiency and waste reduction than demolition and new construction. While renovation can entail additional material use (including for new insulation and windows), the impact on life-cycle GHG emissions can be beneficial because of improvements in energy efficiency (Ardente et al., 2011). Renovation can, however, delay the adoption of high energy standards compared to demolition and construction of a new building. In this respect, renovation – and the concomitant opportunity for increased energy efficiency in operation – play a crucial role in determining whether extension of building lifetimes leads to GHG emission reductions (as discussed in section 3.3.1).

Reuse can also be pursued at the whole building level through adaptive reuse that leaves the basic structure of the building intact and changes its use through refurbishment (Langston et al., 2008). Adaptive reuse can be facilitated by emphasis on modular design that enables extensive renovation. Adaptability for conversion and reuse depends on the building geometry, ground plan, construction and technical installations (Federal Ministry of the Interior, Building and, 2019). Natural renovation moments, related to maintenance cycles, can present cost-effective opportunities to replace components with more efficient versions. Knowledge of likely future uses is a key factor in successful design of buildings to facilitate adaptive reuse. By preventing deterioration of building components, better maintenance can reduce the potential for demolition of the entire building, thereby increasing the opportunities for adaptive reuse (Material Economics, 2018).

Environmental policies related to building renovation typically mandate improvements in energy efficiency – rather than material efficiency – as a condition of approval for renovation. Policy instruments include energy audits/assessments and energy-performance certificates. Financial incentives include grants, subsidies, tax credits, low-interest loans and third-party financing. Other instruments include neighbourhood renovation schemes, certification and training of contractors and marketing or awareness campaigns (Pombo et al., 2019). In Germany, federal buildings with costs exceeding two million euros must meet the guidelines for renovation set out in the *Guideline for Sustainable Building* (Federal Ministry of the Interior, Building and Federal Ministry for the Environment, 2019).

Germany also requires that a dwelling meet building regulations comparable with those for new construction when more than 20 per cent of components (such as walls, roofs or windows) are changed, (Meijer et al., 2009). In Sweden, components are required to meet the equivalent requirements of a new build. In the United Kingdom, renovation of existing buildings is expected to meet minimum energy-efficiency standards. There are indirect methods to encourage renovation as well (Baek and Park, 2012). Some countries, for example, have

37 Renovation refers to activities that extend beyond mere maintenance and encompass modernization, restoration, retrofitting and rehabilitation (Meijer et al., 2009).

adopted a reserve fund system for the maintenance of social housing. In the case of Denmark, portions of rents from old houses are saved in a central fund to reduce the quality gap between new and old social housing (Baek and Park, 2012).

As with other policies related to material efficiency in this chapter, there is, in the words of one researcher on this topic, "a serious lack of quantitative data on policy effects" and "current policy instruments focus on the adoption of measures, not on what happens after measures have been installed" (Meijer et al., 2009, p. 549).

3.3.4. End-of-life management

End-of-life management takes multiple forms including deconstruction, component and material reuse and recycling of debris. Policy on these end-of-life strategies is usually addressed by governments as a bundle.

3.3.4.1. Deconstruction

Deconstruction involves the careful disassembly of buildings in order to maximize recovered materials reuse and recycling (Chini and Bruening, 2003; Nakajima and Russell, 2014). Although deconstruction takes longer than demolition, research indicates that deconstruction and reuse of materials and components can offer higher environmental and sometimes economic benefits than demolition and recycling (often due to subsidies) (Geyer and Jackson, 2004). Reuse of some materials may be limited by the unintentional movement of contaminants such as asbestos, lead from paint and polychlorinated biphenyls (PCBs). Typically, the process of deconstruction and reuse of materials is more expensive because it lacks the economies of scale enjoyed by new construction. Design of new structures to facilitate the economic recovery of structural components for reuse is important to achieving such benefits (Gorgolewski, 2008).

In the United States, deconstruction has been successfully applied in a wide range of structures such as commercial and residential buildings, churches and closed military bases (Iacovidou and Purnell, 2016). Building codes in the states of Oregon[38] and Washington[39] now allow the reuse of undamaged lumber without re-grading.

Similarly, the State of California's Green Building Code provides useful guidelines to help local governments draft deconstruction ordinances (Urban Sustainability Directors Network (USDN), 2016). The energy and greenhouse gas benefits of deconstruction depend on which components are recovered and materials are used, as well as on the materials and components that they displace (Eckelman et al., 2018).

While many governments set targets for recycling of construction and demolition waste, Cook County, Illinois in the USA, is unusual in that, since 2012, it has included a requirement that 5 per cent of demolition waste from residential buildings must be reused (Cook County, 2020). Waste-management plans must be submitted by contractors along with the relevant permit application before demolition begins, and a materials tracking form must be provided when the work is completed. The county has experienced an increase in diversion of construction and demolition waste from 78 per cent in 2012 to 95 per cent in 2015. Because the county also mandates recycling of 70 per cent of demolition waste from residential and non-residential buildings, it is difficult to know how much of the increased diversion is a result of the reuse requirement. However, the number of businesses involved in the reclaim, reuse and salvage of building materials has grown from 9 to 15 between 2012 and 2017. The county provides significant training for compliance with the ordinance, but finds there is ongoing need for retraining because of staff turnover in demolition companies and the establishment of new businesses (Delta Institute, 2018).

38 See Section 104.9.1 in the Oregon Residential Specialty Code (https://codes.iccsafe.org/content/chapter/10131/) and section of R602.1.1.1 of the 2018 International Residential Code (https://fortress.wa.gov/es/apps/sbcc/File.ashx?cid=8906).

39 Washington State Building Code CR-103P, implementing RCW 34.05.360. Because quality, ungraded salvaged lumber currently cannot be reused in buildings in the state of Washington in a structural capacity without facing high costs of grading or unless approved by the relevant building official, reuse of reclaimed lumber is inhibited. Without grading or certifying the material, wood extracted from one building in order to be reused in another cannot be assumed to be of an approved grade or species. The revision of the building code addresses this problem by assigning the base values of building material to the reclaimed lumber. This allows structural use of the material by limiting it to the capacity of the weakest wood species that would have been used in a previous building (Deller, 2020).

3.3.4.2. Recycling of construction and demolition waste

The management of waste from construction, renovation and demolition activities (typically labelled as construction and demolition (C&D) waste) includes many of the strategies described elsewhere in this review. It can involve upstream strategies including source reduction (less material used and less waste at the time of demolition), prefabrication, component reuse and building adaptation, as well as familiar strategies aimed at recycling C&D waste. This section addresses material recycling of C&D waste, while other strategies to deal with C&D are addressed elsewhere in this report.

C&D waste is generated in the processes of constructing new buildings and renovating or demolishing existing buildings. Construction waste is generated from on-site activities including cutting new material to size as well as from damaged stock material. Demolition waste, as the name suggests, is generated when a building is razed. Renovation waste is a mix of the two. C&D waste is the largest municipal waste stream in the United States of America, Canada and the European Union, with demolition waste making up the largest component of this waste (Brantwood Consulting, 2016; Deloitte, 2017; United States Environmental Protection Agency, 2018b).

The C&D waste stream is primarily composed of metals, concrete and other masonry, wood, plastic, gypsum and asphalt. The material efficiency benefits of C&D recycling arise when recovered materials are substituted for primary materials and are sensitive to, among other factors, the primary materials being replaced and the distance that the recycled materials must be transported. C&D waste can be an effective source of resources if substantial material stocks exist approaching renovation or end of life. This in turn implies that rapidly growing economies that are adding building stock faster than buildings are reaching end of life are less likely to have a supply of secondary materials to close material loops (State of Washington, 2020). This is often the case in developing economies that are only starting to accumulate such stocks.

The environmental benefits of metal recycling from C&D waste are widely acknowledged. The results in the modelling chapter of this report (section 2.3.4.1) indicate that current recycling practices could save on average 40 Mt CO_2e every year up to 2060 in SSP1 and SSP2.

Recycling cement is limited by its chemistry, however, and it is therefore concrete that is recycled instead (often as aggregate) (International Energy Agency, 2019a). As a result, the carbon benefits of recycling concrete are often small and are sensitive to the distance to the site of use and, to lesser extent, the extent of processing needed (Marinković et al., 2010; Scrivener et al., 2018).

While C&D waste has been recycled for many years and has been a focus of government policy around the world as well,[40] legislation targeting C&D management has grown significantly since the enactment of the Waste Framework Directive (WFD) 2008/98/EC in the European Union (Deloitte, 2017). Member states have enacted laws incorporating the 70 per cent C&D recovery targets in the WFD and several countries, such as Germany, the United Kingdom and Belgium, have set the targets even higher. It is important to note that these are "recovery"[41] targets that include recycling, reuse, incineration and backfilling[42] of C&D waste. There are also diverging views on whether all backfilling operations constitute 'genuine' recovery or whether it may rather be necessary to narrow the scope of backfilling to ensure that it contributes to resource efficiency and does not pose a threat to the environment (Vidal-Legaz et al., 2018).

40 A detailed listing of C&D policies can be found in Supplementary Material B.

41 The term recovery has varied meanings across countries and industries. In the United States, it can refer to collection of recyclable waste for materials recycling (see, for instance, US EPA, 2015) or the collection and use of discarded materials for subsequent processing and use more generally (as in the US Resource Conservation and Recovery Act) or waste-to-energy incineration (labelled as "resource recovery" by the industry). In the European Union, recovery is a term that encompasses not only materials recycling, but also other operations through which waste may serve a useful purpose including re-use and incineration with energy recovery.

42 Backfilling is a recovery operation where non-hazardous waste is used for reclamation in excavated areas or for engineering purposes in landscaping. In the EU, waste used for backfilling must replace non-waste materials, be appropriate for the relevant purposes and be restricted to the quantity strictly necessary to achieve those purposes (Teekens, 2019).

Material-specific recycling targets have been set in some states such as Massachusetts, for example, which has a 50 per cent C&D recycling goal by 2020 (Massachusetts Department of Environmental Protection, 2013). Less common are C&D waste prevention targets, such as the Swedish Waste Prevention Plan, which aims to reduce waste generation per metre square built "significantly" by 2020 as compared to 2014 (Deloitte, 2017).

Encouraging or requiring the use of building information modelling (BIM) is a potential method for governments to facilitate reduction of construction and renovation waste in the design, planning and procurement phases. It is also being explored as a tool to facilitate deconstruction (Volk et al., 2014). With respect to C&D waste management, the use of BIM holds the possibility of facilitating building design to minimize the generation of scrap through lean production techniques and other forms of enhanced inventory management (Wilson, 2019). BIM can reduce waste through improved building design, construction management, material ordering and prefabrication.

High recovery rates in the Netherlands, Denmark and Germany following the institution of landfill bans on recyclable material and high landfill taxes suggest these are effective measures when implemented together (Boardman, 2004; Odeleye and Menzies, 2010). Landfill bans without landfill taxes have also resulted in increased C&D waste diversion rates as well, though it is difficult to isolate the impact of bans because they are often coupled with other policies (Canadian Council of Ministers of the Environment (CCME), 2019; Eunomia Research & Consulting, 2012; Vermont Agency of Natural Resources, 2017).[43] Other regulatory policies that enforce recycling of C&D waste have been shown to be effective. This includes the Japanese Construction Material Recycling Law mandating certain projects to sort and recycle all asphalt concrete, concrete and wood. Eight years after enacting this law, Japan achieved recycling rates of 99.5 per cent for asphalt concrete, 99.3 per cent for concrete and 99.4 per cent for wood, which was largely due to the usage of the recycled concrete as aggregate for road-building (Ministry of the Environment, Government of Japan, 2010).

A less commonly used but effective incentive mechanism is deposit-refund permitting. An example of this is Vancouver's Green Demolition Bylaw, which requires a significant demolition deposit at the permit stage that is refunded following completion of demolition. The refund amount is based on documentation of the recycling/reuse rate achieved (Badelt, 2018). After the Bylaw was approved, the average recycling/ reuse rate for qualifying houses[44] increased to 86 per cent, which is 36 per cent higher than the typical rate for home demolitions. The City of Vancouver estimates that there was a 98 per cent rate of compliance with the bylaw, which resulted in the diversion of 40,000 tonnes from landfills over four years (Badelt, 2018).

C&D waste recycling rates are not only influenced by the recyclability of materials, but also by the extent of material sorting. Separating materials prevents contamination of recycling streams, which can compromise recyclability or the quality of recycled content products. Policies that require source separation include Norway's Planning and Building Act. As part of the requirements for waste management plans, in construction, renovation or demolition projects above a specified size, a minimum of 60 per cent of the waste weight generated must be separated by type and delivered to an approved waste collection facility or a resource recovery facility (Bohne and Wærner, 2014; Hobbs, 2011; Norwegian Building Authority, 2017). Other policy mechanisms used to facilitate sorting include lower tipping fees for pre-sorted materials or investments in infrastructure improvements (such as direct ownership of or subsidies for C&D waste processing facilities).

In addition to direct regulatory policies, both national and local governments have adopted soft policy instruments to encourage improved C&D waste prevention and management. Examples of this include initiatives in Vienna, Austria, and

43 A 2009 case study on the landfill bans in the State of Massachusetts provides details on the operation, strengths and weaknesses of this policy instrument (Green Alliance, 2009). For current landfill ban requirements, see Section 19.017 of the Massachusetts Department of Environmental Protection's Solid Waste Management Facility Regulations at 310 CMR 19.000.

44 As of October 2019, the requirements applied to houses built before 1950 (City of Vancouver, 2019).

Brussels, Belgium. The Waste Reduction in Vienna programme provides guidelines for sustainable management of C&D waste, while Brussels has designated C&D waste a priority waste stream with an emphasis on prevention by providing tools, guidance and training (Deloitte, 2017). Policies focusing on the reuse aspect of C&D waste management and deconstruction are discussed in the renovation and refurbishment section (section 3.3.1.).

3.4. Passenger vehicles

Some possibilities for improvements in material efficiency of passenger vehicles are analogous to those in building and construction, while others are more specific to automobile production, use and disposal. As with buildings, strategies can address materials, parts and the product as a whole (in other words, entire vehicles). Policies related to material efficiency strategies for passenger vehicles are grouped into the following four broad categories:

- Material choice and light-weighting
- More intensive use and the sharing economy
- Product life extension: repair
- Increased recycling and sorting for waste management

A summary of potential policy instruments for encouraging material efficiency in passenger vehicles can be found in table 2 of the Executive Summary.

3.4.1. Material choice and light-weighting

Automobile manufacturers have developed technologies to reduce vehicle weight by replacing some iron and steel with wrought aluminium, carbon fibre reinforced plastic, high performance alloys or magnesium. Although such material substitution can lead to higher GHG emissions in vehicle production (Oliveux et al., 2015), most studies have found that the increase is outweighed by the improvement in fuel economy due to vehicle light-weighting (Cheah et al., 2010; Kelly et al., 2015; Kim and Wallington, 2013; Modaresi et al., 2014; Serrenho et al., 2017). Replacing automotive steel with wrought and cast Al was modelled in chapter 2 (section 2.4.3) and the results are in line with this conclusion. However, the recycling of composite materials is still hampered by various technological and economic barriers, and can generate significant environmental impacts of its own (Oliveux et al., 2015).

While no policies or regulations were found to explicitly mandate the reduction of material consumption in automobile manufacturing,[45] compliance with fuel economy standards has nonetheless led to vehicle light-weighting, especially in passenger cars (compared to how vehicles would otherwise be designed to maximize speed or safety performance).[46] Light-weighting (in other words, mass reduction) of vehicles through material substitution has been one of the major approaches for automobile companies to meet the increases in fuel economy standards in the United States (National Research Council, 2002). Other common approaches to meet fuel economy standards such as the use of different fuels, engine technology improvement, hybridization/electrification and transmission improvement have indirect and more complex impacts on material efficiency. While light-weighted design may entail a higher cost of production, most automobile manufacturers are still deploying this method in combination with aerodynamic improvements and low-rolling-resistance tyres to improve fuel efficiency (Lipman, 2017).

United States data show a drastic reduction in vehicle weight in correlation to an increase in fuel economy standards, such as the United States Corporate Average Fuel Economy (CAFE) Standards,[47] in the late 1970s (Klier and Linn, 2011). Thereafter, vehicle weight in the country has gradually increased while complying with the relatively stable fuel economy standards. This is because there is often a trade-off between vehicle light-weighting and the performance and comfort of vehicles. An and DeCicco (2007) and Knittel (2011) suggest that almost all the improvements

45 Norway had a policy that implicitly encouraged smaller vehicles until 2007: a vehicle registration tax based on weight, engine power and engine size. However, the basis of registration tax was changed to CO_2 intensity in 2007. Research suggests that the CO_2-based tax indirectly continued to encourage smaller vehicles (Yan and Eskeland, 2018).
46 EU regulations on emission performance standards for light-duty vehicles: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32007R0715&from=en.
47 https://www.transportation.gov/mission/sustainability/corporate-average-fuel-economy-cafe-standards.

in vehicle technology since the 1990s aimed to "increase power and weight without sacrificing fuel economy".

In order to comply with the aggressive fuel economy targets, further light-weighting will be needed for new vehicle models (Cheah and Heywood, 2011). The movement towards zero emissions vehicle policies in jurisdictions such as California and China has an uncertain impact on how vehicle attributes such as weight and size will evolve on a corporate average (fleet) level. Here again, the material efficiency implications are indirect and complex.

The trade-offs within and between material and energy efficiency are multiple. For instance, more GHG emissions in production (for aluminium) can reduce vehicle weight and fuel consumption/GHG emissions in use. Heavier materials in vehicles (diesel engines) may allow technologies with lower GHG emissions in use. Lighter, advanced materials in cars may lower fuel use, but present challenges for end-of-life management (carbon fibre). The trade-offs highlight the critical importance of life-cycle approaches to material-efficiency policies. The modelling of material efficiency in the form of light-weighting through material substitution in the RECC study (section 2.5.4) suggests that downsizing vehicles is a particularly important strategy for the reduction of GHGs.

3.4.2. More intensive use

Finding policy pathways through which existing products be can more creatively utilized for multiple purposes and passengers can provide win-win outcomes of material efficiency and climate change mitigation (Shaheen and Cohen, 2019). This is particularly relevant in the transport sector, where the average passenger vehicle is parked over 90 per cent of the time, and most rides are single-passenger trips (Material Economics, 2018; United States Department of Transportation, 2018). More intensive use of vehicles could have implications for both material use and energy consumption. Most notably with higher utilization, the same amount of mobility needs could be fulfilled by a smaller number of vehicles. Because the production and end-of-life management of each vehicle requires a 'fixed' investment of materials and energy, increasing use intensity of vehicles would mean gaining more use out of that same stock of materials (Makov and Font Vivanco, 2018). In material efficiency terms, more intensive use could lower material intensity per passenger kilometre traveled. However, the ultimate effectiveness of such policies is dependent on how more intensive use will impact demand for new cars and transportation services as a whole.

3.4.2.1. Shared mobility

Shared mobility in the form of car-pooling (when a driver and passengers share a single vehicle for a trip) is a well-known practice, long encouraged by governments, local authorities and business. In today's context, more intensive use of vehicles is increasingly realized through what is often called the "sharing economy" or shared mobility systems (Chan and Shaheen, 2012). Broadly speaking, shared mobility allows consumers access and use of a private vehicle without the burden of ownership.

Prominent examples for shared mobility models include:

1. Ride-hailing platforms[48] such as Uber and Lyft, which use digital platforms to connect drivers utilizing their personal vehicles as de facto taxis with passengers. New platforms also provide non-commercial ride-sharing and car-pooling opportunities, such as TwoGo by SAP in Germany or GoMore in France, Spain, Denmark, Norway, Sweden, Finland and Iceland.
2. Centralized and free-floating car–sharing platforms such as Zipcar and Car2Go, which own and manage vehicle fleets that are rented by the hour to their members.
3. Peer-to-peer (P2P) car-sharing platforms such as Turo (formerly Relayrides) and GoMore, which facilitate direct peer-to-peer car rental (where one user rents a vehicle privately owned and maintained by another).
4. Ride-sharing, familiar as car- or van-pooling,[49] has evolved to use app-based platforms, such

48 Also known as ride-hailing or transportation network companies (TNCs) – a legal term initially used by the California Public Utilities Commission.
49 What is called car-pooling in North America and Australia (and this report) is termed car share in the UK. What is labelled as car-sharing in this report is called car clubs in the UK.

as Waze and Scoop, to match drivers and passengers with similar origin-destination pairings.

The success of ride-hailing, car-sharing and ride-sharing platforms demonstrates that shared mobility, in its various forms, holds considerable appeal for consumers. However, it is important to note that ride-hailing and ride-sharing on the one hand, and car-sharing on the other, represent two fundamentally different business models, diverging in vehicle ownership structure (individual versus primarily centralized), as well as the type of service provided (a ride versus access to a vehicle). Due to these differences, the nature and opportunities each model offers for material efficiency, as well as the relevant policy interventions, may vary from one model to the other (Cooper et al., 2015). Policy aiming to enhance material efficiency by encouraging shared mobility should consider the structural differences between shared mobility models and the potential implications for new car sales and overall demand for transport.

3.4.2.1.1. Impacts of car-sharing on vehicle ownership

Shared mobility severs the link between vehicle ownership and vehicle access and use. Reducing private (households') vehicle ownership is often cited as one of the major pathways through which shared mobility could improve material efficiency. Studies show that some consumers are indeed willing to forgo private vehicle ownership once their mobility needs can be met via shared transport (Becker et al., 2018; Klincevicius et al., 2014; Martin and Shaheen, 2016). In particular, car-sharing seems to reduce ownership of special-use vehicles, such as 7-seat and bigger passenger vehicles, all-wheel drive, long-range vehicles or vehicles with a large trunk (Sprei and Ginnebaugh, 2018). Critically, however, in a sharing economy context, where vehicles are also owned and maintained by shared mobility platforms, household vehicle ownership rates do not necessarily reflect overall demand for new passenger vehicles. While relieving consumers of the burden of car ownership might hold economic and societal benefits, from a material efficiency perspective what matters is whether shared mobility reduces overall demand for new cars, leading to a drop in overall car production. Therefore, to better understand the impacts shared mobility can have on material efficiency, it is important to examine new car sales rather than household car ownership rates.

3.4.2.1.2. Impacts of shared mobility on vehicle sales

Several factors affect demand for and sales of new vehicles, including the distance travelled by each vehicle over its full lifespan (km per vehicle) and overall demand for passenger vehicle transport (kilometres per year) (Keith et al., 2019). Therefore, to examine the potential material efficiency implications of shared mobility, it is important to consider system-wide effects on these two factors.

In those markets where vehicle lifespan is more a factor of use (distance traveled) than age, the more intensively a vehicle is used, the faster it wears out and the sooner it needs to be replaced. Higher utilization and faster replacement rates could potentially offset the material efficiency benefits delivered from smaller vehicle fleets (Enkvist and Klevnas, 2018). Therefore, the material efficiency benefits of reduced vehicle fleets should be assessed over time by examining not only the number of vehicle in service (stocks of vehicles in the economy), but also changes in stocks (in other words, the turnover of vehicles).

Shared mobility also affects demand for transport. Car-sharing and ride-hailing increase the marginal costs of a trip substantially but remove the fixed costs of ownership. For individuals who would otherwise own a car and who have public transport alternatives, the higher marginal costs are likely to reduce car use, while for individuals who could not afford their own car, the availability of a shared vehicle makes occasional car driving affordable (Vanderschuren and Baufeldt, 2018).

The immense popularity of shared mobility platforms can be seen as an indication of unmet consumer demand. Some initial evidence suggests that ride-hailing may lead to an increase in overall vehicle kilometres travelled (VKT) and associated greenhouse gas emissions (San Francisco Transportation Authority, 2018; Schaller, 2018, 2017; Yin et al., 2018). The possible increase in VKT and emissions is due, in part, to the approximately

20 per cent to 40 per cent of total distance spent deadheading (driving without a passenger or heading to pick up a passenger) that is inherent in the ride-hailing service model (Cramer and Krueger, 2016; San Francisco Transportation Authority, 2018).[50] While such deadheading is less likely in car-sharing, since consumers typically access vehicles parked in their neighbourhood, it is possible that some consumers use car-sharing as an affordable way to gain access to a vehicle they could otherwise not afford. While such an increase in overall mobility could have important societal benefits, it could also displace more material efficient forms of transport. A recent report suggests that ridership in bus and light rail transport declined by 6 per cent and 3 per cent respectively following the entrance of ride-hailing apps (such as Uber and Lyft) in major cities in the United States (Clewlow and Mishra, 2017). Research on ride-sharing has focused on motivation and behaviour of users (Shaheen and Cohen, 2019); studies of car ownership were not found.

In sum, while shared mobility is expected to reduce fleet size, how faster replacement rates and changes in demand for overall transport services will come into play is not well understood. As a result, despite great interest in shared mobility, it remains unclear whether sharing indeed leads to an overall reduction in vehicle sales. While some predict a steep decline in car sales (Parkin et al., 2017), others report no change (Bert et al., 2016) or even an overall increase in demand for new passenger vehicles (Keith et al., 2019; Parkin et al., 2017) peer-to-peer car-sharing, and\nautonomous taxis.

Nonetheless, shared mobility could have material efficiency benefits even if sales of new cars do not decline. If closed-loop recycling can be achieved, a smaller stock of materials would be needed to provide a given service level. In addition, more intense utilization and faster replacement cycles could increase fuel efficiency by affecting vehicle fleet composition — the types and sizes of the cars used. For example, since the fuel cost in both ride-hailing and car-sharing is often borne by the mobility provider (the Uber or Zipcar driver) and not the consumer, shared mobility models potentially incentivize the use of more fuel efficient vehicles (Bellos et al., 2017). In addition, faster replacement cycles allow updating of the vehicle fleet and take advantage of more efficient technologies incorporated into newer models (Allwood et al., 2012). Beyond fuel efficiency improvements, greater utilization could shorten the payback period for investment in electric and autonomous vehicles and potentially encourage faster adoption (Material Economics, 2018). Shared mobility could also allow consumers to optimize car size for each trip, reducing the amount of travel in larger, less material-efficient vehicles. Finally, shared mobility could lower demand for parking space with the associated reduction in materials consumed for that purpose and reduce travel (Chen and Kockelman, 2016).

More intensive use through car-and ride-sharing is modelled in this study (section 2.4.4). Assuming that up to 25 per cent of rides are shared and 25 per cent of vehicles are car-shared, reductions in cumulative life-cycle emissions of vehicles in the SSP1 scenario would be 8 $GtCO_2e$ (17 per cent) in 2016-2060.

3.4.2.1.3. Policies toward shared mobility

Ride-sharing, long viewed as a strategy to reduce congestion, emissions and fossil fuel dependency through reduction of vehicle kilometres travelled, is often encouraged through infrastructure support and access to public rights-of-way, such as park-and-ride facilities, high occupancy vehicle (HOV) lanes and loading zones (Chan and Shaheen, 2012; Shaheen and Cohen, 2019).

In the San Francisco Bay area of California, HOV lanes and pricing of bridge tolls with discounts for ridesharing during commuting times, have led to an informal, hybrid of carpooling and hitchhiking called "casual carpooling" and "slugging" in other communities. In this practice, which emerged in the 1970s (Shaheen et al., 2016), a driver picks up passengers at known locations such as businesses or commuter parking lots. By having more passengers in the car, the driver is entitled to a discount on the

50 However, no study of ride-hailing has yet to directly compare the reduction of VKT arising from sales of existing vehicles owned by households and postponed vehicle purchasing to the VKT produced by ride-hailing services. Thus there is no conclusive evidence on whether ride-hailing generally increases or decreases VKT and greenhouse gas emissions at present.

bridge toll. The primary policy intervention is the creation of the HOV lanes and pricing through the Bay Area Toll Authority, though the transportation planning, financing and coordinating agency for the nine-county San Francisco Bay area, Metropolitan Transport Commission, provides signage for pick-up and drop-off sites (Jones, 2015). While one study estimated that slugging in San Francisco is conserving approximately 1.7 to 3.5 million litres of gasoline per year — primarily due to the reduction of congestion (Minett and Pearce, 2011) — no research was found addressing the impact on car ownership.

Currently, public policies targeting ride-hailing companies focus on regulating the behaviours of drivers and companies through fees, licences and authorizations, insurance coverage and financial responsibility, driver and vehicle requirements, operational requirements, passenger protections and sometimes data reporting (Goodin and Moran, 2016). Most of these regulations aim to ensure the orderly operation of ride-hailing and do not explicitly address the material efficiency-related impacts. Other policies that are not directly related to material efficiency include zero-emission vehicle requirements, transit discounts and participant subsidies. Restrictive policy, however, is emerging in some communities as with the recent cap on new ride-hailing company licenses in New York City (Marshal, 2019). Such policies may indirectly stimulate increased capacity utilization with implications for material efficiency (Kim et al., 2018; Schaller, 2018).

Some United States cities are beginning to explore pricing policies of ride-hailing services in order to achieve stated policy goals, such as reduced congestion or increased revenues. The city of Chicago uses a portion of its per-trip ride-hailing tax to fund specific public transit improvement projects (Greenfield, 2018). New York City gives pooled rides (such as uberPOOL or Lyft Shared rides) a US $0.75 discount per passenger on its per-trip fee ($2.75) for ride-hailing trips that enter or occur mostly in Manhattan (Hu, 2019). Policy mechanisms that account for ride-hailing's negative effects on downtown traffic congestion and that incentivize higher-occupancy shared rides by funding public transit or incentivizing pooling could advance material efficiency. These changes could contribute to reduced vehicle ownership and thus material efficiency.

For ride-hailing services employing current automotive technology, potential emissions reduction from lowered fuel use — and by implication distance traveled or use of more fuel-efficient vehicles — is probably more significant than avoided car production (Rademaekers et al., 2018). Current resource and environmental policy discussions about shared mobility therefore focus on filling transport gaps and increasing public transit ridership. Reduction of vehicle ownership and vehicle utilization rates is less frequently the focus of policy. Seya et al. (2016) investigate the sensitivity of car ownership to the cost of parking in Japan, finding that price increases can encourage a reduction in ownership, but observe no indication that it is used to as a policy instrument for that purpose.

Timely data collection and analysis are crucial to understanding the material efficiency implication of a particular shared mobility programme. Critically, the degree to which shared mobility affects material efficiency can vary substantially among specific shared mobility programmes. For example, later adopters of car-sharing may not have the same levels of changes in vehicle ownership and VKT compared to early adopters (Namazu, MacKenzie, Zerriffi and Dowlatabadi, 2018). Therefore, policymakers should be cautious with applying a universal emission factor across the board when evaluating the environmental benefits of a car-sharing programme (Martin and Shaheen, 2011). Instead, evaluations should be based on timely and location-specific data collection and analysis.

Data availability is a challenge in the development of policy aimed at achieving shared mobility. Companies active in the shared mobility market are notably resistant to sharing data, thereby making informed policymaking difficult (Cooper et al., 2015). In some cases, ride-hailing companies have threatened to end services in a market because of city regulations including the provision of data while in others, such as Portland, Oregon, in the USA, ride-hailing companies provided data in return for reduced regulation.

Policies toward car-sharing frequently focus on parking and zoning issues. In some communities, such policies are intended to spur adoption of car-sharing; in others, the goal is to manage emerging demand for the use of parking spaces by car-sharing services (Cohen and Shaheen, 2016). Bischoff and Nagel (2017) argue that designated on-street parking spaces for free-floating car-sharing programmes, such as the shared vehicle permit programme in San Francisco, California, and Vancouver, Canada, can effectively promote the use of these services and induce a reduction in private car ownership.[51] Reducing the number of parking spaces required for new real estate development also enables more developers to include car-sharing programmes on-site (Shaheen, Cohen, and Roberts, 2006).

In 2013, Portland, Oregon, created an auction process for car-sharing parking. Car-sharing operators can bid annually for exclusive use of on-street metered parking spaces from a list compiled by the city's Bureau of Transportation. The city establishes a minimum bid for each parking space based on the forgone meter revenue, plus the installation, maintenance and city administrative costs. The city also includes a "utilization clause" in the management of the leased parking spaces: the spaces are considered underused if they generate under 60 trips per month for at least three months. The Portland Traffic Engineer can claim the underutilized space and convert it to another use (Cohen and Shaheen, 2016; Portland Bureau of Transportation, 2014).

Some governments are experimenting with the use of car-sharing in lieu of government-owned fleets. In the United States, the federal General Services Administration (Rein, 2014; U.S. General Services Administration, 2019) and the State of Massachusetts (National Council of State Governments, 2020) have established such car-sharing programmes using commercial car-sharing services.

No studies of policy effectiveness were found that were related to material efficiency of shared mobility.

3.4.3. Repair, part reuse and remanufacturing

Repair of vehicles can extend the lifespan of vehicles with the associated delay in material production arising from their manufacture. The resulting material efficiency would be measured in terms of the mass of materials used to maintain a vehicle over a given period of time relative to the delay in the use of a quantity of materials used in production of a new car. It could also be measured in terms of vehicle lifetimes, but this would not capture the resources used in the repair process. As with all product lifespan extension, there is a trade-off between material efficiency and energy efficiency in operation. No studies of the relationship of repair to material efficiency were identified.

Secondhand parts can be used in vehicle repair, as indicated by the extensive market in salvaged automobile parts. According to Sato et al. (2019), for example, the Japanese government estimates that 20 to 30 per cent of the weight of each scrapped vehicle in Japan is reused as spare parts. Reuse of parts depends on the degree to which vehicles are utilized fully or retired early. The resource and emissions reduction benefits of reusing automobile parts depend on the type and composition of the part. Sato et al, (2018) estimate that reuse of automobile parts saves 35.3 gigajoules (GJ) and 1,887 kg CO_2 per vehicle.

Repairing different parts of a vehicle, however, can yield varying levels of improvement in fuel economy. For instance, fixing out-of-tune engines improves fuel economy by, an average of 4 per cent, while a 10 per cent decrease in a tyre's nominal rolling resistance improves it by 1 to 2 per cent (National Research Council and Transportation Research Board, 2006; United States Environmental Protection Agency, 2011).

51 For examples of shared vehicle permit programmes, see San Francisco, California, United States (https://www.shareable.net/san-francisco-prioritizes-parking-for-car-sharing/) and Vancouver, British Columbia, Canada (https://globalnews.ca/news/5460469/vancouver-car-share-parking/).

Remanufacture of automotive components is a well-established activity[52] that has been carried out for decades (Nasr et al., 2018; Smith and Keoleian, 2004). It is estimated that, for example, the market for remanufactured vehicle's parts in the European Union is about 10 per cent of the total economic volume of the aftermarket sector (Parker et al., 2015).

Remanufacture and other value-retaining processes (VRPs), however, face challenges of inconsistent definitions and standards across industries and countries (Nasr et al., 2018; Parker et al., 2015). Differing definitions of what is deemed to be a waste for regulatory purposes under the Basel Convention, the EU Waste Framework Directive and the US Federal Trade Commission can inhibit trade and industry growth.[53]

Policies on repair often focus on consumer rights and protection, rather than environmental or material impacts. Policies dictating periodic inspection and repair exist in some countries and may lead to longer lifespans for cars.[54] Policies guaranteeing the right to repair and laws to improve the quality of repair services can help encourage more repairable products and access to quality repair services for consumers. In 2010, the European Commission removed the competition rule exemption for automobile manufacturers and their authorized repair shops, making it difficult for the manufacturer to keep repair information and spare parts away from independent repair shops.[55] In the latter part of 2019, the 28 European Union member countries voted on a set of eco-design regulations. One of the outcomes is a requirement that washing machine and dishwasher manufacturers, but not auto manufacturers, provide access to repair information and spare parts for seven years.

In the United States, the Federal Vehicle Repair Cost Savings Act of 2015[56] encourages federal agencies to use remanufactured automobile parts to maintain federally-owned vehicles if doing so would reduce costs without delaying the return of vehicles to service or reducing the quality of vehicle performance. In the United States, right-to-repair laws have been proposed that require automobile manufacturers to provide independent repair shops with the same information, tools and parts as are available to automobile dealerships.[57] As of 2019, such legislation has been introduced in 19 states. Such policies raise issues as to whether providing more access to repair information and components infringes on the manufacturers' or designers' intellectual property. Because of trends such as driver assistance, vehicle dynamics, electrification, connectivity and autonomous driving, future vehicle designs are expected to deploy an increasing amount of electronic parts (Schmidt et al., 2016), thereby involving more software. Emerging policies regarding electronics right-to-repair may also affect the ease of automotive repair.

3.4.4. More recycling

Recycling is perhaps the most direct manifestation of efforts to transition to a circular economy. Material recycling from end-of-life vehicles (ELVs) is no exception.

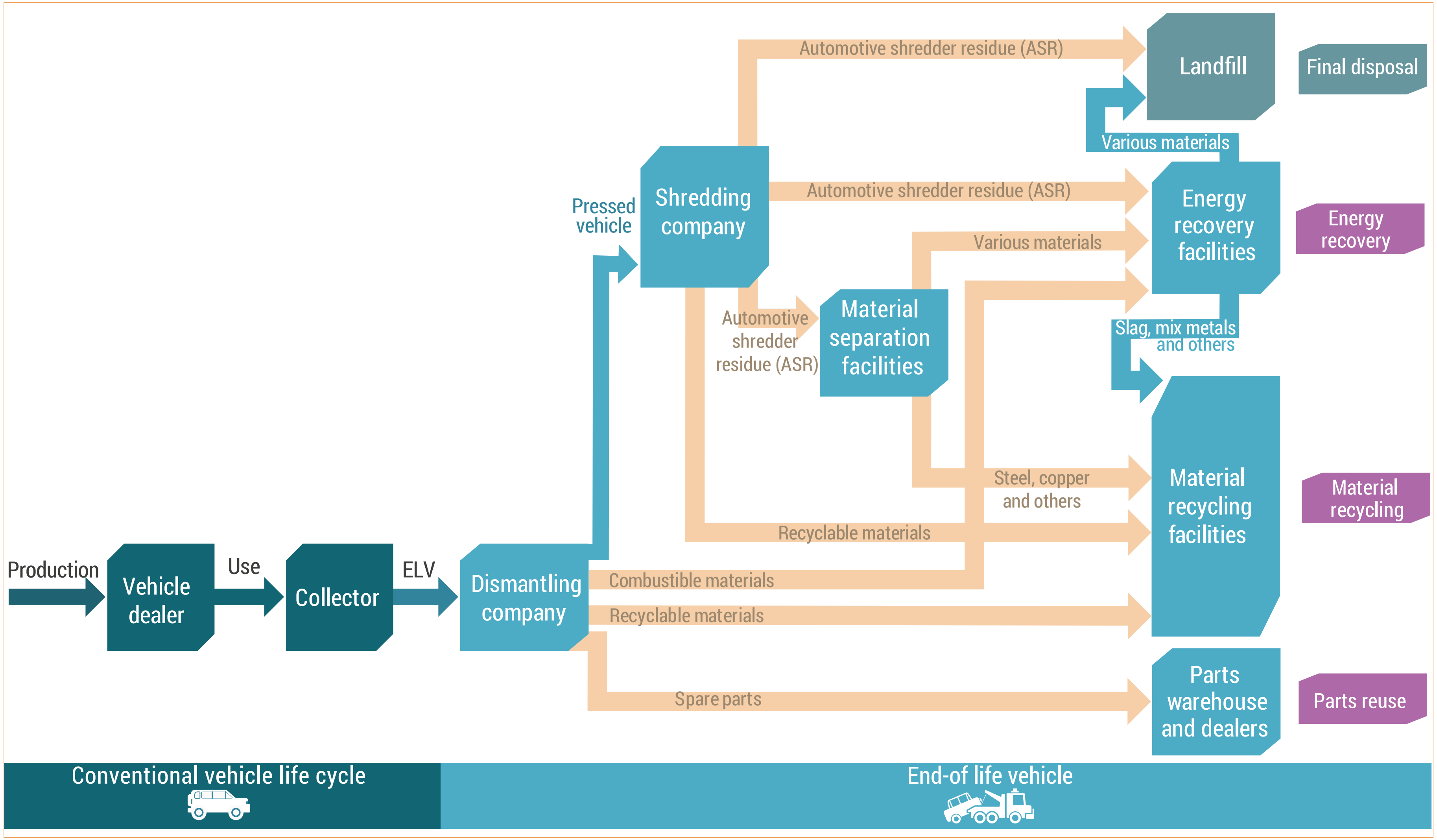
3.4.4.1. End-of-life vehicle management and material efficiency

End-of-life vehicles (ELV) are defined as vehicles taken out of use because they have reached the end of their lifespan, or when they are critically damaged in accidents (Wordsworth, 2011). The exact standard for ELV retirement varies by jurisdiction (Sawyer-Beaulieu and Tam, 2006).

End-of-life management of an ELV typically begins with the dismantling of valuable or hazardous

52 Remanufacturing in the automotive industry is primarily geared to trucks and heavy-duty off-road (HDOR) vehicles, as is the retreading of tyres. Salvage of parts from junked vehicles for spare parts typically involves a less intensive form of refurbishment.
53 The EU Waste Directive includes End-of-Waste (EOW) criteria that refer to the conditions under which certain specified wastes cease to be designated and thus regulated as waste under the Directive; The Basel convention defines waste as substances or objects that are disposed of or are intended to be disposed of or are required to be disposed of by the provisions of national law. The US Federal Trade Commission has issued the Green Guide that outlines different conditions for biodegradable waste, recyclable material and so forth.
54 Inspections may also result in a vehicle being taken out of service.
55 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02007R0715-20121231&from=EN.
56 https://www.congress.gov/bill/114th-congress/senate-bill/565.
57 https://www.congress.gov/bill/112th-congress/house-bill/1449.

Figure 25. Automobile life cycle with emphasis on end-of-life stages



Source: Based on Sato et al. 2019.

vehicle parts and removal of polluting fluids (see Figure 25). The remainder of the vehicle is shredded in a hammer mill into fist-sized pieces of metal and a residue composed of a mix of rubber, plastics, glass, dirt, carpet fibres and seat foam often called automobile shredder residue (ASR).

Vehicle parts that can be salvaged from ELVs and reused include air conditioning compressors, carburetors, alternators, starters, engines, batteries and tyres. The rest of the ELV is composed of between 75 per cent and 85 per cent recoverable and recyclable metals and 15 per cent to 25 per cent shredder residue (Simic and Dimitrijevic, 2013). Markets for the metals recovered from shredding are well-established, whereas markets for shredder residue or its components are not. The technologies for sorting and recovering resources from the shredder residue have been evolving, but varying amounts of non-recyclable materials are incinerated or landfilled, depending on the technologies and markets available in the area. California enacted a series of regulations regarding pollution from automobile shredders in 2012, which were evaluated for efficacy in 2017. However, the emissions evaluation focused on hazardous emissions such as lead, VOCs and particulates rather than carbon (Edmund G. Brown, Jr. et al., 2018).

Life-cycle assessments of these recycling processes have indicated that recovery of materials and/or energy recovery can lead to a net reduction of emissions,[58] while certain types of recovery from shredder residue can be too labour- or energy-intensive to carry out (Duval and MacLean, 2007; Puri et al., 2009; Simic and Dimitrijevic, 2013). The greatest impact that can be achieved in terms of GHG mitigation in this domain is from reuse of parts and specific forms of closed loop recycling as demonstrated by a recent study in Japan (Sato et al., 2019). The results in the modelling chapter show that reuse of parts in the G7, in conjunction with improving fabrication yield and EoL recovery rates, could lead to a 38 per cent reduction in annual GHG emissions related to the material cycle for vehicle manufacturing by 2050.

3.4.4.2. Recycling systems and policies for ELV management

The European Union, Japan, Korea, China, and Canada (British Columbia) are among the jurisdictions with legislation emphasizing recovery targets for ELVs. In contrast, the United States and other Canadian provinces have relied on the market to realize a similar level of recycling for ELVs with regulations that focus on minimizing environmental impacts of the recycling processes, as shown in the table summarizing ELV policies in the Supplementary Material to this chapter (Staudinger et al., 2001). In the United States, air emissions resulting from treatment of ELVs (such as refrigerants) are regulated under the federal Clean Air Act.[59] Management of fluids from dismantling and recycling are regulated under the stormwater provisions of the federal Clean Water Act.[60] In most cases, regulatory authority has been delegated to state governments and details vary by state. Recycling rates are not regulated by the federal or state governments.

The EU and Korea use extended producer responsibility (EPR) as a core element of ELV policy. Japan also uses a form of EPR in combination with a fee paid by consumers and an emphasis on producer collaboration, as described in the text box below.

Recycling rate goals of 95 per cent for ELVs are not uncommon in legislation. The specific target percentage of materials recovered, recycled and used, however, varies by jurisdiction. The EU also sets minimum recyclability/recoverability targets (measured according to the ISO 22628 standard) for new vehicles to stimulate the recycling via improved design (Smith, 2015). A summary of ELV legislation in select countries and subnational jurisdictions as of 2019 can be found in Supplementary Material B.

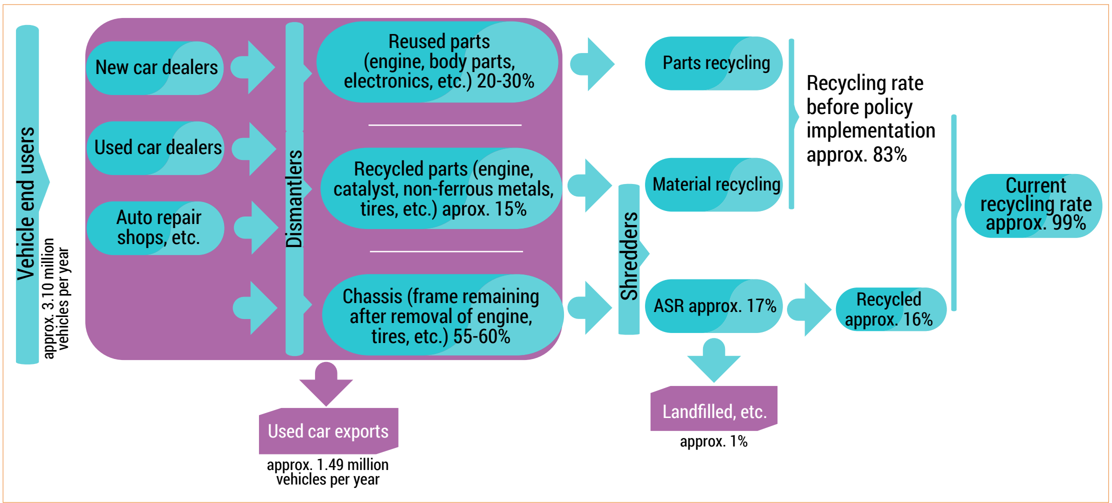
58 The GHG reduction arising from incineration of ASR is sensitive to the energy source it displaces, as shown by Sato et al. (2019).
59 United States Clean Air Act – Sections 608 and 609.
60 United States Clean Water Act – National Pollution Discharge Elimination System (NPDES) – 33 USC Sec. 1251 et seq.

Box 6. Automobile recycling in Japan

Japan is a leader in policy and technological innovations in the global car recycling industry. In Japan, cars have a short lifetime and about half of used vehicles are exported to other countries for reuse. For the half that reaches end-of-life in Japan, the recycling rate is 99 per cent by mass (Ministry of the Environment Japan, 2017). In 2005, the Government of Japan implemented the Automobile Recycling Law, which introduced an ELV recycling fee for consumers and made automobile manufacturers and importers responsible for recovery and disposal of fluorocarbons, airbags and automobile shredder residue (ASR). The law also set recycling rate targets for ASR of at least 30 per cent by 2005, 50 per cent by 2010 and 70 per cent by 2015 (Government of Japan, 2006). At the time, almost all of the ASR produced in Japan annually was landfilled, which significantly contributed to the depletion of landfill space. The recycling fee collected from vehicle owners was used to lower the cost of recycling fluorocarbons, airbags and ASR. However, the recycling costs for ASR remained too high for it to be economically viable.

To overcome this challenge, two competing partnerships (led by Toyota and Nissan) were formed by the 12 Japanese car makers and 8 major car importers to foster competition and drive down recycling costs (Japanese Economy Division, 2006). In addition, effective gasification systems for ASR processing were developed to convert the combustible components of ASR into fuel and the remainder into recyclable slag and metals (Koshiba, 2006). Other measures have been implemented by various producers to improve the cost-effectiveness of recycling, such as designing cars to be easily dismantled (Koshiba, 2006). While most manufacturers including Toyota and Nissan reported operating losses from ASR recycling in fiscal year 2005, recycling became profitable for most by 2015 (Togawa, 2015). In fiscal year 2013, Toyota and Nissan reported a net profit of 540 million yen and 43 million yen, respectively (Togawa, 2015). Also by 2015, 95 per cent by weight of the approximately 600,000 tons of ASR generated annually in Japan was being recycled through direct energy recovery, energy recovery with gasification and material recycling (Ministry of the Environment Japan, 2017). This translated into a 99 per cent overall recycling rate for the approximate 1.6 million vehicles being recycled in Japan per year (see Figure 26).

Figure 26. Flow of end-of-life vehicle management in Japan, 2015. Translated from Ministry of the Environment, Japan, 2017



Source: Based on Sato et al., 2019.

Note: ASR: Automobile shredder residual.

End-of-life vehicle regulations that include recycling targets are usually measured in terms of mass. The resulting incentives typically allow or encourage a focus on the challenge of processing and finding uses for the non-metallic component of ELVs(such as ASR). This has both positive and negative implications for GHG emissions reduction. Estimates of how improving ASR recovery can potentially impact global warming impact of range from an increase of 0.2 kg CO_2-eq per kg ASR recovered through energy recovery alone, to a reduction of 1.0 kg CO_2-eq per kg ASR recovered through a combination of material recycling and energy recovery (Vermeulen et al., 2012).

The emphasis on the residues from shredding is not usually accompanied by a focus on the material and greenhouse gas impacts of current steel recycling practices in the context of ELVs. Copper and steel are mixed during shredding, thereby limiting the closed-loop recycling of steel. Ohno et al. (2015) estimate that only about 7 per cent of the steel recovered from auto recycling goes back into car production. Instead, steel containing copper contaminants is primarily used to make steel rebar for construction – a lower value use that requires the addition of primary steel to dilute the amount of copper to acceptable levels. This has no impact on the ELV recycling rate, but prevents the highest and best use of the recovered steel. If markets for steel containing copper contaminants become saturated, then the recycling of steel from ELVs will be diminished, thereby lowering ELV recycling rates and, perhaps more importantly, reducing the GHG benefits of ELV recycling (Daehn et al., 2017).

3.4.4.3. The European Union's approach to evaluating ELV policy: Considering trade-offs

The European Union has conducted two evaluations of its ELV policies relevant to this chapter: one ex-ante study in 2007 projecting likely impacts and a second in 2014 assessing outcomes up to that point. Both evaluations were part of a larger assessment of several EU Directives on waste with a focus on packaging waste and waste electrical and electronic equipment (WEEE).

The ex-ante study examined various recycling and recovery targets from 2015, as provided for in the European ELV Directive.[61] According to the study, setting recycling/recovery targets would affect not only the size and composition of fractions of ELV residual waste, but also the development of the technology to treat it. This is particularly the case of plastics (representing about 7 per cent by weight of ELVs).

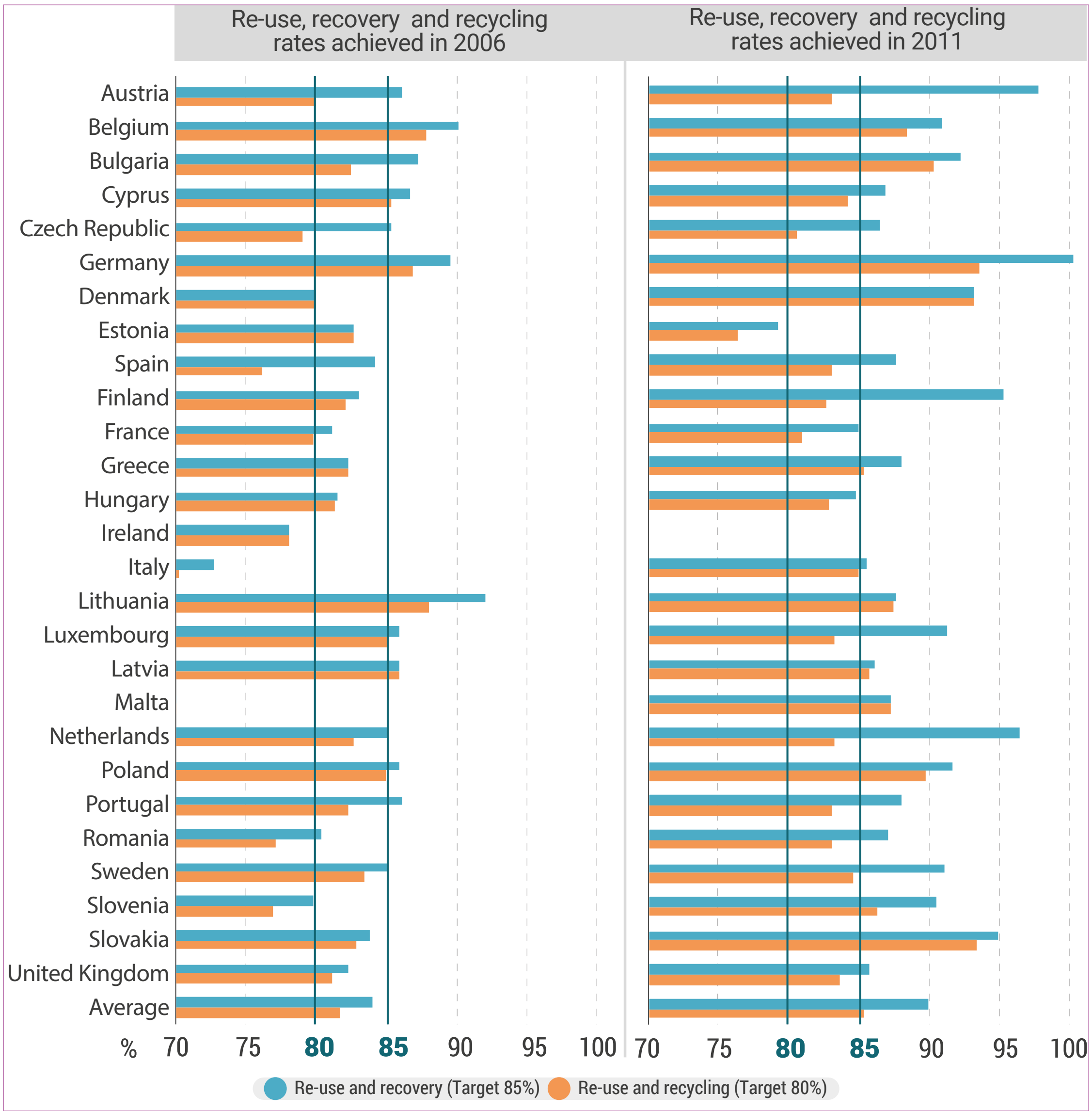
The study estimated that increasing the recycling and recovery targets (to 85 per cent and 95 per cent, respectively) would save approximately 10 million tonnes of CO_2 equivalent over 10 years and substantial other environmental benefits (compared with the manufacturing of virgin plastic) (European Commission, 2007).[62]

In contrast, increasing only the recovery targets would significantly slow down development of new recycling technologies for plastics, removing incentives for technological development, while promoting only their energy recovery. In this case, a key finding of the study was that such a strategy could cause "for example, 500,000 tonnes of additional CO_2 emissions … [to] be produced per year, or an indicative 5 million tonnes over a 10 year period" (European Commission, 2007). At the same time, the study concluded that higher targets for recycling or recovery could remove flexibility with no corresponding gain to innovation.

In the last decade, European policies on vehicles mainly focused on reduction of GHG emissions during the use phase for new vehicles (see, for instance, Regulation 715/2007, Regulation 443/2009). However, the European Action Plan for Circular Economy refocused attention on the durability of products (European Commission, 2019a). EU Regulation 715/2007, however, recognizes the relevance of repair, and mandates the disclosure of information by manufacturers. A different situation could emerge for future vehicles, with significant potential impacts during manufacturing and use. A preliminary analysis by the European Commission's Joint Research Centre (JRC) on potential reuse of electric vehicle batteries to be repurposed in stationary applications, for instance, suggests that such applications are environmentally beneficial when the repurposed battery replaces newly manufactured energy storage, and mainly when the battery is used to increase the self-consumption of energy produced from renewables (Bobba et al., 2018b, 2018a).[63]

61 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20130611&qid=1405610569066&from=EN.
62 These estimates relate to polyolefins, such as a PP/EPDM bumper, and may not hold for other resins.
63 See also Richa et al. (2017)

Figure 27. End-of-life management of vehicles in EU member states in 2006 and 2011



Source: EU Ex-post assessment across member state implementation of the EU Directive (2000/53/EC) on ELV vehicles (European Commission, 2014).

The 2014 ex-post assessment of various EU directives, including the ELV Directive (2000/53/EC), is qualitative and based on stakeholder interviews. The assessment noted that "stakeholders agreed that the Directive had with no doubt significant environmental benefits in saving resources through reuse, recycling, and recovery, this again corresponding to savings in greenhouse gas emissions. The most obvious success is the reduction of hazardous substances in ELV" (European Commission, 2014). In another qualitative assessment, the following was observed in terms of the efficacy of the EU's directives related to waste streams recovery: "The high targets under the [ELV] Directive (95% reuse and recovery and 85% reuse and recycling) have largely been met and a substantial reduction in the use of hazardous substances in the new cars has been achieved. The Commission undertook an ex-post evaluation of five waste streams to assess if the legislation is "fit for purpose" as part of the 2010 Commission's Work Programme, including the ELV Directive in 2014. [...]. For the ELV Directive, two major challenges have been identified: the illegal ELV treatment operators and the illegal shipment of ELVs" (European Commission, 2018a)

While the 2014 assessment is largely qualitative, it includes a compilation of reuse, recycling and recovery rates across EU member states (see Figure 27). The data indicate substantial improvement with respect to reuse, recycling and recovery targets between 2006 and 2011, but with considerable variation across member states. Correlations between the outcomes and specific policy implementations are not addressed.

3.5. Cross-cutting policy strategies and challenges

In addition to the material efficiency strategies reviewed so far, there are several policy strategies that cut across sectors.[64] A summary of potential policy instruments for encouraging material efficiency across sectors can be found in Table 3 of the Executive Summary.

3.5.1. Green public procurement

Green public procurement (GPP), the integration of environmental criteria[65] into the purchase of goods and services by governments (Evans et al., 2010), is widely used in the G7 and throughout the world (Cheng et al., 2018). The rationale for the use of government purchasing power in the pursuit of environmental goals is straightforward, though the execution of that strategy is often less so. GPP requires identifying the specific goals to be pursued, the environmental criteria to be used, the products and economic sectors targeted, the mechanism for implementing the GPP goals in the purchasing process (such as vendor-selection criteria) and the management and assessment of the GPP process. Evaluating the effectiveness of GPP depends on the objective and structure of each GPP programme. A basic criterion addresses whether the purchase of a targeted product has increased as a result of GPP relative to a business-as-usual baseline (Querol and Schaefer, 2013). A more ambitious, significant and complex evaluation would attempt to quantify the reduction of environmental impacts attributable to specific GPP policies.

Economic analysis (Marron, 2004) suggests that GPP has the most potential when government is the primary source of demand, or in markets with significant private demand, and when GPP focuses on the development and commercialization of green products with latent demand. Conversely, Marron (2004) maintains that it will produce only minor environmental gains when it merely switches government purchases from existing non-green products to existing green products, because government purchasing often makes up less than 5 per cent of many markets. The potential for displacement - where the public sector purchases more expensive green goods to replace the private purchase of those goods - is a particular concern.

In a critical analysis of GPP, Lundberg et al. (2016) emphasize that the effectiveness of a GPP policy instrument should be judged on the basis of cost and the achievement of objectives (such as emission reduction), rather than intermediate measures. They argue that GPP policy should not be evaluated merely in terms of how the public sector allocates its purchases between green and brown products; accounting for market structure and response from the private sector is also necessary (Lundberg et al., 2016).

GPP is used by many levels of government in countries across the world. Almost all OECD countries have GPP policies (OECD, 2019b). In the EU, for example, GPP is a voluntary instrument for promoting a more resource-efficient economy, with procurement guidelines for more than 20 GPP criteria. Criteria in the EU guidelines use two levels of stringency: core criteria that are designed for easy application of GPP, and comprehensive criteria that encompass more ambitious requirements and/or more aspects of environmental performance than are addressed by the core criteria. The priority sectors for implementing GPP were selected through a multi-criteria analysis (European Commission, 2019b). Although most EU members employ voluntary criteria, Austria, the United Kingdom, Italy and the Netherlands have introduced mandatory GPP for their central governments (Hasanbeigi et al., 2019). A summary of EU Directives and policies related to GPP can be found in Supplementary Material B.

Government purchasers at the national and

64 Potential actions to make material efficiency a more significant aspect of European Union energy and climate policies can be found in section 7 of Supplementary Material B.
65 Many argue that green public procurement should be extended to incorporate social and economic considerations, such that GPP becomes sustainable public procurement (SPP) (Uttam et al., 2014). Whether GPP should be broadened in this manner is beyond the scope of this chapter.

subnational level are increasingly using cooperative purchasing agreements or "green group purchasing" to clearly communicate shared specifications for green products and services to the marketplace and collectively negotiate competitive prices for those goods and services. To the extent that these agreements include requirements for material efficiency that deliver GHG emission reductions, they represent an important tool for achieving policy objectives (Pearson, 2019).

3.5.1.1. GPP and material efficiency

GPP can be applied to many of the material efficiency strategies described in this report including, in the construction sector, energy efficiency in renovation, use of certification systems and recycled content (Testa et al., 2016; Uttam et al., 2014). With regard to automobiles and other light-duty vehicles, GPP has a strong focus on tailpipe emissions but also can incorporate requirements related to tyre, lubricant and refrigerant type/management (Adams, 2019; Quintero et al., 2019).

Of particular relevance to material efficiency are calls for the development of circular public procurement (Alhola et al., 2019). While GPP has often incorporated criteria to promote the 3Rs, circular procurement can entail criteria or requirements for durability and product lifespan extension, intensity of use and avoidance of hazardous substances in the cycling of materials. The efficacy of such criteria has yet to be assessed (Alhola et al., 2019). Life-cycle-based GPP can include some circular elements that go beyond simple EoL concerns (such as recyclability and recycled content) to recycling in production or nontoxic cycles, but are less likely to extend to promotion of product-service systems or other new business models (Alhola et al., 2019). Experiences in procurement of product-service systems for transport, however, do exist. For example, the German municipality of Bremen replaced its fleet of vehicles by a local car-sharing service with an online booking system (European Commission, 2017).

Prominent forms of GPP relevant to material efficiency include mandates for the purchase of goods and materials containing recycled content. Japanese public regulatory agencies (whose spending accounts for some 17 per cent of GDP) must purchase recycled goods under the Law of Green Purchasing, including 100 per cent recycled paper (Higashida and Jinji, 2006). The United States Environmental Protection Agency also had comprehensive guidelines on paper for procuring agencies, as well as sets of recycled content recommendations for sectors such as construction, landscaping, and transportation (Iida, 2011), while 12 US states have mandatory recycled content standards for newsprint. Recycled content mandates are also beginning to be incorporated into building and construction projects, again led by public authorities. In the United Kingdom, for instance, WRAP provides a summary of initiatives being undertaken by regional governments in their procurement and construction contracts (Sweett, 2009)

3.5.1.2. Measurement of GPP impacts on material efficiency

There are at least three stages in which GPP outcomes might be evaluated with respect to material efficiency: in the choice of policy and product targets; in the evaluation of competing bids in a tendering process; and in assessment of the impacts of a GPP programme.

Large corporate and governmental organizations increasingly analyse their overall spending portfolio to identify priority categories that merit a unique strategy or approach. For public entities seeking to achieve policy objectives such as GHG emission reductions, economic input-output life-cycle assessment (EIOLCA) methods are sometimes included in these analyses to identify categories generating the highest overall levels of supply chain or life-cycle GHG emissions relative to other categories. Such analyses have been conducted by the United States General Services Administration and the California Department of General Services to guide their prioritization of green public procurement categories (Pearson, 2019).

In the procurement process, green public procurement faces measurement challenges specific to material efficiency. As indicated in Figure 23, there are multiple steps between an ME policy and greenhouse gas reduction. With respect to GPP, policies need to include ME strategies. Many do just that, especially with regard to recycling and recycled content.[66] Those strategies must, in turn, generate material use reductions in practice. Finally, the reductions in material use must lead to GHG emission reductions. The last step warrants particular attention. Material reduction can occur in one stage of the life cycle of a building or vehicle, but not lead to net reductions across the product life cycle. This is a familiar challenge assessed in the modelling described in this report. One example is strategies to reduce GHGs from vehicles, where cars made from aluminium will be lighter than their conventional steel counterparts and have fewer tailpipe emissions, but can have higher GHGs from aluminium production.

With buildings, the primary focus of climate change policy has been on energy efficiency, with modest efforts at material efficiency reductions as described earlier in this report. As a result, there is less attention to measurement on a life-cycle basis, but tools have emerged and efforts are expanding.

Material and GHG measurement must go beyond individual building components. GPP guidelines for office buildings prepared by the European Union reflect the fact that interactions between construction products can cause complex impacts; therefore, the entire life cycle of the whole building has to be assessed to determine the environmental contribution of construction materials and products as well as building elements (Dodd et al., 2016).

Life-cycle measurement of building GHG emissions for GPP purposes typically takes one of two forms: (1) use of environmental product declarations (EPDs) and (2) integration of life-cycle assessment (LCA) into GPP processes. The EU has developed guidelines and rules for how an LCA should be used for GPP for office buildings and roads as part of its EU Green Public Procurement Criteria (Dodd et al., 2016; Garbarino et al., 2016).

EPDs are a type of environmental label that follow ISO standard 14045 of the International Standards Organization. They are a tool used in conjunction with the declaration of data and information regarding the environmental impacts of a product based on LCA methodology (Environdec, 2019).[67] EPDs can be aggregated – if appropriate standards for comparability, transparency and attention to relevant objectives are met – for evaluations of competing buildings designs. Some national certification systems for buildings (such as BREEAM, the German Sustainable Building Certificate (DGNB); and Haute Qualité Environnementale (HQE) in France) use EPDs in varying degrees (Dodd et al., 2016). Such certification programmes can also form the basis of GPP programmes (similarly to how certification programmes can play a role in the evolution of building codes as described in section 3.3.1).

LCA and life-cycle costing (LCC) can form the basis for the development of GPP criteria, as in the European Union. A full life-cycle assessment (LCA) can also form the basis of tendering. The European Union and its Member States, including the Netherlands, have been leaders in this respect.

Credit: Federico Rostagno/iStock/Getty Images Plus

66 GPP may address objectives, such as vehicle fuel economy, that indirectly incentivize material efficiency.

67 EPDs are a voluntary declaration of the life-cycle environmental impact and having an EPD for a product does not imply that the product is environmentally superior to alternative products. To ensure comparability of the LCAs on which EPDs are based, each product category needs rules and requirements, known as product category rules (PCRs), which indicate how EPDs must be developed (Environdec, 2019).

Box 7. Netherlands LCA-based GPP

For material efficiency policies to lead to GHG reductions, a life-cycle framework needs to be employed. The Netherlands has pioneered the use of life-cycle assessment in GPP through the use of two tools for procurement of infrastructure: DuboCalc and the CO2 Performance Ladder. DuboCalc assesses the environmental impacts of the "product" (infrastructure), while the CO2 Performance Ladder assesses the GHG impacts of work processes.

DuboCalc

DuboCalc is a life-cycle-based software tool that quantifies a wide range of environmental impacts of construction materials. Using DuboCalc, all embedded environmental impacts of material use can be estimated for the entire product life cycle, from raw material extraction and production to demolition and recycling. For evaluation of infrastructure, use phase energy consumption can be calculated.

Based on the materials used, DuboCalc calculates a single value for all of the environmental effects called the environmental cost indicator value (ECI value), based on the costs of preventing emissions. Designers can use DuboCalc to calculate ECI values of alternative designs to arrive at a more sustainable design.

The ECI value is used as part of the tendering procedure in procurement. The procuring agency entity provides the supplier with the functional requirements, the latest version of the DuboCalc programme and sets a maximum value permissible value for the EIC. The supplier designs the infrastructure and calculates the price and a monetized ECI value. The procuring agency selects the supplier with the lowest combined cost.

The CO_2 Performance Ladder

The CO_2 Performance Ladder (CO_2PL) is a voluntary certification system developed by ProRail, the Netherlands rail agency, and managed by an independent non-profit party, SKAO. The ladder has five levels ("rungs") and a tenderer indicates which level will be pursued and the measures to be taken to limit CO_2 emissions within the company, in projects and in the supply chain. Certification of a CO_2PL level obligates the tender to meet the relevant target using the methods and working processes it has specified. Higher rungs in the CO_2PL include commitments to reduction in supply chain CO_2 emissions (Scope III), providing an element of life-cycle management, but do not address materials use. The certificate allows the bidder's tendering price to be reduced by a value proportional to the effort made to reduce CO_2 emissions.

These tools provide a useful example of the integration of life-cycle-based measurement for GPP.

Sources: European Commission (2013); OECD (2016).

3.5.1.3. Policy evaluation of GPP

According to a survey of some EU Member States conducted by PriceWaterhouse (Woittiez, 2009), the use of GPP in the construction sector was relatively low in 2009. However, in the last decade the EU promoted the development of several novel criteria, studies and best practices (European Commission, 2016), including the recent GPP criteria for "Office Building Design, Construction and Management" and "Road Design, Construction and Maintenance" (Garbarino et al., 2016). A recent evaluation study by the European Parliament also observed that a substantial number of EU GPP criteria are already linked to circular economy strategies, with indications of a shift from conventional business models of acquiring and owning goods to service-based and more circular approaches (Neubauer et al., 2017)works and supplies cover\nabout 14% of European gross domestic product (GDP

Evaluation of GPP often focuses on the level of uptake of GPP policies by various governments. While inventories of GPP programmes are a crucial step in assessing the impact of GPP, more targeted analysis is needed if, as discussed herein, desired outcomes (such as increased material efficiency and lowered GHG emissions) can be confidently tied to GPP policies.

Studies were not found to document the extent to which large-scale public procurement of green products may mitigate challenges facing GPP through, for example, building markets for new technologies and thereby reducing overall prices for green products in the long term. Environmental assessment of GPP has been limited, and LCA studies have been particularly scarce (Cheng et al., 2018). Systematic ex-post quantitative evaluations of GPP that address material efficiency policies were not found.

3.5.2. Virgin material taxation, royalties and subsidies for materials production

A 'virgin material tax' (VMT), often synonymous with a 'raw materials tax', is a tax on the use of previously unexploited but industrially and commercially important materials including metals, minerals, petrochemicals and timber. A summary of the concepts and underlying rationale in the literature on VMT is provided in the Supplementary Material.

Bahn-Walkowiak and Steger (2015) provide a review of 'resource targets' in international, European and national strategies, programmes and initiatives. They cite several examples of implemented mineral taxes. Table 15 presents their summary of such taxes and levies in the European Economic Area (EEA) as of 2013. Although they find that some have experienced limited success, they also argue that this taxation was almost exclusively introduced without any time frames and quantitative targets, have mostly not been revisited since the 1990s when material efficiency policies were not yet an issue, and largely addressed domestic supply issues rather than attempting to steer behaviour in line with particular environmental goals. They argue that "almost without exception, all countries impose very low taxes with probably little or no incentive effect", and suggest that increased levels of taxation on primary materials used in construction would contribute to resource efficiency.

Several modelling studies (Bigano et al., 2016; Ekvall et al., 2016; Söderholm, 2011) have, in fact, estimated varying degrees of increased material efficiency arising from green tax reforms (including VMT). However, these are usually achieved by assorted 'policy mixes', including complementary and supportive facets such as a materials tax, extended producer responsibility, technical requirements and stringent environmental taxes (see Ekvall et al. (2016)).

Table 15. Taxes and levies on minerals in EEA countries, 2013

Country	Name of tax, charge or duty	Taxable object	Year of introduction	Tax rates[a]
Bulgaria	Mining charge	Sand and gravel	1997	0.03–0.08 €/m³
Croatia	Extraction charge	Sand, gravel, crushed stone, limestone and clay	n/a	0.41 €/m³ (sand) 0.55 €/m³ (gravel)
Cyprus	Quarrying charge	Materials extracted from quarries	Ca. 1998	0.26 €/t
Czech Republic	Payments for mineral extraction	Aggregates	1993	Up to 10 % of the market price for minerals
Denmark	Tax on raw materials	Stone, sand, gravel, peat, clay and limestone	1990	≈0.67 €/m³ (since1990 fixed at 5 DKK/m³)
Estonia	Material extraction charge	Dolomite, granite, gravel, sand, limestone, clay, peat, phosphate rock and oil shale	1991	n/a
France	Tax on extracted minerals (granulates)	Minerals (granulates)	1999/2000	0.09 €/t (natural mineral grains; EC database) 0.20 €/t (extracted minerals; OECD database)
Latvia	Material extraction charges	Gravel, limestone and clay	1991	≈0.11 €/m³ (sand) ≈0.13 €/m³ (dolomite) ≈0.18 €/m³ (limestone) ≈0.21 €/m³ (sand-gravel)
Lithuania	Mineral extraction charge	Minerals	1991	≈0.14 €/m³ (sand) ≈0.17 €/m³ (gravel) ≈0.38 €/m³ (dolomite) ≈0.50 €/m³ (limestone)
Sweden	Natural gravel tax	Gravel, sand, cobble and boulder	1996	1996: ≈0.57 €/t 2006: ≈1.41 €/t
United Kingdom	Aggregates levy	Sand, gravel and crushed rock	2002	2002: ≈2.61 €/t 2010: ≈2.30 €/t

[a] Note: conversion factor of sand; gravel; crushed rock, ≈1.8 t/m³; and limestone, ≈2.8 t/m³
Source: Bahn-Walkowiak and Steger (2015).

VMTs face challenges common to policy instruments targeting economic or environmental performance. If the goal is to have the target and size of VMTs correspond to environmental impacts, detail is needed on a per-material basis that distinguishes between resources obtained through environmentally friendly or unfriendly extraction and production processes. If the VMT is to account for impacts across the entire life cycle, the task is that much more complicated (Bigano et al., 2016). Taxation could also shift production to locations with less stringent environmental regulations.

The practical effectiveness of VMTs within broader material efficiency policymaking is likely to become much clearer in the coming decade, as increasing political and public weight is thrown behind the adoption of such measures. For instance, in 2018, the WWF and Resource Association (Hogg et al., 2018) and the Green Alliance (Peake et al., 2018) presented reports to the United Kingdom government strongly calling for the introduction of a VMT on plastic goods, while a recent UK Treasury consultation on 'Tackling the plastic problem' (HM Treasury, 2018) elicited a strong industry and civil society response. Similar arguments have been made in both France (Rush, Claire, 2018) and the United States.

It is important to note that, instead of promoting VMT, many jurisdictions have subsidized their primary resource industries (particularly in mineral extraction-dependent economies). The topic of "perverse subsidies" that lead to errant environmental outcomes has been widely studied for both agriculture and energy. In many cases, these policies indirectly lead to climate change impact because they preclude markets from moving to greener, more resource efficient options. Although much of the literature in this arena has focused on fossil fuel subsidies and "stranded assets" (McCarthy and Börkey, 2018; OECD, 2005), the subsidies for non-fuel primary material extraction are also significant. A 2009 study by the Pew Charitable Trusts calculated that mining subsidies in the United States arising from the 1872 Mining Act would represent $1.6 billion over the coming decade (PEW, 2009).

In a working paper for the OECD, McCarthy and Börkey (2018) mapped the full range of subsidies and other support measures to the metals sector in 2017. They find a wide range of direct and indirect subsidies for primary metals. However, they point out that there is no comprehensive cross-country database of government support that covers a broad range of measures and commodities. Sophisticated research on the relative magnitude of support across countries and the impact of different forms of support is therefore hindered. They note, however, that "the handful of existing studies find that support for the metals sector, (i) can be significant, extending into the billions of dollars in some countries, and (ii) typically accrues disproportionately, in both absolute and per unit of output terms, to the primary sector". They also find that primary resource extraction is more responsive to subsidies than secondary processing and thus that "secondary producers are less able to take advantage of lower input prices or higher output prices" (McCarthy and Börkey, 2018). This suggests that policy interventions that limit subsidies to primary extraction are likely to have more impact than further subsidizing secondary production.

3.5.3. Recycled content mandates

'Recycled content mandates', 'recycled content standards' and 'recycled content requirements' (hereafter referred to as RCMs) are interchangeably used to refer to requirements that newly produced products must contain a certain percentage of recycled material. While recycled materials are routinely used in some products within private industrial and commercial operations, the focus here is on legally binding policy and legislation – as opposed to industry-driven initiatives to improve environmental performance.

Promotion of recycled content by governments is common globally, as with the Japanese Law for the Promotion of Effective Utilization of Resources (Ministry of Economy, Trade and Industry (METI), Recycling Promotion Division, 2015) and the Fundamental Plan for Establishing a Sound Material-Cycle Society (Government of Japan, 2018). Through these laws, large paper and glass container producers are urged to use recycled content; manufacturers of copy machines must use recycled parts; and the construction industry has to use recycled asphalt and concrete.

RCMs discussed in this section differ from recycled requirements incorporated into green public purchasing in that RCMs apply across the economy, whereas the GPP for recycled content only applies to purchases by the public sector.

Although the examples of paper and construction materials are a good start for incorporating RCMs into economic spheres, they are very specific examples. Paper, for instance, is often not subject to the same consumer scrutiny as other materials and has well-established networks for recycling. As for building materials, their bulk, weight and relatively low value, there is limited geographic scope of circulation for recovered materials (such as aggregate and waste wood). RCMs face challenges when applied to more complex materials and products (Dalhammar, 2016; Iida, 2011; Mayers, 2016). The consensus in the literature is that the main (interrelated) issues confronting RCMs are market competitiveness and compliance.

The intuitive appeal of RCMs for material efficiency is obvious: what was previously waste material can be used towards a productive end, rather than extracting primary material. Recycling industries also generally welcome policy requirements on minimum recycled content, since these can increase market demand (especially for recycled materials with low residual value) (Institute of Scrap Recycling Industries, 2019).

The actual impact of RCM is still under debate. Ilda (2011) suggests that "the use of recycled material reduces the quality of the product relative to that which has been produced entirely from virgin material" and that, as a result, "a regulator faces a trade-off between environmental quality and product quality when setting the recycled content rate". In a similar modelling exercise, (Sugiyama and Koonsed, 2017) find that "a stricter RCS reduces both the output of final goods and the degree of green design and decreases the price of recycled materials. The profits of the recycler and the final goods firms also decrease". Mandating firms to improve their RCM may well adversely affect the desired outcome of stimulating innovation in the use of recycled materials.

A survey of different firms on the subject of material efficiency policies by Dalhammar (2016) also suggested an aversion to legally required RCMs as 'either unworkable or undesirable'. Aside from affecting the quality of the final product, companies reported that the potential administrative burdens were massive, and provided examples of issues with their 'green performance' under existing legislation. Producers have also objected to the cost of RCMS. Dinan (1992) suggest that tradable credits could be used to mitigate the costs of RCM to regulated entities.

Administrative complexities and challenges for a broad range of economic sectors – particularly those with long, complex and multinational supply chains – are likely to become relevant with increasingly stringent targets for RCM and collection/recycling of material more broadly. A major barrier in the policy use of recycled content targets lies in the need for proper methods to verify recycled content claims (Ardente and Mathieux, 2014b). Indeed, there is no laboratory testing to measure the amount of recycled materials used in a product, and verification must thus be exclusively based on self-declaration supported by technical documentation (such as material flow analysis and receipts from suppliers). This verification problem indicates why recycled content targets have been implemented primarily as voluntary policies, for example, environmental labelling schemes. The EU is currently proceeding with standardization activities to cope with such barriers.

From the perspective of an electronic or automotive manufacturer, for instance, it is a major exercise to ensure that suppliers of the myriad components that make up its product/s adhere to any requested RCM compliance (Andersson et al., 2019; Tam et al., 2019). There is also an issue of whether the RCM needs to be tailored for the country of sale: most modelling and conceptual exercises thus far have focused on the EU because its member states have common overall targets (Unger et al., 2017). Yet, in reality, each country in the world can, within reason, define its specific parameters for RCM as part of material efficiency goals. The ability of economic actors to meet specified RCMs (and for regulators to enforce them) is largely untested, and thus no ex post evaluations of effectiveness were found (see Ladou and Lovegrove, 2008).

3.5.4. Rebound effects

Material efficiency strategies aim to reduce the absolute environmental impacts associated with the provision of a product or service. However, while it is reasonable to expect that a 25 per cent improvement in material efficiency would yield a 25 per cent reduction in material use — and associated GHG emissions — in practice this is seldom the case. Instead, a variety of consumer and market responses to improved efficiency have been shown to affect demand and lead to an overall increase in consumption relative to a baseline in which these responses do not occur. As a result, the expected environmental benefits of efficiency strategies often fall short of expectations (Sorrell, 2007). This paradox, by which the benefits of efficiency are partially or fully negated through behavioural or systemic responses, has been dubbed the rebound effect.

Research into rebound effects has been led by energy economists, and well-documented examples include: increased energy demand following household energy efficiency improvements, longer distances driven in response to more fuel efficient vehicles and cheaper operating costs and lights left on for longer after installation of energy-efficient light bulbs (Brookes, 1990; Greening et al., 2000; Jevons, 1866; Khazzoom, 1980; Schleich et al., 2014). More recently, the study of rebound effects has expanded to include environmental efficiency more broadly, and researchers have examined rebounds in response to efficiency strategies related to construction materials (Bahn-Walkowiak et al., 2012), dietary changes (Wood et al., 2018), food waste (Chitnis et al., 2014), material use (Font Vivanco et al., 2016) and consumer electronics (Makov and Font Vivanco, 2018).

In addition to economic rebound effects, research in consumer behaviour and behavioural economics has explored so-called 'socio-psychological' or 'mental' rebound effects (Girod and de Haan, 2009; Santarius and Soland, 2018). Mental rebound arises because consumption patterns have a normative basis that defines their acceptable financial, social and environmental costs. When increased efficiency reduces the environmental costs associated with a product or service, people might feel that they have a 'moral license' to consume more of it (Tiefenbeck et al., 2013). For instance, research shows that consumers tend to use more paper when they have the option to recycle (Sun and Trudel, 2017).

Critically, when policy appraisals fail to account for rebound effects, the materials, energy and emissions 'saved' by such measures may be overestimated (Font Vivanco et al., 2016; Zink and Geyer, 2017). Therefore, the size of the rebound — how much of the expected benefit is offset — has important implications for material efficiency policies. Of particular interest are policy-induced rebound effects — as opposed to those arising from changes in markets or technology (and the ways in which policy interventions influence overall consumption). While some suggest that energy or resource efficiency policies can 'backfire' to increase, rather than reduce, overall environmental burdens, on average the microeconomic rebound effects tend to offset 20 per cent to 40 per cent of the expected benefits of efficiency policies (Gillingham et al., 2016). For a review, see Font Vivanco et al. (2018) and Gillingham et al. (2016). However, when the embodied, full life-cycle impacts or rebounds are included, these estimates could rise (Font Vivanco et al., 2014). In sum, policy interventions aiming to improve material efficiency should consider the degree to which rebound effects are expected to curb the effectiveness of the measures proposed.

Rebound effects can be reduced through the use of policy instruments that directly or indirectly raise the cost of production or consumption (van den Bergh, 2011; von Weizsäcker et al., 2014). Taxes on materials that become cheaper to use as a result of efficiency strategies are a salient way to mitigate rebound; cap and trade systems indirectly raise the cost of production or consumption and can have a similar effect. Because many policies for material efficiency are relatively new, and because non-energy rebound is less extensively studied, the magnitude of rebound and the efficiency of "anti-rebound" strategies are difficult to predict.

3.6. The role of Nationally Determined Contributions (NDCs)

A key policy element of the Paris Agreement under Article 4 (paragraph 2) is the requirement of signatory countries to "prepare, communicate and maintain successive Nationally Determined Contributions (NDCs) that it intends to achieve". NDCs provide guidance for national and subnational climate actions, as well as for international monitoring and investment. The first NDCs were submitted by 2015 and signatories have committed to submit updated NDCs – with the aim to be more ambitious – every five years, meaning the next submissions are expected by 2020 (UNFCCC, 2015).

As decided in COP20 in Lima, countries are encouraged to disclose information on "scope and coverage, planning processes, and assumptions and methodological approaches" in their NDCs, leaving the choice, or even disclosure, of concrete mitigation instruments up to each country (UNFCCCC, 2014).

Where mitigation approaches are specified in the existing NDCs of G20 countries, the majority refer to energy production and energy efficiency. Energy efficiency is referenced in 13 of the total 16 G20 NDC documents. The NDCs of the United States of America, the European Union and Mexco do not specify mitigation measures and, therefore, do not refer to energy efficiency.

Concepts of resource efficiency, resources management, material efficiency, circular economy or consumption-side instruments are scarcely mentioned in the NDCs, appearing as explicit mitigation measures only in the Intended Nationally Determined Contributions (INDCs) of Japan, India, China, Turkey and Chile (the latter not having been ratified as of 2019). Waste management commitments, which partially overlap with material efficiency strategies, have a modest presence in NDCs. Building energy efficiency codes (a resource policy with connections to and precedents for material efficiency) have a larger role in NDCs.

3.6.1. Material efficiency policies within NDCs

China's NDC makes extensive reference to material efficiency, framing its NDC around a stated commitment to the efficient use of materials, along with energy. Policies and measures that China intends to put into place include: creating a "recyclable agricultural system"; "improving efficiency and lifespan of existing and new buildings" along with "promoting recycled construction materials"; and "improvement of civil and industrial recycling." It also considers a "pricing and taxation regime for energy-and resource-based products" (National Development and Reform Commission of People's Republic of China, 2015).

Chile includes the circular economy as part of its NDC through a law establishing extended producer responsibility; incentives for innovation projects and job creation in new markets arising from the management of priority products; and proposals on circular economy solicited by CORFO (the national economic development agency).

Japan's NDCs include targets for reduction of GHG emissions in its commercial and industrial sectors (Japan, 2015). These intended savings are not solely the result of efficient energy use but also efforts surrounding the efficient use of materials to reduce emissions. For instance, iron and steel making processes have been improved; 'environmentally harmonized' improvements have been made in the efficiency of producing new paper from recycled paper; and recycled plastic is used in manufacturing and energy production across various sectors. Japan has also committed to the use of blended cement, a material efficiency strategy discussed in section 1.3.1.

India refers to recycling, "enhanced resources efficiency and pollution control" (in addition to energy efficiency) and the general need to "use natural resources wisely" (India, 2015). Other G20 NDCs refer to natural resource use efficiency and protection exclusively in relation to water, forest or wildlife resources. These include the NDCs of Saudi Arabia (2015), South Africa (2015), Russian Federation (not ratified) (2015) and Indonesia (2016).

It is important to note that, in existing NDCs, the referencing of material efficiency approaches does not correlate with mitigation ambition (based on the ambition evaluations by the Climate Action Tracker).[68] Material efficiency can be advanced not only by broadening the scope of targets in the NDCs but also by increasing the magnitude of the intended mitigation ambition.

3.6.2. Waste management commitments

A comprehensive study of the waste management commitments within NDCs has been conducted in a sector with the potential to incorporate material efficiency strategies (Powell et al., 2018). They found that, as of 2017, 137 of the 174 countries that submitted NDCs (representing approximately 85 per cent of all global emissions) included waste-sector emission mitigation actions. About half (67) of those countries identified policy actions or infrastructure to meet mitigation commitments. However, these methods differ extensively in their scope and level of detail (see Figure 28). The most frequently cited waste sector strategy was landfilling (47), closely followed by generating energy from waste through a variety of technologies (42). Powell et al. did not indicate whether or how many NDCs included waste strategies specific to buildings and construction or light-duty vehicles, presumably because such information was not included in the NDCs.

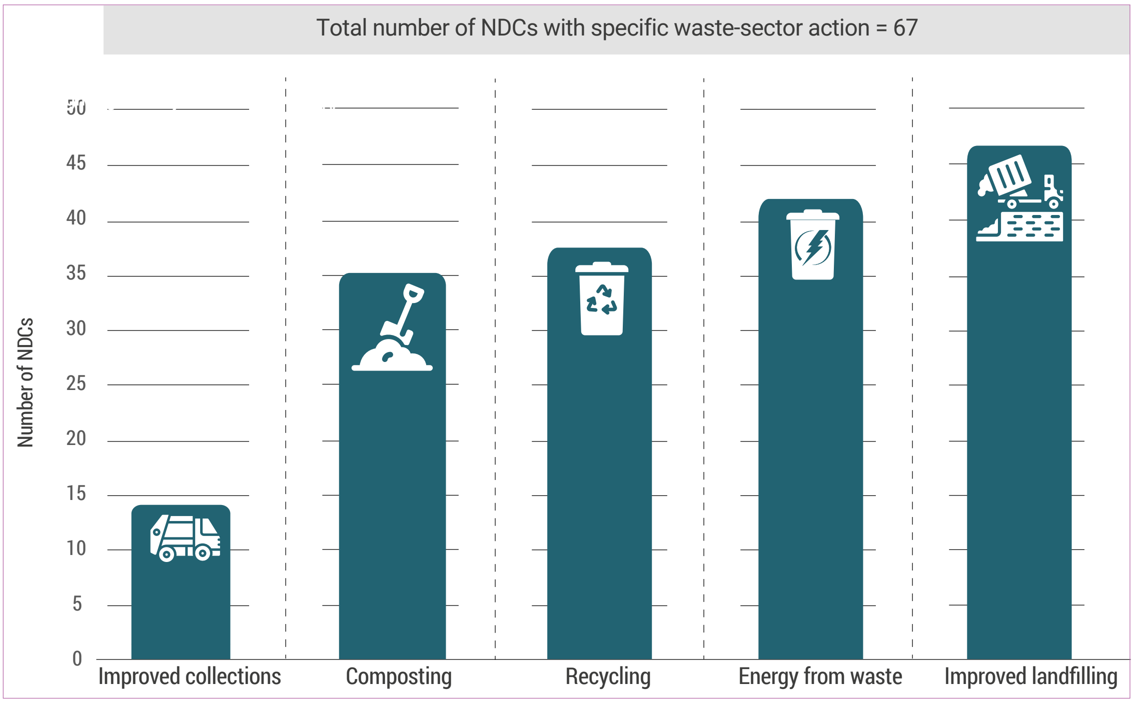
The emphasis on landfilling and energy from waste indicates that the broader material efficiency gains that could be harnessed from the range of technical measures and resultant policies described in this chapter are not explicitly pursued.

3.6.3. Energy-efficiency building codes

As indicated earlier the report, energy building codes have implications for material efficiency policy – both as examples of the opportunities and challenges arising from strategies based on code development and as a key element in energy retrofits that are needed as part of strategies aimed at increasing building lifetimes.

As of 2018, a total of 136 NDCs reference the buildings sector, though most NDCs do not have specific targets or policy actions on buildings (Abergel et al., 2018). According to the

Figure 28. Waste management commitments in NDCs as of 2017



Source: Powell et al. 2018.

68 The Climate Action Tracker, a collaboration between Climate Analytics and the New Climate Institute, tracks government climate action and measures it against the globally agreed Paris Agreement (https://climateactiontracker.org/).

Global Alliance for Buildings and Construction (GlobalABC), of those 136, 62 had country policies on building energy codes and 46 had NDCs on such codes. There were 84 countries with policies on building energy certification, but only 2 had building energy certifications as part of their NDC. Only 5 NDCs mention measures to address embodied carbon in buildings (separate from commitments to decarbonize industrial production): China, Niger, Cameroon, Senegal and Burkina Faso (see Table 16). The GlobalABC (Abergel et al., 2018) notes that "The majority of NDCs today do not explicitly cover buildings sector emissions relative to specific mention of measures countries intend to take to address building energy use and emissions".

Table 16. Intentions within NDCs relating to embodied carbon in buildings

Country	Intentions within NDCs relating to embodied carbon in buildings
China	Intention to control emissions from key sectors, including steel and building materials manufacturing, through energy conservation and efficiency improvement.
Niger	Ambition to promote low-carbon construction through frame-free buildings.
Cameroon	Has expressed interest in building a low-carbon construction and renovation value chain, in addition to increasing the insulation performance of building envelopes.
Senegal	Proposes using locally available materials such as bulrush (a water plant) for insulation, as well as innovative construction techniques (such as Nubian vaults) to reduce the carbon footprint of the buildings and construction sector.
Burkina Faso	Interest in promoting climate-friendly materials for building construction in rural and semi-urban areas. Around 3,000 community buildings will be targeted, while subsidies and tax breaks will favour the construction of another 20,000 low-carbon private residences. The promotion of metal-free and wood housing for 17,000 citizens is also targeted to provide greater resilience to climate change in rural and semi-urban areas. Public R&D funding for architectural and construction technologies will support the development of climate-resilient buildings using low-carbon materials.

Source: Abergel et al. (2018).

The status of current NDCs suggests that many countries have not yet recognized the GHG emission reduction opportunities that lie in material efficiency, or are only taking modest steps to take advantage of such opportunities. At the same time, current NDC commitments are "old" in the sense that attention to the circular economy and insights about the potential GHG reduction benefits of material efficiency were not as extensive in 2015 as they are now. Upcoming revisions to the NDCs offer an opportunity to expand the range of NDC measures to incorporate material efficiency.

Material efficiency measures could be considered in the NDCs in several ways, including:

- considering material efficiency (both in terms of efficient production processes and smarter consumption models) in calculating the overall mitigation potential and setting more ambitious emission targets
- considering material efficiency measures, including material substitution, explicitly in sectoral targets and action plans, and
- including material efficiency in a more generic list of approaches to be utilized for implementation, if sectoral plans are not being disclosed.

Within the past three years, the G7 launched the Alliance for Resource Efficiency and the G20 launched a Resource Efficiency Dialogue (G7, 2017). Both these avenues of policy action provide opportunities for making the connection to climate change targets. These material efficiency strategies are also especially important for developing countries, as future major infrastructure investment will happen in the Global South (Müller et al., 2013; Swilling et al., 2018).

National NDC stakeholder consultation processes, encouraged by the COP20 conclusions to form part of the NDC processes, can be used to deepen insight. Local industries and circular economy initiatives can provide country context-specific data on mitigation potential and implementation pathways. Guidance material prepared for the upcoming revision of the NDCs similar to that prepared by the World Resources Institute and the UN Development Program (WRI and UNDP 2015) for the 2015 NDCs could also explore specific country possibilities in considering material efficiency measures.

3.7. Discussion and conclusion

3.7.1. Main findings

In general, climate change policies have focused on energy efficiency rather than materials efficiency as a central strategy for GHG emissions reduction. Material efficiency policies typically emerged through efforts to improve the environmental and resource dimensions of waste management – as exemplified by attention to the 3Rs – with limited linkage to climate change mitigation (European Environment Agency, 2016; Worrell et al., 2016). As the modelling presented in this report indicates, for material efficiency to contribute to climate mitigation, strategies must move beyond end-of-life management to encompass production and use. That extension of scope can add new GHG emission-reduction opportunities but also new challenges.

The policies identified in this rapid assessment do not align well with the results from the modelling. In some cases, this is because of the historic focus of policies related to material efficiency on recycling. The modelling suggests that more intensive use offers larger GHG emissions reductions than increased recycling. In other cases, material efficiency strategies have been the subject of limited policy development (as with the use of mass timber in construction), or material efficiency has not been the focus of policy (as with shared housing or mobility). Also, rigorous quantitative ex-post policy evaluation is uncommon. In those cases, knowledge of policy efficacy is simply very limited, making judgments speculative as to how best to use policy to realize the benefits indicating by the modelling. Nonetheless, this review reveals useful insights about focus areas to develop policy for material efficiency.

Before addressing specific policies and sectors, it is worth noting several insights that relate to the overall nature of policies for material efficiency and their evaluation.

Clarity of purpose and intentional policy change are crucial to link material efficiency and climate change mitigation. The sharing economy, both for lodging and transportation, has generated considerable enthusiasm in environmental circles as an impetus for resource efficiency and even an autonomous pathway to that goal. The research on sharing reviewed in this chapter serves as a reminder that sustainability must be "designed in." Without policy steering and regulation, other societal benefits may result from these new developments, but not emission reductions. Market forces provide incentives for some actors to save money by using less material, but not all markets generate such incentives.

Interest in shared mobility and lodging has drawn attention to the issue of rebound. Rebound, however, may occur with any of the strategies that lead to cost savings by those employing the strategies. If tourist travel becomes cheaper through the use of Airbnb, do air travel and GHG emissions then increase? This is a challenge for any policy promoting efficiency, not just material efficiency. Rebound is extensively studied — and debated — with respect to energy efficiency. Careful study is less common for material efficiency. One important implication of the challenge of rebound is the need to consider policy instruments that not only induce improvements in efficiency, but also modulate demand (such as taxes and cap-and-trade programmes). As noted in the IRP's 2014 report on decoupling (von Weizsäcker et al., 2014, pp. 39–40), "the implication of the rebound effect is that successful decoupling of economic growth from resource consumption will require clarity of purpose and intentional policy change. Without this, the interactions in our complex economic system appear likely to reduce the resource-saving effect of any efforts to decouple".

Material efficiency strategies and policies have very different time horizons. Designs that use less material, shifts to lower carbon materials or improved yields during fabrication can offer rapid emissions reductions, particularly in contrast to decarbonization strategies that rely on substantially new or unproven technologies. Strategies focused on the design for disassembly and reuse of building elements, however, for example, inherently include a large time gap between implementation and avoided emissions because the lifetime of a building is very long. This has implications for embodied carbon in material choice. Material-intensive designs aimed at operational efficiency that are mass- and GHG-intensive at the beginning of the life cycle can nonetheless yield beneficial results that persist over that same long lifetime. Furthermore, end-of-life strategies may not be as impactful as those upstream (Chau et al., 2015), but result in quicker savings. The policies themselves may have temporal dimensions in terms of diffusion, as with the pace of building code updates or adoption of certification standards. These differences in time horizons present policymakers with additional options, but also added complexity. They also mean that coordination is needed in the value chain, such that actors involved in design and construction need to understand the requirements of those involved in end-of-life management. Conversely, EoL actors need information about upstream decisions, so that those carrying out deconstruction know how the building was constructed in order to maximize recovery rates.

One more pattern that emerged from the review is worth noting: co-benefits, mostly unintentional, of non-material efficiency policies. In P2P lodging, restrictions on the extent of short-term rentals (intended to mitigate disruption in housing markets) may help steer shared lodging to the use of underutilized capacity. Similarly, policies to reduce congestion arising from ride-hailing services may induce more shared rides. In the design of cars, regulations concerning fuel efficiency and GHG emissions lead to light-weighting.

3.7.2. Evaluation of material efficiency policies

In this review, very limited comprehensive research was found on the efficacy of material efficiency policy. In addition, not much research was found on enforcement of such policy. Where material efficiency strategies or policies are new, the absence of evaluation is not surprising. Where the strategies and policies are more established, this indicates that more work needs to be done if policy is to be well targeted and effective. Moreover, it is crucial that policies be measured not on the basis of number of programmes or participants, but in terms of the outcomes (both in terms of mass – as a starting point – and GHG emissions plus other environmental impacts).

Monitoring of policies related to material efficiency is extensive in many G7 countries. Macro-level resource indicators using domestic material consumption (DMC) are tracked in the EU for all member states as part of the Seventh Environment Action Programme's priority objective 2 (EU, 2013) of improving resource efficiency by 2020 (EU 2019). As part of its effort to monitor progress toward a circular economy, the EU tracks self-sufficiency in raw materials, green public procurement, waste generation, recycling rates overall and for specific waste streams, the contribution of recycled materials in meeting raw materials demand and trade in recyclable raw materials (European Commission, 2018b; European Union, 2018). The EU also tracks compliance with requirements for waste prevention and waste management plans in member states. This and other similar monitoring programmes provide an important indication of progress on public goals and of policy uptake and implementation. Quantitative evaluation of specific policies, however, is scant.

The need for research that carefully links policies to outcomes is key in all domains. The monitoring of outcomes in many countries indicates if targets have been achieved, but does not reveal if the outcome is the result of the policy of interest. As noted at the beginning of this chapter, to establish the connection between policies for material efficiency and GHG reductions, the relationship between policies and material efficiency strategies and then to material efficiency strategies and outcomes need to be demonstrated. Counterfactual impact analysis can provide insight as to whether a given policy is responsible for the outcome of interest by comparing what actually happened when a policy was implemented with what would have happened in the absence of that policy, typically using sophisticated statistical techniques. While this may seem like an ambitious agenda for evaluation of material efficiency policy, the availability of big data and microdata creates possibilities for this sort of analysis (Crato, 2017)

Analysis of material efficiency strategies and policies faces additional requirements that are typical of environmental and resource policy. The evaluation of material efficiency policies is challenging because of the absence of appropriate and verifiable metrics and standards for the assessment. Assessment on a life-cycle basis is crucial if environmental burdens are to be reduced, rather than simply shifted to other stages in the product chain, other sectors, other locations or from one impact to another (Talens Peiró et al., 2019). LCA may also highlight GHG benefits of material efficiency otherwise overlooked, such as decreases in demand reduction that lead to carbon reductions cross-nationally. Efforts in several countries to employ LCA and life-cycle metrics in green public procurement (in infrastructure and office buildings, for instance) are an encouraging indication that measurement of this sort is not only possible, but already in use.

Identification of trade-offs needs to be more prominent in policy guidance. Increasing building lifetimes is an intriguing strategy (albeit one infrequently discussed from the material efficiency perspective), but it faces the same challenge as with all product life extension — namely, making sure that prolonged lifetimes do not create lock-in and prevent exploitation of improved technology and other means of GHG reduction. In some cases, this means use of comprehensive LCAs. In other cases, this involves estimates of rebound or even the (somewhat) simpler recognition that, for example, ride-hailing may reduce personal car use or ownership by riders but lead to the purchase of new and even larger vehicles by shared mobility drivers.

3.7.3. Material efficiency policy in buildings and construction

Overall, our policy review found that the construction sector has a range of policy leverage points to harness direct material efficiency benefits that could result in greenhouse gas reductions. Some are both well studied and subject to overt policy throughout the world (as with construction and demolition recycling), many are regulated to achieve energy efficiency goals (including requirements for upgrades when buildings are renovated), and others still are largely at the exploratory stage (as is the case for deconstruction of buildings). Energy-efficiency policies present opportunities to borrow insights from long-standing practice and research. They also present opportunities for co-benefits, as with forms of shared housing that lower both material and energy use.

Design is a crucial point of intervention for many material efficiency strategies, albeit one indirectly shaped by policy through building codes. Decisions at the design stage affect material choice, construction techniques, opportunities for increased building lifetimes and end-of-life opportunities (including deconstruction, component reuse, the value of construction and demolition recycling). This suggests that careful attention be paid to both the content of building standards/codes and to their diffusion and adoption by the level of government responsible for codes within G7 countries. Building certification systems present a related pathway for influencing design and construction, especially if governments are integrating certification systems into building codes or otherwise using them in urban and land-use planning. Here too, the details of the system matter – especially the point systems used for ratings.

Market transformation and other soft policies for technologies and practices that are not yet to scale are another means of influencing design choices that are not conducive to mandatory policies. Many of the material efficiency strategies described in this chapter fall into this category (such as building component reuse, mass timber construction and changes in the composition and use of cement and concrete).

Increased intensity of use of residential buildings through shared and smaller housing is also shaped by building codes but also zoning and land use regulation, property, carbon and other taxes, demographic trends and consumer preferences. Shared and smaller housing can be encouraged through changes in regulation and taxation, but will also require changes in behaviour and lifestyle.

Policies for end-of-life management (such as construction and demolition debris reuse and recycling) are widespread but are often focused on landfill diversion. If material efficiency is to lead to climate change mitigation, policy targets need to shift to, or at least include, GHG emission reduction goals.

3.7.4. Material efficiency policy in personal transportation

Currently, material efficiency policies related to cars largely revolve around material choice and end-of-life management. Reduction in materials consumption through material choice and light-weighting has been a side-effect of policies aimed at reducing fuel consumption and GHG emissions in vehicle operation. Some forms of light-weighting can present trade-offs between increased carbon emissions in production and reduced emissions during use.

End-of-life management has focused on de-pollution and increasing recycling rates, with the resulting attention on recovery of non-metallic residues of car shredding. Policy has been less focused on the GHG implications of ELV management targets. Adjustment of ELV policy to incorporate considerations of avoiding downcycling and lost opportunities to reduce GHGs warrants attention.

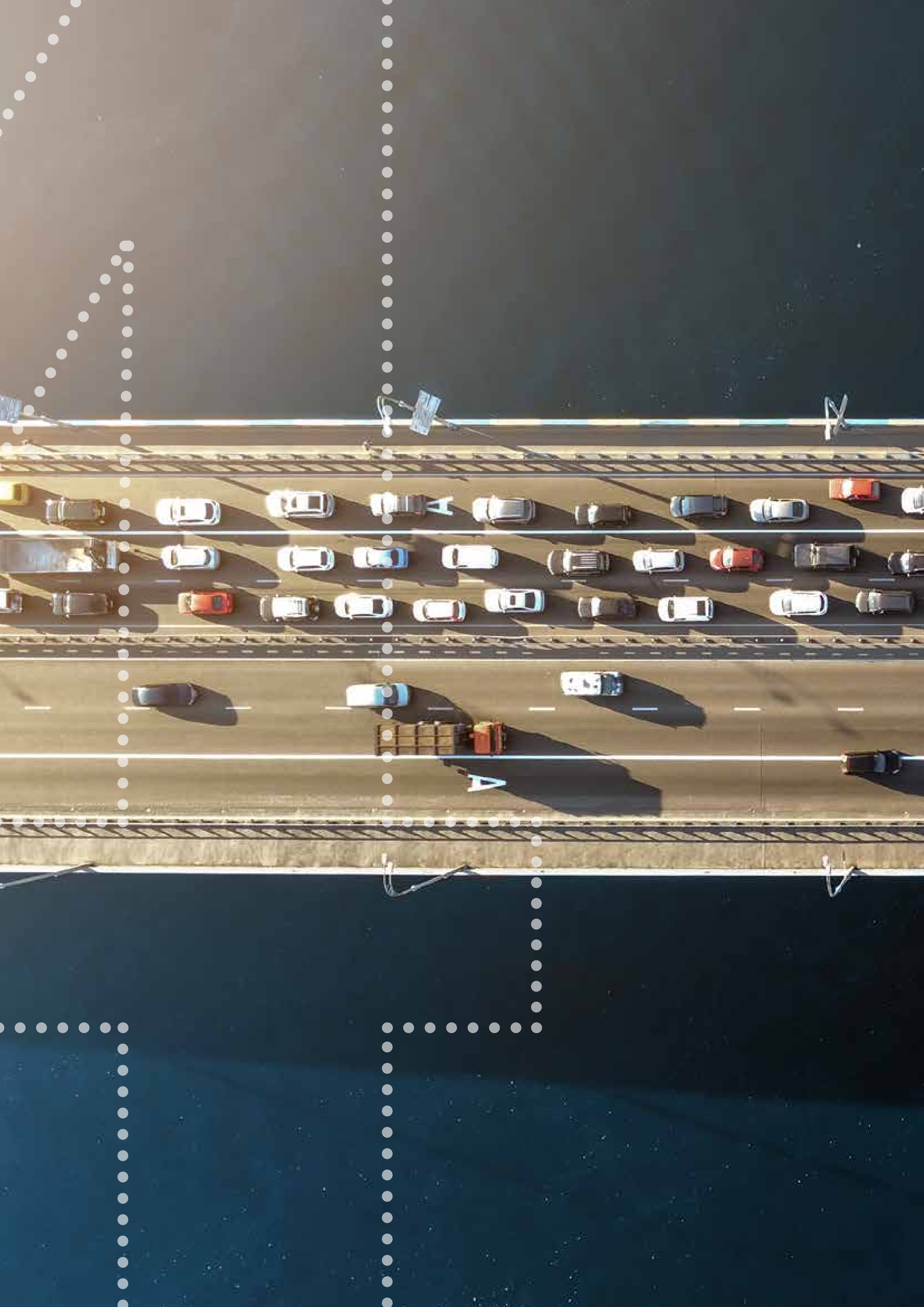
Shared mobility in the form of car-sharing and ride-hailing is developing very rapidly around the world. As with shared use of dwellings, the eventual form of such service is especially difficult to predict. Current policy is appropriately focusing on issues of company and driver behaviour, impacts on public transit use and congestion. While emissions from vehicle travel are part of policy discourse, material use is rarely discussed other than in advocacy pieces.

Car-sharing and ride-hailing have different environmental and resource impacts and should be distinguished in policymaking. There is early evidence that car-sharing leads to a reduction in household vehicle ownership – a trend not found for ride-hailing. Two especially important imperatives for material efficiency-related policy on shared mobility are: ongoing, systematic access to data; and incentives for ride-splitting and other practices that steer shared mobility toward the use of underutilized capacity rather than purchase and use of additional vehicles.

3.7.5. Cross-cutting policies

Several policies that can encourage multiple material efficiency strategies for both homes and cars were reviewed. As noted above, building codes and standards can be a means of advancing or hindering material efficiency. Green public procurement (GPP) is widely used in the G7 and is already being applied to elements of material efficiency in building and construction (primarily end-of-life management). Although the material and GHG benefits of GPP are not routinely assessed, they need to be if this policy instrument is to be used effectively. Virgin material taxes (VMTs) appear to be limited to mineral construction materials. The analytical basis for the magnitude and focus of VMTs needs to be improved to provide clear policy justification in the face of likely political opposition by resource industries. Interest is growing in recycled content mandates (RCMs). Like VMTs, an analytical basis is needed for decisions about magnitude and focus. Verification of recycled content is an important challenge for this policy instrument. While not a policy instrument per se, the reduction and removal of subsidies for primary material production warrants particular attention, as research suggests that subsidies are large. This is probably depressing demand for secondary materials and reducing revenues for governments.

Overall, our policy review suggests the need for a life-cycle approach to policy delivery and monitoring. It is tempting to focus on material efficiency policies only at production and manufacturing phases, or conversely only at end of life, but the climate change benefits are most likely to be harnessed effectively through a life-cycle approach to policymaking and evaluation.



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About the International Resource Panel

Aim of the Panel

The International Resource Panel was established to provide independent, coherent and authoritative scientific assessments on the use of natural resources and their environmental impacts over the full life cycle. The Panel aims to contribute to a better understanding of how to decouple economic growth from environmental degradation while enhancing well-being.

Benefiting from the broad support of governments and scientific communities, the Panel is constituted of eminent scientists and experts from all parts of the world, bringing their multidisciplinary expertise to address resource management issues. The information contained in the International Resource Panel's reports is intended to:

- Be evidence-based and policy relevant,
- Informing policy framing and development, and
- Supporting evaluation and monitoring of policy effectiveness.

Outputs of the Panel

Since the International Resource Panel's launch in 2007, more than 30 assessments have been published. The assessments of the Panel to date demonstrate the numerous opportunities for governments, businesses and wider society to work together to create and implement policies that ultimately lead to sustainable resource management, including through better planning, technological innovation and strategic incentives and investments.

Following its establishment, the Panel first devoted much of its research to issues related to the use, stocks and scarcities of individual resources, as well as to the development and application of the perspective of 'decoupling' economic growth from natural resource use and environmental degradation. These reports include resource-specific studies on biofuels, water and the use and recycling of metal stocks in society.

Building upon this knowledge base, the Panel moved into examining systematic approaches to resource use. These include looking into the direct and indirect impacts of trade on natural resource use; issues of sustainable land and food system management; priority economic sectors and materials for sustainable resource management; benefits, risks and trade-offs of low-carbon technologies; city-level decoupling; and the untapped potential for decoupling resource use and related environmental impacts from economic growth.

Upcoming work

In the forthcoming months, the International Resource Panel will focus on scenario modelling of natural resource use, the socioeconomic implications of resource efficiency and the circular economy, the role of resources in environmental displacement and migration, and the connections between finance and sustainable resource use, among others. The Secretariat is hosted by the United Nations Environment Programme (UNEP).

More information about the Panel and its research can be found at:

Website: www.resourcepanel.org
Twitter: https://twitter.com/UNEPIRP
LinkedIn: https://www.linkedin.com/company/resourcepanel
Contact: unep-irpsecretariat@un.org

More information about the Panel and its research can be found at: http://www.resourcepanel.org/.

Resource Efficiency and Climate Change:
Material Efficiency Strategies for a Low-Carbon Future

The International Resource Panel (IRP) was established to provide independent, coherent and authoritative scientific assessments on the use of natural resources and their environmental impacts over the full life cycle. The Panel aims to contribute to a better understanding of how to decouple economic growth from environmental degradation while enhancing well-being. The Secretariat is hosted by the United Nations Environment Programme.

IRP assessments demonstrate the opportunities for governments, businesses and wider society to work together to create and implement policies that ultimately lead to sustainable resource management, including through better planning, technological innovation and strategic incentives and investments.

Materials are vital to modern society, but their production is an important source of greenhouse gases. Emissions from material production are now comparable to those from agriculture, forestry, and land use change combined, yet they have received much less attention from the climate policy community. The IPR authors propose looking beyond energy efficiency to reduce global carbon footprint.

This report was developed by the IRP in response to a request from the Group of 7. It conducts a rigorous assessment of the contribution of material efficiency to GHG abatement strategies. More concretely, it assesses the potential reduction of GHG emissions from material efficiency strategies applied in residential buildings and light duty vehicles, and reviews policies that address these strategies. The IRP modelling results show that increasing material efficiency can help enhance efforts in moving towards the 1.5° C target set by the Paris Agreement.

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