Material efficiency in clean energy transitions

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Abstract

Materials are the building blocks of society, making up the buildings, infrastructure, equipment and goods that enable businesses and people to carry out their daily activities. Economic development has historically coincided with increasing demand for materials, resulting in growing energy consumption and carbon dioxide (CO_2) emissions from materials production. Clean energy transitions must decouple these trends. Material efficiency strategies can contribute to CO_2 emissions reduction throughout value chains. Despite being an often-overlooked emissions mitigation lever, opportunities for material efficiency exist at each life-cycle stage, from design and fabrication, through use and finally to end of life. Pushing these strategies to their practical yet achievable limits could enable considerable reductions in the demand for several key materials. Conversely, the demand for some materials may moderately increase while delivering favourable emissions benefits at other points in the value chain. As a result, improved material efficiency can reduce some of the deployment needs for other CO_2 emissions mitigation options while achieving the same emissions reduction, thus contributing to clean energy transitions. This analysis examines the potential for material efficiency and the resulting energy and emissions impact for key energy-intensive materials: steel, cement and aluminium. It includes deep dives on the buildings construction and vehicles value chains, and outlines key policy and stakeholder actions to improve material efficiency. Important actions include: increasing material use data collection and benchmarking; improving consideration of the life-cycle impact in climate regulations and at the design stage; and promoting repurposing, reuse and recycling at end of product and buildings lifetimes.

Highlights

- **Economic development has historically relied on increasing material demand,** which has led to growing energy consumption and carbon dioxide (CO_2) emissions from materials production. Applying material efficiency strategies throughout value chains can help to decouple these trends.

- **Clean energy transitions will affect established material demand trends.** In the Clean Technology Scenario, material efficiency and technology shifts result in lower material demand relative to the Reference Technology Scenario, in which material demand trends broadly follow historical trends. By 2060, in the Clean Technology Scenario, material demand is lower than in the Reference Technology Scenario: 24% lower for steel, 15% lower for cement and 17% lower for aluminium. Material efficiency contributes approximately 30% of the combined CO_2 emissions reduction for these three materials between the two scenarios in that year.

- **Considerable potential exists to push material efficiency even further** than in the Clean Technology Scenario. Pursuing material efficiency to highly ambitious yet achievable limits in a Material Efficiency variant leads to additional demand reductions for steel (16%) and cement (9%) in 2060. Demand for aluminium increases slightly relative to the Clean Technology Scenario (by 5% in 2060), but CO_2 emission benefits at other stages of the value chain outweigh this increase.

- **Material efficiency strategies result in more moderate deployment needs for low-carbon industrial process technologies** to achieve the same decarbonisation outcome. In the Material Efficiency variant, cumulative industrial CO_2 emissions are the same as in the Clean Technology Scenario, although the emissions intensity is higher for steel (by 4% in 2060) and cement (by 7% in 2060). The emissions intensity of aluminium is somewhat lower (by 9% in 2060). Combined cumulative capital investment on low-carbon industrial process technologies for steel, cement and aluminium is 4% lower by 2060 in the Material Efficiency variant than in the Clean Technology Scenario.

- **Efforts from governments, industry and the research community are needed** to enable greater uptake of material efficiency. Key actions include: increasing material use data collection and benchmarking; improving consideration of the life-cycle impact in climate regulations and at the design stage; and promoting repurposing, reuse and recycling at end of product and buildings lifetimes.

Executive summary

Clean energy transitions require decoupling of economic growth from material demand

Economic development has historically relied on ever-increasing material demand. However, producing materials consumes resources and energy, resulting in carbon dioxide (CO_2) emissions and other environmental effects. **Clean energy transitions will affect established material demand trends,** through a combination of technology shifts and pursuit of material efficiency strategies. Potential for material efficiency exists throughout value chains, including through designing for long life, lightweighting, reducing material losses during manufacturing and construction, lifetime extension, more intensive use, reuse and recycling. This report examines material efficiency opportunities and implications for three energy-intensive materials – steel, cement and aluminium – and includes deep dives on two major material consuming value chains: buildings construction and vehicles.

Material efficiency can contribute to reducing CO_2 emissions. In the Clean Technology Scenario, which aligns with the objectives of the Paris Agreement, material demand is reduced compared to in the Reference Technology Scenario: by 24% for steel (equivalent to about six times the production in the United States in 2017), 15% for cement (two and a half times the production in India in 2017) and 17% for aluminium (1.2 times the primary production in the People's Republic of China in 2017) in 2060. Material efficiency contributes approximately 30% of the combined emissions reduction for these three materials in the Clean Technology Scenario in 2060.

In the buildings sector, reduced materials demand contributes 10 gigatonnes of cumulative emissions reduction to 2060 in the Clean Technology Scenario, which is a 10% reduction in CO_2 emissions from steel and cement use in buildings relative to the Reference Technology Scenario. The demand reduction is largely because of extended buildings lifetimes that are pursued in concurrence with energy efficiency retrofits. **In the transport sector, vehicle lightweighting contributes approximately 10% of the global 2060 total passenger light-duty vehicle use-phase emissions reduction** in the Clean Technology Scenario relative to the Reference Technology Scenario. This is a substantial portion in the context of the many other emissions reduction strategies such as engine and powertrain efficiency measures and fuel switching (including electrification) being pursued in road vehicles.

Further ambitions on material efficiency can reduce deployment needs for low-carbon industrial process technologies and achieve emissions reduction throughout value chains

Considerable potential exists to push material efficiency beyond the Clean Technology Scenario. The Material Efficiency variant achieves the same degree of energy sector decarbonisation as the Clean Technology Scenario. But it pursues material efficiency strategies to even more ambitious, yet achievable, limits, considering real-world technical, political and behavioural constraints. Strategies pushed considerably further are those more challenging to adopt from the perspective of requiring greater regulatory efforts, stakeholder co-ordination, value chain integration, investment, training, shifts in business practices or behavioural change (e.g. improved buildings design and construction, substantial vehicle lightweighting and material reuse). This leads to further material demand reductions compared to in the Clean Technology Scenario, especially for steel (16%) and cement (9%) in 2060. Aluminium use increases (by 5% in 2060) due to vehicle lightweighting outweighing other strategies that put downward pressure on demand.

Material efficiency strategies lead to more moderate deployment needs for low-carbon industrial process technologies for the same CO_2 emissions outcome. The Material Efficiency variant achieves the same cumulative industrial emissions as the Clean Technology Scenario, but with a higher emissions intensity for steel (by 4% in 2060) and cement (by 7% in 2060). The emissions intensity of aluminium is somewhat lower (by 9% in 2060). The required cumulative capital investment on low-carbon industrial process technologies is 4% lower by 2060 compared to in the Clean Technology Scenario. For example, cumulative captured and stored CO_2 emissions are 45% lower in the cement sector when material efficiency strategies are pursued to such an extent.

Additional material efficiency efforts can achieve emissions reduction beyond the Clean Technology Scenario in some value chains. For example, in the vehicle supply chain, improved fuel efficiency through additional vehicle lightweighting in the Material Efficiency variant reduces net emissions beyond the Clean Technology Scenario by 17% for passenger light-duty vehicles and 9% for light commercial and heavy-duty vehicles in 2060. Total emissions from material production for vehicles increase moderately due to higher production of aluminium, plastics and composites. But this rise is outweighed by emissions savings during vehicle use. In the buildings sector, additional material efficiency efforts relieve pressure on industry without necessarily decreasing buildings use-phase emissions.

Policy and stakeholder efforts are needed to improve material efficiency

Material efficiency does not come without challenges and costs. Real and perceived risks, costs, time constraints, fragmented supply chains, regulatory restrictions and lack of awareness are some of the many barriers to greater uptake of material efficiency strategies. Improving material efficiency will in many cases incur costs, although estimates suggest that these may fall within a reasonable range compared to other emissions mitigations options.

Efforts from all stakeholders will enable greater uptake of material efficiency. Governments and industry can work together to further develop regulatory frameworks and business models in support of material efficiency. Industry can consider the life-cycle impact when designing products and buildings, facilitated by increased data collection and rigorous life-cycle assessment conducted in partnership with researchers. Increasing efforts on end-of-life repurposing, reuse and recycling are also key. Consumers can play a role by increasing demand for material-efficient products that contribute to reducing CO_2 emissions.

Findings and recommendations

Policy recommendations

- Increase data collection on material use and the life-cycle impact to set benchmarks and promote best practices.
- Improve consideration of the life-cycle impact in climate regulations to promote material-efficient choices at the design stage.
- Adopt policies that promote durability and long lifetimes to incentivise, for instance, refurbishing and repurposing of buildings instead of demolition.
- Set incentives to reuse and recycle to reduce the need for higher-emission primary materials production, and improve integration of supply chains to facilitate these strategies.
- Shift from prescriptive to performance-based design standards, so that efforts to use materials more efficiently are not unnecessarily restricted.
- Promote education and training programmes on material efficiency.

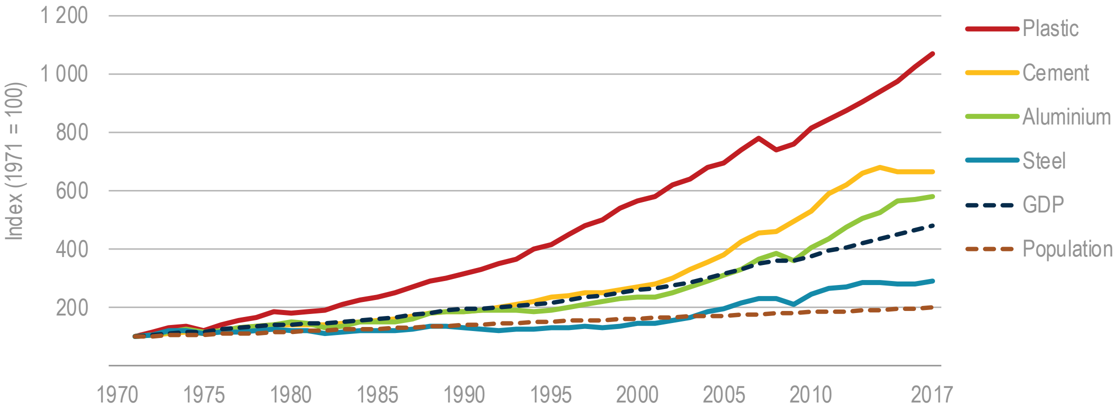
Historical demand trends for materials

Materials are the fundamental building blocks of society. They make up the buildings, infrastructure, equipment and goods that enable businesses to operate and people to carry out their daily activities. They enable services such as transport, shelter and mechanical labour, in many cases through the use of energy.

Global demand for key materials has grown considerably over past decades. Since 1971, global demand for steel has increased by three times, cement by nearly seven times, primary aluminium by nearly six times and plastics by over ten times. Material consumption growth has coincided with population and economic development. In the same period, global population doubled, while global gross domestic product (GDP) grew nearly fivefold.

Although materials bring benefits to society, they are also a source of environmental impact. Converting raw materials into materials for use results in substantial energy consumption and carbon dioxide (CO_2) emissions. Along with growth in material demand, energy and emission effects from materials production have grown substantially, by more than one and a half times over the last 25 years. Industry accounted for nearly 40% of total final energy consumption and nearly one-quarter of direct CO_2 emissions in 2017.

Figure 1. Demand growth for key materials, GDP and population

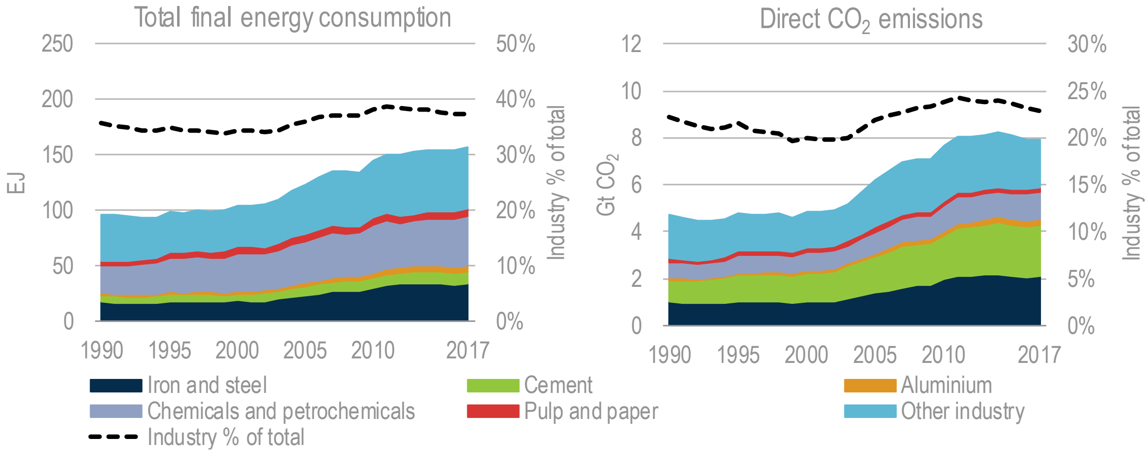


Notes: Outputs of different industrial sectors are displayed on an index basis referred to 1971 levels. *Aluminium* refers to primary aluminium production only. *Steel* refers to crude steel production. *Plastics* include a subset of the main thermoplastic resins.

Sources: Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use and fate of all plastics ever made", https://doi.org/10.1126/sciadv.1700782; worldsteel (2018), Steel Statistical Yearbook 2018, www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf; IMF (2018), World Economic Outlook Database, www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx; USGS (2018a), 2016 Minerals Yearbook: Aluminium, https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2016-alumi.pdf; USGS (2018b), 2015 Minerals Yearbook: Cement, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2015-cemen.pdf; USGS (2017), 2015 Minerals Yearbook: Nitrogen, https://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2015-nitro.pdf. Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", https://doi.org/10.1021/acs.est.7b04573.

Demand for materials has grown considerably over past decades. Much of the growth since 2000 has been due to rapid development in the People's Republic of China ("China").

Figure 2. Global industry final energy consumption and direct CO_2 emissions



Notes: *Industry % of total* is industry divided by industry plus non-industrial sectors (including buildings, transport, power generation and heat plants, agriculture, other energy uses and non-energy use). *Total final energy* consumption includes electricity consumption; *direct CO_2 emissions* do not include indirect emissions from producing the electricity consumed. EJ = exajoules; $GtCO_2$ = gigatonnes of carbon dioxide.

Industrial total final energy consumption and direct CO_2 emissions have grown more than one and a half times over the last 25 years.

Enabling strategies to move towards more sustainable material use

With expected population and economic growth over the coming decades, global demand for steel is expected to increase by approximately 30%, cement by 10% and aluminium by about 75% through to 2060 relative to 2017 levels. This is in the absence of significant changes in the way materials are consumed. The increasing material demand poses challenges for sustainability, including an increase of approximately 15% in CO_2 emissions compared to 2017 levels. Therefore, material production and consumption need to be managed.

The Clean Technology Scenario considers substantial reductions in industrial CO_2 emissions, which fall by about 45% by 2060 from the 2017 level. While not eliminating the need for strong efforts to reduce emissions intensity of material production, reducing the quantity of materials demanded can contribute to overall emissions reduction, thus reducing deployment needs for low-carbon industrial process technologies for the same CO_2 emissions outcome.

Box 1. Scenarios discussed in this analysis

These scenarios should not be considered as predictions, but as analyses of the impact and trade-offs of different technology choices and policy targets, thereby providing a quantitative approach to support decision-making in the energy sector.

The **Reference Technology Scenario** accounts for current country commitments to limit emissions and improve energy efficiency, including nationally determined contributions pledged under the Paris Agreement. By factoring in these commitments and recent trends, this scenario already represents a major shift from a historical "business as usual" approach with no meaningful climate policy response. However, global emissions increase by 8% by 2060 above the 2017 level, which is a pathway far from sufficient to achieve the objectives of the Paris Agreement.

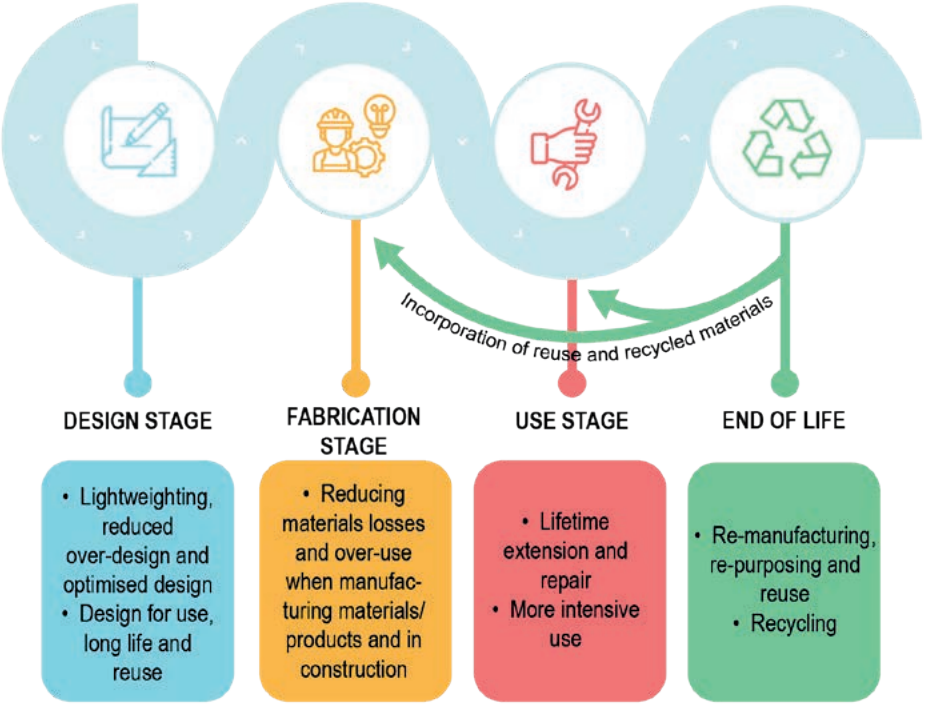
The **Clean Technology Scenario** lays out an energy system pathway and a CO_2 emissions trajectory in which CO_2 emissions related to the energy sector are reduced by around three-quarters from today's levels by 2060. Among the decarbonisation scenarios projecting a median temperature rise in 2100 of around 1.7-1.8 degrees Celsius in the Intergovernmental Panel on Climate Change database, the trajectory of energy- and process-related CO_2 emissions of the Clean Technology Scenario is one of the most ambitious in the medium term and remains well within the range of these scenarios through to 2060. The Clean Technology Scenario is the central climate mitigation scenario used in this analysis. It represents a highly ambitious and challenging transformation of the global energy sector that relies on a substantially strengthened response compared with today's efforts. It opens the possibility of the pursuit of ambitious global temperature goals, depending on action taken outside the energy sector and the pace of further emissions reduction after 2060.

A Material Efficiency variant illustrates the outcome of pursuing material efficiency strategies to their practical yet achievable limits in key value chains, while achieving the same CO_2 emissions outcome as the Clean Technology Scenario. Strategies pushed considerably further in the variant are those more challenging to adopt from the perspective of requiring greater regulatory efforts, stakeholder co-ordination, value chain integration, investment, training, shifts in business practices or behavioural change. While highly ambitious on material efficiency, the variant remains within real-world technical, political and behavioural constraints.

Different material efficiency strategies can be applied at each stage of supply value chains, including strategies that reduce material demand, those that increase demand for some materials while enabling outweighing CO_2 emissions benefits at other stages of the value chain, and those that shift to using lower-emission materials or lower-emission production routes. Some material efficiency strategies interact with each other, leading to synergies in some cases and limitations in others. Key examples of strategies at various stages include the following:

- Design stage – lightweighting and optimisation strategies may enable using fewer materials to provide the same service; designing for long life could result in higher initial material demand but enable outweighing life-cycle emissions savings.
- Fabrication stage – waste and overuse can be reduced when manufacturing materials, during production and in construction; higher-emissions materials can be substituted by lower-emissions materials.
- Use stage – more intensive use and extending product or buildings lifetimes through repair and refurbishment can reduce the need for materials to produce new products.
- End of life – reuse can reduce new materials needs; recycling can enable lower-emission secondary production routes.

Figure 3. Material efficiency strategies across the value chain



Numerous material efficiency strategies can be applied in the design, fabrication, use and end-of-life stages.

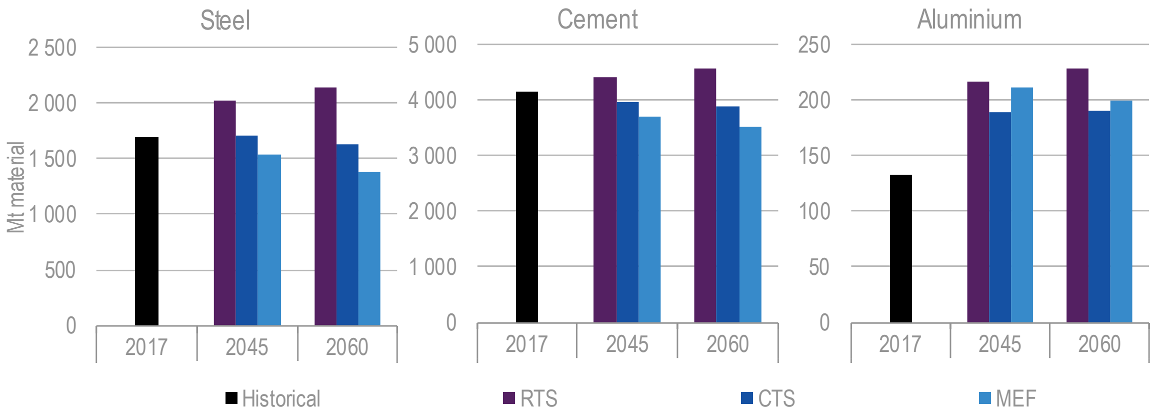
Implications of deploying further material efficiency strategies

Material demand

The Clean Technology Scenario sees considerable divergence from the material demand trends in the Reference Technology Scenario. In 2060, in the CTS, demand is 24% lower for steel (equivalent to about six times the production in the United States in 2017), 15% lower for cement (two and a half times the production in India in 2017) and 17% lower for aluminium (1.2 times the primary production in China in 2017) relative to the RTS.

Considerable potential exists to push material efficiency beyond the Clean Technology Scenario. The Material Efficiency variant achieves the same climate ambitions as the Clean Technology Scenario while pushing material efficiency strategies to highly ambitious yet achievable limits, considering real-world technical, political and behavioural constraints. This leads to further material demand reductions compared to in the Clean Technology Scenario, especially for steel (16% in 2060) and cement (9% in 2060). Aluminium use sees an increase (by 5% in 2060) due to vehicle lightweighting outweighing other strategies that put downward pressure on demand.

Figure 4. Demand for steel, cement and aluminium by scenario



Notes: Mt = million tonnes. RTS = Reference Technology Scenario. CTS = Clean Technology Scenario. MEF = Material Efficiency variant.

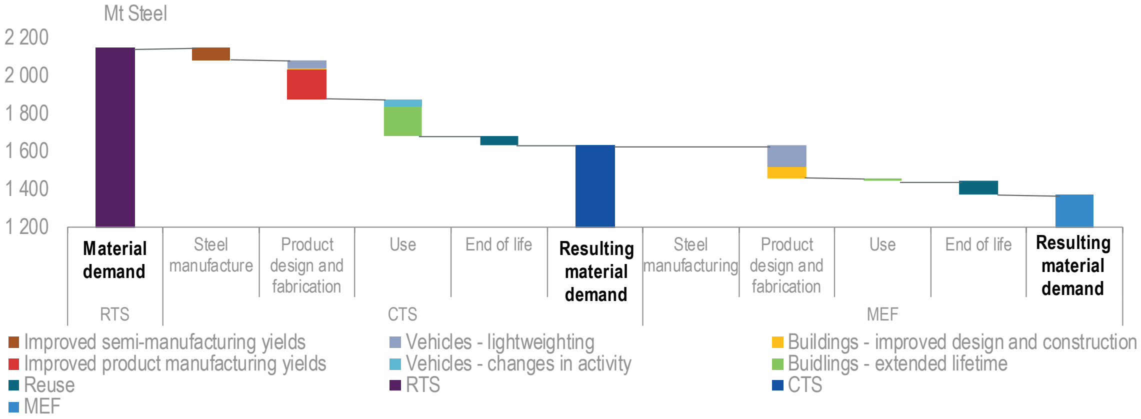
While material demand grows over time in the RTS, it is considerably reduced in the CTS and MEF.

Steel

For steel, the largest cumulative demand reductions from the Reference Technology Scenario to the Clean Technology Scenario occur in the product design and fabrication stage and the use stage, with substantial savings from improving product manufacturing yields and buildings lifetime extension. In the Reference Technology Scenario many buildings would be demolished and rebuilt before the end of their useful life, but major investment in energy efficiency retrofits in the Clean Technology Scenario leads to many of these buildings staying in service longer.

In the Material Efficiency variant, the largest additional savings in steel demand occur from vehicle lightweighting. Significant contributions also come from improving buildings design and construction and reusing steel.

Figure 5. Steel demand change by value chain stage across scenarios in 2060



Notes: RTS = Reference Technology Scenario. CTS = Clean Technology Scenario. MEF = Material Efficiency variant.

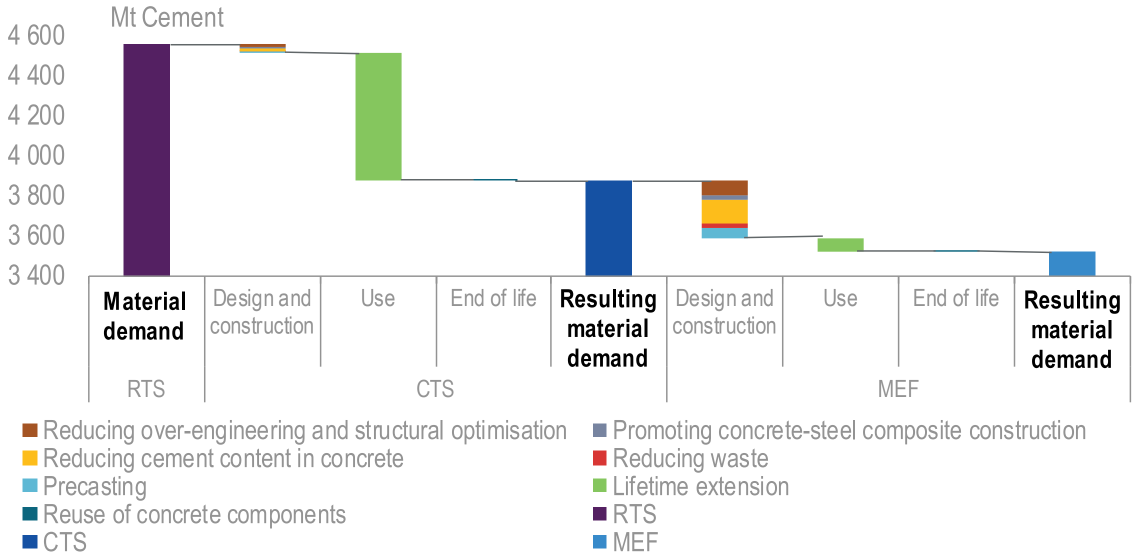
There is considerable potential to reduce steel demand at all stages of product and buildings life cycles.

Cement

Buildings lifetime extension contributes to nearly all of the cement demand reductions in the Clean Technology Scenario relative to the Reference Technology Scenario. This lifetime extension is again the result of retrofits and repurposing pursued in concurrence with buildings energy retrofits.

In the Material Efficiency variant, improvements to buildings design and construction are pursued much more aggressively, contributing to most of the additional reductions beyond the Clean Technology Scenario. The strategies include reducing concrete over-engineering and structural optimisation, promoting concrete-steel composite construction, reducing cement content in concrete and reducing on-site construction waste.

Figure 6. Cement demand change by value chain stage across scenarios in 2060



Notes: RTS = Reference Technology Scenario. CTS = Clean Technology Scenario. MEF = Material Efficiency variant.

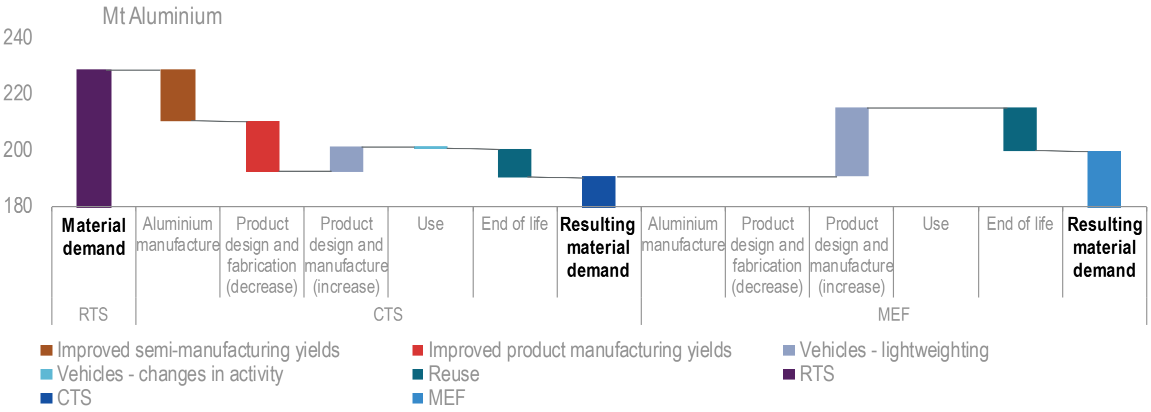
The buildings use phase offers the largest potential to reduce cement demand, followed by the design and construction stage.

Aluminium

In the Clean Technology Scenario, a considerable downward pressure on aluminium demand occurs because of improved aluminium semi-manufacturing yields and improved product manufacturing yields. However, vehicle lightweighting puts a substantial upward pressure on aluminium demand, as manufacturers substitute aluminium for steel to meet fuel efficiency objectives. The net result is a decline in aluminium demand.

Conversely, in the Material Efficiency variant, additional vehicle lightweighting has the largest effect and results in a net increase in aluminium demand relative to the Clean Technology Scenario. However, a large proportion of the increase from lightweighting is offset by reductions from aluminium reuse.

Figure 7. Aluminium demand change by value chain stage across scenarios in 2060



Notes: RTS = Reference Technology Scenario. CTS = Clean Technology Scenario. MEF = Material Efficiency variant.

While reductions in aluminium demand can be achieved at various stages in value chains, a large portion of these reductions is offset by increases in demand from lighter vehicles.

Energy and CO$_2$ emissions

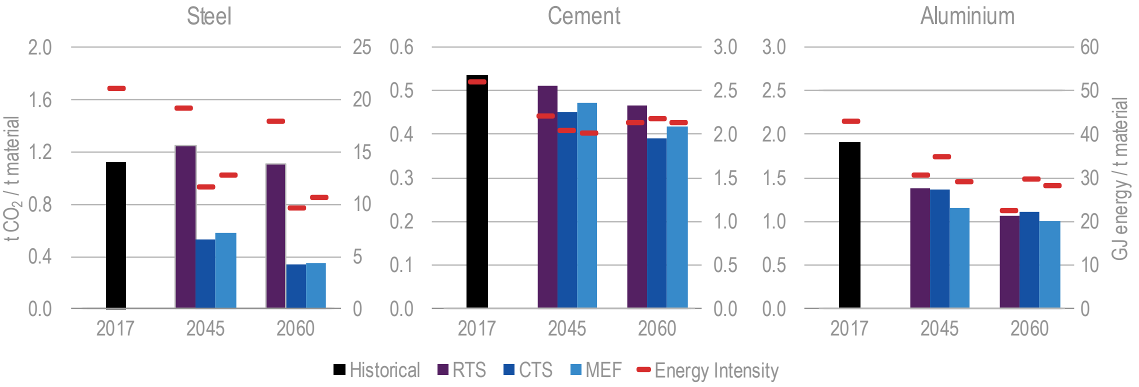
Improving material efficiency can help in achieving emissions reduction, by enabling more moderate deployment of other industry CO$_2$ mitigation levers and by facilitating emissions reduction in other sectors.

In the Clean Technology Scenario, material efficiency assists industry in reducing industrial emissions from the Reference Technology Scenario, contributing approximately 20% of the total emissions reduction for steel, 70% for cement and 30% for aluminium. Material efficiency accounts for approximately 30% of the combined emissions reduction for these three materials in the Clean Technology Scenario in 2060.

Pushing material efficiency further in the Material Efficiency variant leads to more moderate deployment needs for low-carbon industrial process technologies to achieve the same industrial emissions reduction objectives as in the Clean Technology Scenario, particularly when these strategies lead to lower material demand levels. In 2060, the global average direct CO$_2$ emissions intensity of steel production is 4% higher and that of cement is 7% higher in the Material Efficiency variant than in the Clean Technology Scenario, despite achieving the same level of CO$_2$ emissions.

Conversely the global direct CO$_2$ intensity of production of aluminium decreases in the Material Efficiency variant (by 9% in 2060), as the higher material demand requires greater uptake of emission abatement technologies to achieve the same overall emissions levels. This somewhat increased technological effort in the aluminium sector reduces deployment needs for other mitigation options in the transport sector, given that the higher aluminium demand is caused by vehicle lightweighting to reduce transport use-phase emissions.

Figure 8. Direct CO_2 and energy intensity of production for steel, cement and aluminium by scenario



Note: GJ = gigajoules; t = tonne; tCO_2 = tonnes of carbon dioxide. RTS = Reference Technology Scenario. CTS = Clean Technology Scenario. MEF = Material Efficiency variant.

Lower material demand levels result in higher direct CO_2 intensity of production in the MEF while remaining within the CTS industrial emissions level.

Changes in manufacturing direct emissions intensity in the Material Efficiency variant mean that other carbon mitigation technologies need to be deployed at different rates compared to in the Clean Technology Scenario. For steel and cement, lower total material demand means lower cumulative capital technology investment by 2060 in the Material Efficiency variant compared to in the Clean Technology Scenario. For aluminium, the investment is increased. The investment reductions in steel and cement outweigh the increase in aluminium, resulting in a total cumulative technology investment 4% lower in the three subsectors combined. An example of the reduced investment is that cumulative captured and stored CO_2 emissions are 45% lower in the cement sector in the Material Efficiency variant than the Clean Technology Scenario.

Instead of reducing deployment needs for low-carbon industrial process technologies while achieving the same decarbonisation levels, material demand reductions could result in additional CO_2 emissions reduction. If the Clean Technology Scenario emissions intensity of production were maintained to produce the Material Efficiency variant level of material demand, combined direct emissions in steel, cement and aluminium would be reduced by 7% in 2060 relative to the Clean Technology Scenario. In reality, pushing material efficiency to practical limits would likely result in a combination of reduced industrial emissions and reduced deployment needs for low-carbon industrial process technologies, rather than one or the other only.

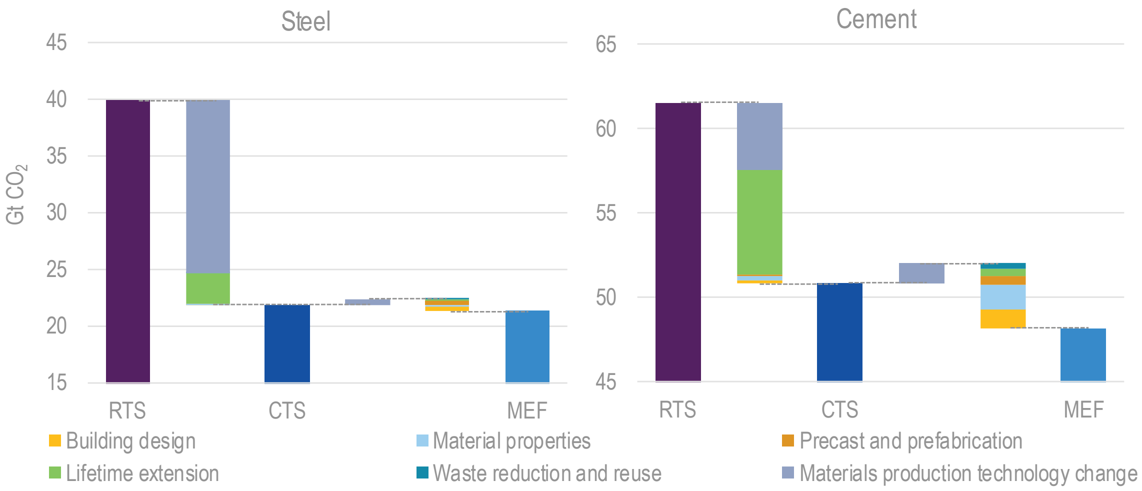
Buildings construction value chain

In the buildings sector, material demand in the Reference Technology Scenario increases to over 30% by 2060 above 2017 levels for both steel and cement. This is because rapid construction rates in urban areas coupled with limited efforts to put in place material efficiency strategies sustain recent material demand trends. Steel and cement manufacturing for buildings construction and renovation are responsible for an average of 2.3 gigatonnes of carbon dioxide ($GtCO_2$) annually to 2060, the equivalent of all of India's emissions in 2017.

In the Clean Technology Scenario, with widespread adoption of buildings codes and standards, demolition rates shrink considerably. Developed countries also implement large-scale deep energy retrofit programmes, which leads to buildings being used for longer. As a result, steel and cement demand are reduced by one-quarter in 2060 relative to the Reference Technology Scenario, with buildings lifetime extension contributing over 90% of the reductions.

These material demand reductions lower CO_2 emissions from buildings steel and cement use by 10% (10 gigatonnes [Gt]) cumulatively from 2017 to 2060 in the CTS. For steel, material demand reductions account for 16% of the cumulative emissions reduction relative to the Reference Technology Scenario, with the remainder of reductions resulting from changes to lower-emission technologies and process routes to produce steel. For cement, 63% of the emissions reduction is attributable to material demand reduction. While the cumulative reduction in demand for steel and cement is similar (12%), the larger contribution of material demand reduction to reducing cement than steel emissions occurs due to the greater difficulties in decarbonising cement production.

Figure 9. CO_2 emissions related to steel and cement use for buildings construction and renovations by scenario, cumulative from 2017 to 2060



Notes: Emissions from material lost in the semi-manufacturing are not included. RTS = Reference Technology Scenario. CTS = Clean Technology Scenario. MEF = Material Efficiency variant.

Material demand reductions in the buildings sector help reduce steel and cement emissions in the CTS, while reducing some of the need for material production technology change in the MEF.

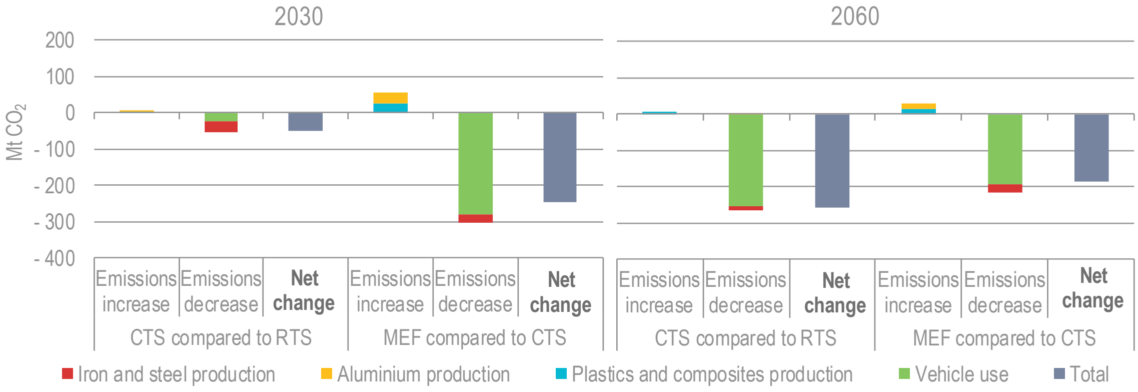
Pursuing material efficiency strategies to their practical limit in the Material Efficiency variant reduces steel use by an additional 15% and cement use by another 17% in 2060. The additional material demand reductions in the MEF reduce some of the deployment needs for low-carbon materials production process technologies. This results in higher emissions intensity of steel and cement production while still achieving the same carbon budget as in the Clean Technology Scenario. Yet, the steel and cement cumulative CO_2 emissions attributable to buildings are lower in the MEF than in the CTS by 5 Gt. This is due to greater reductions in deploying low-carbon industrial process technologies in regions with higher proportions of material demand from end uses other than buildings.

For steel, the largest contributors to material demand reduction in the Material Efficiency variant beyond the Clean Technology Scenario are improvements in buildings design and precasting. Each of these contribute to around 40% of the cumulative emissions reduction attributable to steel demand reduction beyond the Clean Technology Scenario. For cement, improved materials properties (i.e. reducing the cement content in concrete) makes the largest contribution, equal to over one-third of the emissions reduction attributable to cement demand reduction.

Vehicles value chain

For passenger light-duty vehicles, in the Reference Technology Scenario a combination of increasing stocks and lightweighting leads to demand for steel in 2060 that is approximately 20% higher than that in 2017. For aluminium, it is four times higher, and for plastics and composites, it is two times higher. In the Clean Technology Scenario, a combination of reduced vehicle sales, more aggressive lightweighting, improved manufacturing yields and increased reuse results in a considerable reduction in demand for steel (50% lower than in the Reference Technology in 2060), a moderate reduction in demand for aluminium (7% in 2060) and plastics and composites (10% in 2060). The greater push for lightweighting in the Material Efficiency variant results in a further decline in demand for steel (by an additional three-quarters in 2060 relative to the Clean Technology Scenario) and an increase in aluminium (one-quarter in 2060 relative to the Clean Technology Scenario) and plastics and composites (one-third). The material use trends for commercial light-duty and heavy-duty vehicles are similar to those for PLDVs.

Figure 10. **CO_2 emissions savings from lightweighting throughout the passenger light-duty vehicle value chain by scenario**



Notes: $MtCO_2$ = million tonnes of carbon dioxide. RTS = Reference Technology Scenario. CTS = Clean Technology Scenario. MEF = Material Efficiency variant.

Passenger light-duty vehicle lightweighting leads to net emissions savings in the CTS and additional savings when pushed further in the MEF. Absolute savings in 2060 in the MEF are lower than in 2030, primarily due to increased vehicle electrification, which lowers use-phase emissions savings.

Lightweighting – the primary material efficiency strategy pushed further for vehicles in the Material Efficiency variant – results in substantial value chain emissions savings for road vehicles. For passenger light-duty vehicles, lightweighting contributes approximately 10% of the global 2060 total vehicle use-phase emissions reduction in the Clean Technology Scenario over the Reference Technology Scenario, which is a substantial portion in the context of the many other strategies (e.g. modal shifting and fuel switching) that are being pursued in the sector. For commercial light-duty vehicles and heavy-duty vehicles (trucks and buses), lightweighting contributes 3%.

Pushing lightweighting further to its realistic limits leads to additional use-phase emissions reduction in the Material Efficiency variant, equivalent to an additional 20% of Clean Technology Scenario passenger light-duty vehicle use-phase emissions in 2060. While the materials required for this additional lightweighting lead to a moderate increase in emissions for passenger light-duty vehicle material production relative to the Clean Technology Scenario, this is greatly outweighed by the savings in the vehicle use phase. In the Material Efficiency variant, lightweighting results in a net decrease in passenger light-duty vehicle value chain CO_2 emissions of 17% in 2060 compared to in the Clean Technology Scenario. Light commercial vehicles and heavy-duty vehicles follow similar trends, with an additional net emissions saving of 9% in 2060 in that value chain.

The absolute CO_2 emissions saving in 2060 is about 25% lower than in 2030 in the Material Efficiency variant, despite more aggressive lightweighting. The reason is that a considerable portion of passenger light-duty vehicles have shifted to low-emission fuels, resulting in lower savings potential from lightweighting. While the net change in emissions for battery-electric vehicles depends on the carbon intensity of the electricity grid used to power the vehicle (together with many other factors), in some cases, pushing battery-electric vehicle lightweighting may result in a net increase in value chain emissions. This does not necessarily mean that lightweighting should not be pushed in battery-electric vehicles. Particularly in earlier periods when battery costs are still high, lightweighting could enable larger ranges or lower battery costs, thus facilitating greater uptake of battery-electric vehicles. In later periods, the pressure on increasingly scarce or expensive materials needed to produce batteries may be reduced because lighter vehicles can achieve the same performance (including range) with lighter batteries. For commercial light-duty and heavy-duty vehicles, net absolute emissions savings increase to 2060, as a large portion of these vehicles (particularly trucks) are still running on fossil fuels.

Enabling policy and stakeholder actions

Various challenges need to be overcome to ensure effective use of materials. Without any incentive or requirements to pursue material efficiency, or explicit demand from consumers, designers and manufacturing or construction companies may be unaware of the possible benefits of material efficiency; or they may chose not to pursue material efficiency due to real and perceived risks, financial costs or lost revenues and time constraints. Fragmented supply chains may present challenges for achieving material efficiency, such as when users or demolition contractors are not connected to construction companies to facilitate end-of-life materials reuse. The regulatory environment may also restrict pursuit of material efficiency, such as when prescriptive design standards prevent uptake of new materials or design methods.

Efforts from governments, industry, the research community and society will be needed to overcome these challenges and accelerate the efficient use of materials. Policy and action priorities include the following:

- **Increase data collection, life-cycle assessment and benchmarking:** more-robust data and analysis on material inputs to end uses and trade-offs throughout value chains related to material inputs and use-phase emissions are needed. This would assist in developing benchmarks, understanding best practices, facilitating optimal decisions in the design stages that consider the life-cycle impact, developing programmes that incentivise material efficiency and adopting mandatory regulations that address the emissions impact of materials.

- **Improve consideration of the life-cycle impact at the design stage and in climate regulations:** life-cycle impact should be considered at the design stage so that design can help minimise life-cycle emissions. This could be facilitated by expanding the scope of regulations that focus on reducing CO_2 emissions in the use phase to cover the full life cycle of products. Life-cycle-based regulations could incorporate end-of-life requirements to help provide the expected emissions outcomes and standardised life-cycle assessment procedures to reduce the time and cost of compliance.
- **Increase end-of-life repurposing, reuse and recycling:** extending buildings or product lifetimes through repurposing and refurbishing, aided by government policies promoting durability and long lifetimes, should be prioritised in cases where doing so will not lock in considerably higher use-phase emissions. Greater uptake of reuse and recycling can be facilitated through better integration of supply chains, developing materials inventories, mandating a proportion of reused materials in certain products, expanding the coverage of recycling requirements and requiring producer responsibility.
- **Develop regulatory frameworks and incentives to support material efficiency:** moving from prescriptive to performance-based standards, including design, health and safety and fire protection standards, would facilitate efficient use of materials while ensuring their intended objectives are achieved. Other government policies to enhance material efficiency include carbon pricing, green certification programmes and government procurement.
- **Adopt business models and practices that advance circular economy objectives:** integrating policies at the corporate level of businesses can urge decision makers throughout companies to use materials wisely. Planning, monitoring and reporting will promote a culture of material efficiency and deter practices that may increase material use. More-innovative and new business models can also reduce material use, including those that promote a sharing economy and increased digitalisation.
- **Train, build capacity and share best practices:** material efficiency considerations should be included in education and training programmes for actors throughout value chains. These should include designers, engineers, construction workers, manufacturing companies and demolition companies. Government-supported capacity building would help to ensure compliance when adopting standards that require efficient material use. Best practice sharing among companies would be helpful to promote high standards of material efficiency.
- **Shift behaviour towards material efficiency:** as consumers, the public can direct demand towards products that are designed and fabricated with material efficiency in mind, and towards sharing economy-focused business models. Material-efficient consumer choices at product and buildings end of life are also important. Citizens can vote in support of government policies and investments that aim to reduce carbon emissions, which would aid and accelerate consumer shifts towards material efficiency.

Technical analysis

1. Introduction

The historic Paris Agreement marked a decisive shift in global discussions on climate change. So far, 185 parties have ratified the agreement to limit the global average temperature increase to well below 2 degrees Celsius (°C) above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5°C. With two-thirds of all greenhouse gas emissions linked to energy use, implementing the Paris Agreement has far-reaching consequences, and requires a transformation of the global energy system of unprecedented scope and ambition. A portfolio of clean energy technologies covering energy demand and supply will need to be commercialised and adopted; contributions from all sectors and regions will be needed.

Industrial sectors provide the key materials that are essential components for adequate quality of life and social and economic well-being. These materials include: iron and steel; chemicals; aluminium, copper and other non-ferrous metals; cement, glass and other non-metallic minerals; and pulp and paper. The construction of homes, schools, hospitals, transport systems and infrastructure for clean water and energy supply relies on considerable material inputs. Materials also play an important role in daily lives – they are embodied in goods consumed or used, from mobile phones to food wrappers. Materials are also an important enabler of carbon emissions mitigation technologies (e.g. those for generating renewable electricity).

While vital to human well-being, the manufacture of materials and their transformation into end-use products account for considerable use of resources and environmental effects. Industry currently represents about 40% of global final energy demand (approximately 150 exajoules in 2017) and around one-quarter of global carbon dioxide (CO_2) emissions.[1] Reducing CO_2 emissions in energy-intensive industries such as iron and steel, cement, aluminium and chemicals remains particularly difficult. Many widely established industrial processes are dependent on fossil fuels, including for high-temperature heating. Some industrial activities also release CO_2 as an inherent part of their established processes. Examples include the calcination of limestone for cement production, the use of coke to reduce iron ore for steel production or the consumption of carbon anodes in primary aluminium smelting. These process emissions currently account for approximately one-quarter of direct industrial emissions. Furthermore, industry tends to have capital-intensive production assets with long stock turnovers, which poses barriers to rapid technology shifts.

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[1] Unless otherwise specified, references to energy demand in this publication include energy used for feedstock, and energy sector CO_2 emissions include industrial process emissions.

However, there is growing recognition in the public and private sectors that greater attention and resources are needed to accelerate progress in clean energy transitions for industry. There are generally four key levers to reducing industrial CO_2 emissions: reducing the amount of energy consumed through deployment of energy-efficient best available technologies; switching towards fuels and feedstocks that are less carbon intensive; deploying innovative technologies, including carbon capture utilisation and storage (CCUS) and alternative process routes; and reducing the amount of carbon-intensive materials produced through material efficiency strategies.

Each of these levers presents opportunities but also challenges. For example, the potential for fuel switching depends on the availability and costs of alternative low-carbon options, sustainable biomass, electricity generated from renewable sources of energy and hydrogen. Uncertainties exist surrounding the development and deployment of innovative technologies that can considerably reduce industrial sector emissions. These include CCUS, alternative cement constituents and binding materials, and alternative low-carbon iron and steel production routes.

Considering the challenges and uncertainties in achieving significant CO_2 emissions reduction in the industrial sector, the analysis in this report focuses on an emissions mitigation lever that has received less widespread attention: material efficiency. Understanding how the demand of materials might evolve in the future is integral to projecting energy and emissions trends in industry. Using materials more efficiently can enable reduced demand for materials, thus helping reduce emissions and leading to more moderate deployment needs for low-carbon industrial process technologies. Furthermore, material use has linkages to emissions mitigation efforts in other sectors. In some cases, mitigation efforts in other sectors will also reduce material demand, but in other cases, increases in material use may enable greater reductions at other points in the supply value chains, providing overall lower value chain emissions. Thus, understanding the role of material use and material efficiency and the linkages among sectors will be important for overall energy system emissions reduction efforts.

For over a decade, the *Energy Technology Perspectives* series has focused on the role of energy technologies in achieving multiple societal objectives, including delivering cost-effective mitigation options for meeting global climate ambitions. Past editions of the *Energy Technology Perspectives* have explored a variety of critical themes including energy systems integration, electrification, sustainable urban energy systems and innovation. This report builds on the past analysis to look deeper at the role of material demand and material efficiency in clean energy transitions.

Central to the analysis is the use of scenarios to assess the implications of different pathways in the development of the energy system to 2060. Beyond the Reference Technology Scenario (RTS) and the Clean Technology Scenario (CTS), which are used as the benchmark for the analysis (see Box 2 and Annex I), this report focuses on a Material Efficiency variant (MEF). This variant looks at the implications of pushing material efficiency strategies to their practical limits, with a focus on three key energy and emissions-intensive materials: steel, cement and aluminium. It aims to achieve the same cumulative emissions budget and thus climate objectives as the CTS. Given the challenges in drastically reducing CO_2 emissions in energy-intensive industrial sectors and uncertainties around the development, deployment and costs of key emissions mitigation technologies, it considers accelerated and more ambitious material efficiency strategies than in the CTS, thus reducing the need for technology shifts as required in the CTS.

Box 2. Scenarios discussed in this analysis

The scenarios should not be considered to be predictions, but instead as analyses of the impact and trade-offs of different technology choices and policy targets, thereby providing a quantitative approach to support decision-making in the energy sector. The scenarios are constructed through a combination of projecting the long-term implications of near-term trends already known and "backcasting" to develop pathways to a desired long-term outcome. The technology portfolio considered does not include any unforeseen breakthroughs over the projection period to 2060. All options adopted are based on either commercially available technologies or those in the innovation pipeline that have reached pilot or demonstration stage, meaning they are assumed to become commercially available within the scenario period. Annex II gives additional details on the Energy Technology and Policy modelling framework.[2]

The RTS accounts for today's commitments by countries to limit emissions and improve energy efficiency, including the current nationally determined contributions pledged under the Paris Agreement. By factoring in these commitments and recent trends, this scenario already represents a major shift from a historical "business as usual" approach with no meaningful climate policy response. However, global emissions increase by 8% by 2060 from 2017 levels – a pathway far from sufficient to achieve the Paris Agreement objectives.

The CTS lays out an energy system pathway and a CO_2 emissions trajectory in which CO_2 emissions related to the energy sector are reduced by around three-quarters from today's levels by 2060. Among the decarbonisation scenarios projecting a median temperature rise in 2100 of around 1.7-1.8°C in the Intergovernmental Panel on Climate Change database, the trajectory of energy- and process-related CO_2 emissions of this scenario is one of the most ambitious in the medium term and remains well within the range of these scenarios through to 2060. The CTS is the central climate mitigation scenario used in this analysis. It represents a highly ambitious and challenging transformation of the global energy sector that relies on a substantially strengthened response compared with today's efforts. It opens the possibility of the pursuit of ambitious global temperature goals, depending on action taken outside the energy sector and the pace of further emissions reduction after 2060.

Annex I gives a more detailed overview of the RTS and CTS.

A key new feature developed for this report is a partial bottom-up assessment of material demand. The technological transition embedded in the CTS sets different material to gross domestic product linkages compared to historical dynamics, as alternative technologies are deployed and more lightweighting and long-lasting strategies are prioritised. Intentional material efficiency efforts also affect material demand. The RTS material demand curves are developed by considering historical material demand trends and future projections of economic and population growth, with consideration of improvements in manufacturing yields, reuse and recycling within industry. The CTS and the MEF look at changes in material demand from the RTS, based on further material efficiency improvements within industry but also changes due to technology shifts, changes in consumer behaviour and material efficiency within the buildings construction and vehicles value chains. The analysis involved developing a bottom-up

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[2] See annexes available at the end of this report.

assessment of material demand for buildings and vehicles, based on activity levels and material demand intensities (material use per unit of activity). By integrating analysis of materials production and demand, this method allows for assessing how materials can be used efficiently to enable optimal emission outcomes throughout value chains. Note that throughout this publication, 2017 values are estimates based on data from 2015 and 2016, unless stated otherwise.

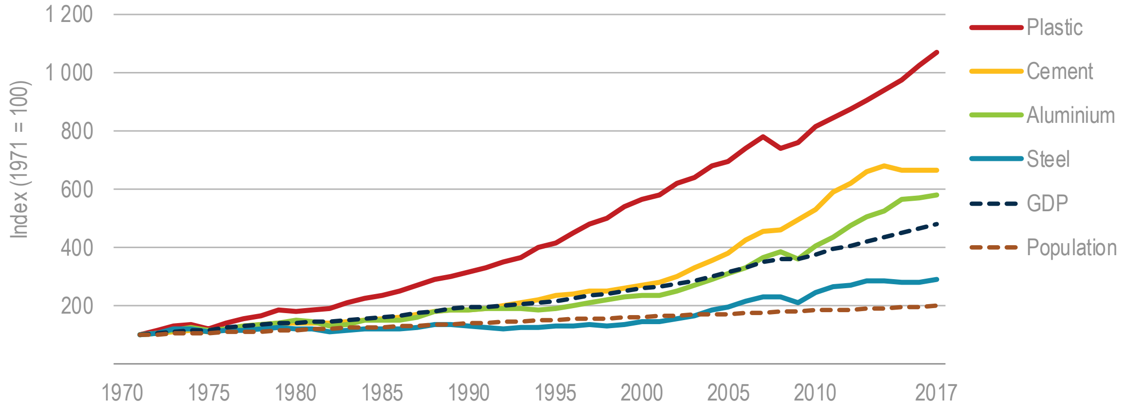
The remainder of this publication focuses on the implications of material demand and efficiency. Chapter 2 provides an overview of historical and current demand trends for key energy and emissions-intensive materials: steel, cement and aluminium. Chapter 3 discusses the need to transition towards more sustainable use of materials and highlights supportive material efficiency strategies at different stages of supply chains. Chapter 4 outlines the overall emissions and energy implications of deploying further material efficiency. Chapters 5 and 6 provide deep dives into the buildings construction and vehicles value chains. Chapter 7 concludes with a discussion of stakeholder policy and action priorities that can help overcome the challenges of increasing material efficiency.

2. Historical demand trends for materials

Materials are the fundamental building blocks of society. They make up the buildings, infrastructure, equipment and goods that enable businesses to operate and people to carry out their daily activities. They enable services such as transport, shelter and mechanical labour, in many cases through the use of energy. They will also play an important role in enabling clean energy transitions.

Global demand for key materials has grown considerably over past decades. Since 1971, global demand for steel has increased by three times, cement by nearly seven times, primary aluminium by nearly six times and plastics by over ten times (Figure 11). Material consumption growth has coincided with population and economic development. In the same period, global population doubled, while global gross domestic product (GDP) grew nearly fivefold. Rapid economic development in the People's Republic of China ("China") has resulted in most of the growth in material demand since 2000, particularly for cement, steel and aluminium.

Figure 11. Demand growth for key materials, GDP and population



Notes: Outputs of different industrial sectors are displayed on an index basis referred to 1971 levels. *Aluminium* refers to primary aluminium production only. *Steel* refers to crude steel production. *Plastics* includes a subset of the main thermoplastic resins.

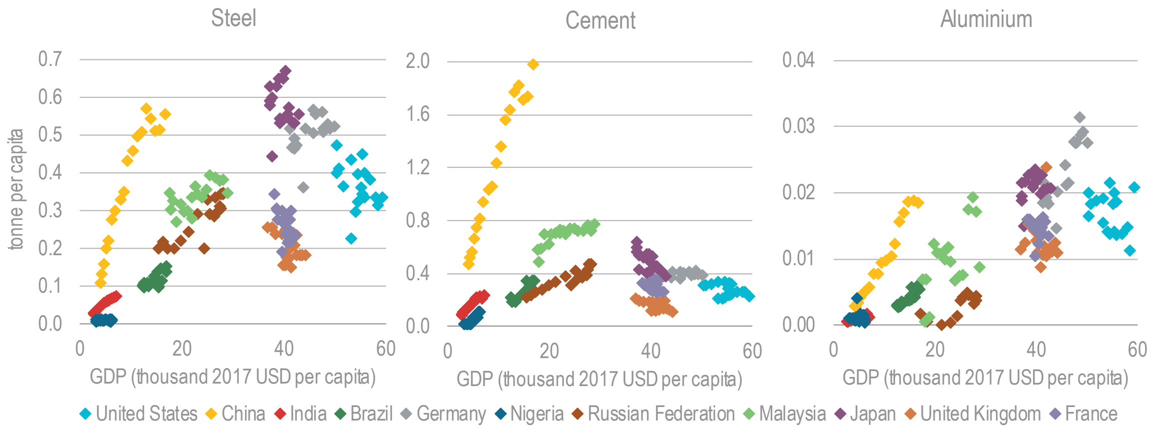
Sources: Geyer, R., J.R. Jambeck and K.L. Law (2017), "Production, use and fate of all plastics ever made", https://doi.org/10.1126/sciadv.1700782; worldsteel (2018), Steel Statistical Yearbook 2018, www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf; IMF (2018), World Economic Outlook Database, www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx; USGS (2018a), 2016 Minerals Yearbook: Aluminium, https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2016-alumi.pdf; USGS (2018b), 2015 Minerals Yearbook: Cement, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2015-cemen.pdf; USGS (2017), 2015 Minerals Yearbook: Nitrogen, https://minerals.usgs.gov/minerals/pubs/commodity/nitrogen/myb1-2015-nitro.pdf. Levi, P.G. and J.M. Cullen (2018), "Mapping global flows of chemicals: From fossil fuel feedstocks to chemical products", https://doi.org/10.1021/acs.est.7b04573.

Demand for materials has grown considerably over past decades. Much of the growth since 2000 has been due to rapid development in China.

The relationship among material demand and macroeconomic and social developments is complex. In general, at lower levels of economic development, per capita demand for materials tends to be relatively low. As economies develop, urbanise, consume more goods and build up their infrastructure (e.g. high-rise buildings, roads and electricity generation infrastructure), material demand per capita tends to significantly increase. Once industrialised, material demand per capita may level off and even begin to decline. At that stage, materials are used primarily for replenishing and renovating rather than building up stocks, particularly for materials like steel and cement that are key inputs to infrastructure. Short lifetimes of some products and behavioural patterns geared towards acquiring more new and modern products may increase demand for other materials such as aluminium and plastics.

Historical data on per capita apparent consumption in different countries demonstrate the general correlation between increasing material demand and increasing economic development (Figure 12). However, they also highlight that there is no simple and uniform relationship between material demand and GDP. For example, countries having reached advanced stages of economic development may still have different per capita demand for materials, as is the case of the greater steel consumption in Japan than in the United Kingdom. In another example, cement consumption in China has reached levels that are more than three times higher than the global per capita average. Part of the explanation for the high levels of material demand in China is the rate of economic development, as well as growth in exports. From 2000 to 2015, per capita GDP in China grew fourfold, in comparison to, for example, a more than doubling in India and an almost doubling in Nigeria. Differing material per capita consumption for countries with similar GDP levels is also the result of factors such as the make-up of the economy (i.e. oriented towards industrial versus service-based activities), contrasting manufacturing and construction practices and different behavioural patterns.

Figure 12. Per capita material apparent consumption and per capita GDP for selected countries from 2000 to 2017



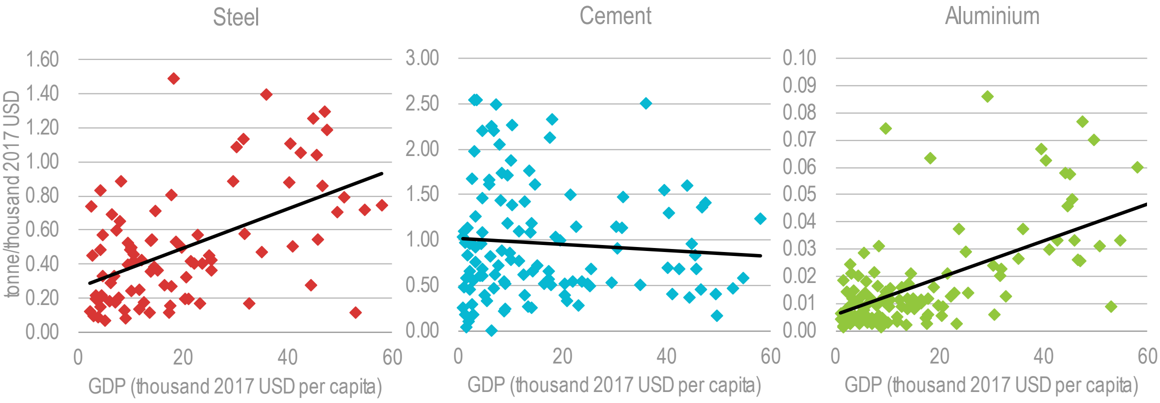
Notes: For cement, apparent consumption is assumed equal to production, given limited international trade; 2016 is an estimate and 2017 is an extrapolation of trends since 2000. For steel, apparent consumption is that reported by worldsteel. For aluminium, apparent consumption is primary production reported by the United States Geological Survey (USGS), adjusted for exports and imports as reported by the United Nations Commodity Trade Statistics Database (UN Comtrade); 2017 is an extrapolation of trends since 2000. Aluminium apparent consumption does not include secondary production, as historical secondary production statistics are limited. Apparent consumption refers to bulk materials as opposed to manufactured components. USD = United States dollars.

Sources: worldsteel (2018), Steel Statistical Yearbook 2018, www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf; IMF (2018), World Economic Outlook Database, www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx; USGS (2018a), 2015 Minerals Yearbook: Aluminium, https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2015-alumi.pdf; USGS (2018b), 2015 Minerals Yearbook: Cement, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2015-cemen.pdf; United Nations (2018), UN Comtrade Database, https://comtrade.un.org/.

Generally, economic development leads to higher levels of material demand per capita.

The material requirements to achieve further economic development are different at different levels of economic development (Figure 13). Achieving a unit of economic growth tends to require increasing per capita demand for steel and aluminium consumption as GDP rises. This is due to the dependency on metals of higher-value segments (e.g. vehicles and digital devices) beyond infrastructure developments, which are more prevalent in economies at moderate levels of GDP. While the relationship between cement demand and GDP growth is less pronounced, achieving a unit of economic growth tends to require somewhat declining per capita cement consumption as GDP rises. The largest cement demand per unit of GDP tends to occur at low to moderate levels of economic development as a result of expanding basic infrastructure. This demand tends to fall moderately at higher levels of GDP for many countries, as major infrastructure developments have been accomplished. Yet there is significant variability of demand for all three materials at a given level of GDP, indicating the influence of individual country circumstances and economic structure on material demand.

Figure 13. Cumulative material apparent consumption demand per unit of GDP growth from 2000 to 2017 for selected countries



Notes: For cement, apparent consumption is assumed equal to production, given limited international trade; 2016 is an estimate and 2017 is an extrapolation of trends since 2010. For steel, apparent consumption is that reported by worldsteel. For aluminium, apparent consumption is primary production reported by the United States Geological Survey (USGS), adjusted for exports and imports as reported by the UN Comtrade; 2017 is an extrapolation of trends since 2010. Aluminium apparent consumption does not include secondary production, as historical secondary production statistics are limited. Apparent consumption refers to bulk materials as opposed to manufactured components. The vertical axis shows the sum of material demand from 2000 to 2017 per capita divided by the change in GDP per capita from 2000 to 2017. The horizontal axis shows the average GDP per capita from 2000 to 2017. Each data point represents one country; extreme outliers and countries where GDP declined from 2000 to 2017 are excluded. The black lines are the linear trend lines of the data.

Sources: worldsteel (2018), Steel Statistical Yearbook 2018, www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf; IMF (2018), World Economic Outlook Database, www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx; USGS (2018a), 2015 Minerals Yearbook: Aluminium, https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2015-alumi.pdf; USGS (2018b), 2015 Minerals Yearbook: Cement, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2015-cemen.pdf; United Nations (2018), UN Comtrade Database, https://comtrade.un.org/.

Economic development requires greater quantities of steel and aluminium per capita, while the highest cement demand per capita occurs at moderate levels of GDP to support infrastructure developments.

Although materials bring benefits to society, they are also a source of environmental impact. Converting raw materials into materials for use results in substantial energy consumption and carbon dioxide (CO_2) emissions. Along with growth in material demand, energy and emissions effects from material production have grown substantially, increasing by more than one and a half times over the last 25 years (Figure 14). Industry accounted for nearly 40% of total final energy consumption and nearly one-quarter of direct CO_2 emissions in 2017.[3]

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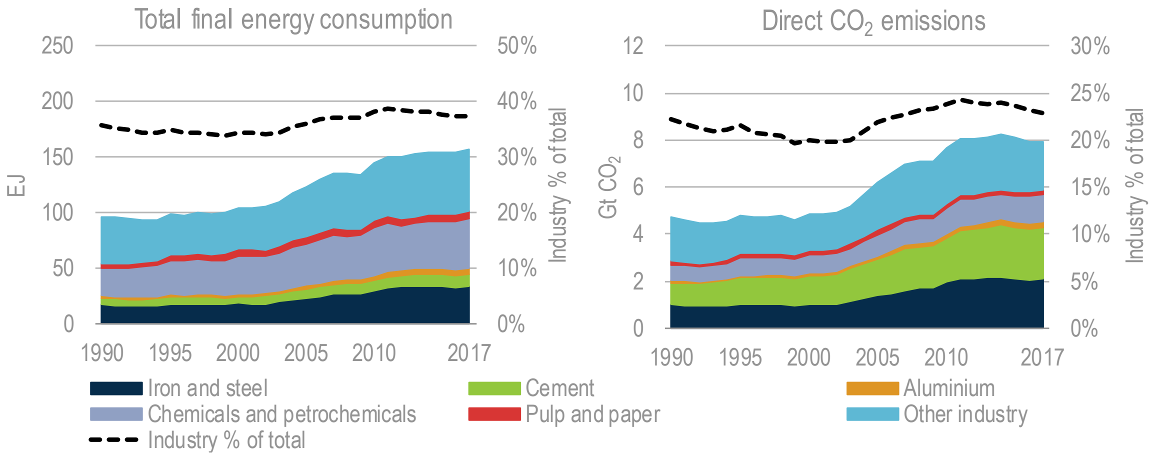
[3] Direct CO_2 emissions include energy-related and process emissions.

Figure 14. Global industry final energy consumption and direct CO_2 emissions



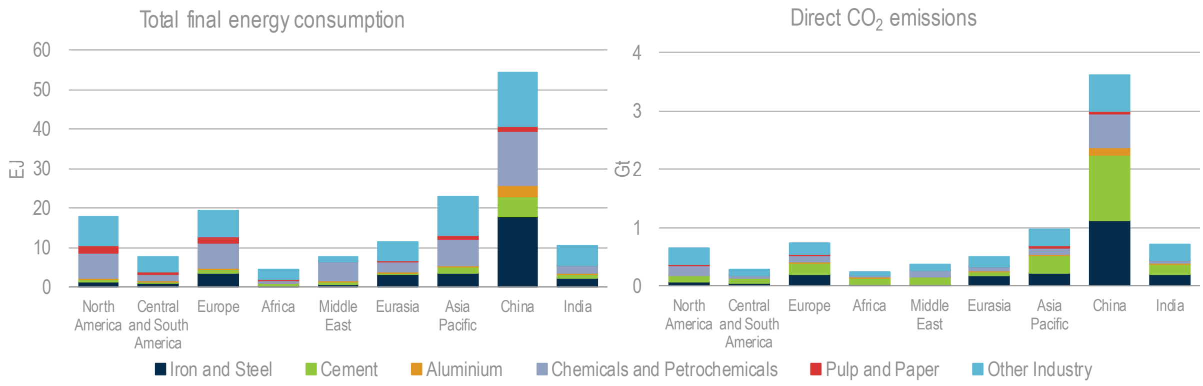
Notes: *Industry % of total* is industry divided by industry plus non-industrial sectors (includes buildings, transport, power generation and heat plants, agriculture, other energy uses and non-energy use). *Total final energy consumption* includes electricity consumption; *direct CO_2 emissions* do not include indirect emissions from producing the electricity consumed. EJ = exajoules; $GtCO_2$ = gigatonnes of carbon dioxide.

Industrial total final energy consumption and direct CO_2 emissions have grown more than one and a half times over the last 25 years.

China currently accounts for the largest share of global industrial energy consumption (35%) and industrial CO_2 emissions (nearly 50%) due to its dominant role in global materials manufacturing (Figure 15). The next largest key contributors are the Asia Pacific region excluding China and India (15% of energy consumption and 12% of emissions), Europe (12% of energy consumption and 9% of emissions), North America (11% of energy consumption and 8% of emissions), and India (7% of energy consumption and 9% of emissions). A large portion of industrial CO_2 emissions in these regions come from industrial activities that are not energy intensive (food and beverage, machinery, etc.) and the chemical and petrochemical sector. These regions play a much smaller role than that of China in steel, cement and aluminium manufacture.

Steel, cement and aluminium production are three of the largest emitting and energy-consuming industrial sources globally, together accounting for 13% of total direct global CO_2 emissions and 12% of final energy consumption in 2017. Thus, the analysis of this chapter focuses on these key bulk materials. Plastics produced by the chemicals sector are also a key source of emissions related to material demand. This analysis addresses plastics and composites demand from the vehicle supply chain. However, due to the diversity of plastics types used in a wide range of end uses, as well as data limitations, a more comprehensive assessment of plastics demand was beyond the scope of the analysis.

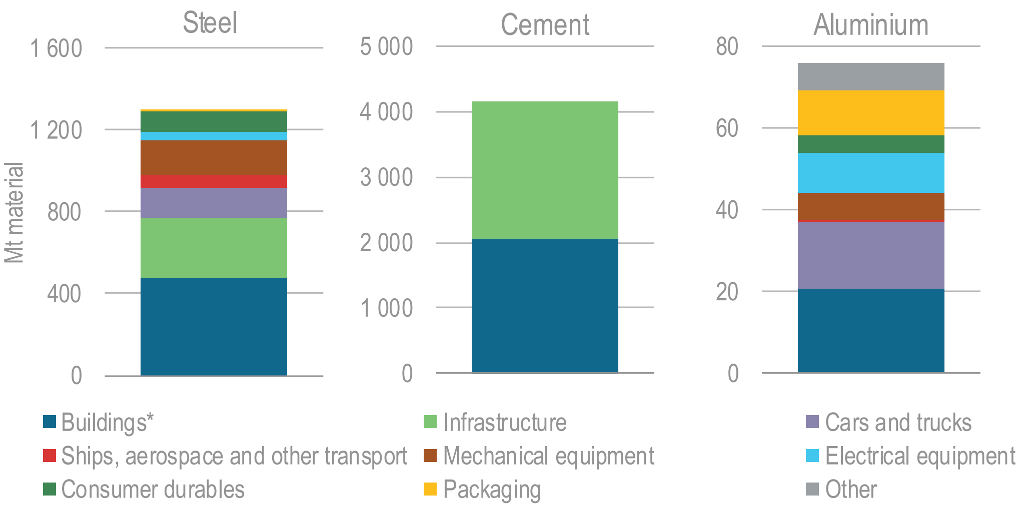
Figure 15. Energy consumption and direct CO_2 emissions from industrial sectors by region in 2017



Notes: Sizes are proportional by area to total regional energy consumption and emissions. *Other industry* refers to industrial subsectors that are not energy intensive, such as equipment manufacturing and food and beverage. Gt = gigatonnes.

China accounts for more than one-third of global industrial energy consumption and almost one-half of industrial emissions.

Figure 16. Estimated global demand of steel, cement and aluminium by end use in 2017



* For aluminium, the buildings category includes demand from all buildings and infrastructure construction, as a breakdown between the two is not available.

Notes: These inflow values do not include material lost in the semi-manufacturing and product manufacturing stages. Mt = million tonnes.

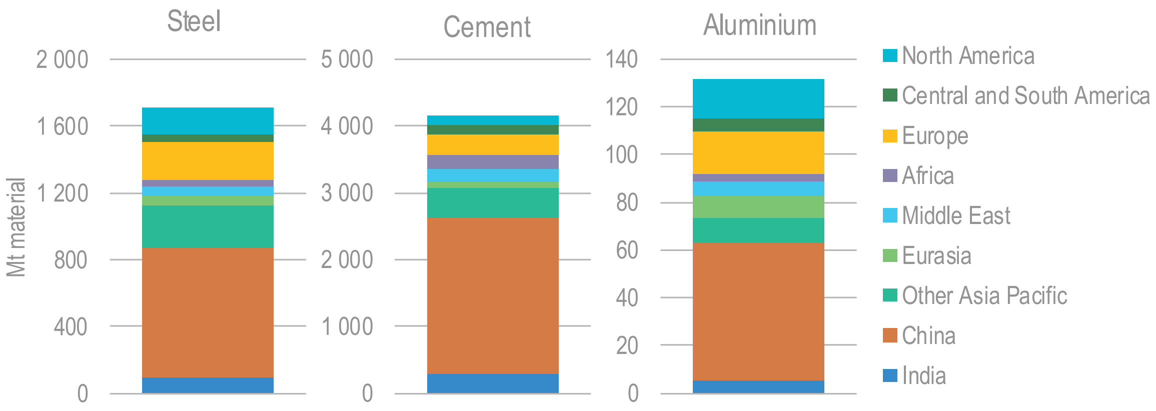
Sources: International Energy Agency analysis informed by Liu, G., Bangs, C. and Müller, D. (2013), "Stock dynamics and emission pathways of the global aluminium cycle", 10.1002/9781118679401.ch46; Pauliuk et al. (2013), "Steel all over the world", http://dx.doi.org/10.1016/j.resconrec.2012.11.008; World Aluminium (2017), Global Aluminium Mass Flow Model, www.world-aluminium.org/publications/.

Steel and aluminium are used in a wide variety of applications, while cement is used for buildings and infrastructure.

Owing to its high-strength properties, steel is used in a wide variety of applications such as in buildings (39%), infrastructure (22%), mechanical equipment (13%) and cars and trucks (11%) (Figure 16). Cement is a key component of concrete, constituting approximately 7-15% of concrete's mass, depending on the application, along with aggregates, water and additives. It is also used as mortar to fill gaps and bind together masonry materials. Buildings construction accounts for approximately one-half of global cement use, while the remainder is used in civil engineering applications such as the construction of roads, bridges and other infrastructure. Aluminium is an important material due to its low density and resistance to corrosion. End uses include cars and trucks (22%), buildings and construction (27%), cans and other packaging (14%) and electrical cables and other electrical uses (13%).

China is the largest consumer of steel, accounting for over 40% of global demand in 2017 (Figure 17). Other large consumers include the United States (6%), India (6%), Japan (4%) and Korea (3%). China is the largest producer and consumer of cement, producing close to 60% of global production. Other major producers include India (7%) and the United States, Viet Nam, Turkey, Indonesia and Saudi Arabia (each contributing approximately 2% of global production). Given that little international trade occurs for cement, production provides a reasonable indicator of consumption. China is also the largest consumer of aluminium (over 40%), followed by the United States, India, Canada, Japan, Germany and the Russian Federation (each accounting for 3-8% of global apparent consumption).

Figure 17. Apparent consumption of steel, cement and aluminium by region in 2017



Notes: These consumption values include material lost in the semi-manufacturing and product manufacturing stages. Cement and aluminium are extrapolations of 2015 and 2016 data, as 2017 data are not yet available.

Sources: worldsteel (2018), Steel Statistical Yearbook 2018, www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf; USGS (2018a), 2015 Minerals Yearbook: Aluminium, https://minerals.usgs.gov/minerals/pubs/commodity/aluminum/myb1-2015-alumi.pdf; USGS (2018b), 2015 Minerals Yearbook: Cement, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2015-cemen.pdf; United Nations (2018), United Nations Commodity Trade Statistics Database, https://comtrade.un.org/.

China dominates the global consumption of bulk materials.

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3. Enabling strategies to move towards more sustainable material use

With expected population and economic growth over the coming decades, the Reference Technology Scenario (RTS) sees world demand for steel grow by approximately 30%, cement by 10% and aluminium by about 75% through to 2060, relative to 2017 levels.[4] The expected future trends differ from observed trends in the past two decades, which saw large increases in cement and steel demand, primarily due to rapid growth in the People's Republic of China ("China").

While a substantial portion of the growth in material production was necessary to facilitate infrastructure development and subsequently economic growth, the rise in production capacity was higher than the growth in domestic demand. This resulted in overcapacity and lowered utilisation rates, particularly for cement, which has a limited potential for trade. The growth in cement and steel production in China is now levelling off. It is predicted that economic development in other regions will result in more moderate growth in demand for cement and steel. Expected shifts in applications (e.g. lightweighting of vehicles under current trends and growth in consumption of electric devices) may result in considerable increases in aluminium demand. Together, the increasing future material demand trajectories pose challenges for sustainability.

Materials demand and production need to be managed to reduce the impact on natural resources, air, water and the climate. Reducing the impact of materials is the foundation of the United Nations Sustainable Development Goal 12: ensure sustainable consumption and production patterns (United Nations General Assembly, 2015). The goal includes a target (target 12.2) to achieve the sustainable management and efficient use of natural resources by 2030. This is measured in terms of the material footprint, which is the amount of primary materials needed to meet a country's needs, and domestic material consumption, which is the amount of natural resources used in economic processes. The goal also aims to substantially reduce waste generation through prevention, reduction, recycling and reuse (target 12.5). However, economic development is also needed to achieve the Sustainable Development Goals. As the preceding chapter has shown, material demand and its associated effects have historically coincided with economic growth. Thus, there is a need to decouple economic growth from a combination of demand for materials and the environmental impact of materials production, to enable achievement of development objectives while ensuring sustainability.

The environmental impact of materials depends on the impact per unit of material produced and the quantity of materials consumed. Looking specifically at carbon dioxide (CO_2) emissions, the emissions per unit of material can be reduced by improving the production processes of a given material. This includes switching to lower-carbon fuels, improving energy efficiency and shifting to innovative low-carbon production processes, or switching to different materials with lower production emissions. The quantity of material demanded can be reduced by employing various material efficiency strategies, which aim to lower material consumption without reducing the quantity or quality of services provided. Other factors, such as technological shifts to help mitigate climate change, can also affect the quantity of materials demanded. Thus, the

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[4] RTS material demand projections are based on historical demand trends, observed material demand saturation levels, and population and gross domestic product projections.

quantity of materials consumed depends on the demand for products and services and the material demand per product or service (referred to here as material intensities).

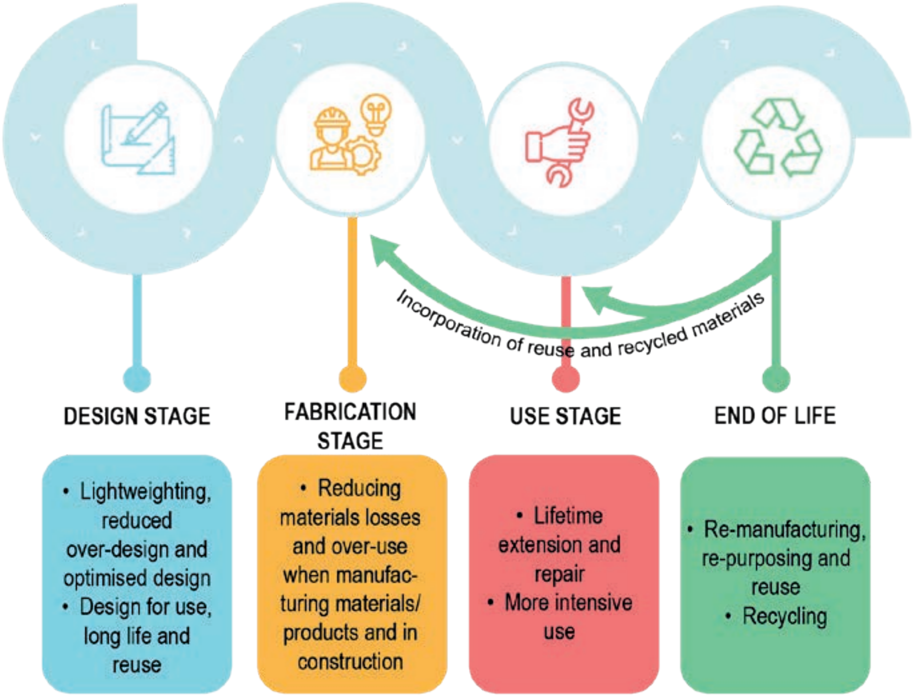
The Clean Technology Scenario (CTS) considers substantial reductions in industrial CO_2 emissions, falling by about 45% by 2060 from 2017 levels, in comparison to an increase of approximately 15% by 2060 in the RTS. The CTS already considers material demand reduction from the RTS through material efficiency strategies. If material demand trends continue in line with growing population and gross domestic product, as in the RTS, this implies that even greater reduction in emissions per unit of material produced will be required. For example, for cement, the CTS sees an approximate 30% reduction in emissions intensity by 2060 relative to the 2017 level. However, if cement demand continues at RTS levels, emissions intensity would instead need to be reduced by approximately 40% to achieve the same CTS emissions reduction. This would be a considerable technical and economic challenge, given the slow progress to date in the development, demonstration and deployment of innovative industrial processes that enable a drastic reduction of their CO_2 footprint. While not eliminating the need for strong efforts to reduce emissions of material production, reducing the quantity of materials demanded through the implementation of material efficiency strategies would contribute to the overall emissions reduction goal, thus leading to more moderate requirements to reduce emissions per unit produced.

Material efficiency strategies

Strategies can be applied to use materials more efficiently to curb growth in material use. Different strategies can be applied throughout the supply chain of a given product, including the design, fabrication, use and post-use stages (Figure 18). Some of these strategies interact with each other, leading to synergies in some cases and limitations in others.

Some material efficiency strategies contribute not only to reducing material demand but also to reducing the environmental footprint of materials manufacturing. An example is increased collection of scrap steel or aluminium. Secondary production routes using scrap materials tend to have lower energy requirements than those using primary materials, while reuse and recycling of collected scrap materials also reduce demand for primary materials. Material substitution – switching from one material to another – reduces the quantity of demand for one material. If the substituted material has lower production emissions, then substitution also reduces emissions per unit of material used. An example of material substitution contributing to both factors would be introducing increasing proportions of alternative cement constituents into blended cement, thus reducing the required quantity of higher-emission clinker. Material substitution may also facilitate energy and emissions savings during the use phase, as in the case of vehicle lightweighting.

Figure 18. Material efficiency strategies across the value chain



Numerous material efficiency strategies can be applied in the design, fabrication, use and end-of-life stages.

Design stage

During the design stage, consideration should be given to how materials can be used most effectively to minimise CO_2 emissions across the product's full life cycle. In some cases, material efficiency involves using lower levels of material inputs. In other cases, emissions from upfront increases in material demand or using materials with higher production emissions may be outweighed by emissions savings at other stages. This may occur when designing a more durable product that does not need to be replaced as quickly or designing a well-insulated building with lower use-phase emissions.

Careful design may enable a product or building to be produced using smaller quantities of materials while still providing the same functionality. For vehicles, lightweighting can improve fuel efficiency and reduce use-phase CO_2 emissions. Lightweighting occurs through a combination of shaping components made of conventional steel to be thinner and more optimised and of substituting conventional steel with other lighter materials such as high-strength steel, aluminium and carbon fibre-reinforced plastics. In the construction sector, designers can strive to reduce overspecification, which involves using higher safety factors than required by codes and to better tailor components to their required functionality. Trade-offs should be considered when determining to what extent to lightweight, such as whether a very lightweight product may be less durable, whether a component highly tailored to a specific purpose may have less opportunities for reuse, and at what point lightweighting may begin to affect performance and safety.

In some cases, design optimisation could be facilitated by moving towards different production frameworks. For example, moving to precast buildings construction may reduce material use. In some cases, material efficiency can be enhanced through digitalisation, such as three-dimensional printing (or additive manufacturing) components to more precise specification. As an example, through additive manufacturing, GE Aviation was able to reduce the weight of its jet engines by approximately 25% and reduce the complexity of the engine from 18 parts to a single part (Geissbauer, Wunderlin and Lehr, 2017). However, it should be noted that there may be instances where digitalised production could increase material or energy use. Life-cycle assessment would help determine opportunities where digitalisation could result in CO_2 emissions reduction.

The design stage should also consider opportunities for maximising a product or building's lifespan and for facilitating reuse and recycling at the end of its life. In the construction sector, non-residential buildings can have relatively short lifespans of less than 50 years. However, in most cases, the buildings could last for much longer time periods: 70-100 years or even longer. If a building is designed in such a way that it can easily be repurposed and re-adapted for another use instead of being demolished, producing materials to construct a new building would be avoided. In cases where a whole building might not be repurposed, modular design could enable reuse of its components. Waste management during the construction and end-of-life stages should also be taken into account when materials composition and design decisions are made.

Fabrication or construction stage

Material losses occur at various stages of production processes. The manufacture of products from metals such as steel and aluminium generally occurs in several stages, each of which experiences some loss of material. For example, crude steel is first formed into semi-manufactured pieces (e.g. rods, tubes and sheets), which are then cut and adapted for use in the final product (e.g. body of a car or a steel beam in a house). Unused material constitutes scrap, which can be collected for re-melting and re-forming. Manufacturing yields for metals vary depending on the type of section or final product, from approximately 60% to close to 100% in the case of cast iron and cast steel[5] (Cullen, Allwood and Bambach, 2012). More generic uses (e.g. as reinforcement in buildings) tend to have the highest metal yields, while more tailored and complex cuts (e.g. car bodies) tend to have the lowest yields. Some losses may be unavoidable, including when forming material-efficient lightweight components that are well formed to their specific use, but there could be potential through more careful and tailored production processes to reduce material losses.

Material losses also occur for non-metallic materials. For instance, construction companies often order more cement than that prescribed to avoid running out due to spillage, overuse or other reasons. While over-ordered unmixed bagged cement could be used elsewhere, over-ordered ready-mix concrete cannot usually be channelled to other uses before it hardens and becomes unusable. Over-ordering may never be eliminated as it is difficult to predict the exact amount needed, but losses could be decreased, through strategies to reduce over-ordering (e.g. improved architectural or engineering specification of cement) or through finding opportunities to channel over-ordered cement or ready-mix concrete to other uses. Spillage and improper storage can also render the cement unusable; better handling and storage practices would reduce such losses.

Materials can also be "wasted" through overuse in the fabrication stage. During construction, contractors may use more material than prescribed in the design specifications. For example, on-site contractors may use more cement than required in the specified concrete mix, either

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[5] Manufacturing yields, sometimes also referred to as formation yields, represent how much of the material is passed on to the next stage or ends up in the final product; the inverse is the amount of material that ends up as scrap.

due to lack of training or because of things like additional but unnecessary safety factors. In regions where on-site mixing is common, shifting increasingly towards ready-mix concrete or better training of on-site contractors can decrease overuse in on-site mixing, as could construction codes that discourage material use beyond design specifications. Additional strategies include greater distinction of material needs. For instance, cement may be overused when the same strength of concrete is ordered for an entire project (e.g. to save time and costs), while concrete of lower exposure classes containing less cement could have be used for different components of a buildings. In large-scale projects, it may be possible to avoid this waste by ordering several concrete mixes of different exposition classes.

Another material efficiency strategy in the fabrication stage is replacing higher-emission materials with lower-emission materials. Such material substitution can be pursued with intermediary materials at the materials production stage and with final materials at the product fabrication or construction stage. For example, cement producers can pursue opportunities to replace a portion of higher-emission clinker with lower-emission alternative cement constituents, such as ground granulated blast furnace slag, fly ash and calcined clay. In buildings construction, a portion of cement or steel could be replaced by sustainably sourced timber or other bio-based materials.

Use stage

One of the most straightforward ways to reduce new materials production may be to use the product for a longer amount of time, thereby reducing the material need for new products. This may mean extending the lifetime for the current user or repurposing the product for another user. For example, non-residential buildings could be repurposed for other uses to extend the lives of the structures. On a smaller scale, consumer goods are increasingly being designed to have short lifespans (e.g. single-use plastics and electronics that are designed for obsolescence). Normalising reusable products and the repair of broken products when possible would reduce the need for new material production. Emerging technologies like additive manufacturing may also encourage repair over disposal and reduce obsolescence, in that spare parts could be produced and acquired more easily (Despeisse and Ford, 2015). This would also reduce material demand by minimising the need for maintaining considerable spare parts inventories that may be unused. In addition, implementing proactive maintenance of buildings and products can facilitate longer lifespans and reduce needs for replacement components.

Trade-offs may exist among extending product lifespans and use-phase emissions and energy consumption. For example, increasing vehicle lifespans would delay stock turnover to more-efficient vehicles and alternative powertrains and would hence increase life-cycle emissions. In other cases, synergies may be possible, for example repurposing a building structure while also undertaking energy efficiency improvements. Careful life-cycle analysis can help determine in which cases lifetime extension would result in life-cycle savings.

Increasing intensity of use can also reduce material demand. If a product is being used to provide a greater amount of services, less of that product will need to be produced to provide the same amount of services. In transport, ride-sharing, car-sharing and car-pooling have the potential to increase the utilisation of vehicles (on average, private vehicles are used less than 5% of the day) and to reduce the number of cars needed to transport the same number of people, and so may reduce the number of cars that need to be produced. Business models for various other consumer goods that prioritise service provision over ownership may similarly reduce the amount of goods that need to be produced. Again, trade-offs should be considered, as increased intensity of use may lead to increasing wear and thus shorten lifespans. Material use can also be reduced by consumers choosing to purchase and use buildings, vehicles and other products that are smaller but provide the same functionality.

End-of-life stage

Alternatives to disposal at the end of a product's life can also help to use materials more efficiently. Reusing a product or material prevents the need for new production. Reuse can occur in various forms, including:

- relocating – the component is used in another product of the same type for the same purpose with little refurbishment
- refurbishing – the component is used in another product of the same type for the same purpose after undergoing significant repair and reconditioning
- cascading – the component is used in a different type of product with little reconditioning
- re-forming – the component is used in a different type of product after significant repair and reconditioning (Cooper and Allwood, 2012).

In most cases, reuse would reduce energy use compared to recycling or new production, although energy use for transportation and re-manufacturing processes would need to be considered. Furthermore, in some cases where reuse and refurbishment would extend the lifespan of old and inefficient energy-using components, replacement may be a better option from a life-cycle energy use perspective.

Reuse rates for most metal components are currently low. While technical factors such as incompatibility or degradation may limit reuse, economic, regulatory and behavioural barriers may also play a key role. For example, it may not be economical to pursue reuse in the absence of financial incentives; regulations tend to favour using new rather than used materials and some constructors may be sceptical about reused materials. Better tracking of materials, development of economical testing procedures, integration of supply chains and adaptation of regulations could help overcome these barriers. A starting point may be easier to achieve opportunities for steel reuse, which include relocation of steel buildings components and re-forming of ship plates and line pipes (Cooper and Allwood, 2012).

Reuse opportunities may be more limited for other materials. In the case of cement, most of the cement particles are reacted with water during the concrete curing process, and the resulting change in chemical properties prevents cement from being used again to form new concrete. Estimates suggest that approximately 30-40% of cement in concrete may be unreacted, leaving potential for recovery of this unhydrated cement for reuse (Bakker et al., 2015). While several technologies are under development to recover unhydrated cement, they have not yet been commercialised and thus their technical and economic potential remains uncertain. Research has shown that recycling concrete fines as an input to cement kilns can reduce process emissions by a factor of three compared to the limestone inputs it would replace (Lotfi and Rem, 2016). A limited number of cements are now available that make use of recycled fines, such as Susteno cement in Switzerland (Holcim, 2018). Some opportunities may also exist to reuse whole concrete components for other purposes, thus reducing the need for new cement. However, difficulties in cutting, transporting and re-forming concrete blocks may limit this potential.

When reuse is not possible, recycling is another option to reduce the need for new materials. Although recycling consumes energy, the consumption is generally substantially less than that from producing primary materials. For example, producing crude steel from scrap consumes three times less energy on average compared to producing primary crude steel. Recycling rates[6] are already high for some materials: steel and aluminium at about 80% and paper at around 60%. However, improved collection rates are still possible, particularly in developing economies where there are less-effective recycling frameworks.

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[6] The recycling rate is defined as the collection rate for recycling after initial use.

4. Implications of deploying further material efficiency strategies

This chapter explores the potential and implications of boosting material efficiency, using scenarios. It builds on the long-term trends that emerge under current policy and technology ambitions in the Reference Technology Scenario (RTS) to explore the potential and implications of material efficiency in the Clean Technology Scenario (CTS), which aims at reducing global energy sector carbon dioxide (CO_2) emissions by almost 75% in 2060 compared to 2017 levels. The CTS embodies ambitious material efficiency strategies as an integral part of its emissions reduction strategies portfolio. Informed by literature analysis and expert judgement, the Material Efficiency variant (MEF) provides a what-if analysis that pushes material efficiency to its practical limit beyond that already occurring in the CTS for three key energy and emissions-intensive materials: steel, cement and aluminium.

Strategies pushed further in the MEF are those considered significantly more challenging to realise in terms of requiring greater efforts from stakeholders. They are applied at levels that are highly ambitious given real-world technical, political and behavioural constraints. Yet the MEF is an achievable strategy if pursued ambitiously and comprehensively. Material efficiency strategies can lead to reduced or increased material demand depending on the particular case. However, in all cases, they lead to lower overall CO_2 emissions across the relevant value chain.

This analysis includes deep dives on two main value chains that contribute to a substantial portion of material demand: buildings construction and vehicles (focusing on cars and trucks). These value chains together account for approximately one-half of today's demand for steel, one-half for cement and one-quarter for aluminium. To understand how material demand may deviate from historical trends, the analysis involved developing material demand estimates for the value chains of focus using data on activity levels and material intensities (material consumption per application), which is referred to as bottom-up methodology. Annex III provides additional information on the method and assumptions.

The CTS already pursues material efficiency strategies in the design and product fabrication and construction phases for the buildings and vehicles supply chains, as well as improved manufacturing yields, clinker substitution in cement production, and improved reuse and recycling rates across all applications. Many of these strategies are pursued to a greater extent in the MEF (Table 1). The CTS includes activity shifts that occur due to pursuing use-phase emissions reduction, including lifetime extension resulting from investment in energy efficiency improvements in buildings and reduced vehicle sales resulting from modal shifting to reduce transport emissions. Semi-manufacturing and product manufacturing yields, clinker substitution and recycling rates are also improved in the CTS, relative to the RTS, spurred on by efforts to reduce the emissions intensity of materials production. Strategies deployed to a considerably greater extent in the MEF include those that require substantial additional regulatory efforts, stakeholder co-ordination, value chain integration, investment, training, shifts in business practices or behavioural change. These include incorporating material efficiency considerations into the design and construction of buildings, vehicle lightweighting and increased metals reuse.

Table 1. Differences in strategies affecting steel, cement and aluminium demand by scenario

Design stage	Strategy	RTS	CTS	MEF
Material manufacturing	Steel and aluminium semi-manufacturing yields	Improvements pursued at one-third of the CTS rate	Pushed to their practical limits	No change from the CTS, due to limited additional potential available
	Clinker substitution in cement manufacture*	Not pursued	Pushed to their practical limits	
Product design and fabrication	Buildings: improved material efficiency in design and construction	Not pursued	Pursued to a limited extent	Pushed far beyond the CTS
	Vehicles: lightweighting	Pursued to a limited extent to achieve RTS implied fuel efficiency improvements	Pursued to a moderate extent to achieve CTS targeted fuel efficiency improvements	Pushed moderately beyond the CTS to its practical limit
	Steel and aluminium product manufacturing yields	Improvements pursued at one-third of the CTS rate	Pushed to their practical limits	No change from the CTS, due to limited additional potential available
Use	Buildings: extended lifetimes	Pursued to a limited extent in accordance with RTS energy performance retrofits	Pushed substantially; given increased investment in retrofits that improve buildings energy performance, efforts would likely be made to maintain the structure for longer time periods	Pushed moderately further than in the CTS for non-residential buildings, given their typically shorter lifetimes; no additional potential considered for residential buildings
	Vehicles: changes in activity (modal shift)	Pursued to a limited extent to achieve use-phase emissions reduction implied by RTS transport policies	Fully exploited to achieve use-phase emissions reduction implied by CTS transport policies	No change from the CTS
End of life	Steel and aluminium reuse	Improvements pursued at up to one-third of the MEF rate, with more limited	Improvements pursued at up to two-thirds of the MEF rate, with more limited	Pushed far beyond the CTS, with variation in reuse rates by end use according to

Design stage	Strategy	RTS	CTS	MEF
		uptake in end uses such as vehicles where reuse may be more logistically challenging	uptake in end uses such as vehicles where reuse may be more logistically challenging	reasonable practical potential
	Concrete buildings component reuse	Not pursued	Pursued to a limited extent	Pursued to a moderate extent
	Steel and aluminium recycling*	Improvements pursued at one-third the CTS rate	Pushed to its practical limits	Pushed to its practical limits

* Clinker substitution and recycling of steel and aluminium are considered in the modelling as material efficiency strategies. However, while clinker substitution reduces the emissions intensity of cement production and recycling affects availability of scrap for lower-emission secondary production, neither changes demand for final materials and thus are not discussed in this analysis as strategies affecting material demand.

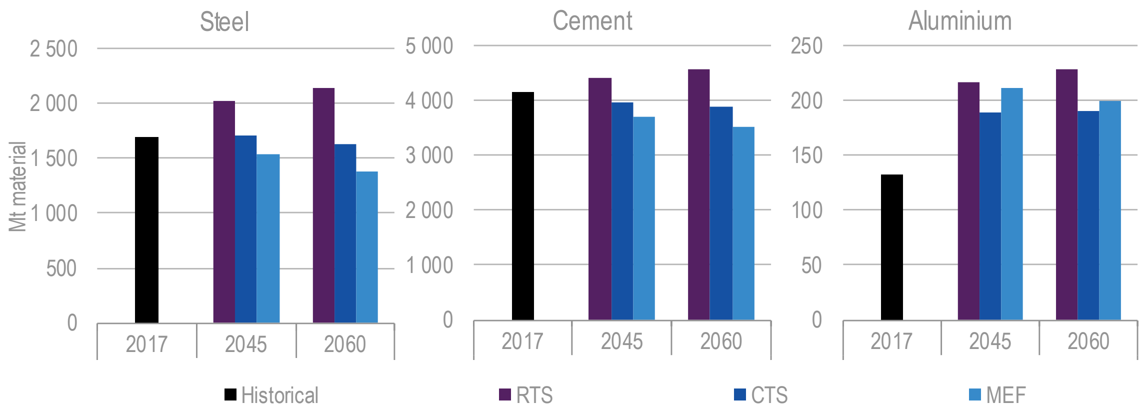
The effect of individual material efficiency strategies for all materials is not additive in all cases – there can be synergies and trade-offs among strategies. For example, extending lifetimes or reducing use of a particular material would make less of that material available for reuse and recycling. By taking an integrated approach that looks at material efficiency across all stages of the life cycle, the analysis can account for the effects of those trade-offs.

It should be noted that the analysis is not a full life-cycle assessment of the examined value chains, nor is it a full assessment of embodied carbon. The focus is on demand and emissions related to steel, cement and aluminium production (as well as plastics in the case of vehicles, along with a brief discussion of battery-electric vehicle battery materials) and changes in use-phase emissions attributable to changes in the use of these materials. Production here includes the stages of converting raw materials into finished materials (for metals, the stages from ore agglomeration to finishing for steel and aluminium; and for cement, the stages from raw material grinding to cement grinding). Other materials are not considered, nor are emissions assessed that arise from extracting raw materials, transporting materials and end-use products, and converting materials into buildings or vehicles during construction and product manufacturing. While a comprehensive portfolio of material efficiency strategies is explored, some strategies have not been examined, such as switching buildings frames from concrete and steel to timber and other bio-based materials.

Material demand outlook by scenario

In the RTS, demand by 2060 grows by approximately 30% for steel, 10% for cement and 75% for aluminium relative to 2017 levels (Figure 19). The CTS and MEF see considerable divergence from RTS material demand trends: steel and cement decline by 2060 in both scenarios, while aluminium increases at a slower rate in the CTS, but increases and then begins to decline by 2060 in the MEF. In the CTS, demand for materials is already reduced compared to in the RTS, by 24% for steel (equivalent to about six times the production in the United States in 2017), 15% for cement (two and a half times the production in India in 2017) and 17% for aluminium (1.2 times the primary production in the People's Republic of China ["China"] in 2017) in 2060. The MEF leads to further demand reductions in 2060 compared to in the CTS, for steel (by 16%) and cement (by 9%), and an increase in aluminium (by 5%).

Figure 19. Demand for steel, cement and aluminium by scenario

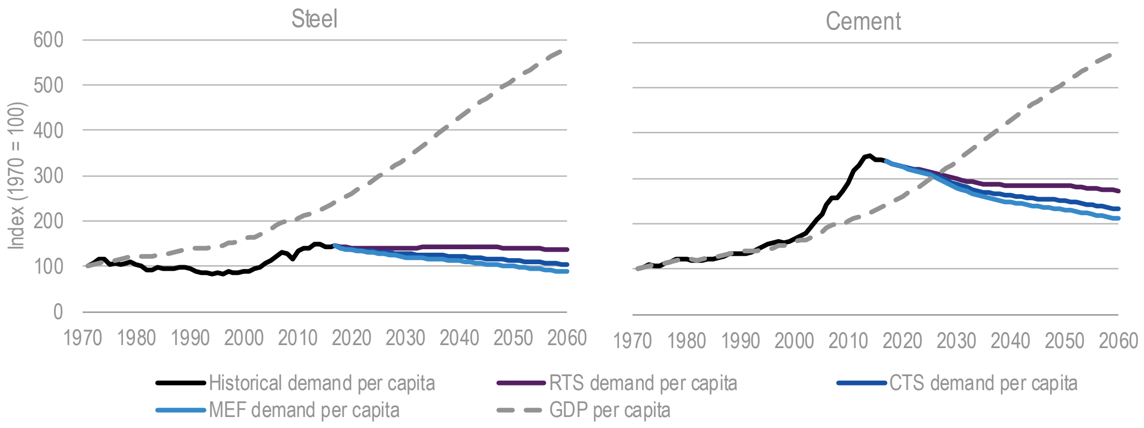


Note: Mt = million tonnes.

While material demand grows over time in the RTS, it is considerably reduced in the CTS and MEF relative to the RTS.

All three scenarios see a substantial divergence from historical trends of global steel and cement demand per capita compared to gross domestic product (GDP) per capita (Figure 20). This suggests a decoupling of demand for these materials from economic growth because of expected future trends and patterns of development. Technological shifts to facilitate clean energy transitions and material efficiency strategies will push the decoupling further than in the RTS.

Figure 20. Global demand for steel and cement per capita by scenario

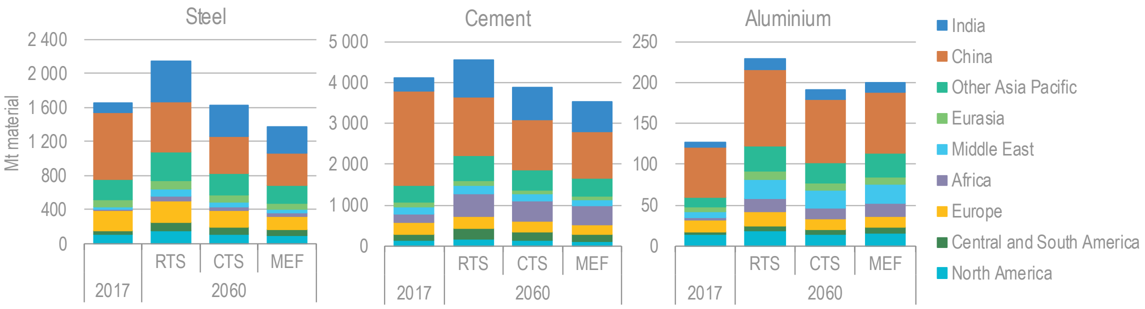


Sources: Projections are based on International Energy Agency analysis. Historical data are from the following: worldsteel (2018), Steel Statistical Yearbook 2018, www.worldsteel.org/en/dam/jcr:3e275c73-6f11-4e7f-a5d8-23d9bc5c508f/Steel+Statistical+Yearbook+2017.pdf; IMF (2018), World Economic Outlook Database, www.imf.org/external/pubs/ft/weo/2018/01/weodata/index.aspx; USGS (2018b), 2015 Minerals Yearbook: Cement, https://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2015-cemen.pdf 2017 values are an extrapolation of 2015 and 2016 data.

Expected future trends in the RTS result in a considerable decoupling of material demand from economic growth. Material efficiency and CTS technological shifts push that decoupling further.

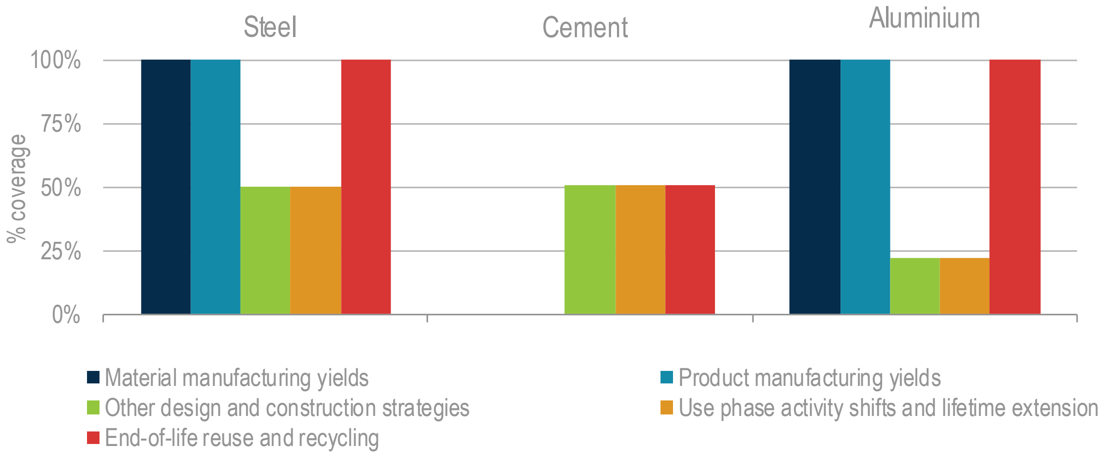
China remains the largest contributor to global production of steel, cement and aluminium across scenarios. It is also the country that sees the largest change in production levels in absolute terms in the CTS and MEF (Figure 21). Asia retains around two-thirds of the global production of steel and cement and nearly 60% of aluminium in 2060 in all scenarios. Developing economies generally see lower levels of material demand reduction, as the underlying increasing material demand to sustain infrastructure developments is less affected by substantial efforts on material efficiency; this is particularly true for cement.

Figure 21. Regional production of steel, cement and aluminium by scenario



Asia retains the largest share of global materials production in the long term across the scenarios.

Figure 22. Proportion of 2017 material demand covered by analysis of material efficiency strategies



Note: *Material and product manufacturing yields* are related to metals and thus not applicable for cement.

While the potential of certain material efficiency strategies was analysed for all demand segments, in some cases, the scope of the analysis was limited due to data availability.

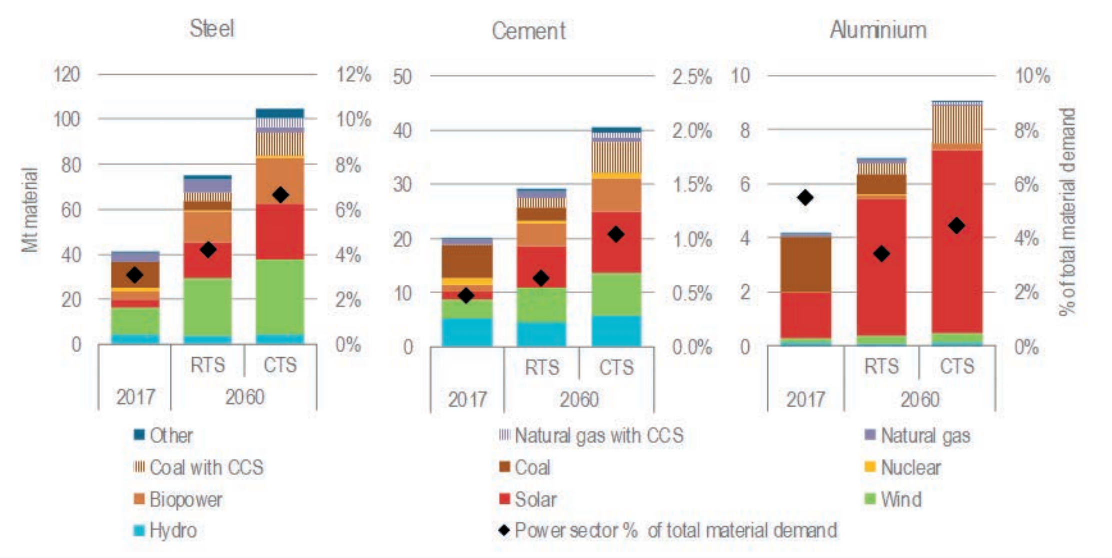
The changes in material demand in the CTS and MEF compared to in the RTS should be considered in light of the fact that the full suite of material efficiency strategies and bottom-up demand considerations were not applied to all sources of demand for each material (limited by data availability). For steel, improved manufacturing yields, reuse and recycling were considered for all end uses, while other strategies in the design, fabrication and use stages covered approximately one-half of the end-use demand (from buildings, cars and trucks) (Figure 22). For aluminium, all end uses were also covered for improved manufacturing yields, reuse and recycling, while other strategies covered approximately one-quarter of the end-use demand (from cars and trucks). For cement, bottom-up analysis considered only the buildings sector, which accounts for approximately one-half of the end-use demand.

Applying material efficiency strategies to a larger proportion of end-use demand could realise additional material demand savings. This potential may differ considerably across end uses. Thus, savings in one end use should not be extrapolated to other end uses. Furthermore, bottom-up activity level consideration of non-covered end uses in this analysis could also put upward pressure on demand (e.g. Box 3). In summary, while this analysis provides an initial assessment of material demand change potential from material efficiency, additional research is needed to provide a more comprehensive evaluation.

Box 3. Material demand for power generation

Power capacity additions currently account for an estimated 3% of global demand for steel, 0.5% for cement and 5.5% for aluminium. Material demand from the power sector is likely to increase in the future, due to growing electricity demand. For steel and cement, the power sector will account for a growing share of total demand. This is particularly the case in the CTS, in which the power sector grows to 7% of total steel demand and 1% of total cement demand in 2060. The reverse is true for aluminium, given the high expected growth in aluminium for other end uses, including lightweight vehicles. In the CTS, aluminium demand falls to 4.5% of the total demand in 2060.

Demand for steel, cement and aluminium from the power sector by scenario



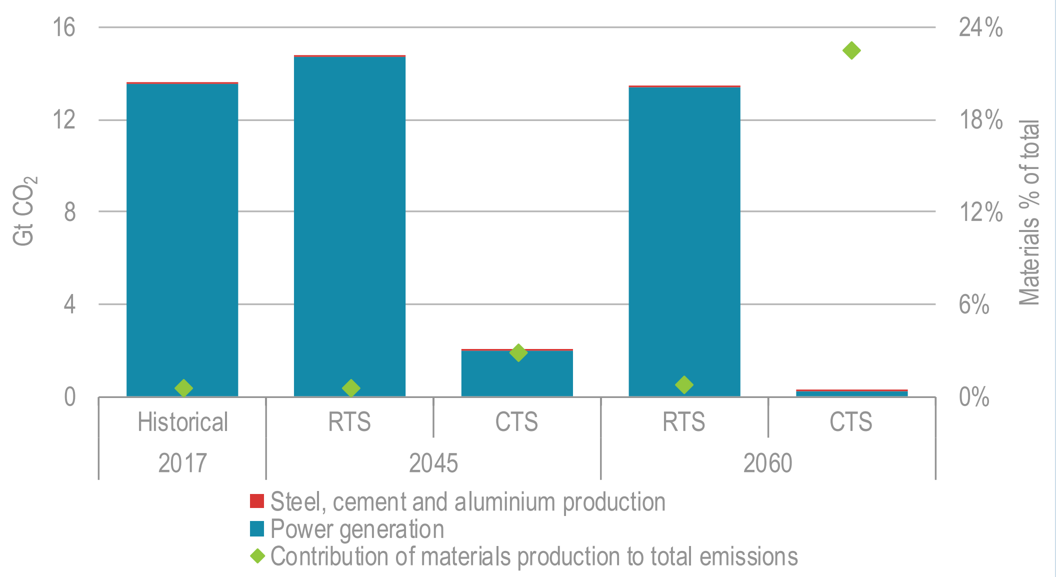
Notes: *% of total material demand* considers material inputs to end uses as total demand; it does not include material lost in the semi-manufacturing and product manufacturing stages. *Other* includes geothermal, tidal, wave and energy storage. *Material demand* includes material used for manufacturing of power plants and associated infrastructure, the production of fuels and the operation and dismantling of power plants. CCS = carbon capture and storage.

More materials will be required for building electricity generation infrastructure to facilitate clean energy transitions in the CTS than in the RTS.

While total global electricity demand grows at approximately the same rate in the RTS and CTS (a doubling from present to 2060), electricity generated from renewable sources of energy grows by

40% more in the CTS than in the RTS. The differences in the type of capacity additions result in greater demand for materials in the CTS than in the RTS, by approximately one-third in 2060 for each of steel, cement and aluminium. For steel and cement, wind and solar account for the largest proportion of material demand, given that they account for a large proportion of capacity additions (approximately 20% for wind and 50% for solar of capacity additions in 2060 in the CTS). Biopower also accounts for considerable demand, despite contributing a smaller proportion of capacity addition (6% in 2060 in the CTS). Solar is the largest contributor to aluminium demand, accounting for nearly 75% of power sector demand in 2060 in the CTS.

Power sector CO_2 emissions from materials production and power generation



Reduced power generation emissions far outweigh increased material production emissions in the CTS.

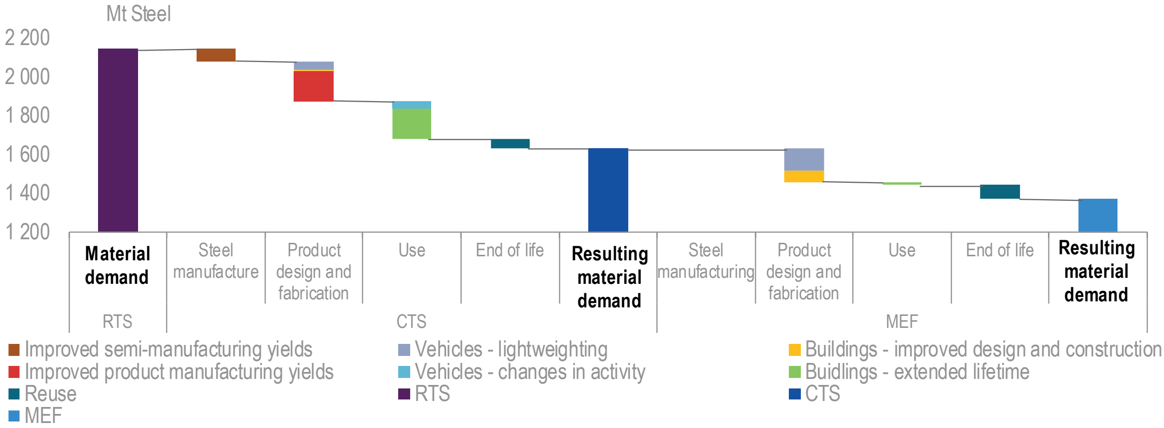
Notes: Material intensity estimates were based on the work of Gibon et al. (2017), which was a comprehensive life-cycle assessment of a global low-carbon electricity scenario that included estimates of regionalised material demand per capacity addition of different supply technologies. Estimates were obtained from the authors and are not directly available in the article itself. The RTS uses the baseline scenario material intensities of Gibon et al., while the CTS uses their Blue Map scenario material intensities, which incorporate material efficiency improvement considerations. $GtCO_2$ = gigatonnes of carbon dioxide.

The combined emissions from steel, cement and aluminium in the CTS are one-third lower than in the RTS in 2060, despite increased material demand. This is due to aggressive efforts to reduce the emissions intensity of material production in the CTS. Material production emissions account for a larger proportion of total power sector emissions: in the CTS in 2060, steel, cement and aluminium production account for approximately one-quarter of combined emissions from these materials and power generation emissions (compared to less than 1% in the RTS). Yet, combined emissions in the CTS from power generation and from steel, cement and aluminium production for power capacity additions are less than 2% of those in the RTS in 2060. Thus, the additional inputs of these materials to the power sector are a worthwhile investment to facilitate the low-carbon transition. While not analysed here, consideration should also be given to demand, material efficiency and emissions for other materials that will play a key role in decarbonising the power sector (e.g. silicon use for solar photovoltaics and lithium and cobalt use for battery storage).

Steel

The CTS sees a decline in annual global demand for steel by 24% relative to the RTS by 2060 due to a combination of technological changes to reduce CO_2 emissions and material efficiency strategies (Figure 23). A stronger push for material efficiency results in an additional 16% reduction in steel demand in the MEF relative to the CTS by 2060. Cumulatively by 2060, the CTS reduces demand compared to the RTS by 12 gigatonnes (Gt) (14% reduction from the RTS) and the MEF by an additional 6 Gt (8% reduction from the CTS).[7] The largest reductions in demand from the RTS to the CTS occur in the product design and fabrication phase and the use phase (each accounting for 40% of the cumulative reduction from the RTS to the CTS), while the largest additional reductions in the MEF occur in the product design and fabrication stage (74%), followed by the end-of-life stage (23%).

Figure 23. Steel demand change by value chain stage across scenarios in 2060



Notes: While recycling reduces primary steel production, it does not reduce final demand for steel and thus is not shown here as a material efficiency strategy.

There is considerable potential to reduce steel demand at all stages of product and buildings life cycles.

Improving product manufacturing yields makes the largest cumulative contribution to steel demand reduction in the CTS relative to the RTS, accounting for close to one-third of reductions (Figure 24). Product manufacturing yields are variable depending on the end use or part, with yields for some end uses such as buildings already over 90% and for others such as vehicles currently in the 60-75% range. The lower yields offer opportunity for improvement. Steel manufacturing yields are already in the 80-95% range for many steel semi-finished products. Still, improving steel semi-manufacturing yields also offers potential to reduce demand in the CTS, contributing approximately 13% of cumulative demand reduction from the RTS.

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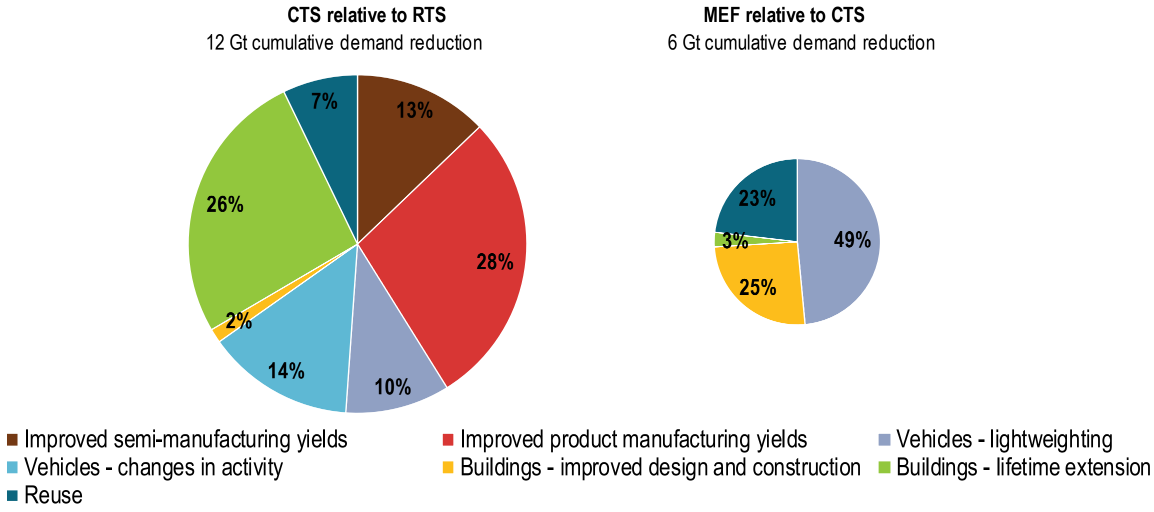
[7] The contribution of each strategy to total reductions is calculated using a decomposition analysis that accounts for synergies and trade-offs among strategies.

Figure 24. Cumulative contribution by 2060 of material efficiency strategies to changes in steel demand by scenario



Improvements in manufacturing yields, lifetime extension in buildings and changes in transport activity lead to the largest reductions in steel demand in the CTS. Vehicle lightweighting, increased reuse rates and improved buildings design and construction lead to considerable additional reductions in the MEF.

Changes to use-phase activity levels contribute substantial reductions in steel demand in the CTS. Transport activity changes (primarily reduction in vehicle kilometres travelled from avoid-shift policies)[8] reduce demand for steel to produce cars and trucks, contributing to 14% of the cumulative demand reduction from the RTS. In the buildings sector, substantial deep retrofits of buildings occur to achieve use-phase energy efficiency improvements. As major investment has been made in energy retrofits, it is assumed that they would be used for longer periods of times through extension of their current uses or repurposing for other uses. This buildings lifetime extension contributes 26% of steel demand reduction from the RTS.

In the MEF, the largest additional savings in steel demand occur from vehicle lightweighting, accounting for one-half of additional cumulative reductions. Improved buildings design also makes a considerable contribution, accounting for 25% of additional reductions. Steel reuse, which is currently limited, also offers substantial potential for material demand savings, accounting for 23% of the reductions from the CTS to the MEF. Improving reuse rates to their maximum practical potential would likely require targeted efforts not already occurring in the CTS, such as setting up collection and inventories and better integration throughout value chains.

It is assumed that savings from improved steel and product manufacturing yields would be at a maximum in the CTS and thus that additional savings opportunities are limited in the MEF. Changes in the use phase also make a much more limited contribution to additional MEF reductions. For vehicles, pursuing lifetime extension as a material efficiency strategy may be counterproductive by slowing uptake of alternative powertrains, and so no changes in activity level in the MEF are assumed. Buildings lifetime extension is pushed slightly further in the MEF

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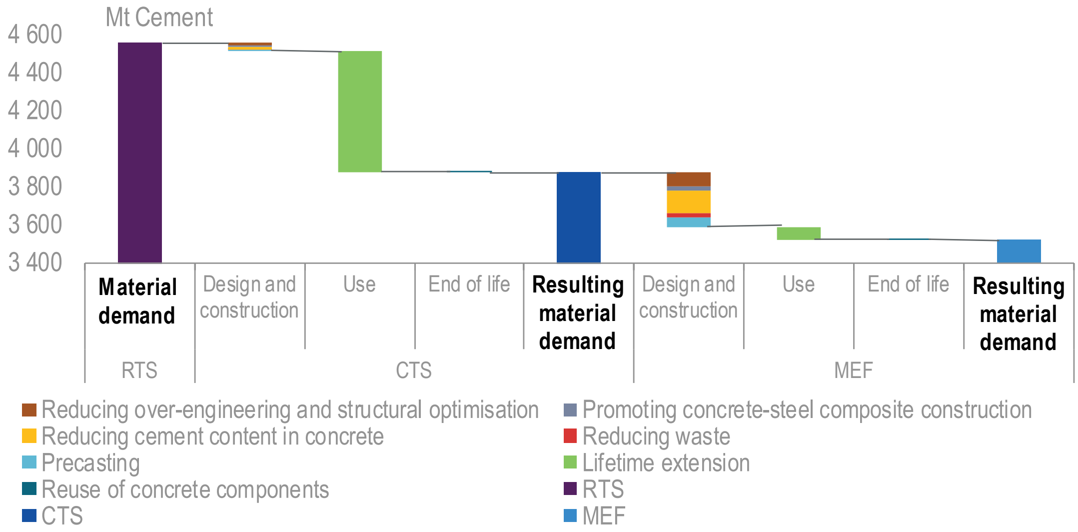
[8] Avoid-shift measures are those that result in fewer and shorter trips, increased public transport use and adoption of non-motorised transport solutions (e.g. walking and cycling).

through deliberate design of non-residential buildings for multiple uses and long life, contributing to 3% of additional cumulative demand reduction in the MEF.

Cement

In 2060, annual global demand for cement sees a 15% decline in the CTS relative to the RTS, as a result of increased retrofits and other material efficiency improvements in the buildings sector (Figure 25). A strong application of material efficiency in the MEF results in an additional 9% reduction in cement demand in 2060 relative to the CTS. Cumulatively from 2017 to 2060, the CTS reduces demand by 14 Gt (8% from the RTS) and the MEF by an additional 8 Gt (5% from the CTS). The largest cumulative reductions in demand from the RTS to the CTS occur in the use phase through lifetime extension (92%), while the largest additional reduction in the MEF occurs in the buildings design and construction stage (88%).

Figure 25. Cement demand change by value chain stage across scenarios in 2060



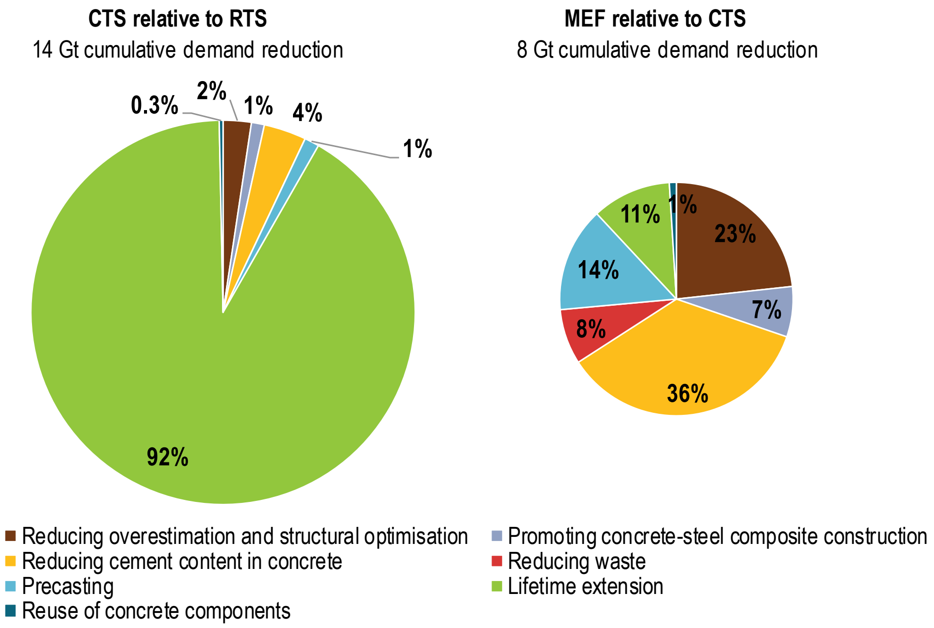
Note: While clinker substitution in blended cements reduces demand for clinker, it does not reduce final demand for cement and thus is not shown here as a material efficiency strategy.

The buildings use phase offers the largest potential to reduce cement demand, followed by the design and construction stage.

Buildings lifetime extension contributes to nearly all (92%) of cumulative reductions in demand for cement in the CTS relative to the RTS (Figure 26). The pursuit of energy efficiency retrofits drives this lifetime extension. In the RTS, many buildings would be demolished and rebuilt before the end of their useful life, but major investment in energy efficiency retrofits in the CTS leads to many of these buildings staying in service longer. It is assumed that other material efficiency strategies in the design, construction and end-of-life stages would be pursued to only a limited degree in the CTS, given that more targeted efforts would be required to adopt them.

In the MEF, improvements to buildings design and construction are pursued much more aggressively, thus contributing to 88% of cumulative cement reductions relative to the CTS. The strategies include reducing concrete over-engineering and structural optimisation, promoting concrete-steel composite construction, reducing cement content in concrete and reducing on-site construction waste. The additional lifetime extension pursued in non-residential buildings in the MEF also leads to modest reductions of 11% of the cumulative reductions from the CTS.

Figure 26. Cumulative contribution by 2060 of material efficiency strategies to changes in cement demand by scenario



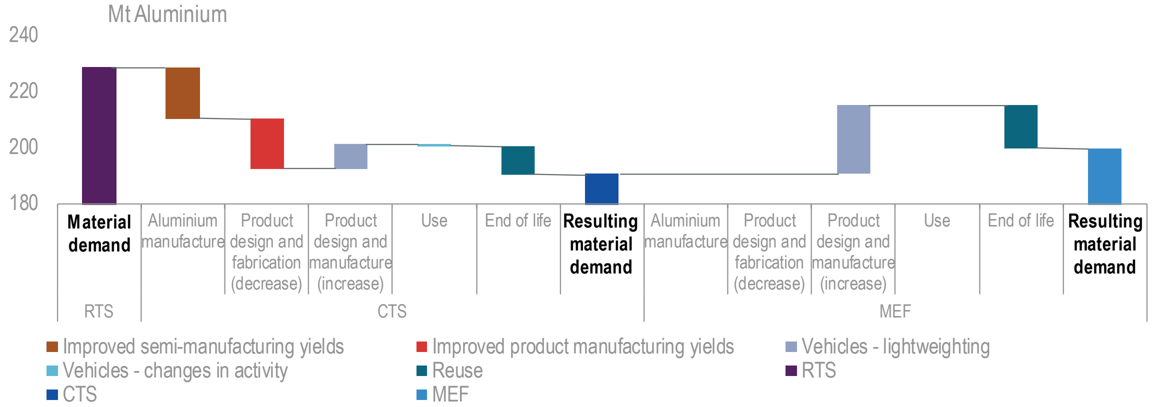
Lifetime extension in buildings leads to the largest cumulative reduction in cement demand in the CTS. Various improvements in buildings design and construction lead to considerable additional reductions in the MEF.

End-of-life contributions to demand reductions are much smaller for cement than for steel. It is more difficult to disassemble concrete than steel without causing damage, more cumbersome to transport large concrete components and more difficult to tailor reused concrete to new uses. It was assumed that a small amount of precast concrete components could be reused, although this strategy contributes to 1% of cumulative reductions in the MEF. While technologies are in development to recover unhydrated cement when crushing end-of-life concrete, these technologies are not yet commercial and thus are not considered in this analysis.

Aluminium

A combination of changes in technologies to reduce emissions and material efficiency leads annual global demand for aluminium to decline by 17% in the CTS relative to the RTS by 2060 (Figure 27). Pushing material efficiency strategies further, including a strong boost for vehicle lightweighting, result in a net increase in global demand for aluminium of 5% in the MEF relative to the CTS by 2060. However, this is still a 13% decline from the RTS 2060 demand. Cumulatively from 2017 to 2060, the CTS reduces demand by 0.9 Gt (11% from the RTS), and the MEF results in a net cumulative increase in demand from the CTS of 0.9 Gt (12% of the CTS cumulative demand). Considerable changes in demand occur in all life-cycle stages in the CTS, while additional changes occur in the design and end-of-life stages in the MEF.

Figure 27. Aluminium demand change by value chain stage across scenarios in 2060



Notes: While recycling reduces primary aluminium production, it does not reduce final demand for aluminium and thus is not shown here as a material efficiency strategy.

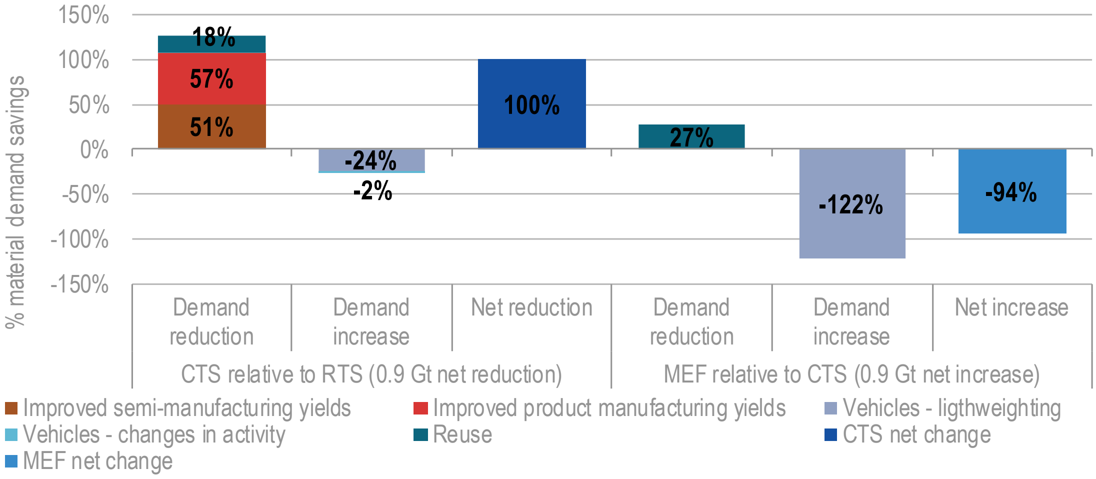
While reductions in aluminium demand can be achieved at various stages in value chains, a considerable portion of these reductions are offset by increases in demand from lighter vehicles.

In the CTS, improving manufacturing yields contributes to considerable cumulative aluminium demand reductions. Improved semi-manufacturing yields contribute reductions equivalent to 51% of the net change from the RTS to the CTS, and product manufacturing yields contribute reductions equivalent to 57% of the net change (Figure 28). Manufacturing yields for aluminium are generally lower than those for steel, with semi-manufacturing yields in the range 50-75% for most semi-manufactured products and below 90% for most end uses (Annex III). This provides opportunity for improvement.

However, vehicle lightweighting leads to a substantial increase in aluminium demand, as manufacturers substitute aluminium for steel to meet fuel efficiency objectives. The cumulative contribution of lightweighting to changes from the RTS to the CTS is equivalent to one-quarter of the net change between these two scenarios.

Avoid-shift policies in the CTS lead to only a small increase in aluminium demand (cumulative contribution equal to 2% of the net change from the RTS to the CTS). While modal shifting for personal transport reduces sales of light-duty passenger vehicles (by approximately 10% in 2060), it increases sales of buses (by one-third in 2060). In freight, heavy-freight truck sales decrease (by approximately 20% in 2060), with some demand shifting to medium-freight trucks and rail. Buses are more likely to be manufactured with a higher weight share of aluminium than other vehicle types. As a result, the increased aluminium demand from increased bus sales outweighs the decreased demand from the other vehicle types, leading to the small net increase. This occurs in contrast to steel, where the steel demand reductions due to lower sales of most vehicle types far outweigh the increase from buses, such that the activity effect results in a net decline in demand. However, the upward pressures on aluminium demand are outweighed by the downward pressures, resulting in a cumulative net savings in demand for aluminium in the CTS.

Figure 28. Cumulative contribution by 2060 of material efficiency strategies to aluminium demand savings by scenario



Notes: Shares of material demand savings are indexed to net change in demand between the CTS and RTS.

Improved manufacturing yields reduce demand for aluminium in the CTS, while vehicle lightweighting increases it. Additional material reductions in the MEF are realised through increasing reuse, while considerable additional increases result from further vehicle lightweighting.

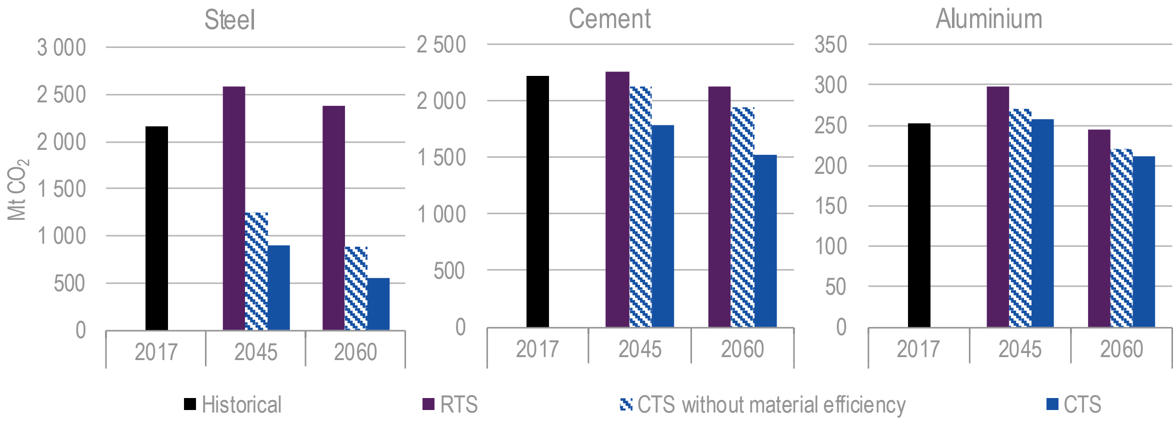
In the MEF, there is a cumulative net increase in aluminium demand. Vehicle lightweighting results in a demand increase approximately five times greater than that of the CTS. Although not enough to outweigh increased demand from lightweighting, improved aluminium reuse puts a significant downward pressure on demand for aluminium, accounting for 27% of the cumulative changes in the MEF compared to the net change from the RTS to the CTS. As with steel, reuse rates for aluminium are currently low and could be pushed further for many end-use applications, particularly in the MEF if attention is specifically given to inventories and supply chain management to facilitate reuse. It is assumed that opportunities for improvements in manufacturing yields are fully achieved in the CTS, leaving limited room for improvement in the MEF.

CO_2 emissions and energy implications of material efficiency

Demand for materials – particularly energy-intensive materials like steel, cement and aluminium – is a key determinant of industrial sector energy consumption and CO_2 emissions. As material demand has grown considerably over recent decades, so too has industrial sector energy consumption and emissions. Going forward, material efficiency can help in achieving emissions reduction, by decreasing deployment needs for other industrial CO_2 mitigation levers and by facilitating emissions reduction in other sectors through more material-efficient value chains. Material efficiency as discussed here includes strategies that reduce demand for final materials. It also includes those that increase demand for a particular material while enabling outweighing emissions benefits at other points in the value chain, as well as those that shift to using lower-emission materials (as in the case of substituting higher-emission clinker with alternative cement constituents) and to lower-emission material production routes (as in the case of increased recycling enabling greater uptake of lower-emission secondary steel and aluminium production).

In the CTS, material efficiency makes a large contribution to reducing industrial CO_2 emissions from the RTS (Figure 29). In 2060, material efficiency contributes approximately 20% of the emissions reduction for steel in the CTS relative to the RTS, 70% for cement and 30% for aluminium. Material efficiency accounts for about 30% of the combined emissions reduction from the three materials in the CTS in 2060.

Figure 29. Direct CO_2 emissions from steel, cement and aluminium production by scenario



Note: $MtCO_2$ = million tonnes of carbon dioxide.

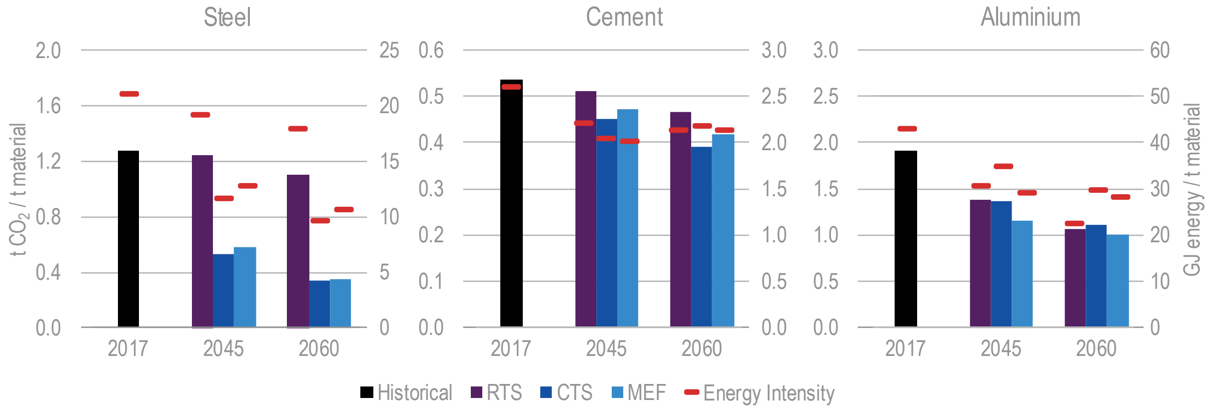
Material efficiency contributes considerably to industrial emissions reduction in the CTS.

Pushing material efficiency further in the MEF leads to more moderate deployment needs for low-carbon industrial process technologies for the same emissions outcome as in the CTS, particularly when these strategies lead to lower material demand levels. In 2060, the global average direct CO_2 emissions intensity of cement production is 7% higher in the MEF than in the CTS (Figure 30). The energy intensity is 2% lower, largely because of the reduced need for CCS, which is an energy-intensive technology. The reduced energy intensity and production levels lead to 11% lower total energy consumption for cement production.

For steel, by 2045, the global average direct CO_2 emissions intensity is 9% higher in the MEF than in the CTS; by 2060, the difference is reduced (4% higher). In the MEF, the combined effect of reduced demand for steel and material efficiency strategies results in a lower ratio of available scrap to steel production, compared to in the CTS. This is a trend that becomes more visible when approaching 2060, when greater amounts of steel-based products introduced into stocks reach their end of life. Still, the additional steel demand reductions in the MEF relieve significant pressure on technological transformations even to 2060 in some regions such as China, where the MEF emissions intensity is over 60% higher than in the CTS. The energy intensity of production is also higher in the MEF than in the CTS, indicating that material efficiency reduces the need to shift to more energy-efficient technologies and process routes.

For aluminium, the global direct CO_2 intensity of production decreases in the MEF (by 9% in 2060), as the higher material demand requires greater uptake of emission abatement technologies to achieve the same overall emissions levels. The energy intensity of production is also lower (by 6% in 2060). However, this somewhat increased technological effort in the aluminium sector could reduce deployment needs for other mitigation levers in the transport sector, given that the higher aluminium demand is caused by vehicle lightweighting to reduce transport use-phase emissions.

Figure 30. Direct CO_2 and energy intensity of production for steel, cement and aluminium by scenario



Note: GJ = gigajoules; t = tonne; tCO_2 = tonnes of carbon dioxide.

Lower material demand levels result in higher direct CO_2 intensity of steel and cement production in the MEF while remaining within the CTS industrial emissions level.

In addition to direct emissions, changes in material demand would also affect indirect CO_2 emissions from electricity and fuel production. However, given that the electricity grid is mostly decarbonised and fossil fuel consumption declines substantially in the CTS context, changes in cumulative indirect emissions in the MEF from the CTS are small.

Changes in manufacturing direct emissions intensity in the MEF mean that carbon mitigation technologies need to be deployed at different rates compared to in the CTS. For example, the MEF requires less deployment of CCS in the cement sector, with cumulative emissions captured being 45% lower (2.3 Gt lower) in the MEF compared to in the CTS. In iron and steel, the cumulative share of scrap-based electric arc furnace production is approximately 20% lower in the MEF than in the CTS, as the lower steel input into the system results in lower scrap availability relative to the amount of steel demanded.

For steel and cement, lower total material demand leads to lower cumulative capital technology investment by 2060 in the MEF relative to the CTS – by 14% for steel and 10% for cement. Conversely, increased demand for aluminium results in 24% additional cumulative technology investment in that sector by 2060. The investment reductions in steel and cement outweigh the increase in aluminium, resulting in a total cumulative technology investment 4% lower in the three subsectors combined. However, note that this reduced investment in industrial process technologies does not account for investments that may be required throughout value chains to improve material efficiency.

Instead of reducing deployment needs of low-carbon industrial process technologies, material demand reductions could result in additional emissions reduction. If the CTS emissions intensity of production were maintained to produce the MEF level of material demand,[9] combined direct

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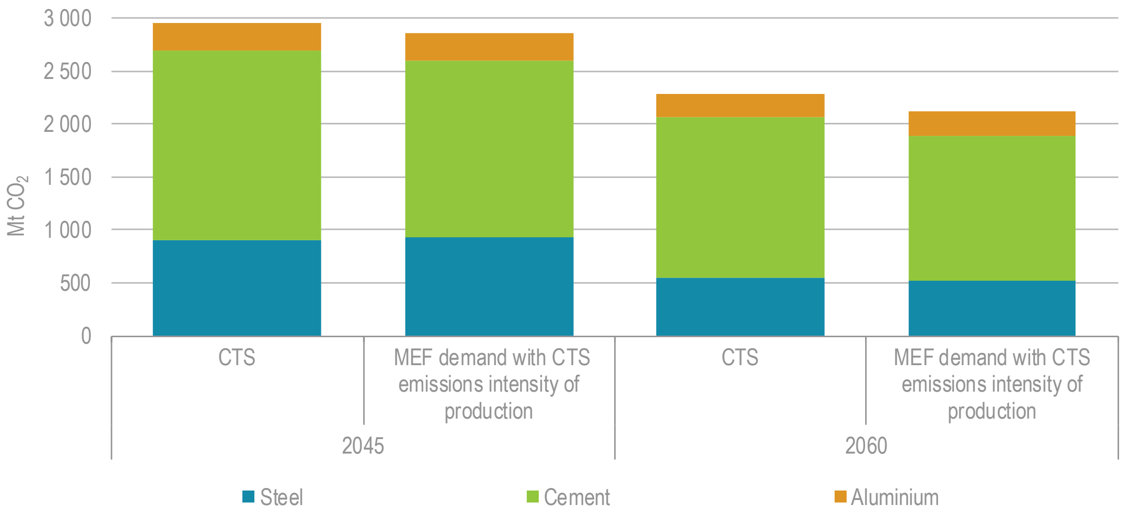
[9] The calculation maintains the same proportion of primary and secondary production in the MEF for steel and aluminium, given that reduced scrap availability in the MEF may hinder achieving the same level of secondary production as in the CTS.

emissions in steel, cement and aluminium would be reduced by 7% in 2060 relative to the CTS (Figure 31). While emissions in aluminium increase by 10% due to a combination of increased material demand and reduced scrap availability, this is far outweighed by the emissions reduction in steel, which decrease by 6%, and cement, which decline by 9%. In reality, pushing material efficiency to practical limits would likely result in a combination of reduced industrial emissions and reduced deployment of low-carbon industrial process technologies, rather than one or the other only.

Figure 31. Direct CO_2 emissions for steel, cement and aluminium in different contexts



Material efficiency could achieve additional CO_2 emissions reduction in industrial sectors.

The emissions and energy implications of material efficiency for steel and aluminium are complex. Scrap-based secondary production is one of the key strategies to reduce emissions and energy demand in these subsectors, and material efficiency strategies affect the total amount of scrap becoming available (Figure 32).[10] In cases where total scrap availability is reduced as a net result of the suite of material efficiency strategies pursued, emissions reduction can be partially offset by a more limited availability to deploy secondary metals production routes. Material efficiency can put upward and downward pressures on scrap availability. Improved manufacturing yields reduce the amount of internal and new scrap related to material losses becoming available at the material and product manufacturing stages. Lifetime extension and reuse hold metals in stocks longer, reducing old scrap availability, while improved end-of-life collection rates increase old scrap availability. Strategies such as lightweighting affect the amount of a given metal entering the value chain, which changes the amount of scrap becoming available at all three stages.

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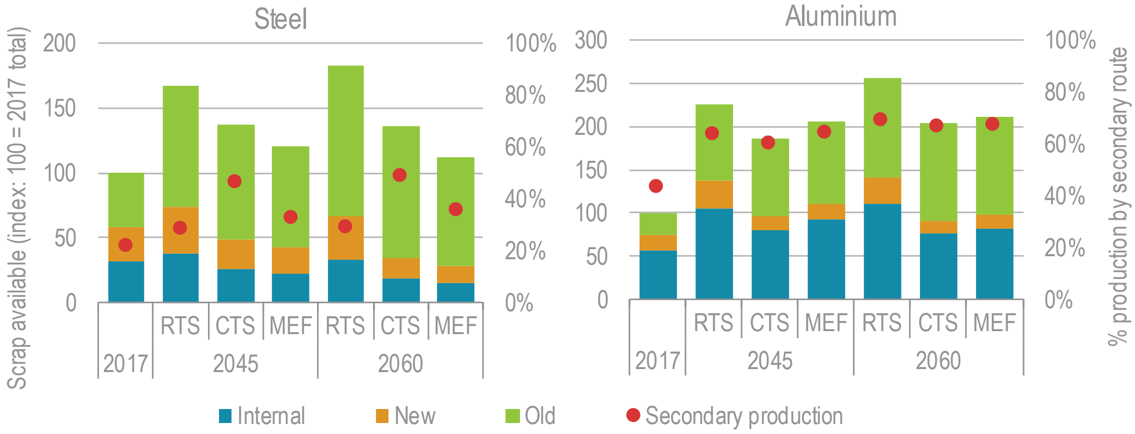
[10] Available scrap is defined here as collected scrap. It does not include theoretically available but not collected scrap.

Figure 32. Scrap availability and secondary production for steel and aluminium by scenario



Notes: *Scrap available* refers to scrap collected. Internal scrap results during semi-manufacturing; new scrap results from product manufacturing and construction; old scrap results from obsolete products at end of life.

Material efficiency changes scrap availability and opportunities for secondary production.

In the MEF, material efficiency strategies result in scrap availability 18% lower for steel and 3% higher for aluminium by 2060 relative to the CTS. For steel, a reduction occurs because most of the material efficiency strategies applied put a downward pressure on scrap availability, as improvements in collection rates are already at their practical limits in the CTS. This results in a lower share of secondary production in the MEF than in the CTS, by 28% in 2060. For aluminium, there are downward pressures (e.g. increased reuse) and upward pressures (e.g. increased aluminium inflow due to vehicle lightweighting) that partially offset each other, resulting in a net increase in scrap availability. The increase is higher in earlier periods (10% in 2045) and declines over time as the downward pressures have an increasing effect (3% in 2060). The share of secondary production in the MEF is higher than in the CTS, by 7% in 2045 and by 1% in 2060. Scrap availability can therefore play a key role in how much secondary production occurs. There are greater incentives to use as much scrap as is available in metals production as pressure to reduce CO_2 emissions increases over time. However, the rate at which scrap utilisation increases as a share of scrap available also depends on other factors including primary production capacity turnover.

Material efficiency changes the relative proportions of the different types of metal scrap, in addition to total metal scrap availability. While total metal scrap availability is lower in the CTS than in the RTS, the proportion of old scrap is higher, primarily as a result of improved manufacturing yields reducing internal and new scrap and improved collection rates putting an upward pressure on old scrap. The quality of scrap typically decreases as it is collected in subsequent steps of the value chain (internal scrap is higher quality than new scrap and new scrap is higher quality than old scrap), as it gets further mixed with other materials. Thus, material efficiency can also affect the usability of the scrap that is collected.

The interaction between material efficiency and industrial emissions is complex and not always additive. However, material efficiency reduces the need for technological transformation in industry to achieve emissions reduction objectives, or can further lower emissions in industry, while also facilitating emissions reduction in other sectors.

The following two chapters explore in more detail the material demand, material efficiency and CO_2 emissions implications for two key value chains: buildings construction and vehicles.

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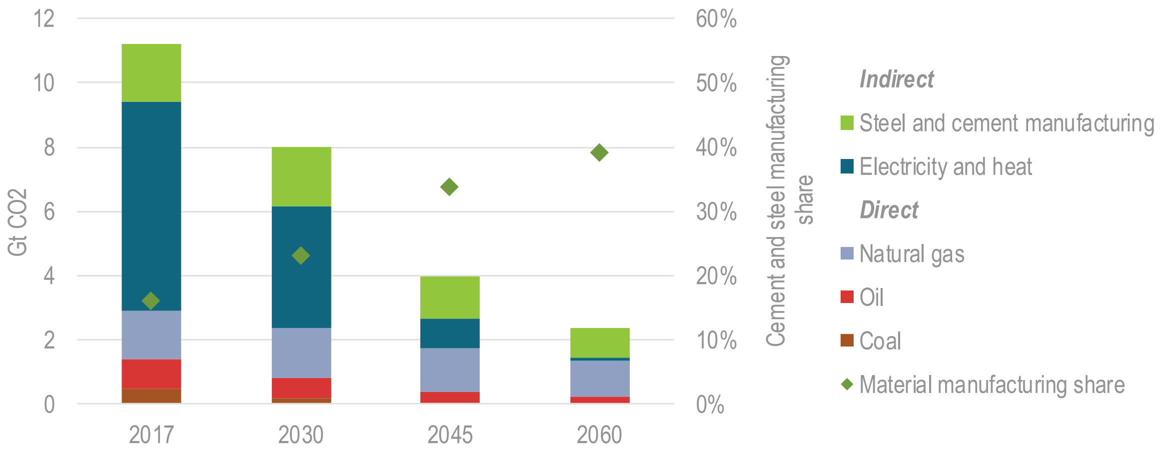
5. Value chain deep dive #1: Buildings construction

The manufacture and use of materials for buildings construction and renovation represented 11% of the global overall energy- and process-related carbon dioxide (CO_2) emissions. This embodied carbon in buildings is greater than the CO_2 emissions of the European Union. More than one-half of emissions related to buildings materials stem from steel and cement. This is because they are used in large quantities and are still produced through carbon-intensive routes on average. Aluminium, glass, insulation, plastics and other materials (e.g. other petrochemical products and copper) are secondary contributors. Steel and cement alone accounted for around 1.8 gigatonnes of carbon dioxide ($GtCO_2$) in 2017, or approximately 15% of total buildings-related emissions, which includes direct emissions from fossil fuel use in buildings and indirect emissions from upstream electricity, heat, steel and cement production (Figure 33).

Figure 33. **Global buildings sector emissions under the Clean Technology Scenario (CTS) and share of steel and cement manufacturing emissions**



Notes: *Direct* CO_2 emissions refer to those from fossil-fuel combustion in buildings. *Indirect* emissions refer to those from the generation, transport and distribution of electricity or commercial heat consumed in buildings, as well as emissions from steel and cement manufacturing. Emissions related to the production and use of other buildings construction materials such as aluminium, glass or insulation materials are not included.

Steel and cement manufacturing accounts for nearly 40% of global buildings-related emissions in 2060 in the CTS.

Emissions related to buildings construction materials and buildings operations[11] are expected to increase marginally by 2060 in the Reference Technology Scenario (RTS). Actions to improve efficiency in buildings energy use are critical for achieving climate ambitions, but as energy-related emissions from buildings decrease, the share of embodied carbon in buildings becomes increasingly important. In the CTS, where actions are taken to reduce direct and indirect emissions from buildings energy use, the share of embodied emissions from steel and cement

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[11] From now on, in Chapter 5, "materials" will refer to steel and cement only.

increases to nearly 40% by 2060. Therefore, material efficiency strategies and other efforts to reduce the carbon footprint of materials (e.g. less carbon-intensive industrial processes) are an important lever to reduce buildings-related emissions.

Material needs across the buildings and construction value chain

The buildings sector consumed 500 million tonnes (Mt) of steel and almost 2 000 Mt of cement and in 2017, or twice that at the beginning of the 21st century (Figure 34). The People's Republic of China ("China") accounted for approximately one-half of the total material demand growth since 2000, as its floor area grew at an average annual rate of 4% between 2000 and 2015. However, steel and cement demand in China gradually levelled off over the past few years. Conversely, material demand in India, Southeast Asian countries and Brazil has increased rapidly in recent years. Since 2015, these emerging economies are the key drivers of growing global demand for steel and cement. Material demand for buildings construction and renovations has remained relatively stable in developed countries and regions such as the United States and Europe.

Demand for materials in the buildings sector includes demand for new builds, but also that for renovations and retrofits. Most light renovations of buildings do not involve significant steel and cement use. However, this could be the opposite when retrofits involve dismantling portions of walls to improve insulation or in the adoption of advanced renovation techniques such as multiple-skin façades[12] for commercial buildings. For instance, dismantling the ground floor to put in more insulation can require approximately 8% of the steel and 10% of the cement initially used for buildings construction (Beccali et al., 2013). Deeper retrofits to extend a building's lifetime that would otherwise have been demolished consume even more materials. An example of an extensive renovation required 60% of the cement quantities that would have been used to construct the building from the ground up, and 75% as much for steel (Gaspar and Santos, 2015).

Key influences on material demand in buildings include framing, height, construction practices and nature of buildings codes. Framing significantly affects buildings material intensities (amount of material used per square metre [m^2] of floor space). Timber-frame buildings (common for residential buildings in the United States and Canada, for instance) typically require less than 50 kilogrammes (kg) of cement per m^2 of floor space; however, other structures using concrete or reinforced cement concrete (RCC) as structural materials typically require from 200 to 300 kg of cement per m^2. Steel use intensities also vary greatly with framing. About 60-90 kg of steel per m^2 is generally used if concrete or steel are the structural materials. However, the use of masonry framing typically more than halves steel use intensity and timber framing reduces it even further.

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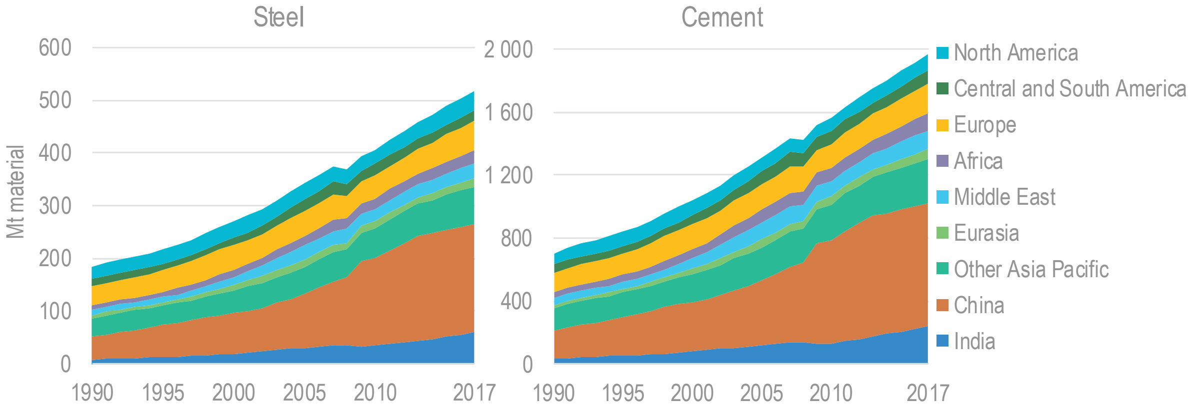
[12] Multiple-skin façades use air channels trapped between envelope layers to increase building insulation.

Figure 34. Historical steel and cement demand for buildings by region



Notes: Demand values do not include materials lost in the semi-manufacturing and buildings construction stages.

Global steel and cement demand for buildings construction and renovations has almost doubled since 2000 and continues to grow rapidly, despite a recent slowdown in China.

Market shifts have contributed to increased material use in buildings. The global share of RCC-frame buildings reached over 50% in 2017, which is an increase of more than 15 percentage-points since 1990. This increase has been caused largely by construction in China and other emerging markets, spurring even more material demand. Although timber remains the dominant framing material in many markets (e.g. those in North America, Japan or the Nordic European countries), new constructions with wooden frames are globally decreasing. This is due to material availability and other construction considerations such as height, tensile strength, moisture and flammability.[13] As the world's largest material consumer, China has experienced such a transition from wood to RCC construction (Wang et al., 2015). Countries in Africa build widely with wood, adobe, unbaked clay bricks, and other natural and local materials.

Buildings height is a strong driver of material demand growth. Past urban development patterns have contributed to large increases in steel and cement use in places like the United States and Japan. Over the past 15 years, particularly as buildings construction boomed in China, the total floor space of buildings of more than 30 storeys more than quadrupled (Council on Tall Buildings and Urban Habitat, 2018). This trend has significantly contributed to material demand growth, as the number of storeys affects structural material quantities and increases material intensities per m^2 of liveable area. Part of this is due to the need to support the self-weight of buildings. For instance, buildings with six to ten storeys typically use 35% more structural materials per m^2 than buildings with five and fewer storeys. When the number of storeys exceeds 20, steel use per m^2 can be four times as high as for low-rise structures with similar framing (De Wolf, 2017).

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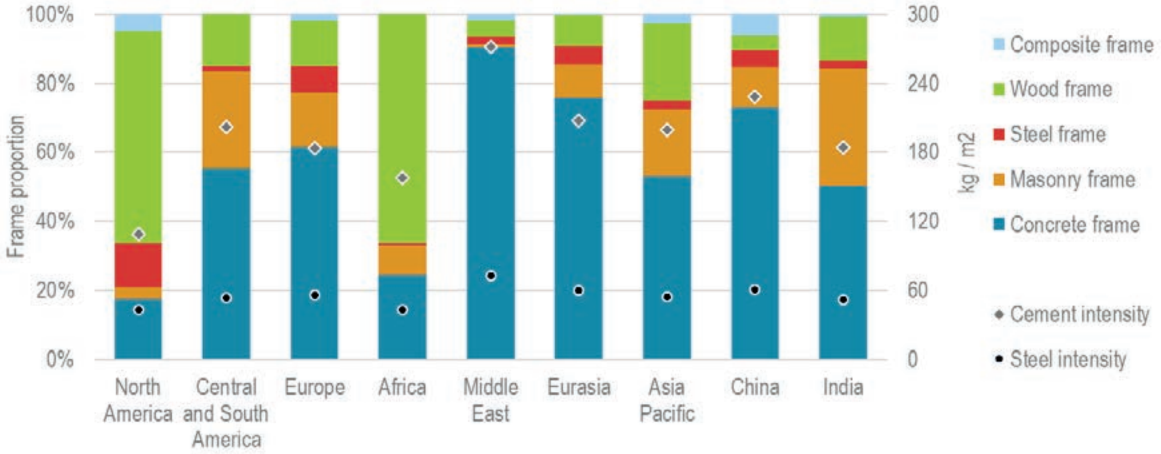
[13] Engineered timber construction illustrates the potential use of wood in construction, although cement and steel remain the dominant material choices in most regions.

Figure 35. Buildings stock broken down by buildings frames in key regions and corresponding material intensities in 2017



Choice of materials for buildings framing significantly varies among regions and greatly influences steel and cement intensities.

In addition to buildings frames and heights, the nature and enforcement of buildings codes may cause regional differences in buildings material intensities. For instance:

- The introduction of construction norms in rapidly developing regions has led to more material use in some cases, for example to enhance buildings safety and quality. The effect on life-cycle material use is typically counterbalanced by longer buildings lifespans, where the average lifetime of buildings in rapidly developing or emerging countries such as China, India and Brazil is still typically under 35 years, compared to as much as 70 years or more in Western Europe or North America.
- Buildings in areas with higher levels of seismic activity or other natural constraints may be built stronger to withstand more stress.
- Construction practices affect steel and cement demand, as material losses, waste management and on-site material management vary greatly across countries.
- Climate change adaptation efforts are likely to change material use trends through stricter safety requirements in buildings codes, the promotion of new construction techniques or the need for new adaptive frames (e.g. elevated structures).

Material efficiency strategies for buildings

Opportunities for reducing material use per m^2 of new build floor area are multiple and spread throughout a building's life cycle (Figure 36). The strategies considered in this analysis fall into the following categories:

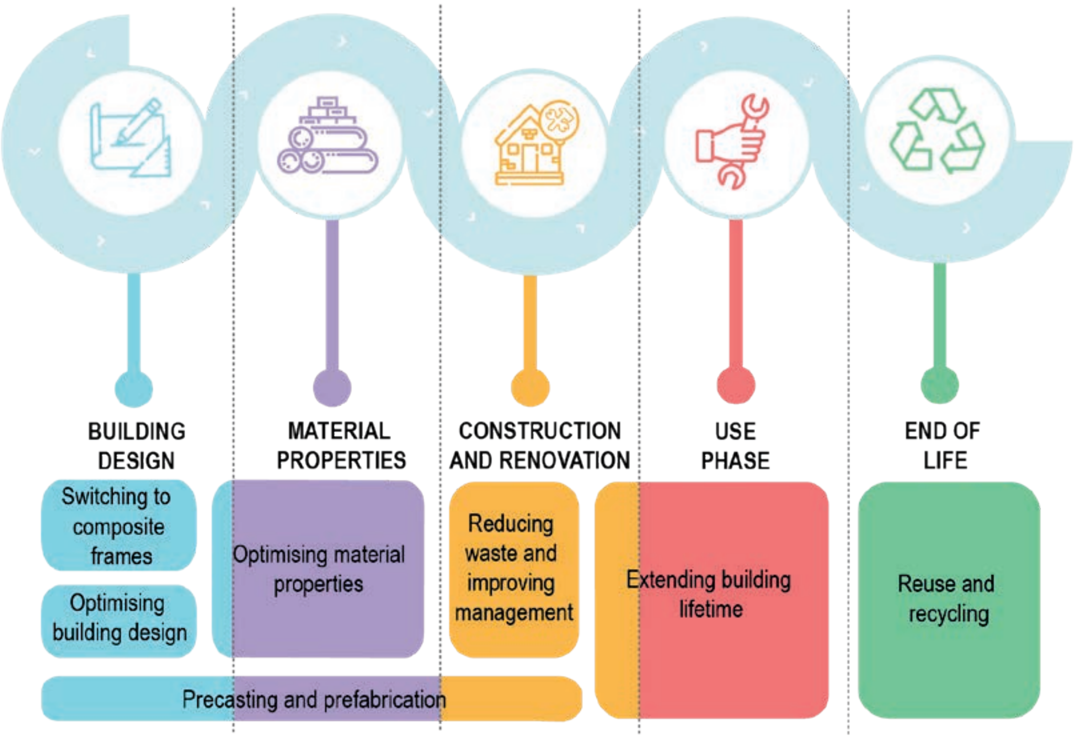
- improving buildings design and specification
- optimising material properties, including using high-strength steel and reducing cement content in concrete
- promoting best construction practices, for instance to reduce material waste
- using buildings for longer time frames, for example through repurposing during the use phase

- handling the end of life of buildings elements through material reuse and recycling.

While the strategies considered in this analysis are extensive, they are not exhaustive. For example, substitution to wood (timber) and other natural materials such as earth, clay or straw bales is not part of the current analysis, which other studies have found to be a strategy for reducing embodied carbon of buildings (Malmqvist et al., 2018). A life-cycle analysis of material substitution opportunities should look at the sustainability and availability of material supply (including potential competition with other uses such as biomass combustion for heat production in the case of wood) and the related energy and environmental consequences of new development patterns incurred by the new structures (on operational energy needs, land-use change, potential urban sprawl, etc.).

Digitalisation is a key enabler of resource efficiency all along the life cycle of buildings. From a project management perspective, digital tools characterise material needs precisely during design and track material flows during buildings construction, renovation and end of life. From a technical angle, they can foresee and produce buildings components tailored to their function. Digitalisation also facilitates off-site task handling such as buildings component preparation to ensure quality and timeliness at reduced labour costs.

Figure 36. Material efficiency strategies across the buildings construction value chain



Notes: The effect of strategies placed in series in this diagram is additive while two strategies placed in parallel are applied on different buildings. Material use reduction from one of these strategies may depend on upstream strategies applied on a given building. For instance, concrete recycling has been considered for precast or prefabricated elements only.

Multiple material efficiency strategies exist throughout the buildings construction and renovation value chains; most of them are interdependent.

Numerous technical options exist to take advantage of each of the strategies. At the design phase, **structural optimisation** tailors buildings components to their specific function. It can reduce over-engineering or overestimation, which occur when buildings are conceived with more materials than required to fulfil their structural function and meet safety specifications. For example, a study based on 30 buildings in the United Kingdom found that 35-45% of structural steel in those buildings was unnecessary to fulfil the load-bearing function of the frame, largely due to overspecification in the design stage (Dunant et al., 2018). Optimisation options include improving the design of structural elements through modelling tools and industrialising parts of the value chain through off-site quality control or material flow management tools.

Composite framing also helps to achieve these objectives as it enables various materials – with complementary physical properties – to be used in the core buildings structure. More advanced practices such as prestressing steel cables in reinforced concrete beams or slabs facilitate optimisation of buildings components. Pretensioned concrete elements provide greater resistance to buildings loads, which allows material savings through thinner slabs, longer beams or a lesser need for load-bearing columns, especially in high-rise buildings.

In addition to structural aspects, **innovative design** can make better use of space and rethink the way that whole-building elements are formulated. An example of a holistic approach is the 3for2 design for tall buildings, which uses façade- and floor-integrated mechanical and electrical elements for enhanced ventilation and thermal gains. Beyond 75% of operational energy efficiency gains, reduced ceiling spaces for equipment storage saves over 15% of material mass and cost (Schlueter et al., 2016). Materials can also be saved through lightweighting buildings components, such as the unreinforced funicular floors and concrete shell roofs under investigation through the NEST HiLo experimental building in Switzerland (Block et al., 2017). Furthermore, buildings layout can be designed in ways that reduce material use, including through terraced housing as opposed to single-detached homes and apartment block layouts whose shapes reduce the lengths of perimeter walls. Holistic approaches, digital design and digital manufacturing are enablers for wider adoption of these types of design strategies.

Beyond design, drawing upon possibilities for **best available concrete and steel** is a key material efficiency strategy. Making concrete strength higher could reduce frame size and cement demand if the increase in cement to achieve higher concrete strength is outweighed by savings from lower concrete requirements. This is particularly the case for large infrastructures and high-rise buildings whose components need to comply with tight requirements for durability, traction and compression. High-strength steel is also beneficial for both steel and cement use. Light-gauge framing uses cold-forming, which enhances the yield strength of steel. Components are lighter to transport and assemble, and can support heavier loads compared to hot-rolled constituents. However, the potential for further savings in advanced economies is more limited as light-gauge framing has been in place in modern designs since the 1990s. Manufacturers may also be able to supply for designated sections only, as cold-forming offers less flexibility to shape and tailor steel.

Another way to draw upon best available materials is to find means to **reduce the amount of cement in concrete** while achieving the same physical properties. For instance, optimising the size of aggregates when mixing concrete could require less cement to fill the spaces for a concrete of the same strength. It is known as improved concrete packing. Using admixtures (e.g. plasticisers or dispersants), can improve workability and reduce cement requirements for a given strength of concrete (MPA the Concrete Centre, 2018). The amount of admixtures used is generally so small compared to the quantity of cement that carbon emissions from admixture production is negligible (Latawiec, Woyciechowski and Kowalski, 2018). Fillers such as ground limestone, dolomite, basalt and quartz can also be added to concrete to reduce cement content. Increasing industrialised material production (e.g. moving from bagged cement to bulk delivery) will help the development of improved concrete packing. An additional layer of emissions reduction related to material efficiency involves reducing the clinker content in cement, through substituting materials such as blast furnace slag or fly ash (Box 4). While clinker substitution tends to occur in cement plants during cement production, there may also be opportunities to add clinker substitutes along with cement into concrete on constructions sites.

Box 4. Blended cements support CO_2 emissions reduction in cement manufacturing

Cement is a key component of concrete – it is the active ingredient that binds together aggregates when it reacts with water. Clinker, in turn, is the active binding material and main component of most currently used cements. Ordinary Portland Cement (OPC), the most common type of cement, generally contains more than 90% clinker, with the remainder being gypsum and fine limestone. Clinker production is highly emissions intensive, due to the high energy inputs that are needed for the calcination process and the CO2 that is released directly from raw materials during calcination.

Reducing the amount of clinker in cement (referred to as the clinker to cement ratio) can play a key role in reducing the emissions impact of cement. Clinker substitutes, which generally have lower production emissions than clinker, can replace a portion of clinker in cement, creating blended cements. These have chemical properties that, together with clinker, enable cement to perform its intended binding function. Examples of clinker substitutes include fly ash, ground granulated blast furnace slag, natural pozzolanic materials, limestone and calcined clay. These clinker substitutes are already used around the globe to produce blended cements. As a result, the global clinker to cement ratio in 2017 was an estimated 66%, compared to over 90% for OPC. While clinker substitutes are generally blended into cement in cement production plants, in some instances, they may be used to substitute a portion of cement directly on construction sites.

The use of blended cements can be considered a method of reducing cement production emissions and a material efficiency strategy. Replacing clinker reduces the emissions per unit of cement, while also enabling more-efficient use of emissions-intensive clinker. The modelling for this report takes into account strategies to reduce the clinker to cement ratio in the production phase of cement.

Respecting specifications is important to reduce material use in buildings. Designers generally characterise concrete elements with a class corresponding to specific requirements related to strength, composition and aggregates, etc. For simplicity reasons, a widespread practice is to use concrete with the tightest requirements for all elements. To ensure compliance with safety requirements, buildings designers, construction companies and subcontractors may each take a margin, which leads to significant extra use of materials. Practical constraints may also lead to greater material use. For instance, site managers and construction engineers may not order an exact amount of ready-mix concrete to avoid shortages and delays in the construction process. Enhancing the design of buildings could theoretically lead to savings greater than 30% for steel and 15% for cement, but the fragmentation and variability of the construction value chain is a critical hindrance to that material savings potential.

Precasting and prefabrication are levers to tap into the material saving potential from enhanced buildings design, material optimisation and construction practices. They are techniques (e.g. digital construction and buildings information modelling) that provide more control over the size, shape and making process of buildings components. Industrialising the manufacture of large buildings elements facilitates on-site activities while speeding up construction processes. The centralisation of such practices in dedicated workshops also reduces the risks of wasting materials. Prefabrication and precasting is therefore an important lever to scale up low-carbon construction practices. To push this lever even further, additive manufacturing (three-dimensional printing) is a way to design more complex and larger components at once, without assembling various pieces together. Such innovative practices have yet to demonstrate their practical and economic viability at a large scale and for broad applications. Additionally, concrete precasting may facilitate the commercialisation of alternative binding materials for low-carbon cements through the standardisation of processes that capture and store CO_2 during the controlled curing process.

Improving **construction practices** is a means of reducing waste. Poor co-ordination and surplus ordering may result in unused cuttings of paving slabs, bricks or blocks. It also greatly affects other elements such as floor tiles, plasterboard sheets and insulation boards. At the design stage, accurate specification of buildings components reduces the risk of wasting materials. On-site, improved material flow management may reduce damage and inefficient use of materials. Clients can impose waste requirements onto the main contractors, who can then develop waste management plans and report on their achievement through waste handling indicators. Digitalisation also provides opportunities to facilitate monitoring of waste reduction objectives.

Extending buildings lifetime through enhanced modularity, improved design, more durable materials and in-depth retrofits reduces the need for raising new buildings. The average lifetime of residential buildings can exceed 80 years in Western Europe. It is lower in other developed countries such as the United States and Japan.[14] In rapidly developing and emerging economies, high demolition rates may bring average lifetimes down to 30 years (Hong et al., 2014). China demolished nearly 10 million m^2 of floor area every year in the late 2000s (Shanghai Statistical Bureau, 2015), which was approximately 15% of the area built annually during this period. In the non-residential sector, buildings lifespans across the globe rarely exceed 50 years,[15] as commercial activities change frequently. Modular buildings structures allow repurposing buildings without having to demolish them and build new ones from the ground up.

A low embodied carbon strategy would also benefit from deep energy renovations already promoted under the CTS, including thermal insulation, low-emissivity double glazing or cool roofs. Financial investments in these retrofits may create incentives to use buildings for longer to recoup the benefits of the investments. Buildings owners may also take the opportunity to make other non-energy upgrades to buildings while undertaking energy retrofits, leading to more appealing buildings. As a result, buildings lifetimes could be extended to more than 100 years for residential buildings and 70 years or more for others. Choosing to retrofit rather than demolish and build anew will save on structural materials for constructing new buildings. Challenges will need to be overcome to promote a culture of reusing buildings rather than

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[14] This estimate is derived from construction dates of the building stock in the United Kingdom, Sweden, France, Europe (averaged), the United States and Japan.

[15] Multiple press and scientific articles as well as datasets of building stock data by construction dates suggest that non-residential buildings typically last between 25 and 50 years, although well-designed buildings may occasionally last longer.

constructing new buildings, including pressures from land-use policies and economic competition that encourage new construction.

End-of-life reuse and recycling constitute the last category of material saving potential. Steel elements can be reused multiple times without harming their material properties. Light-gauge structures made from cold-formed steel elements are particularly tapping into this potential, as steel frame construction is highly demountable. Standardisation, warranty, storage and quality testing of steel components are the main barriers to their reuse. When steel elements cannot be reused, collection for recycling can help achieve lower production emissions for new steel elements than production from iron ore. In contrast, opportunities for cement reuse and recycling are more limited. Reuse of precast concrete elements may be possible provided consideration is given to reuse at the initial design phase. However, these elements should also be suitable for a new building that is not too far away, to avoid transporting heavy blocks over long distances. While there may be potential for recovery and reuse of unhydrated cement from used concrete, technologies to do this have yet to reach the commercial stage. However, recycling concrete aggregates is possible and widespread. While this has benefits in terms of reducing the need for virgin aggregates, aggregates are not an emissions-intensive component of concrete and thus the emissions benefits of recycling cement, if it were possible, would be substantially higher.

Many interactions exist among the aforementioned strategies. Some of them may facilitate the adoption of others. For instance, using high-strength steel could enhance the development of composite buildings and generate cement savings as the steel load-bearing structure becomes more robust. Predefined buildings elements are also easier to optimise and could be used on many construction sites. However, there are also trade-offs among strategies. Designing buildings for long lifetimes may require a higher upfront material input to ensure durability and adaptability to new uses. Designing for reuse would favour less-tailored modular buildings elements being used in different buildings designs, the opposite of designing elements that are highly optimised to one particular function. The whole-building life cycle should be considered to obtain optimal life-cycle material benefits.

Annex III provides more details on buildings value chain assumptions and the modelling methodology, including the strategies considered in the assessment.

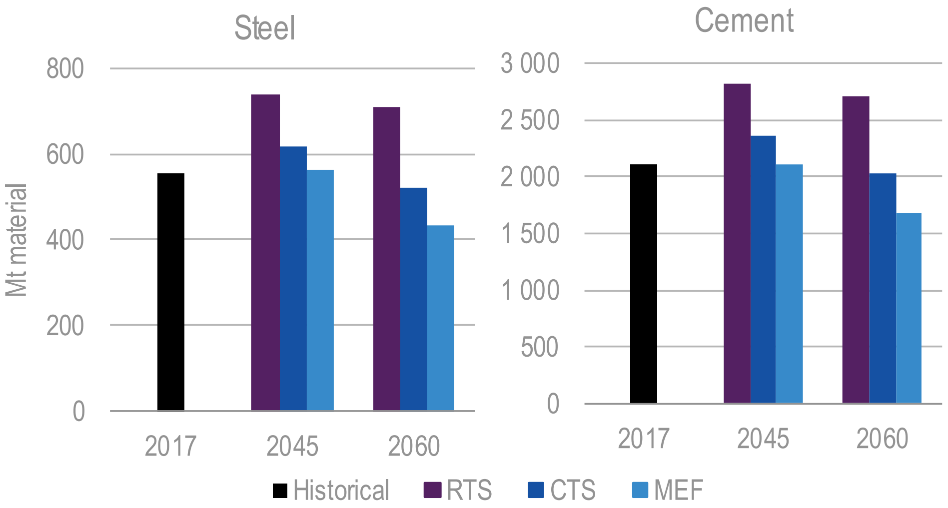
Outlook and implications for steel and cement use in buildings

Projected steel and cement demands in buildings vary considerably among scenarios, reflecting the effects of different technologies and policies over the coming decades.

In the RTS, material demand continues to increase, to over 30% by 2060 above 2017 levels for both steel and cement (Figure 37). Rapid construction rates in urban areas coupled with limited efforts to put in place material efficiency strategies sustain recent material demand trends. This means that cement consumption for buildings construction over the next 30 years would be more than twice the cement consumed over the past 30 years. In the RTS, steel and cement manufacturing for buildings construction and renovation is therefore responsible for an average of 2.3 $GtCO_2$ annually to 2060, the equivalent of all of India’s emissions in 2017.

In the CTS, with widespread adoption of buildings codes and standards, demolition rates decrease considerably. Developed countries implement large-scale deep energy retrofit programmes to reduce the energy used during the operational phase of buildings, which has implications for materials demand but also extends the lives of buildings. The transformation of the global construction market lowers both steel and cement demand by one-quarter in 2060 relative to the RTS.

Figure 37. Global steel and cement requirements for buildings by scenario



Note: Demand values include material lost in the buildings construction stage and demand reductions from reused materials; they do not include material lost in the metals semi-manufacturing stage.

Material efficiency strategies at the design, construction, use and end-of-life stages could considerably reduce buildings sector steel and cement consumption.

Pursuing material efficiency strategies to their practical limit reduces steel use by an additional 15% and cement use by another 17% in 2060 in the Material Efficiency variant (MEF) relative to the CTS. Material efficiency strategies include pathways to reduce material use per unit of floor area during buildings construction or renovation and other activity effects related to extended buildings lifetimes or increased renovation rates.

Box 5. Other materials used in buildings construction and renovation such as aluminium, glass and plastics

Beyond cement and different steel types, buildings use numerous other energy-intensive materials as outlined in the following:

- About a quarter of all aluminium produced world wide is used in construction (World Aluminium, 2017). Over the coming decades, rising global floor area will contribute to increased aluminium alloys demand for construction, particularly as aluminium properties fit new aspirations for light, flexible or high-rise buildings structures. In 2030, aluminium industry product net shipments for construction are predicted to reach 34 gigatonnes (Gt), up from 23 Gt in 2018 (World Aluminium, 2017).
- Around 70% of flat glass tonnage is consumed in windows for buildings (NSG Group, 2019). Construction, new architectural trends (e.g. all glass façades) and energy efficiency

(e.g. double-glazed or triple-glazed windows) are the main drivers for rising flat glass demand. Buildings also account for one-third of the global glass fibre market, most of which is used for buildings insulation (Transparency M. Research, 2016).

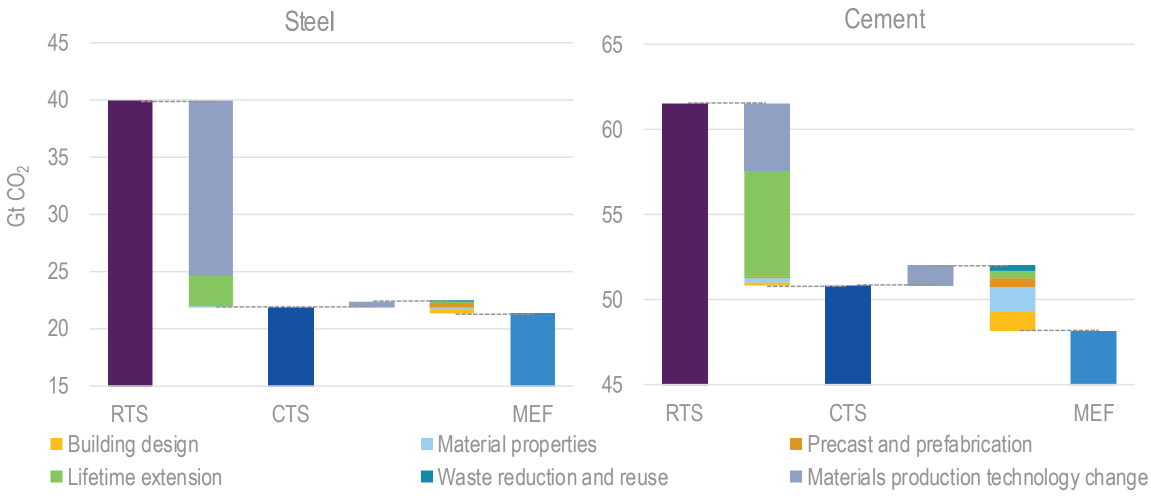
- Over the past 15 years, buildings construction consumed around 19% of polymer resin production, almost one-half of which was polyvinyl chloride for window or door profiles and for piping in buildings. The rest consists mainly of polyurethane derivatives for thermal insulation (including cellular matrices and spray foam), wood products and glazing (Geyer, Jambeck and Law, 2017).

Given the complexity and variety of materials used in buildings, setting horizontal performance-based metrics (e.g. life-cycle CO_2 emissions per m^2) will promote low-carbon buildings construction. These account for interdependencies among CO_2 emissions sources within the value chain while prescriptive requirements by subsector could lead to inefficiencies in abating CO_2 emissions. For instance, CO_2 emission ceilings for glass manufacturers could hinder double-glazed window production, whereas life-cycle-based requirements would encourage it when emissions from glass production are offset by avoided emissions from the reduction of the thermal load in the buildings use phase.

In the CTS, material demand reductions contribute to reducing CO_2 emissions from steel and cement use in buildings by 10% (10 Gt) cumulatively from 2017 to 2060 relative to the RTS (Figure 38). For steel, material demand reductions account for 16% of the cumulative emissions reduction in the CTS relative to the RTS, with the remainder of reductions resulting from changes to lower-emission technologies and process routes to produce steel. For cement, 63% of the emissions reduction in the CTS is attributable to material demand reduction. While the cumulative reduction in demand for steel and cement is similar (12%), the larger contribution of material demand reduction to reducing cement than steel emissions occurs due to the greater difficulties in decarbonising cement production. The technological options available for reducing cement production emissions are fewer and more challenging, thus leaving greater room for material demand reductions to contribute. Of the material demand reduction strategies deployed in the CTS, buildings lifetime extension contributes to over 90% of the reductions for both steel and cement.

The additional material demand reductions in the MEF reduce some of the need for changes in materials production technologies. Owing to material demand reductions across sectors, the MEF achieves the same total system-wide emissions budget as the CTS, with a global average emissions intensity of production that is 4% higher for steel and 7% higher for cement in 2060 in the MEF relative to the CTS. Yet, the steel and cement cumulative CO_2 emissions attributable to buildings are lower in the MEF than in the CTS by 5 Gt. This is due to greater reductions in deploying low-carbon industrial process technologies in regions with higher proportions of material demand from end uses other than buildings. Material demand reductions in the MEF account for nearly 50% of emissions reduction related to steel and cement use in buildings relative to the RTS.

Figure 38. CO_2 emissions related to steel and cement use for buildings construction and renovations by scenario, cumulative from 2017 to 2060



Notes: Emissions from material lost in semi-manufacturing are not included. *Materials production technology change* includes clinker substitution for cement production and increased use of secondary routes aided by increased recycling for steel production.

Material demand reductions in the buildings sector reduce steel and cement emissions in the CTS, while reducing some of the need for material production technology change in the MEF.

For steel, the largest contributors to material demand reduction in the MEF beyond the CTS are improvements in buildings design and precasting. Each of these contribute to around 40% of the cumulative emissions reduction attributable to steel demand reduction beyond the CTS. The improved buildings design results from improved structural optimisation and reduced over-engineering. For cement, improved materials properties (i.e. reducing the cement content in concrete) makes the largest contribution, equal to over one-third of the emissions reduction attributable to cement demand reduction. Improved buildings design also makes a large contribution.

A moderate amount of emissions reduction also occurs from extending buildings lifetimes, reducing waste and reuse. Strategies to extend buildings lifetimes, including modular designs and buildings repurposing, are pushed further in the MEF than in the CTS, as are efforts to reduce cement waste and reuse steel.

Buildings sector material demand and emissions reduction should be considered in light of the fact that shifts to different construction materials (e.g. timber) were not included in this analysis. If timber were available to the buildings sector within reasonable cost and sustainability criteria, considering competing demands from biofuels and other uses, it could be possible to push steel and cement demand reductions further in the buildings sector. This would further reduce deployment needs for low-carbon industrial process technologies.

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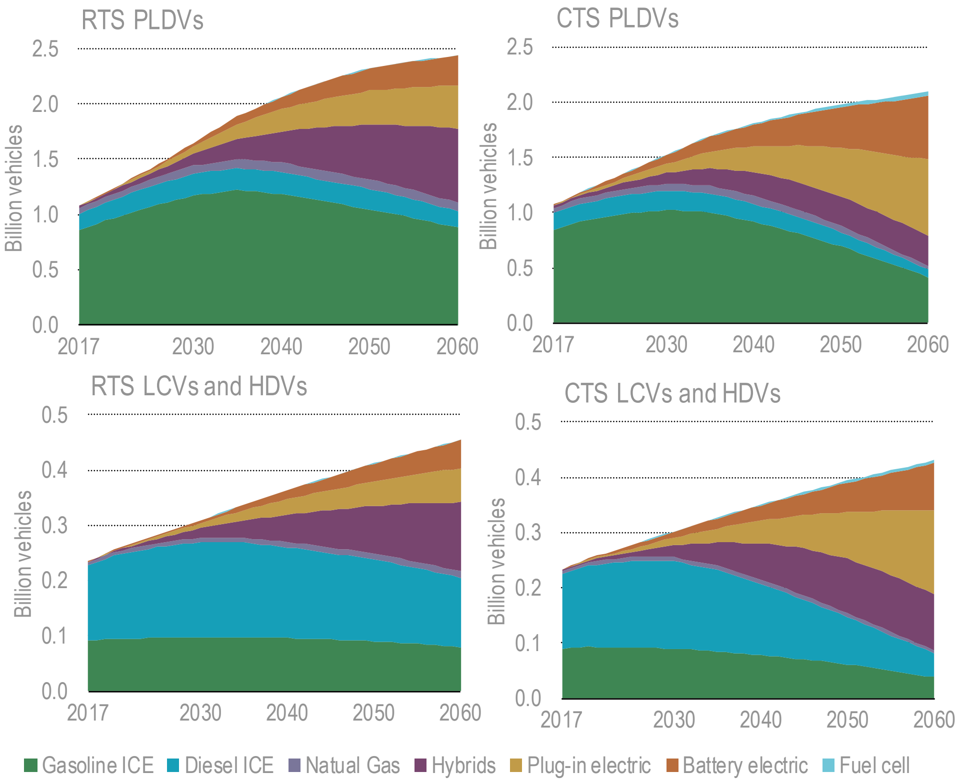
6. Value chain deep dive #2: Vehicles

As society shifts towards low-carbon transport systems, it will become increasingly important to consider the contribution of materials to transport sector emissions. Fuel-related emissions account for more than 85% of life-cycle energy and emissions (excluding emissions from roads and parking infrastructure) for conventional internal combustion engine (ICE) cars and trucks running on gasoline or diesel (Chester and Horvath, 2009). Fuel-related emissions include operational exhaust-pipe and fuel production emissions, which are referred to as "well-to-wheels" emissions. The remaining 15% of life-cycle emissions are incurred by the industrial activities along the entire supply chain that mine, form, refine and shape the materials that become cars and trucks. In transitioning from ICE to alternative fuel vehicles, such as battery-electric vehicles (BEVs) running on low-emission electricity, the emissions from material production will make up an increasingly larger proportion of vehicle life-cycle emissions. Efforts to lightweight vehicles to achieve fuel economy savings also have implications for vehicle production emissions. Taking a life-cycle approach to assess vehicle emissions will be useful in enabling the most efficient use of materials in terms of value chain emissions reduction.

The transition to a clean energy system will also involve broader changes in the transport sector beyond switching to more fuel-efficient and alternative fuel vehicles. A suite of policies (including fuel taxation, vehicle purchase and usage taxation and city-level travel demand management) would be needed to shift transport choices increasingly towards car-pooling, public transit and active transportation modes such as cycling. Urban planning may reduce transport distances and congestion. Fewer vehicles will therefore be sold, thus requiring less materials for vehicle production. For freight, policies will improve the volume of goods that trucks haul and the competitiveness of rail freight with respect to trucking. In 2060, the Clean Technology Scenario (CTS) sees approximately 15% fewer passenger cars and trucks (passenger light-duty vehicles [PLDVs]) and 5% fewer light commercial vehicles (LCVs) and heavy-duty vehicles (HDVs) on the road globally than in the Reference Technology Scenario (RTS). Efforts on multiple carbon dioxide (CO_2) emissions levers result in a considerable shift in the fuels being consumed (Figure 39). Annex IV provides additional details on transport policies in the scenarios and their effects on transport activity.

Figure 39. Road vehicle stocks in the RTS and CTS



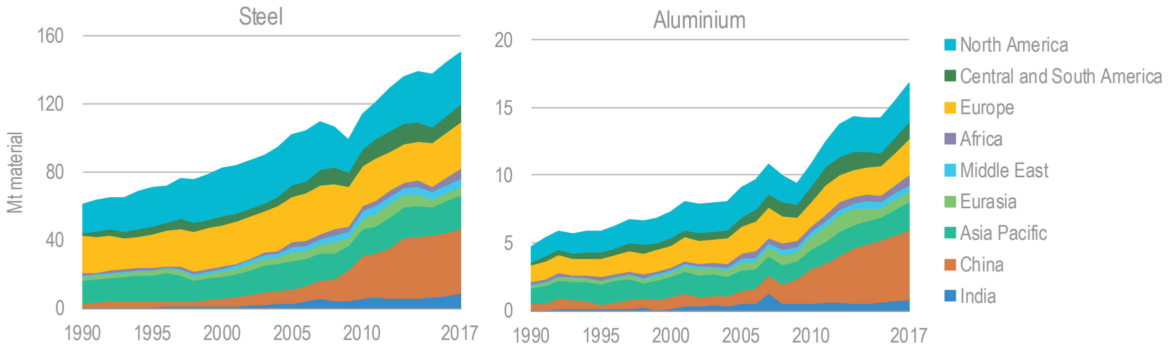
Notes: PLDVs = passenger light-duty vehicles, which include passenger cars and trucks. *LCVs* = light commercial vehicles. *HDVs* = heavy-duty vehicles, which include medium and heavy-freight trucks, buses and minibuses.

Vehicle powertrains diversify in the CTS, and total stocks are lower than in the RTS.

Material needs of vehicles

Road vehicles constitute a major demand sector for materials. Most automotive bodies and nearly all frames are currently made primarily of steel. Other key materials include aluminium and plastics. PLDVs currently account for approximately 7% of global demand for steel and 12% of global demand for aluminium, while LCVs and HDVs account for approximately 4% of steel and 10% of aluminium demand. In the past few decades, steel and aluminium inflows to road vehicles have grown considerably, with growth across regions and particularly large recent growth in the People's Republic of China ("China") (Figure 40).

Figure 40. Historical steel and aluminium demand in road vehicles by region



Note: Demand values do not include material lost in the materials semi-manufacturing and vehicle manufacturing stages. Mt = million tonnes.
Source: International Energy Agency (IEA) estimates, including use of data from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (Argonne National Laboratory, 2017) and provided by Ricardo-AEA from a study commissioned by the Directorate-General Clima of the European Commission (Hill et al., 2015).

Global steel demand for road vehicles has more than doubled since 1990, while global aluminium demand for road vehicles has more than tripled.

Major determinants of the material demand of vehicles include the vehicle class and constituent components, the type of powertrain and the extent to which the vehicle is intentionally lightweighted to achieve fuel economy improvements.

The average passenger vehicle has been getting heavier over time. The Global Fuel Economy Initiative (n.d) estimated that the global average weight of newly registered vehicles increased by more than 5% from 2010 to 2015. The causes of this trend include an increasing shift from cars to sports utility vehicles (SUVs) and trucks, and added features and functionality, which add weight and require more supporting material like steel. The type of powertrain also affects vehicle material demand. For example, electric powertrains contain more aluminium and less steel compared to ICEs, although batteries weigh more than ICEs. Plug-in and conventional hybrid vehicles tend to have even heavier powertrains, which may require more supporting materials.

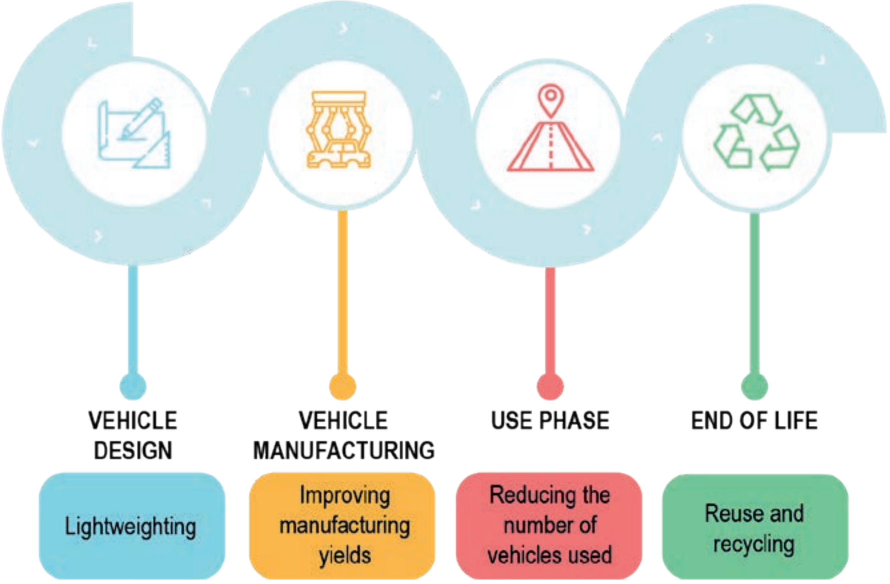
Lightweighting has been pursued as a strategy to improve the fuel economy of vehicles in recent decades. The adoption of advanced materials has played a growing role in vehicles from the mid-1970s and in the North American market. Over the past decade, lightweighting has contributed to safer and more powerful vehicles, which, despite being larger, consume more than 20% less fuel (Isenstadt and German, 2017). In countries and regions imposing fuel economy or CO_2 standards, lightweighting through advanced materials and new designs is one of the top strategies that manufacturers cite for regulatory compliance. Of the companies surveyed in a survey by WardsAuto, nearly one-half (49%) cited lightweighting as their main strategy for meeting the 2017-25 fuel economy regulations in the United States, followed by engine efficiency (39%) and electrification (26%) (Winter, 2014). Recent tracking of vehicle weights and material ratios show that new manufacturing processes, stronger alloys and computer-assisted vehicle design have enabled vehicle designers to achieve weight reductions of approximately 5-15% within one to five model years (Isenstadt and German, 2017).

Material efficiency strategies for vehicles

Life-cycle analysis is important for assessing the material efficiency strategy potential in vehicles. The strategies considered in this analysis fall into the following categories (Figure 41):

- lightweighting vehicles
- improving manufacturing yields
- reducing the total number of vehicles used, through strategies such as modal shift and intensified vehicle use (ride and car-sharing and car-pooling)
- end-of-life reuse and recycling.

Figure 41. Material efficiency strategies across the vehicle value chain



Multiple material efficiency strategies exist throughout the vehicle value chain.

Lightweighting is one of the key material efficiency strategies applied to vehicles. It can be pursued through a combination of reducing the weight of components within the same material and substituting with other lighter materials. An example of reducing weight within the same material is thin-walling for cast iron components, which was able to achieve up to 40% weight reductions for those components (Jhaveri et al., 2018). Reducing the vehicle mass through component mass savings can also enable secondary mass savings in supporting vehicle parts. This savings potential can be maximised by designing vehicles using methods that do not lock in specific, costly subsystem and component designs (Alonso et al., 2012). Moving towards smaller overall vehicles is closely related to lightweighting. Counteracting recent consumer preferences towards SUVs and other larger vehicles will be important so that material reductions from component lightweighting are not offset by increasingly larger average vehicle size.

With regard to material substitution, no single material or design method has dominated across manufacturers or vehicle types. As drivers of capital investment, car bodies have been the focus of much lightweighting design innovation, although body design is subject to multiple design constraints (e.g. safety, strength, stiffness and noise). Promising materials for substitution include the following:

- **High-strength steel.** Steel suppliers have responded to demand for lighter steel by developing new grades of high-strength and advanced high-strength steel. "Third-generation" steels with micro-alloys of manganese, molybdenum and silicon can be cast to thin-walled shapes and complex geometrics. They are more ductile than previous grades and provide extremely high specific strength after heat treatment.
- **Aluminium.** This material provides weight reductions compared to steel, and does not have such high costs as more advanced materials. Optimistic industry forecasts expect that by 2025, most car bonnets, one-half of all door materials and between one-quarter and one-third of boots, roofs and wings will be made of aluminium, with large potential for increased reliance on aluminium in the automotive industry (Isenstadt and German, 2017).
- **Plastics and composites.** These account for about one-half of a car's material volume, but only approximately one-tenth of its mass. Despite their low density, new materials being developed are capable of providing high strength and rigidity, and are recyclable. Plastic and composite materials are increasingly being used to replace steel in bodies and chassis as they provide not only superior strength and rigidity, but also better resist corrosion and have greater ease of design integration. Carbon fibre-reinforced polymers are starting to be incorporated into vehicles, although greater uptake faces challenges related to cost and recyclability.

Other materials such as magnesium may show more potential if development and cost reductions occur in the future.

The primary reason for pursuing lightweighting tends to be use-phase fuel savings, which reduce emissions. For light-duty passenger cars, a general rule is that a 6-7% reduction in specific fuel consumption can be achieved for each 10% reduction in vehicle kerb weight (Luk et al., 2017).[16] Vehicle mass reductions are most effective in heavier vehicles; that is, the same percentage of lightweighting leads to more cost-effective and larger absolute reductions in fuel consumption (Hill et al., 2015; Kim, Keoleian and Skerlos, 2011). Thus, the greatest potential for this strategy in the light-duty fleet exists for larger vehicles such as pickups, minivans and SUVs. In trucking, the relationship is more complicated because fuel savings are influenced by the actual payload of operations, which may be limited by operational or goods volume constraints. Similar considerations apply to buses, and limit the economic incentive to lightweight in such applications.

From an emissions reduction perspective, the objective of lightweighting should be a net life-cycle savings. Depending on the type and extent of lightweighting, the emissions from material production may increase in some cases. However, in many cases, this increase can be far outweighed by use-phase savings. The extent to which life-cycle emissions decrease (or, in some cases, increase) because of lightweighting depends on various key assumptions and parameter estimates such as the following:

- **Material substitution ratio.** This is the mass of lightweight material needed to replace a unit mass of conventional material. Steel is typically used as the baseline material for comparison.
- **Direct CO_2 intensity of material production.** Using less of a given material (e.g. making a steel component out of less steel) will always save emissions from a production perspective. In some instances, material substitution may involve substituting a more emissions-intensive but lighter material. The combination of the relative emissions

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[16] This estimate assumes engine downsizing accompanies lightweighting. No net impact is thereby incurred on vehicle size, safety and performance (Isenstadt and German, 2017). This estimate is also a midpoint "consensus" value; the full range of fuel-mass coefficients reported in studies is from 0.315 to 0.71 (Kim and Wallington, 2013).

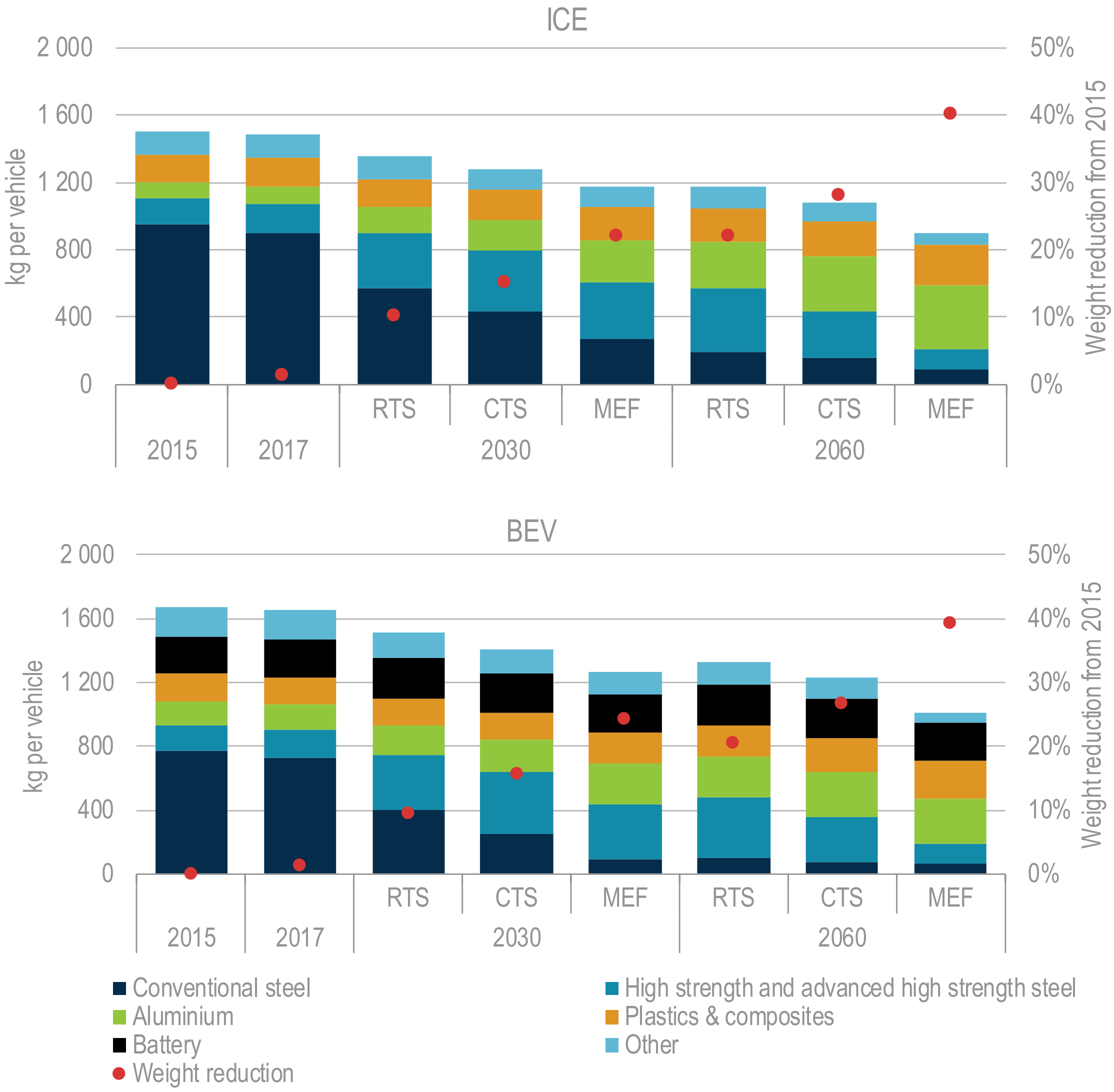
intensity of the two materials and the material substitution ratio may result in a net increase or decrease in production emissions.

- **Lifetime driving distance and share of city versus highway driving.** These affect the amount of fuel consumed in the use phase. The drive cycle affects the actual fuel savings potential of lightweighting.
- **Vehicle powertrain and fuel efficiency and emissions intensity of use-phase energy.** The vehicle fuel efficiency and powertrain, and the emissions intensity of the fuel used (including upstream production and exhaust-pipe emissions), affect the amount of use-phase savings. For example, lightweighting an inefficient ICE vehicle running on gasoline will result in more use-phase emissions savings than a battery-electric or hydrogen fuel-cell vehicle running on near-zero-emission electricity or hydrogen. There may be motivations other than use-phase emissions savings for lightweighting electric vehicles (EVs), such as reducing the battery size or maintaining the battery size but increasing the vehicle range.
- **Fuel reduction value.** The amount of fuel savings from lightweighting depends on various factors such as the drive cycle, the starting fuel economy and the rolling resistance (Sullivan, Lewis and Keoleian, 2018). The drive cycle is the largest determining factor, with the greatest reductions occurring in transient, stop-start cycles.

Engineering and academic literature tends to support the case that lightweighting generally results in substantial life-cycle energy and CO_2 emissions benefits. Kim and Wallington (2013) found that vehicle lightweighting reduced life-cycle energy demand and emissions in 21 out of the 26 published life-cycle assessments of vehicle lightweighting they reviewed. Luk et al. (2018) assessed the sensitivity of life-cycle emissions to variation in assumptions when lightweighting a case study vehicle glider. Using a Monte Carlo analysis, they found the life-cycle probability of the lightweight glider reducing life-cycle emissions to be 100% for an ICE vehicle or hybrid electric vehicle (HEV) running on various combinations of gasoline and ethanol and 74% for a BEV powered by electricity of varying carbon intensity.

In the present analysis, it is assumed that if material efficiency were pushed to its practical limits, the average passenger car could see a 40% reduction in weight by 2060 relative to in 2015, for both ICEs and BEVs (Figure 42). The economic incentive for lightweighting in vehicles tends to be greater with a lithium-ion battery and pure BEVs in particular, as lighter BEVs can either increase the range for a given weight of battery or enable battery downsizing to maintain the same range. The battery currently makes up about one-half of the cost of a BEV (Lutsey et al., 2018), and may continue to make up a large share of the vehicle cost for at least the next few decades. Therefore, efforts to lightweight to improve range or reduce purchase price are likely to be pursued aggressively by automotive original equipment manufacturers even without fuel economy standards or other regulatory drivers. However, as lithium-ion battery costs fall, energy densities and durability rise, and lightweighting opportunities are exploited, it is possible that the greater economic incentives for lightweighting BEV bodies and other non-battery components will diminish, perhaps as early as in the 2030s.

Figure 42. Mass composition and weight reduction for a benchmark passenger car



Notes: Passenger cars are the smaller size class of PLDVs (the larger size class is light trucks). For batteries, increasing capacity (enabling increased range) and energy density over time are assumed, offsetting one another such that the battery weight is relatively constant over time. kg = kilogrammes.

The potential for total vehicle lightweighting differs between conventional ICE vehicles and BEVs, due to the weight and composition of the engine and powertrain, as well as differences in the economic incentives for lightweighting.

Design and production considerations other than lightweighting may also improve material efficiency, including **improving manufacturing yields**. Currently, considerable amounts of steel and aluminium are lost during vehicle manufacture, with typically about 70 to 80% of steel and 80 to 85% of aluminium entering the manufacturing plant ending up as part of the vehicle. These are some of the lowest yields among end-use applications (Cullen, Allwood and Bambach, 2012; Liu, Bangs and Müller, 2013). The losses occur in part because the quickest and most cost-effective manufacturing methods are used. Giving a priority to material use reduction could improve these yields, such as by increasing the efficiency of operation of existing manufacturing processes, developing new processes with higher yields and using components designed with geometries closer to those of semi-finished outputs.

In the vehicle use phase, **reducing total vehicle use** will result in fewer vehicle sales, and therefore less material will be used to produce vehicles. This includes reducing the demand for travel by vehicles through modal shift, which can be facilitated by urban planning to reduce travel distances, and increasing the intensification of use per vehicle through ride-sharing and car-sharing. It is assumed modal shifting is already pushed to its maximum potential in the CTS. Slowing the trend of increasingly larger vehicles would also reduce material demand. Future uptake of more revolutionary changes to transport systems, including shared vehicles and autonomous vehicles (AVs), may lead to additional reductions in material demand by a combination of reducing vehicle sales and better tailoring vehicle size to required function (see Box 6).[17]

If vehicles were to be designed with modular and replaceable (ideally also recyclable) components, the strategy of extending vehicle lifetimes could be another use-phase strategy to reduce material demand for vehicles. However, unless powertrains and energy storage systems are also easily replaceable, this strategy would slow stock turnover and thereby slow the shift to vehicles that are more energy efficient. Given this trade-off and that use-phase emissions currently account for most life-cycle emissions, it is unlikely that extending vehicle lifetimes would result in life-cycle savings unless replacement, recycling and modularity are incorporated into vehicle design.

At the end of the vehicle lifetime, **reuse and recycling** can reduce value chain emissions. There is limited reuse of steel and aluminium components from vehicles currently. However, it could be increased in the future through better co-ordination between vehicle manufacturers and vehicle recyclers. When direct reuse of metals is not possible, recycling will help reduce emissions from new materials production. Unlike reuse of components, rates of vehicle collection for recycling are high in advanced economies, but have potential for improvement globally.

Annex III provides additional details on vehicles value chain assumptions and the modelling methodology.

Box 6. Material implications of revolutions in transport: shared, autonomous, electric vehicles

AVs demonstrate great promise to improve the safety, accessibility and convenience of road transport. Questions around the deployment, use, regulations and extent to which AVs will be shared make it difficult to predict their long-term consequences on energy and materials.

AVs could drastically change how passenger vehicles are designed and built. For instance, a reduction in the frequency and severity of collisions (including from improved active safety systems like crash avoidance and from low-speed operations in geo-fenced areas) would mean lower "passive safety" requirements and equipment (including crumple zones). This could create a shift towards the development and adoption of more durable, lighter-weight materials, such as advanced composites, aluminium and lightweight steel alloys. In vehicles that operate in more-controlled traffic conditions, tyres and brakes may last longer (or be re-optimised for new operating

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[17] Note that potential for shared and autonomous vehicles is not incorporated into the current analysed modelled scenarios, but may be in future.

conditions). Depending on regulations and AV technology roll-out, some vehicle components such as steering wheels, pedals and mirrors may even be eliminated.

If AVs are deployed by mobility service fleets, they can be right-sized for distinct usage profiles, optimising vehicle designs across a variety of passenger loads and trip purposes. The higher utilisation of such shared AV fleets would demand the use of more durable materials and potentially favour an increasingly modular design to allow for easier/cheaper component replacement.

Shared AV fleets will likely favour powertrains with low operational costs and higher efficiencies such as BEVs. More heavily utilised cars imply that a smaller vehicle fleet can provide the same level of activity (in vehicle kilometres [km]), thus requiring fewer materials to provide the same service. High utilisation rates and rapid stock turnover of shared AV fleets could also accelerate the innovation cycle for electric powertrain and vehicle designs. This could further ease battery replacement in the vehicle fleet, with widespread implication for material demand, notably for batteries.

A transition to increasingly shared and automated mobility may also have broader implications for road materials. Lighter vehicles may mean roads will wear more slowly, but greater vehicle km (because of the rebound effect from lower costs) may negate these benefits. AVs may also catalyse the adoption of new road materials (e.g. inductive charging) that facilitate business models of shared AV fleets.

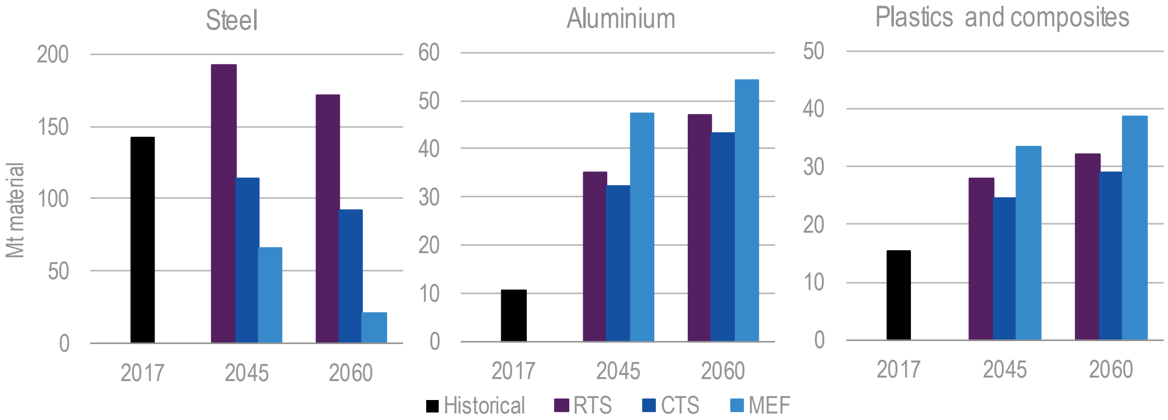
AVs could also have long-term implications on material use beyond transport. They are likely to reduce the perceived costs of time for users (due to more productive use of travel time). In the absence of policy, widespread adoption of private AVs could allow users to live further away from city centres or their place of work, thus exacerbating urban sprawl. As these dynamics may enable people to live in bigger homes at lower density, they could have profound effects on the urban form. Such developments may make energy, climate and other sustainability goals more difficult to achieve.

Outlook and implications for vehicle material use and life-cycle emissions

Future demand for vehicle materials will differ depending on the extent of technology shifts and application of material efficiency strategies. For PLDVs, in the RTS, demand for steel initially increases, due to growing vehicle stocks, then begins to fall again, as reduced steel use from lightweighting outweighs growth in vehicle stocks (Figure 43). Steel demand from PLDVs in 2060 is approximately 20% higher than that in 2017. The combination of increasing stocks and lightweighting leads to growing demand for aluminium by more than four times the 2017 level by 2060, and plastics and composites by two times.

In the CTS, a combination of reduced vehicle sales, more aggressive lightweighting, improved manufacturing yields and increased reuse results in a considerable reduction in demand for steel and a moderate reduction in demand for aluminium and plastics and composites, relative to the RTS. While reductions in vehicle stocks and material substitution put downward pressure on demand for steel, lightweighting puts upward pressure on aluminium demand and plastics and composites demand. This partially counteracts reductions from reduced vehicle stocks and improved manufacturing yields. Therefore, in 2060, demand in the CTS relative to the RTS is nearly 50% lower for steel, 7% lower for aluminium and 10% lower for plastics and composites. The greater push for lightweighting in the Material Efficiency variant (MEF) results in a further decline in demand for steel (by an additional three-quarters in 2060 relative to the CTS) and an increase in aluminium (one-quarter in 2060 relative to the CTS) and plastics and composites (one-third).

Figure 43. Global material requirements for PLDVs by scenario



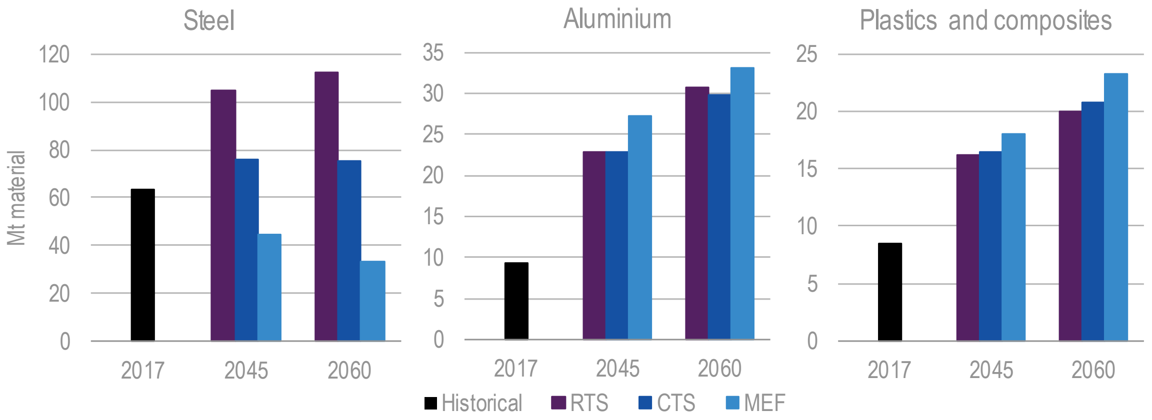
Notes: Demand values include material lost in the vehicle manufacturing stage and demand reductions from reused materials; they do not include material lost in the metals semi-manufacturing stage.

Source: IEA estimates, including use of data from GREET (Argonne National Laboratory, 2017).

While material efficiency and reduced road activity lead to reduced demand for steel from PLDVs in the CTS and MEF, material substitution leads to increased aluminium and plastics demand in the MEF.

The material use trends in LCVs and HDVs are similar to those in PLDVs (Figure 44). In the RTS, steel demand by 2060 nearly doubles compared to that of 2017, while demand for aluminium grows by over three times and demand for plastics and composites more than doubles. In the CTS, in 2060, demand for steel is 33% lower than in the RTS, while changes in demand are marginal for aluminium (3% lower) and plastics and composites (4% higher). The greater push for lightweighting in the MEF results in an additional decline of approximately 50% for steel and 10% both for aluminium and for the combination of plastics and composites, relative to the CTS.

Figure 44. Global material requirements for LCVs and HDVs by scenario



Note: Demand values include material lost in the vehicle manufacturing stage and demand reductions from reused materials; they do not include material lost in the metals semi-manufacturing stage.

Source: IEA estimates, including use of data provided by Ricardo-AEA from a study commissioned by the Directorate-General Clima of the European Commission (Hill et al., 2015).

LCVs and HDVs follow trends similar to PLDVs. Steel demand is reduced in the CTS and MEF compared to the RTS, while aluminium and plastics demand grows in the MEF.

There is lower potential in LCVs and HDVs (compared to PLDVs) for materials substitution to contribute to lightweighting and for activity reductions. As a result, the overall share of steel, aluminium and plastics in LCVs and HDVs out of all vehicles increases in all scenarios. In the RTS, of the total steel demanded by all road vehicles, the share required by LCVs and HDVs grows from 30% in 2017 to 40% in 2060. In the MEF, that share in 2060 is over 60%.

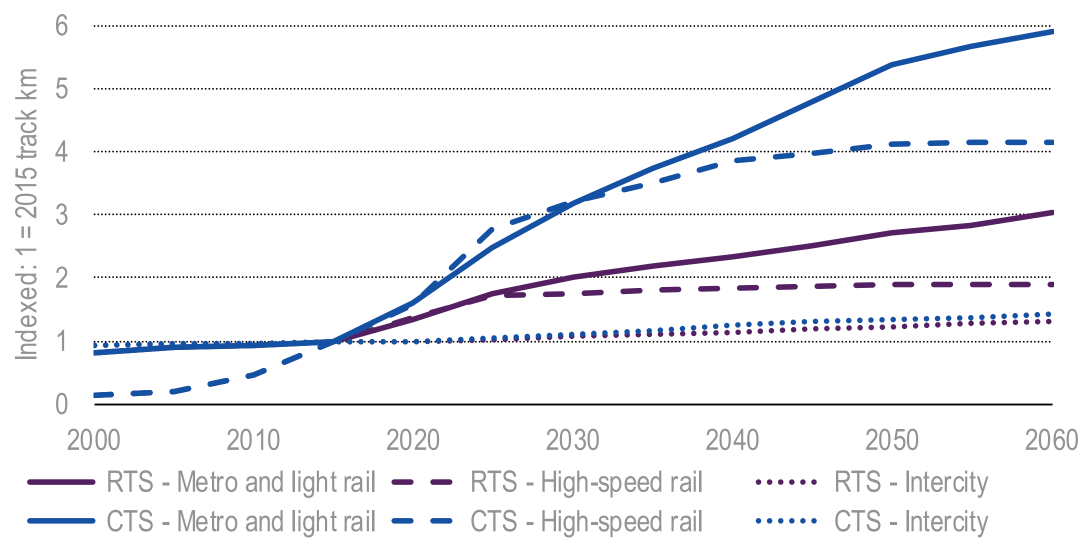
While this analysis focuses on vehicles, changes in the transport sector will also affect other aspects of material demand. For example, a push for modal shift in passenger and freight transport will require additional build-out of rail infrastructure, thus putting upward pressure on demand for steel and cement (see Box 7). Complex interactions between roads and the vehicles that use them can affect emissions from material production for road construction and repair and the fuel efficiency of vehicles (see Box 8). The material implications of transport infrastructure is an area of possible future additional research.

Box 7. Material implications of modal shifting: rail build-out

Shifting to lower-emission transport systems will result in an increased build-out of rail infrastructure. In the CTS, total track km in 2060 is 15% higher as in the RTS. The largest growth is in urban metro and light rail, and high-speed rail.

The demand for materials (in tonnes per km) of rail is highly variable and depends on the design of the particular system. This design is a function of various considerations, including the required functionality of the system, applicable design regulations, budgetary constraints, geology and geography of the area, and other economic and political factors. A major determinant of the materials intensity is its vertical alignment, that is, whether a given section of track is at-grade, elevated, underground or in a tunnel. Elevated track generally requires more material than at-grade track, while underground and tunnelled tracks require more material than at-grade and elevated tracks. Lack of detailed regional or network data on the share of track by vertical alignment profile makes it difficult to estimate with any level of accuracy or precision a national average material intensity for rail. Annex III provides additional discussion and analysis.

Build-out of rail infrastructure by scenario

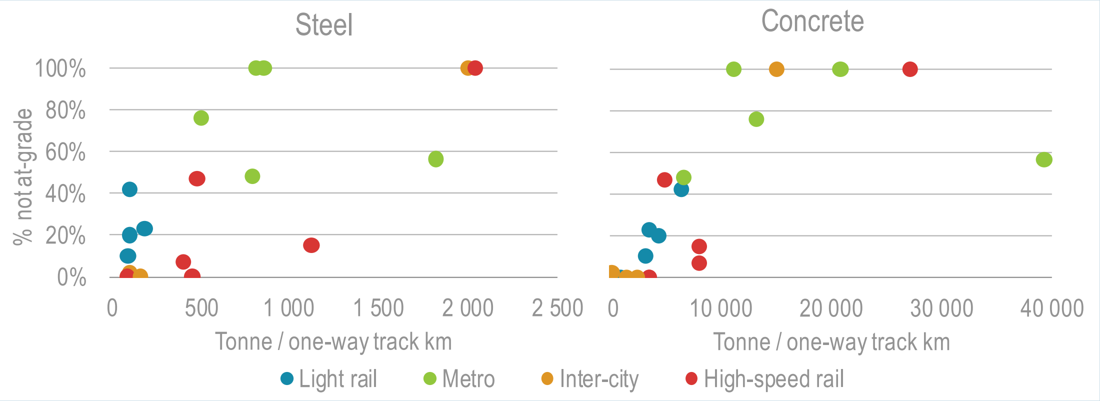


Shifting from road modes and aviation to rail will require investments and build-out of rail infrastructure.

The potential to reduce material use in infrastructure such as rail may be more limited than the potential in other areas such as buildings. Infrastructure must handle substantial stress, such as weight of rail carriages, and can be highly exposed to weather events and climatic fluctuations. These factors may also limit end-of-life material efficiency opportunities, for instance with the reuse of steel. Some elements of transport infrastructure such as bridges and certain rail lines may be subject to considerable corrosion and fatigue damage from use, making their reuse not possible. Cooper and Allwood (2012) estimate a technical potential of only 11% reuse of steel in infrastructure, in contrast to 38% for steel in buildings. Furthermore, there may be trade-offs between upfront emissions from material used to construct infrastructure and life-cycle emissions effects. Building more durable infrastructure may reduce future material needs for repair and rebuilding. Targeted material efficiency strategies may offer some degree of potential to reduce material consumption in infrastructure. As one example, Milford et al. (2013) estimated that the lifetime of rail tracks could be doubled through reuse of steel in secondary routes, using higher strength steels and restoration.

As with road vehicles, the energy use and emissions embodied in the construction of rail tracks are offset by the savings that come with the efficiency of trains compared to other modes of transport (cars, trucks and aeroplanes). A quick payback on the initial energy and emissions (and also monetary) investment is promoted by high utilisation. *The Future of Rail* publication provides further details on these dynamics, as well as a discussion of the potential energy, environmental and societal benefits of rail (IEA, 2019).

Material intensity estimates for rail by vertical alignment



Notes: Each data point represents an estimate of rail material intensity; the data points were found in the literature and through communication with experts. In instances where the source did not directly specify it, the proportion of track km by vertical alignment was inferred. The percent not at-grade is a sum of track km that is underground, tunnelled or elevated, divided by the total track km.

Sources: Asplan Viak AS (2011), Life cycle assessment of the Follo Line – infrastructure, Document no. UOS-00-A-36100; Chang, D. and Kendall, A. (2011), "Life cycle greenhouse gas assessment of infrastructure construction for California's high-speed rail system", DOI 10.1016/j.trd.2011.04.004; Chester, M. personal communication in 2017 on life-cycle assessment, http://chester.faculty.asu.edu/research.php; Italferr (n.d.), "Carbon footprint in construction: The experience of Italferr", DOI 10.4324/9780203077320; Jones, H. et al. (2017), "Life cycle assessment of high-speed rail: a case study of Portugal", DOI 10.1007/s11367-016-1177-7; Li et al. (2018), "Calculation of life-cycle greenhouse gas emissions of urban rail transit systems: A case study of Shanghai Metro", DOI 10.1016/j.resconrec.2016.03.007; Network Rail, (2009), Comparing environmental impact of conventional and high speed rail; Rozycki et al. (2003), "Ecology profile of the Germany high-speed rail passenger transport system, ICE", DOI 10.1007/BF02978431; Saxe et al. (2017), The net greenhouse gas impact of the Sheppard subway line, DOI 10.1016/j.trd.2017.01.007; TERI (2012), Life cycle analysis of transport modes, volume I.

The large variability in the material intensity of rail systems can be partially explained by the share of track within a network that is at-grade, elevated, underground or in a tunnel.

Box 8. Material implications of road build-out and design

The material demand for road surfaces is influenced by many factors, including design regulations. These regulations are influenced by factors such as regional climate conditions; budgetary constraints; and expected volume, speed and composition of traffic on the road. Cement and steel reinforcement are required for concrete paved roads. Thus, data on the proportion of roads that are paved, and the proportion of roads that are paved with asphalt versus concrete versus composite surfaces, are critical for assessing the material demand of roads. Unfortunately, little country-level data are available on the proportion of asphalt versus concrete versus composite surfaces, posing difficulty for accurately estimating the material demand from roads. Furthermore, within concrete roads, considerable variability exists among the limited number of material intensity estimates found in the literature.

Future demand for materials for roads will be dependent on a variety of influences. Increasing modal shift on the scale that will be needed to meet climate objectives may result in a reduced need to build new and larger roads. The effects of climate change may have an impact on roads and the way roads are built and maintained. More extreme conditions tend to require more durable road surfaces that are designed to withstand specific conditions (e.g. resistance to heat or resistance to cracking during freeze-thaw cycles). Porous road surfaces may be used more frequently to adapt to increasing rainfall and storms due to climate change, which may affect the types and quantities of materials used to construct roads.

Material efficiency strategies could also influence the demand for road materials. Efficient use of materials from a value chain perspective may result in increased demand for materials, due to the complex interactions among vehicle design, road traffic and road design (so-called “road vehicle interactions”). Well-designed, durable and properly maintained roads have the potential to improve the operational efficiency (and hence reduce fuel use) of the vehicles using it. Rolling resistance effects of road surface roughness, texture and deflection can account for 15-50% of total vehicle fuel consumption, depending primarily on vehicle speed (Beuving et al., 2004). Studies have shown that reducing rolling resistance on roads by 10% leads to fuel economy gains of 1-2% (Evans et al., 2009; National Research Council of The National Academies, 2006). More efficiently executed or less-frequent maintenance and rehabilitation needs can also reduce vehicle emissions that occur from traffic back-ups and idling during maintenance events. Thus, designing durable roads from the outset may require more materials, but may lead to considerable emissions reduction over the life cycle.

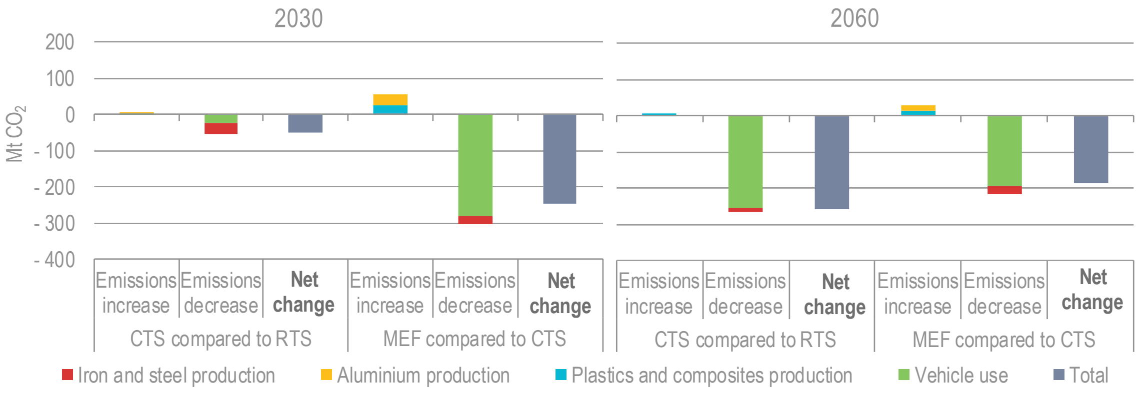
The influence of vehicles on roads also requires consideration, in addition to the influence of roads on vehicle emissions. As the relationship between road degradation and vehicle weight follows a fourth power law, vehicle lightweighting results in reduced road damage. Less-damaged roads would require fewer material inputs for maintenance and rebuilding.

Given these complexities, the future demand for material for road is uncertain and requires further investigation. Annex III provides preliminary estimates and further discussion.

Lightweighting – the primary material efficiency strategy pushed further for vehicles in the MEF – results in considerable value chain emissions savings for road vehicles. For PLDVs, lightweighting contributes approximately 10% of the global 2060 total vehicle use-phase emissions reduction in the CTS relative to the RTS. This is a substantial portion in the context of the many other emissions reduction strategies such as engine and powertrain efficiency measures and fuel switching (including electrification) being pursued in road vehicles (Figure 45).

Pushing lightweighting further to its realistic limits leads to additional use-phase emissions reduction in the MEF, equivalent to an additional 10% of CTS PLDV use-phase emissions in 2030 and 20% in 2060. The materials required for this additional lightweighting increase emissions for PLDV material production relative to the CTS, by approximately 7% in 2060. In the CTS and MEF, there is a significant increase in demand for materials such as aluminium and carbon fibre-reinforced plastics that are currently, on average, more emissions intensive per mass of material to produce than steel. However, due to efforts to reduce production emissions for these materials, as well as a decline in the total lower amount of materials consumed, the increase in material production emissions is small. The increase that does occur is greatly outweighed by the savings in the vehicle use phase. In the MEF, lightweighting results in a net decrease in PLDV value chain emissions of 8% in 2030 and 17% in 2060 compared to in the CTS.

Figure 45. CO_2 emissions savings from lightweighting throughout the PLDV value chain by scenario



Notes: For plastics and composites that substitute steel in order to lightweight, a split of 40% plastics and 60% carbon fibre-reinforced plastics is assumed. Emissions include direct and indirect CO_2 emissions; emissions from material lost in the semi-manufacturing and vehicle manufacturing stages are not included. $MtCO_2$ = million tonnes of carbon dioxide.

PLDV lightweighting leads to net emissions savings in the CTS and additional savings when pushed further in the MEF. Absolute savings in 2060 in the MEF are lower than in 2030, primarily due to increased vehicle electrification, which lowers use-phase emissions savings.

The absolute emissions saving in the MEF in 2060 is about 25% lower than in 2030, despite more aggressive lightweighting. The reason is that a large portion of PLDVs will have electrified, resulting in lower savings potential from lightweighting.[18] Savings from lightweighting are considerably higher for ICEs running on gasoline, given that their use-phase emissions are much higher to begin with. While the net change in emissions for a BEV depends on many factors (including the production emissions of the materials used to lightweight and the carbon intensity of the electricity grid used to power the vehicle), in some cases, pushing

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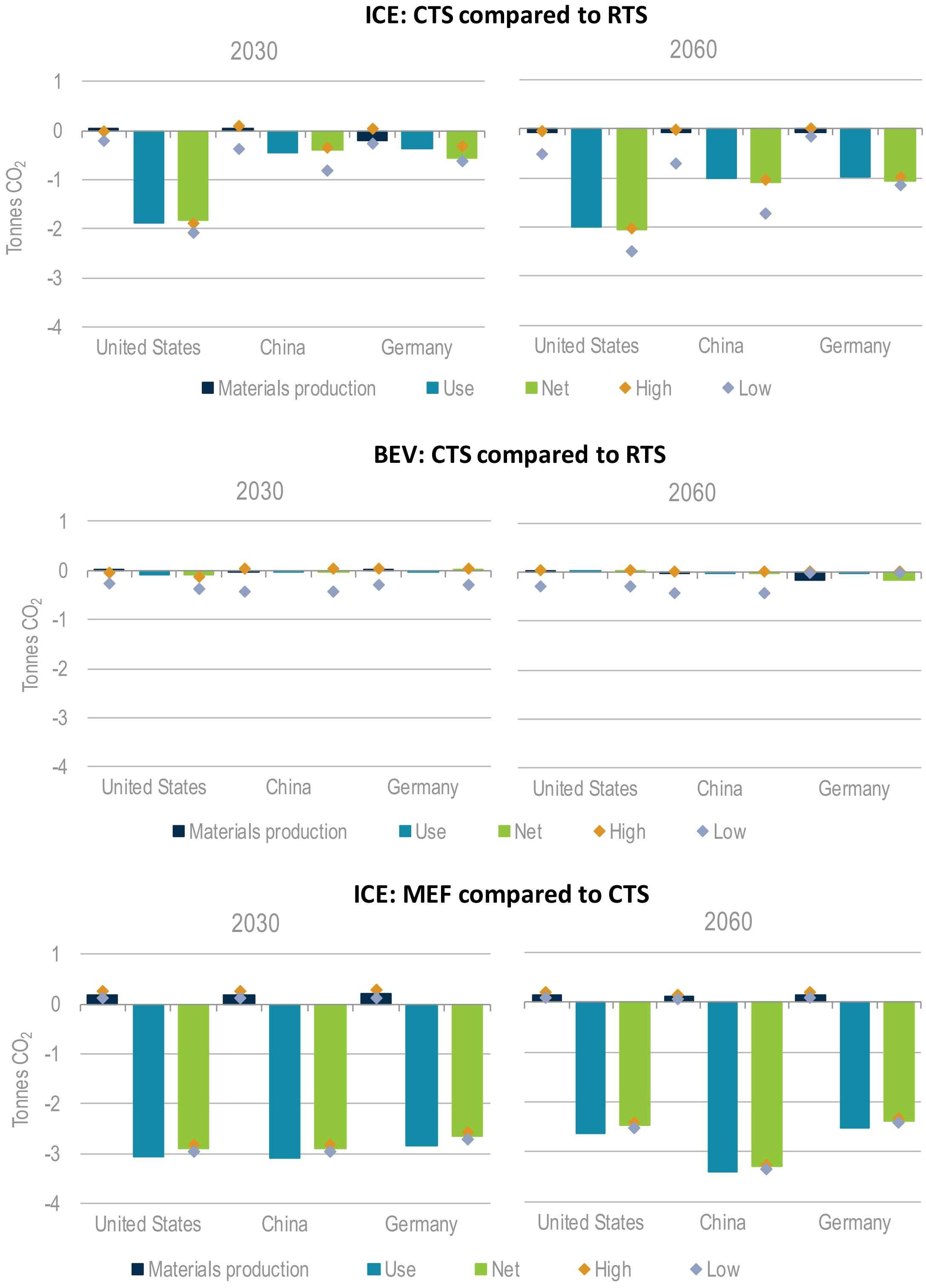
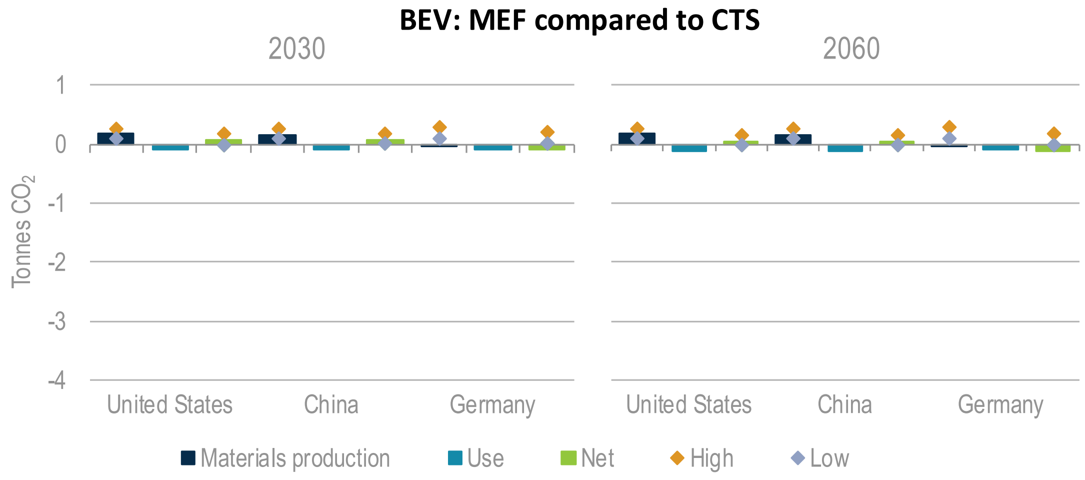
[18] While the absolute savings in the MEF relative to the CTS are lower in 2060 than in 2030, the proportional savings are slightly higher, given that value chain emissions have fallen by over 60% in the CTS by 2060 from the 2030 level.

BEV lightweighting too far may result in a net increase in value chain emissions (Figure 46). However, this does not necessarily mean that lightweighting should not be pushed in BEVs. Particularly in earlier periods when battery costs are still high, lightweighting may facilitate greater uptake of BEVs, as it could enable BEVs with larger ranges or lower costs. In later periods, the need for smaller batteries with lighter vehicles may help reduce the pressure on increasingly scarce materials needed to produce batteries. Possible future advances not accounted for in this analysis in terms of low-emission production methods for novel materials (e.g. carbon fibre-reinforced plastics) may reduce emissions increases from lightweighting, helping to provide a favourable emissions outcome from lightweighting, even in BEVs.

Figure 46. Net change in value chain CO_2 emissions attributable to lightweighting per ICE vehicle and per BEV for PLDVs in selected countries





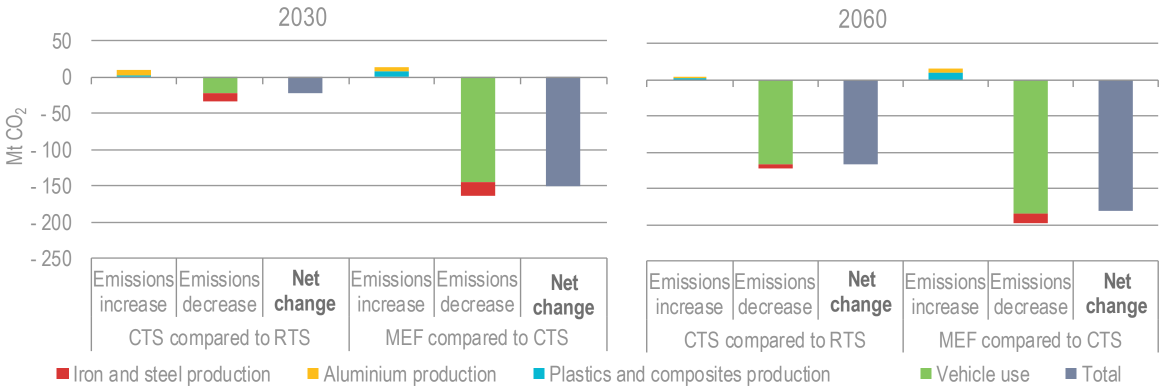
Notes: For plastics and composites that substitute steel in order to lightweight, a split of 40% plastics and 60% carbon fibre-reinforced plastics is assumed. The high and low parameters are a sensitivity analysis on the plastic and composite emissions intensities, given uncertainties about future uptake and production improvements for composites such as carbon fibre-reinforced plastics; the aspects that are varied are the split between plastics and composites (20: 80 in the high sensitivity; 60:40 in the low sensitivity), the type of non-carbon fibre resin used in the composite and the proportion of carbon fibre to binding polymer. Given that emissions from producing all types of plastics and composites have declined considerably in the CTS, changes in emissions from the CTS to the MEF are much less sensitive to the high and low assumptions than when moving from the RTS to the CTS. Lifetime vehicle km travelled are held constant across regions and among scenarios (although there is some variation over time and between ICEs compared to BEVs); thus, differences in net emissions are largely due to differences in lightweighting ambition, emissions intensity of material production and electricity grids and the variation in RTS vehicle fuel efficiency. Emissions include direct and indirect CO_2 emissions; emissions from material lost in the semi-manufacturing and vehicle manufacturing stages are not included.

Lightweighting generally results in net emissions savings for ICE vehicles, but in some cases leads to a net increase in emissions for BEVs.

For LCVs and HDVs, in 2060, lightweighting in the CTS results in use-phase emissions savings over the RTS equivalent to 3% of total LCV and HDV use-phase emissions savings (Figure 47). A stronger push to lightweighting results in additional use-phase savings in the MEF, equivalent to an additional 4% of CTS LCV and HDV use-phase emissions in 2030 and 9% in 2060. Emissions from material production for the LCV and HDVs value chain are marginally higher (about 2%) in the MEF than in the CTS in 2060, which is outweighed by use-phase emissions savings. The result is a net value chain emissions savings of 9% in 2060 in the MEF relative to the CTS.

Lightweighting is pushed less aggressively in earlier periods for LCVs and HDVs compared to PLDVs in both the CTS and MEF. This is because the heavy loads of LCVs and HDVs tend to result in less fuel savings per mass of empty vehicle weight reduction from lightweighting. Additionally, a larger portion of LCVs and HDVs (except for urban buses) are still running on fossil fuels in 2060 in the CTS compared to PLDVs. As a result, the CO_2 benefits of additional lightweighting in LCVs and HDVs increase to 2060 in the CTS and the MEF (as measured in absolute terms), as the potential of lightweight materials that are less emissions intensive has not been fully exploited and there are considerable remaining use-phase emissions to reduce. This contrasts with declining absolute CO_2 savings from lightweighting towards 2060 for PLDVs in the MEF. Nonetheless, PLDVs, LCVs and HDVs all see net savings in value chain emissions from lightweighting to 2060.

Figure 47. Global CO_2 emissions savings from lightweighting throughout LCV and HDV value chains by scenario



Notes: For plastics and composites that substitute steel in order to lightweight, a split of 40% plastics and 60% carbon fibre-reinforced plastics is assumed. Emissions include direct and indirect CO_2 emissions; emissions from material lost in the semi-manufacturing and vehicle manufacturing stages are not included.

LCV and HDV lightweighting leads to net emissions savings in the CTS and additional savings when pushed further in the MEF. In 2060, a considerable proportion of LCVs and HDVs will still run on diesel, resulting in considerable emissions savings from lightweighting.

EV battery materials

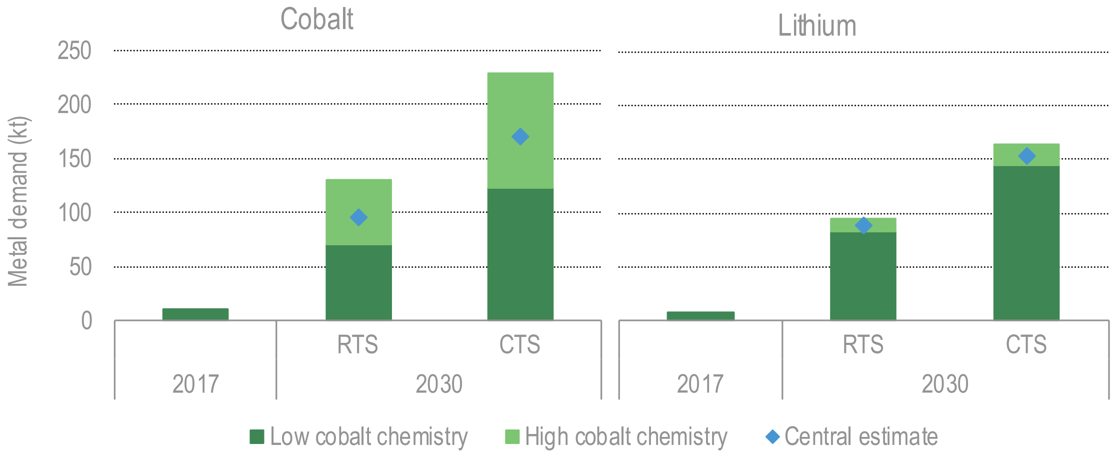
As sales volumes of EVs grow, questions related to battery materials and production will become increasingly important. Three key issues to be addressed are: 1) possible supply constraints for battery materials, 2) the CO_2 emissions related to battery production and 3) the need and possibilities for battery recycling. The following provides a preliminary look into these issues. The IEA *Global Electric Vehicle Outlook 2019* (forthcoming) will provide a more in-depth analysis on batteries.

Battery materials supply

Uptake of EVs will increase demand for several metals used in lithium-ion batteries, namely cobalt, lithium, nickel and manganese. Future demand for such materials will depend on the number of EVs sold and the future chemistry of batteries, as different cathodes have different ratios of constituent metals (Figure 48). In 2030, 11% of the global PLDV and 8% of the LCV and HDV stock is electric (includes BEVs and plug-in hybrid vehicles) in the CTS, in comparison to 6% and 5% in the RTS.

While geological resources may be more than sufficient to meet metal demand in the coming decades, supply constraints may arise due to geopolitical, ethical and economic factors. Supply concerns pertain most significantly to cobalt, which is currently extracted as a by-product of nickel and copper, and whose production is currently concentrated in the Democratic Republic of the Congo (DRC). These factors make it difficult to respond quickly to expected increases in demand and to diversify supply. Stockpiling and speculation along the supply chain also exacerbate the risks of supply bottlenecks and lead to price increases. In addition, the use of child labour in artisanal mining in the DRC is a major concern.

Figure 48. Cobalt and lithium demand for EV batteries



Notes: Demand figures refer to pure metal elements. In the central scenario, nickel-manganese-cobalt oxide (NMC) 811 makes up 50% of battery sales in 2030, NMC 622 makes up 40% and nickel cobalt aluminium oxide (NCA) makes up 10%. In the low cobalt scenario, NMC 811 makes up 90% of battery sales in 2030, with the rest being NCA. In the high cobalt scenario, NMC 622 makes up 90% of sales with the rest being NCA. In all scenarios, battery demand for HDVs is assumed to be 80% lithium iron phosphate oxide and 20% NMC 622. The numbers for each battery type refer to the ratio of materials; for example, NMC 811 contains 80% nickel, 10% manganese and 10% cobalt. kt = kilotonnes.

Source: Adapted from IEA (2018), *Global Electric Vehicle Outlook 2018*, www.iea.org/gevo2018/.

Lithium and cobalt demand from electromobility will increase in the RTS and CTS. Uncertainty over future battery chemistries implies uncertainty in the demand for cobalt.

Action from market participants and policy makers will be needed to overcome supply concerns. Long-term contracts between battery producers and mining companies could address uncertainty and barriers to investment in mining. This could be facilitated by governments setting clear policy targets for EVs, for instance through zero-emission vehicle mandates. Further development of battery chemistries that require less cobalt (e.g. NMC 811) may also reduce pressure on cobalt supply. Additionally, co-operation among governments, international institutions and industry is critically needed to set and enforce minimum labour and environmental standards for raw material extraction.

CO_2 emissions from battery production

A full life-cycle assessment of EVs would include energy consumption and emissions related to raw extraction of battery materials, materials production/refining and battery assembly/manufacturing (in addition to energy and emissions of the vehicle body and non-battery powertrain components). Reviews of the literature have found considerable variability in the energy consumption and CO_2 emissions associated with lithium-ion battery production, with up to an order of magnitude difference among estimates (Dunn et al., 2015; Peters et al., 2017). The battery assembly stage tends to be the most emissions intensive, followed by materials production and lastly materials mining, although this order may vary depending on the relevant processes (Romare and Dahllöf, 2017).

A key factor in the uncertainty around emissions is whether the battery manufacturing plant is operating at full capacity. This is because energy requirements for some equipment (e.g. the dry room) are constant, regardless of the battery throughput (Dunn et al., 2015). The carbon intensity of the grid also has a major impact on the battery production CO_2 intensity. This is because electricity used in battery manufacturing accounts for a considerable proportion of the total energy consumption (Hall and Lutsey, 2018). Energy efficiency improvements, increased plant operational capacity and electricity grid decarbonisation may help in moving towards the lower end of achievable energy and emissions production intensities. Estimates of battery energy and emissions intensities are also affected by assumptions related to battery internal efficiency, energy density, cathode chemistry and end-of-life management (including whether it is used in second-life applications), as well as by the life-cycle assessment methodology used (Peters et al., 2017).

Battery production is one of many factors that affect the relative energy and emissions performance of EVs compared with ICE vehicles. Dunn et al. (2015) estimated that producing an EV is 10-40% more energy intensive than an ICE if the battery assembly plant is operating at full capacity and can be up to 250% more energy-intensive if high estimates of battery production are used. Despite the higher vehicle production emissions and even for high battery production CO_2 intensity estimates, they found that under reasonable assumptions of annual mileage, an EV would likely have lower life-cycle emissions than an ICE, except when the power mix powering the EV was solely coal based. The additional vehicle production emissions would be paid back within the first 25 000 km driven (approximately 2 years for typical vehicle usage) if using the average grid in the United States to charge the vehicle. Similarly, Hall and Lutsey (2018) found that the additional production emissions of an EV would be paid back within 2 years of driving in comparison to an average European ICE, if charging with the average European Union power grid and assuming a middle value for battery production emissions.

Further analysis could elucidate the specific conditions under which the emissions from battery production may lead EVs to have higher life-cycle emissions than ICEs. However, assuming that power grids used for battery production and for charging EVs continue to decarbonise, it is unlikely that battery production would tip the balance towards choosing ICEs over EVs as the lower-emission option.

Battery recycling

With growing EV market share, finding ways to manage end of life will become increasingly important. One option is to use batteries in second-life applications, which some vehicle manufacturers are already starting to pursue (Field, 2018; Stringer and Ma, 2018; Willuhn, 2018). While declining battery performance, in terms of fewer km travelled per charge, may make older batteries no longer suitable for use in EVs, they could still be useful in less-demanding applications (e.g. stationary storage for electricity from wind and solar). When second-life applications are not possible, or following useful second or third-life applications, recycling or safe disposal procedures will be necessary to avoid the release of hazardous battery materials into the environment.

Recycling would provide the advantage of enabling recovery and reuse of battery materials. There are three process types being demonstrated to recycle batteries: pyrometallurgy, which uses high temperatures to react and separate materials from each other; hydrometallurgy, which uses acids to dissolve ions out of solids; and direct recycling, which uses physical processes to recover materials that can be reused without substantial treatment (Gaines, 2018). Each process has advantages and disadvantages (Gaines, 2018; Huang et al., 2018; Zheng et al., 2018). While pyrometallurgy methods are simple to operate and can recover cobalt and nickel, they tend to cost more, use more energy, produce harmful gases and currently cannot easily recover lithium. Hydrometallurgical processes use less energy, cost less and can recover lithium, but involve a larger number of steps and produce considerable volumes of waste acid sludge. Direct recycling has relatively low energy consumption and low cost. However, as the cathode crystal/chemical structure is maintained (i.e. the cathode is not separated into its constituent ions), inputs would need to be separated by cathode type to produce a useful output. The recovered structure may be out of date and of reduced value by the time the battery reaches its end of life, given that battery chemistries are continually evolving.

Many methods for recycling lithium-ion batteries are still in the early stages of development. Further research is needed to determine for which recycling methods and under what conditions recycling is advantageous, as well as how to design batteries in ways that make them easier to recycle. Several analyses suggest that recycling can have considerable advantages from perspectives of cost, energy and emissions savings. An assessment of EV NMC battery recycling in China found recycling to be beneficial from all three perspectives, resulting in 120 United States dollars in net profit per 27 kilowatt hour battery from sale of recovered materials, as well as 4 gigajoules of energy and 1 tonne of CO_2 emissions savings per battery compared to battery production using virgin materials (Qiao et al., 2019). Two studies in the United States found that producing batteries with recycled rather than virgin materials would reduce CO_2 emissions by over 40% and 23% using commercial pyrometallurgical processes (Dunn et al., 2015; Hendrickson et al., 2015). Battery recycling also has considerable benefits in terms of reducing sulphur oxide emissions from raw materials smelting. Furthermore, recycling could create a local material source for large consuming regions such as the United States and Europe, which are currently dependent on battery material value chains that they have little control over (given that raw material resources are in regions such as the DRC, Latin America, China and Australia, and much of material refining occurs in China).

It will likely take another decade before large volumes of EV batteries start to reach their end of life. Thus, recycling will not provide a short-term answer to battery material supply concerns. With expectations of continued high growth in EV sales, even in the medium term, recycled materials are unlikely to be able to supply a large share of material demand. However, recycling could meet a portion of materials demand; it is worth pursuing given the potential for economic, energy and emissions advantages, as well as a reduced mining-related land-use impact.

It is therefore critical that policy makers and industry stakeholders begin a dialogue now, while the industry is still ramping up, of how to tackle end-of-life and recycling issues. Developing and deploying cost-effective recycling methods in the face of potentially changing battery chemistries and designs will require a co-ordinated effort and regulatory frameworks. Early consideration of end-of-life options may also guide production towards battery chemistries and pack designs that are more easily recyclable. A key challenge to overcome is that of diffuse responsibility. Multiple parties are involved in the battery value chain (including mining and refining companies, battery manufacturers, vehicle manufacturers and vehicle users), which may lead each party to personally feel less responsibility for end-of-life treatment, thus collectively resulting in little or no action. Based on the principle of extended producer responsibility, regulations that assign end-of-life treatment to a single group (e.g. battery or vehicle manufacturers) would help resolve this problem. Several regions are making steps towards this end. For example, in 2018, China announced measures that designate vehicle manufacturers as responsible for battery end-of-life management and push battery manufacturers to design batteries in ways that facilitate recycling (China Ministry of Industry and Information Technology, 2018). Adopting and strengthening extended producer responsibility regulations in all regions and ensuring enforcement will mean EV batteries are well managed to their end of life.

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7. Enabling policy and stakeholder actions

As the preceding analysis has illustrated, material efficiency strategies have the potential to play an important role in achieving global emissions reduction objectives. Various challenges will need to be overcome to ensure effective use of materials, including barriers related to cost, delivery times, behaviour, lack of awareness and the regulatory environment. The combined efforts of governments, industry, the research community and society will be needed to overcome these challenges and accelerate the efficient use of materials.

Challenges and costs of material efficiency

Without any incentive or requirements to pursue material efficiency, or explicit demand from consumers, designers and manufacturing or construction companies may be unaware of the possible benefits of material efficiency; or they may chose not to pursue material efficiency due to real and perceived risks, financial costs or lost revenues and time constraints. In some cases, fragmented supply chains may present challenges for achieving material efficiency, such as when users or demolition contractors are not connected to construction companies to facilitate end-of-life reuse of materials. The regulatory environment may also restrict pursuit of material efficiency, such as when prescriptive design standards prevent uptake of new materials or design methods.

An in-depth cost assessment was not part of this analysis. Further analysis will be required to assess to what degree material efficiency would be more cost-effective than other options to reduce emissions, such as carbon capture and uptake of alternative fuels. A recent circular economy analysis by Material Economics indicates the relative cost of many of the strategies examined in the present analysis (Material Economics, 2018). It suggests that considerable potential exists to reduce emissions through material efficiency while achieving savings in financial costs. Strategies with negative abatement costs include car-sharing, reducing waste in buildings construction and increasing collection rates of aluminium. Strategies that account for a considerable portion of material demand reduction in the Clean Technology Scenario are estimated to have positive although moderate costs, such as EUR 50 (euros) per tonne (t) of carbon dioxide (CO_2) abated for buildings reuse and EUR 60/t for reducing steel fabrication losses. Other strategies that account for a substantial portion of the additional material demand reductions in the Material Efficiency variant are at the higher end of the cost curve, such as EUR 85/t abated for material efficiency in buildings design and construction and EUR 100/t for vehicle lightweighting. All strategies in the Material Economics analysis have abatement costs no higher than EUR 100/t. This suggests that while costs of material efficiency may not be negligible in all cases, they are likely to fall within a reasonable range of what will be necessary to achieve low-carbon transition objectives. Thus, in the short term, it would be advantageous to begin pursuit of the lower cost strategies, while also starting to prepare for implementation of a broader range of strategies in the medium to long term.

Policy and action priorities

Increase data collection, life-cycle assessment and benchmarking

Robust data on regional material inputs to key end uses are limited. Only a few life-cycle assessments (LCAs) that specify material quantities are available for certain material applications. These often differ considerably in scope and methodology, making it challenging to draw conclusions about average material intensities per application and by region. Better data are needed on the range and general tendencies of material inputs and use across the life cycle, including production or construction, repair and renovations, and end of life. Such information should be collected and reported according to transparent and standardised procedures, enabling better comparison and interpretation of LCAs. More-robust analysis is needed to understand trade-offs across the life cycle related to material inputs and use-phase emissions.

Improved data and life-cycle insights will be important in developing benchmarks, understanding best practices, facilitating optimal decisions in the design stages that consider the life-cycle impact, developing programmes that incentivise material efficiency, and, perhaps in the medium to long term, adopting mandatory regulations that address the emissions effects of materials. As an example, better data on steel and cement inputs into buildings per unit floor area could be useful in establishing benchmarks that push designers and construction companies to adopt practices that strive towards best practice benchmark material use.

The following are indicative key contributing actions from stakeholders:

- **Governments:** establish frameworks and standardised databases to collect data related to material use; standardise LCAs on national and international levels; encourage reporting of material quantities by designers and manufacturers and construction companies, initially on a voluntary basis with a long-term view of establishing mandatory reporting; and develop national and international benchmarks of best practice material use.
- **Industry:** track and report material use data, particularly via nationally or internationally standardised databases that are publicly accessible (subject to necessary conditions to address data privacy concerns); and conduct LCAs when designing products and buildings.
- **Researchers:** conduct transparent peer-reviewed LCAs while adhering to rigorous standards; clearly state all assumptions of LCAs in publications, including material quantities when assessing life-cycle emissions or other environmentally based life-cycle indicators; assist in developing a clear methodology of how LCAs should be performed and LCA tools that can be used in early design stages; and transfer more engineering, process and user knowledge into LCAs (e.g. technical data on how more intense use of goods may affect lifetimes via increased wear and tear).

Improve consideration of the life-cycle impact at the design stage and in CO_2 emissions regulations

Life-cycle impact should be considered at the design stage, to optimise design to minimise life-cycle emissions. In the case of buildings, use of buildings information modelling tools could assist to design buildings in ways that facilitate efficient material inputs, buildings repurposing, and eventual materials reuse and recycling. Consideration of the life-cycle impact could be facilitated by expanding the scope of regulations that focus on reducing CO_2 emissions in the use phase to cover the full life cycle of products. As an interim measure towards moving to life-cycle-based requirements, regulations focused on use-phase emissions could provide credits towards the regulatory requirement for reducing embodied emissions.

Life-cycle-based regulations have advantages over regulations focused on either use-phase emissions or embodied material emissions alone. For example, vehicle life-cycle CO_2 emissions regulations could ensure that the emission benefits of improved fuel economy through lightweighting are not outweighed by increased embodied emissions from switching to lighter materials. Life-cycle regulations would also not disincentivise cases where an upfront increase in material inputs or embodied emissions may result in decreased life-cycle emissions. As an example, this may be the case for road surfaces when durability and the impact of the repair cycle on vehicle emissions are accounted for. Furthermore, life-cycle emission policies could create a pull for lower-carbon materials and methods of producing materials (e.g. blended cements that are less emissions intensive). Given that LCA requires making many assumptions about aspects such as intensity of use, lifespans and end-of-life treatment, regulations based on life cycle would need to be developed in a way that appropriately addresses uncertainty. Complementary measures such as end-of-life regulations may be needed to provide the expected emissions outcomes. Developing standardised and streamlined LCA procedures and tools would also be helpful to reduce the time and costs of compliance.

The following are indicative key contributing actions from stakeholders:

- **Governments:** implement measures that incentivise or mandate reductions in embodied material emissions, such as through new or expanded emissions standards, or financial incentives; and consider a transition to life-cycle-based regulations for supply chains.
- **Industry:** consider the life-cycle impact in the design stages, including trade-offs between production and use-phase emissions, and, where resulting in a life-cycle emissions reduction, design for long lifespans, repurposing, reuse and recycling.
- **Researchers:** investigate trade-offs between upfront material demand inputs and future emission implications to guide design and regulatory decisions; and develop methods to address uncertainty when quantifying and assessing the life-cycle impact.

Increase end-of-life repurposing, reuse and recycling

Extending buildings or product lifetimes should be prioritised in cases where doing so will not lock in considerably higher use-phase emissions. Consideration of life-cycle effects and options for long lifetimes should be integrated into design and fabrication regulations (e.g. buildings energy codes). Lifetime extension could be facilitated by establishing standards that promote durability and long lifetimes and by government-industry partnership programmes that aim to develop guidance, streamline processes and reduce time frames for adapting old buildings to more modern businesses, thus enabling more cost-effective and timely buildings repurposing. In cases where extended lifetimes would result in considerably higher use-phase emissions compared to newer, more-efficient technologies (e.g. existing inefficient internal combustion engine vehicles or household appliances), pursuing materials reuse and recycling at end of life is preferable to extending lifetime.

Better integration of supply chains may help establish channels to reuse and recycle materials. For example, this may be done through contracts between construction companies and suppliers that urge suppliers to buy back unused materials during construction or used materials for recycling. Setting up materials inventories would also be useful in identifying opportunities for reuse (e.g. reuse of parts from retired vehicles). Other policies and incentives to promote reuse and recycling may include setting high-level resource efficiency targets, mandating a proportion of reused materials in certain products, adopting or expanding recycling requirements to cover the largest possible range of end uses and requiring producer responsibility. Where recycling and recovery options are not currently commercially available, as is the case with unhydrated cement in concrete, further research and development could expand the range of end-of-life material efficiency possibilities.

The following are indicative key contributing actions from stakeholders:

- **Governments:** incentivise lifetime extension, such as through taxing buildings demolitions and rebates or loan-interest rate finance for buildings retrofits; raise awareness of the benefits of designing modular; develop guidance, streamline processes and reduce regulatory barriers related to buildings repurposing; establish standards that promote durability of key components, such as buildings frames and road surfaces; facilitate reuse of materials; ensure stringent recycling requirements; and adopt landfill disposal fees.
- **Industry:** prioritise repurposing over demolitions, including through corporate policies and training that integrate the concept of long-life buildings at the design stage; set up channels to track materials and facilitate their reuse; and make use of reused and recycling materials in products.
- **Researchers:** conduct rigorous LCAs that gain a better understanding of the value of buildings modularity, repurposing and long-lived buildings; expand the range of end-of-life options through research and development, including further research into recovery and reuse of unhydrated cement; undertake behavioural research to better understand what incentives and frameworks could be established to encourage lifetime extension and material reuse and recycling; and research material quality degradation during use.

Develop regulatory frameworks and incentives to support material efficiency

Many design standards are prescriptive in their specified requirements. This may hinder designers and construction companies from reducing use of emissions-intensive materials, even when doing so would not have a detrimental effect on performance and safety. For example, many concrete specifications require a minimum cement mass content in concrete that exceeds what is necessary to achieve concrete strength and durability requirements (Taylor et al., 2012; Wassermann, Katz and Bentur, 2009). Moving from prescriptive to performance-based standards (including design, health and safety and fire protection standards) would facilitate efficient use of materials while still ensuring their intended objectives are achieved. This includes facilitating use of lower-emission materials, such as recycled materials or blended cements with lower clinker content, which may be impeded by prescriptive standards. As checking compliance will be more complex for performance-based requirements than prescriptive requirements, planning, investment and government-industry co-ordination will be needed to develop and implement testing procedures.

Other policies, initiatives and incentives could also support material efficiency. Adopting and gradually raising carbon prices, either through carbon taxes or cap and trade, would provide a broad signal throughout the economy to reduce emissions, including emissions from material production and use. Green labelling and certification programmes could include embodied emissions in their rating systems, allowing consumers to choose products and buildings with lower embodied emissions. Other examples include government procurement of products with low embodied carbon to stimulate demand, buildings codes that allow larger floor areas for designs with improved life-cycle emissions profiles, and developing requirements and monitoring programmes to ensure contractors build to low-carbon specifications.

The following are indicative key contributing actions from stakeholders:

- **Governments:** move from prescriptive to performance-based design specifications; adopt sufficiently targeted (carbon) price signals while ensuring international competitiveness; reward products with low embodied emissions; develop labels on the carbon intensity of materials used to make products and buildings; and provide other incentives that encourage material efficiency.
- **Industry:** state support during consultations for governments modifying regulations and adopt (internal) carbon pricing; and participate in incentive and green certification programmes.
- **Researchers:** provide research into what requirements would be necessary to ensure performance and safety when moving to performance-based standards.

Box 9. Material efficiency in progress: examples of existing initiatives

Various efforts are already under way in jurisdictions around the world to promote efficient use of materials. Several existing efforts are highlighted here, demonstrating some of the initiatives that could be adopted or further expanded to boost material efficiency.

Embodied carbon reporting and regulation in the Netherlands. Since 2013, the Netherlands has had a policy in place that requires whole-building LCA at the buildings permitting stage. This is facilitated by a national Environmental Product Declaration database and a standardised LCA method (Zizzo, Kyriazis and Goodland, 2017). A mandatory cap was adopted in 2018 for the "environmental profile" of new homes and offices (Government of Netherlands, 2018). The environmental profile translates multiple criteria, including embodied carbon, into a single monetary metric. The cap is set at EUR 1.0 per square metre. The government is examining how the requirement for homes and offices could be strengthened in the future, and expanded to cover other buildings types and circular economy measures such as reparability and disassembly.

Preliminary steps towards considering life-cycle vehicle regulations in the European Union. The European Union has begun exploring possibilities for incorporating life-cycle considerations into its vehicle CO_2 emission performance standards. In November 2017, the European Commission proposed a new regulation to reduce CO_2 emissions from new passenger cars and vans, which would include requirements to develop a common methodology for reporting life-cycle CO_2 emissions by 2025. This was to prepare for mandatory life-cycle emissions reporting and to analyse options for life-cycle regulatory measures (European Parliament, 2018a). Trilogue negotiations on the regulation among the European Commission, European Parliament and European Council began in October 2018 and will determine whether the regulation will be adopted (European Parliament, 2018b).

Singapore Concrete Usage Index. The Singapore Building and Construction Authority has developed a voluntary green buildings rating system called Green Mark. One of the indicators contributing to the Green Mark score is the Concrete Usage Index, a measure of the amount of concrete used per unit of floor area (Building and Construction Authority, 2012). The indicator encourages consideration of efficient use of concrete during the buildings design and construction phases.

Urban Mine Platform. As part of the Prospecting Secondary raw materials in the Urban mine and Mining wastes (ProSUM) project, 17 collaborating institutions in Europe and Japan have developed the Urban Mine Platform, an inventory database on secondary raw materials from end-of-life vehicles, electronic equipment, batteries and mining waste (ProSUM, 2018). This type of inventory can facilitate reuse and recycling of end-of-life materials.

Building Code of Australia. Introduced in 1996, the Building Code of Australia is a leading example of performance-based design and construction standards. The code was developed with the intent of enabling greater innovation in terms of buildings materials, technologies and design (Australian Building Codes Board, 2017). Australia is actively involved in international efforts to promote the shift from prescriptive to performance-based buildings codes (Foliente, 2005).

Structural Engineers 2050 Commitment Initiative and the Massachusetts Institute of Technology database of embodied Quantity outputs (deQo). The Carbon Leadership Forum, an industry-academic collaboration hosted at the University of Washington, has started an initiative to encourage structural engineers to contribute to meeting embodied carbon benchmarks (University of Washington, 2017). To establish benchmarks and measure progress, the initiative asks engineers to contribute data to deQo, which is an online database of construction project embodied emissions and material quantities.

Willis-Knighton Health System adaptive buildings reuse. The Willis-Knighton Health System, a non-profit health care provider in the state of Louisiana (United States), has undertaken over 20 adaptive reuse projects (Elrod and Fortenberry, 2017). The projects involve repurposing abandoned or idle buildings into new health care facilities. Adaptive reuse has become a core part of the organisation's strategy, and new construction is considered only when buildings reuse opportunities are not available to meet expansion needs.

Adopt business models and practices that advance circular economy objectives

Businesses across supply chains can contribute to improved material efficiency. Integrating policies at the corporate level of businesses can urge decision makers throughout a company to use materials wisely. Planning, monitoring and reporting will promote a culture of material efficiency and deter practices that may increase material use. An example of perverse incentive would be the indexation of revenues of engineering, architecture or design firms to the overall cost of construction projects. This would mean revenues increase as more materials go into buildings. Monitoring and reporting could reduce this type of incentive to use more materials than the minimum needed.

More-innovative and new business models can also reduce material use. Efforts to realise the sharing economy (e.g. car-sharing and office space sharing) can reduce overall demand for production and construction. Moving towards increased prefabrication in the buildings sector could help optimise material use. Increasing digitalisation of production methods and digital tracking of materials could also enhance opportunities for material efficiency. Research and development towards new materials with a lower carbon footprint could also provide new business opportunities.

The following are indicative key contributing actions from stakeholders:

- **Governments:** ensure regulatory frameworks facilitate and do not hinder adoption of new business models that reduce material use.
- **Industry:** normalise material efficiency considerations in business practices; and develop business models that make more effective use of materials, including sharing models, prefabrication and digitalised production.
- **Researchers:** research the benefits and opportunities of different circular economy business models; research the behavioural and social barriers to the circular economy and how these could be overcome; and research and develop new lower-carbon materials.

Train, build capacity and share best practices

Lack of awareness and skills may be a primary barrier to more-efficient use of materials in some circumstances. Material efficiency considerations should be included in education and training programmes for actors throughout value chains. These actors should include designers, engineers, construction workers, manufacturing companies and demolition companies. For example, capacity building could increase understanding among designers and construction workers on what minimum requirements are necessary to ensure performance and safety, thus helping reduce over-engineering or overestimation that may occur by being overly cautious. Capacity building could also urge designers, architecture and engineers to think about aspects such as modularity, lightweighting and reusability in the design stages. In emerging economies, skills development for construction workers could lead to better construction practices, thus reducing waste. Government-supported capacity building would complement and help ensure compliance when adopting standards that require efficient use of materials. Sharing of best practices among companies would also help promote high standards of material efficiency.

The following are indicative key contributing actions from stakeholders:

- **Governments:** fund education and training programmes on material efficiency.
- **Industry:** provide training to employees; and share best practices and guidance among fellow industry participants, including through professional bodies and associations.
- **Researchers:** share information on the quantities of materials needed to ensure performance.

Shift behaviour towards material efficiency

The public can also contribute to driving efficient use of materials. As consumers, the public can direct demand towards products that are designed and fabricated with material efficiency in mind, such as through purchasing smaller, more fuel-efficient vehicles and homes certified under green labelling schemes that consider materials production emissions. People can also influence demand for the sharing economy, including car-sharing and office sharing, which enables more intensified use of materials and lower material demand. Consumer involvement at product and buildings end of life will be key for improving the efficient use of materials. This includes proper disposal of products for recycling. It also includes acceptance of refurbishment and reuse, such as purchasing homes with retrofitted rather than new buildings frames, or purchasing products with a high proportion of reused rather than new materials. As citizens and taxpayers, the public can also vote in support of government policies and investments that aim to reduce carbon emissions, including those that promote material efficiency. Such policies and investments would aid and accelerate consumer shifts towards material efficiency.

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General annexes

Annex I. Reference and Clean Technology Scenarios

Global total energy-related carbon dioxide (CO_2) emissions reached a historic high of 34.9 gigatonnes of carbon dioxide ($GtCO_2$) in 2017[19]. Power and energy transformation accounted for 43%, industry for 24%, transport for 23% and buildings for 9%. If emissions from electricity generation are attributed to end-use sectors, the shares of energy-related emissions in buildings and industry rise significantly – to approximately 25% for buildings and nearly 40% for industry. In 2017, global total primary energy demand reached 585 exajoules (EJ), having risen at an average annual rate of 2.0% since 2000.[20] Fossil fuels represent most of the total primary energy demand, with a share of approximately 80% in 2017 (nearly unchanged since 2000). The final energy demand drives the total primary energy demand. In 2017, final energy demand reached 420 EJ, with the industry[21] sector accounting for the largest share (37%), followed by buildings (30%), transport (28%) and agriculture and other[22] (5%).

Announced policies and commitments considered in the Reference Technology Scenario (RTS) are not enough to significantly bend the emissions curve. In the RTS, emissions continue to grow until 2045, when they level off at just over 39 $GtCO_2$ before gradually beginning to decline post 2050 to 38 gigatonnes (Gt) by 2060. This is up 8% from the 2017 level, and more than four times above the path towards energy sector decarbonisation as outlined in the Clean Technology Scenario (CTS). Primary energy demand grows by 38%, to over 800 EJ by 2060. Fossil fuels remain the largest source of energy supply, but their share declines to two-thirds in 2060 as the share of renewable sources of energy (renewables) and nuclear energy reaches one-third. Final energy demand grows to approximately 580 EJ, an increase of about 40% above the 2017 level. Electricity shows the largest increase in absolute terms, more than doubling between 2017 and 2060, and reaching a share of 28%. However, it is still below that of oil, which falls slightly to 33%.

The CTS represents a markedly different path from the RTS. Energy sector emissions in the CTS decline to 8.7 $GtCO_2$ by 2060, which is 75% below the 2017 level. All sectors will need to reduce CO_2 emissions, with power reaching near decarbonised levels to facilitate further decarbonisation of the end-use sectors. Cumulative emissions abatement to 2060 is highest in the power sector at 300 $GtCO_2$, followed by transport and industry with each abating 150 $GtCO_2$ (Figure 49). Cumulative abatement in buildings is just under 100 $GtCO_2$, while the transformation sector reduces about 50 $GtCO_2$. Energy efficiency across end-use sectors accounts for the largest share of total emissions reduction, representing 39% of cumulative reductions, followed by renewables (36%), carbon capture, utilisation and storage (CCUS) (13%), and switching to lower-carbon fossil fuels (7%) and nuclear power generation (5%).

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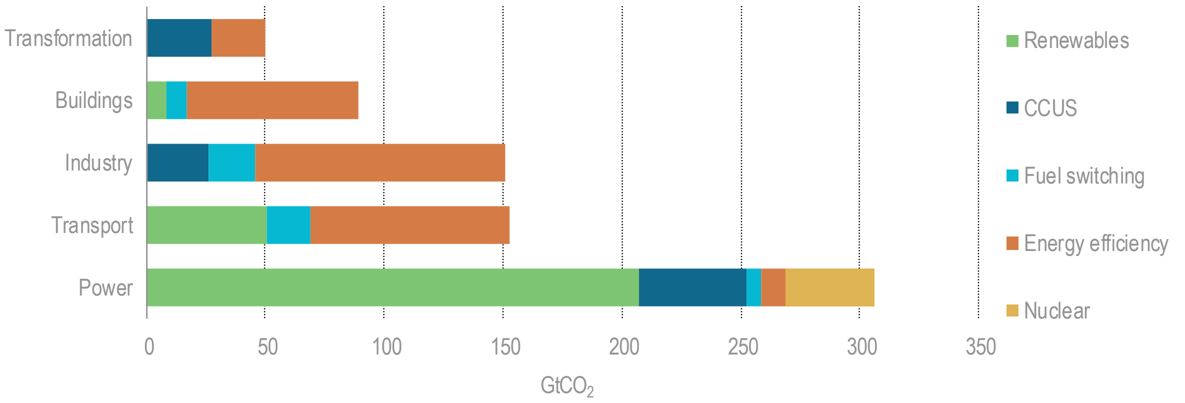
[19] Energy-related emissions include fuel combustion emissions and industrial process emissions.

[20] Growth is calculated as compound annual growth rate.

[21] Includes energy use for coke ovens, blast furnaces and chemical feedstocks.

[22] Includes non-energy use for refineries and other non-specified.

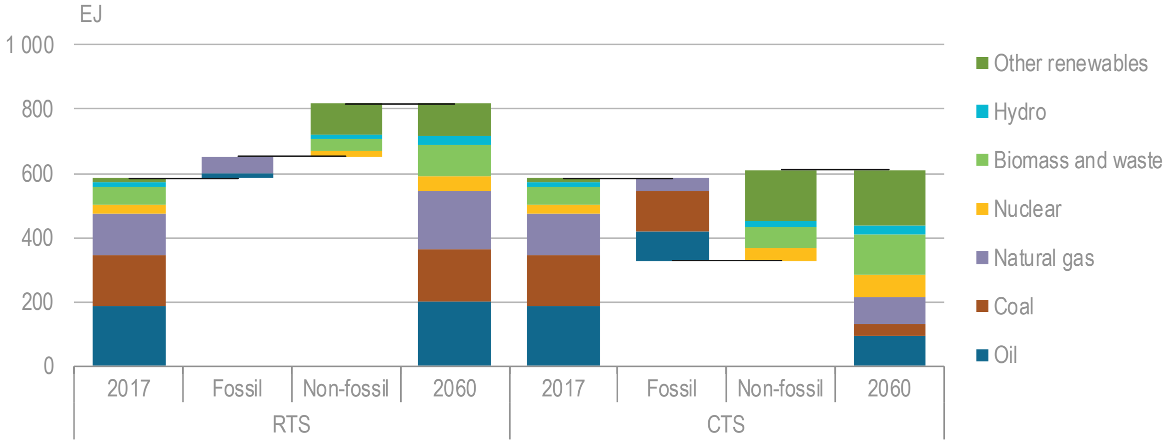
Figure 49. Cumulative global CO_2 emissions reduction by 2060 split by technology area: RTS to CTS



Energy efficiency, renewables and CCUS are central to reducing energy-related emissions.

Under the CTS, a dramatic shift in the global energy mix is needed. The share of non-fossil fuel sources surpasses that of fossil fuels to reach nearly two-thirds of the total primary energy demand in 2060 compared to just one-third under the RTS (Figure 50). Renewable energy from solar, wind, geothermal and ocean energy becomes the largest fuel source category (28%), followed by biomass and waste (20%).[23] Oil remains the largest fossil fuel (15% of total fuels), as it continues to be the largest fuel source for aviation, shipping, trucking and chemical feedstock; however, its use is more than halved compared to in the RTS. Total final energy demand falls by 4% by 2060 relative to 2017, compared to the substantial increase seen in the RTS, as stringent energy efficiency measures are assumed to be adopted. Electricity becomes the largest end-use fuel, reaching a share of 36%, with absolute electricity consumption nearly doubling between 2017 and 2060.

Figure 50. Global primary energy demand by scenario



Non-fossil fuel energy will meet more than two-thirds of primary energy by 2060 in the CTS.

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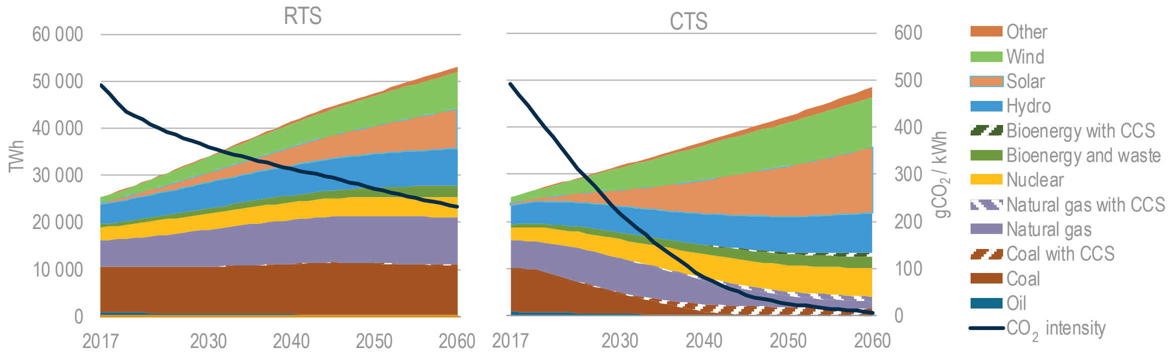
[23] Biomass and waste includes solid biomass, gas and liquids derived from biomass, industrial waste and the renewable part of municipal waste. It includes traditional and modern biomass.

The decarbonisation of the **power sector** is central to any strategy to transform the energy system. In the RTS, gross electricity generation more than doubles, reaching nearly 53 000 terawatt hours (TWh), by 2060 (Figure 51). The share of fossil fuel generation falls from 65% in 2017 to 40% by 2060, as the share of renewables (mainly wind, solar photovoltaics [PVs] and hydro) reaches over 50%. Emissions intensity of power generation continues its steady decline. By 2060, it falls to 250 grammes of carbon dioxide per kilowatt hour (gCO_2/kWh), less than half the 2017 level. While this shift towards decarbonised electricity is encouraging, it is not sufficient to achieve a deep reduction in power sector emissions.

In the CTS, the CO_2 intensity of electricity reaches the very low level of 4 gCO_2/kWh by 2060. This will require a rapid roll-out of renewable electricity generation technologies (accounting for approximately 80% of total electricity generation by 2060), and a range of flexibility measures to support high levels of variable renewable generation.[24] The share of fossil fuel generation declines to just 8%, of which more than 60% will be with carbon capture and storage (CCS). Nuclear generation in the CTS sees a renewal, with generation more than doubling and its share rising to 13% by 2060. The CTS leads to a revolution of the **fuel transformation sector**,[25] with a rapid decline in energy for fossil fuel extraction and oil refining, and strong growth in demand for liquid and gaseous biofuels. Biofuel production plants equipped with CCS allow the fuel transformation sector to reach net negative CO_2 emissions levels of -1 $GtCO_2$ in 2060.[26]

In the **industrial sector**, limited progress is expected in the development and deployment of low-carbon measures in the RTS. Demand for energy-intensive materials such as steel, cement and chemicals remains high as emerging economies continue to develop their infrastructure and their population grows. Many of these materials are highly traded commodities that compete in global markets, which poses concerns in some countries about the effectiveness of implementing domestic CO_2 emissions reduction mechanisms. Total energy demand in industry grows sharply (up approximately 40% by 2060 compared to in 2017), and remains dependent on fossil fuels (63% in 2060 versus 70% in 2017). Direct energy and process emissions from industry grow by approximately 15%, reaching 9.7 $GtCO_2$ by 2060, which is slightly below a peak in emissions around 2045 at 9.9 $GtCO_2$.

Figure 51. Global electricity generation by scenario



Notes: *Other* is geothermal and ocean energy. *Hydro* does not include generation from pumped storage.

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[24] Variable renewable energy sources are onshore and offshore wind, solar PVs, run-of-river hydropower and wave energy. The focus here is specific to the integration of wind and PVs, so the discussion of variable renewable energy is limited to these two.

[25] The fuel transformation sector covers energy use for coal mining, oil and gas production, and further conversion of primary energy into final energy carriers (except electricity and heat).

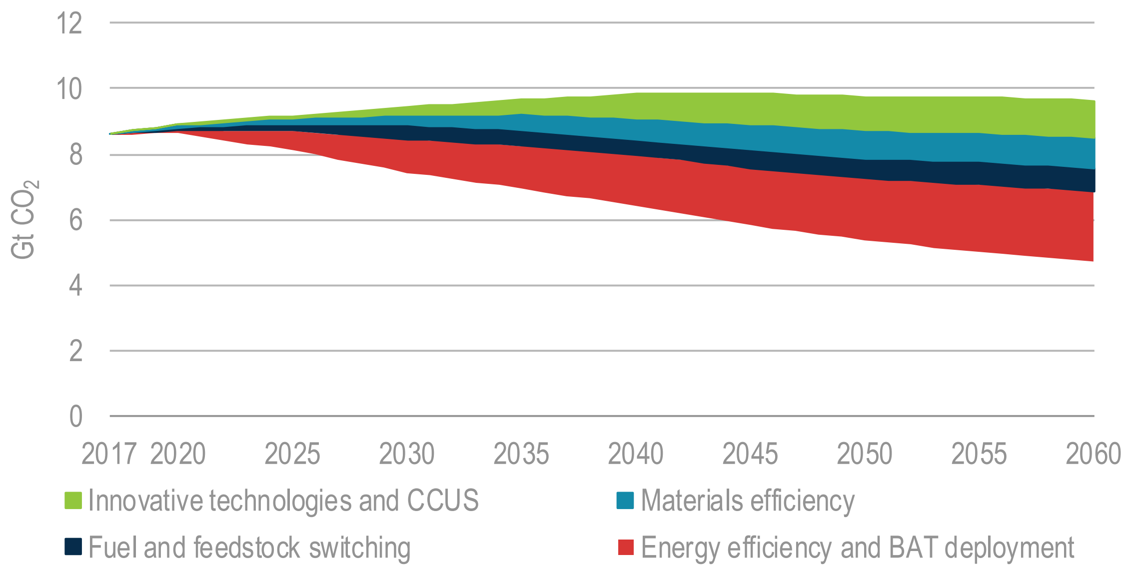
[26] Biofuel consumption remains within an International Energy Agency estimated budget of sustainable biomass availability.

Electricity generation will reach near decarbonised levels by 2060.

To achieve a low-carbon and cost-effective transition in industry as outlined in the CTS, industry-related emissions peak by 2020. They then fall by about 45% below the 2017 level by 2060, to just under 5 $GtCO_2$, which is half the level reached in 2060 in the RTS (Figure 52). Energy efficiency strategies and deployment of best available technology (BAT), particularly in emerging economies, help to curb total energy demand, which declines by almost 30% under the CTS in 2060 relative to the RTS. The share of fossil fuels in industry falls to about 55% by 2060, from approximately 70% today. This is due to a combination of increased electrification and a move away from coal towards biomass. Energy efficiency and fuel switching account for 46% and 15% of cumulative emissions reduction to 2060 in the CTS relative to the RTS.

Material efficiency strategies account for 19% of cumulative emissions reduction to 2060 in the CTS relative to the RTS. These strategies include improving manufacturing yields, reusing material by-products across industrial processes, designing products and buildings that require less materials, and increasing recycling and reuse after disposal. Development, demonstration and deployment of innovative low-carbon industrial processes will also play an important role in addressing industrial emissions, accounting for 20% of cumulative emissions reduction. Innovative low-carbon industrial processes include production routes that rely on renewable electricity (either directly or through electrolytic hydrogen), use of alternative raw materials and use of CCUS to reduce process and energy emissions.

Figure 52. Industry sector direct CO_2 emissions reduction in the CTS relative to the RTS



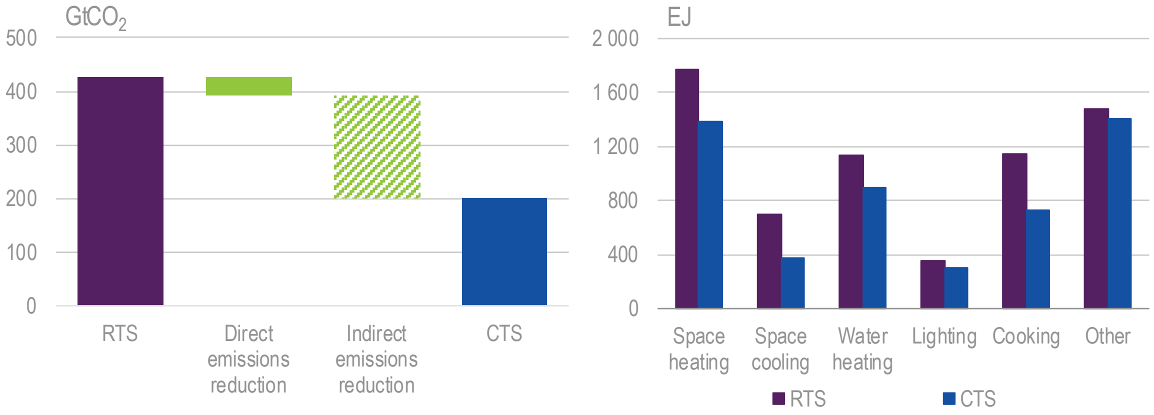
Energy efficiency accounts for almost half of the cumulative industrial emissions reduction in the CTS relative to the RTS, with other strategies contributing similarly to the remaining reduction effort.

In the **buildings sector**, final energy demand rises by nearly 40% between 2017 and 2060 in the RTS. This is because economic development drives rapid growth in floor area alongside increases in consumer demand for energy services. In particular, cooling energy demand more than triples by 2060 as expectations for cooling comfort grow, especially in hot and humid climates. Electricity is the largest fuel source, and sees its share rise from one-third in 2017 to one-half in 2060. Fossil fuel use continues to decline, but still represents about 25% of the final energy demand in 2060 (compared to approximately 35% in 2017).

Energy efficiency in all buildings end uses is central to achieving CTS ambitions in the buildings sector. Final energy demand by 2060 in the CTS is one-third lower than in the RTS. Energy efficiency equally allows for greater electrification of end uses while still consuming 20% less electricity than in the RTS. For example, the CTS uses approximately half as much final energy cumulatively as the RTS to meet the same cooling service, due to more-efficient air conditioners and improved buildings design (Figure 53). Efficient lighting also reduces electricity demand growth, although a considerable portion of that potential is being accounted for in the RTS, as the sales share of light-emitting diodes already exceeded 30% in 2017. Shifts to high-efficiency equipment and renewable sources for space and water heating also help to decarbonise heat, which accounted for more than 50% of the total final energy demand in buildings in 2017.

Cumulative buildings-related emissions (direct and indirect) to 2060 in the CTS are just over 50% lower than in the RTS. This is due to a combination of lower fossil fuel use, efficiency measures that reduce overall energy use, and lower indirect emissions owing to the decarbonisation of electricity supply.

Figure 53. Buildings sector cumulative CO_2 emissions and energy use by activity, 2017-60



Note: *Indirect emissions reduction* includes the impact of energy efficiency, which lowers electricity use, as well as the decarbonisation of electricity and heat production.

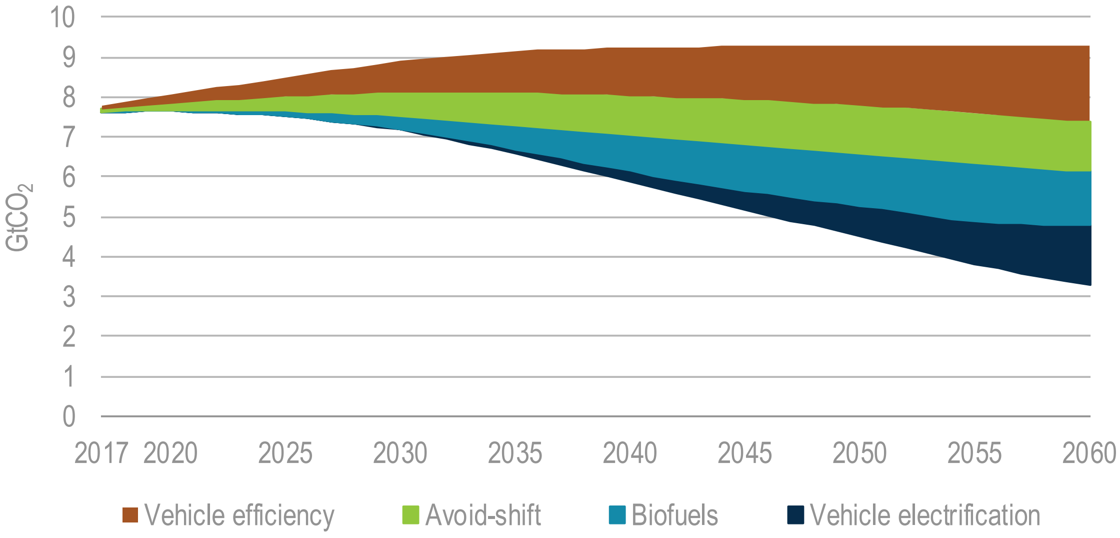
In the CTS, buildings sector cumulative emissions to 2060 are halved relative to the RTS owing to energy efficiency, fuel switching and power sector decarbonisation measures.

In the RTS, final energy demand in the **transport sector** continues rising rapidly, by nearly 40% in 2060 compared to the 2017 level. The largest increase will come from passenger road transport, as rising incomes cause consumers in emerging economies to prefer the convenience and comfort of private cars versus other modes. This leads the projected number of vehicles to nearly double over the next 40 years. Oil remains the dominate fuel, although its share is projected to decline to about 80% by 2060 as the shares of electricity (9%), biofuels (7%) and natural gas (5%) rise, supported by policies to address local air pollution.

Under the CTS, improvements in efficiency combined with rapid transition towards low- and zero-carbon fuels help to curb overall transport energy demand, which falls by approximately 10% in 2060 relative to 2017. Electrification of light-duty vehicles, buses, and two- and three-wheelers leads the share of electricity in transport final energy demand to reach over 25% by 2060, from just over 1% in 2017. The share of biofuels sees the largest increase, reaching nearly 30% by 2060. It will be particularly important in helping to decarbonise long-range transport such as aviation, trucking and shipping. Oil's share falls by nearly 50 percentage points, to about 45% from over 90% today. In the CTS, the difficult-to-decarbonise transport sectors of shipping, aviation and trucking maintain oil as the largest fuel source.

Transport-related direct CO_2 emissions in the CTS decline by nearly 60% of their 2017 level, reaching 3.3 Gt in 2060, and are 65% less than in the RTS. A combination of measures leads to cumulative direct CO_2 reductions in transport of approximately 140 $GtCO_2$ by 2060 (Figure 54). Vehicle efficiency measures accrue the largest savings. As electric vehicles are adopted at faster rates than in the RTS, the contribution of efficiency gains from hybrid- and pure-electric powertrains accounts for over one-third of cumulative emissions reduction. Biofuels and avoid-shift measures (which include avoided demand and modal shifting)[27] account for 25% (biofuels) and 27% (avoid-shift measures) of the cumulative emissions reduction between the RTS and CTS. The remaining 13% reduction is attributed directly to vehicle electrification.

Figure 54. Transport sector global direct CO_2 emissions reduction in the CTS relative to the RTS



Transport emissions could be cut in half by 2060 with efficiency, electrification, biofuels, and avoid and shift strategies.

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[27] Avoid-shift measures are those that result in fewer and shorter trips, increased public transport use, and adoption of non-motorised transport solutions (e.g. walking and cycling). Fiscal policies that make car and air travel more expensive reduce the volume of discretionary trips and lead to more-efficient use of resources (e.g. through trip-chaining or strategic vehicle choice). Smart urban planning can avoid the need to rely on motorised vehicles through mixed-use and transit-oriented development and by planning multicentric cities. Together with densification, these measures can reduce the annual distances travelled by road vehicles. Infrastructure planning and policies that promote convenient, accessible, reliable and attractive public transport, as well as walking and cycling alternatives to cars, can similarly shift transport activity to modes with lower energy and emissions intensities. Similar shifts can be realised in freight. Note that autonomous vehicle uptake is not considered, although it may be in future modelling work.

Annex II. Energy Technology and Policy modelling framework

This analysis applies a combination of backcasting and forecasting over each scenario to 2060. Backcasting lays out plausible pathways to a desired end state. It makes it easier to identify milestones that need to be reached or trends that need to change promptly for the end goal to be achieved. The advantage of forecasting, where the end state is a result of the analysis, is that it allows greater consideration of short-term constraints.

The analysis and modelling aim to identify an economical way for society to reach the desired outcome. However, the scenario results do not necessarily reflect the least-cost ideal, for a variety of reasons. Many subtleties cannot be captured in a cost-optimisation framework, such as political preferences, feasible ramp-up rates, capital constraints and public acceptance. For the end-use sectors (buildings, transport and industry), doing a pure least-cost analysis is difficult and not always suitable. Long-term projections inevitably contain significant uncertainties, and many of the assumptions underlying the analysis are likely to be inaccurate. Another important caveat to the analysis is that it does not account for secondary effects resulting from climate change such as adaptation costs. By combining varied modelling approaches that reflect the realities of the given sectors, together with extensive expert consultation, this analysis obtains robust results and in-depth insights.

Achieving the Clean Technology Scenario (CTS) and Material Efficiency variant (MEF) does not depend on the appearance of unforeseen breakthrough technologies. All technology options introduced in this analysis are already commercially available or at a stage of development that makes commercial-scale deployment possible within the scenario period.[28] Costs for many of these technologies are expected to fall over time, making a low-carbon future economically feasible.

The analysis takes into account those policies that have already been implemented or decided. In the short term, this means that deployment pathways may differ from what would be most cost-effective. In the longer term, the analysis emphasises a normative approach, and fewer constraints governed by current political objectives apply in the modelling. The objective of this methodology is to provide a model for a cost-effective transition to a sustainable energy system.

To make the results more robust, the analysis pursues a portfolio of technologies within a framework of cost minimisation. This offers a hedge against the real risks associated with the pathways. If one technology or fuel fails to fulfil its expected potential, it can more easily be compensated by another if its share in the overall energy mix is low. The tendency of the energy system to comprise a portfolio of technologies becomes more pronounced as carbon emissions are reduced. This is because the technology options for emissions reduction and their potential typically depend on the local conditions in a country. However, uncertainties may become larger, depending on the level of maturity of a given technology and the risk of not reaching expected technological development targets.

Combining analysis of energy supply and demand

The Energy Technology and Policy (ETP) modelling framework, which is the primary analytical tool used in this analysis, supports integration and manipulation of data from four soft-linked models:

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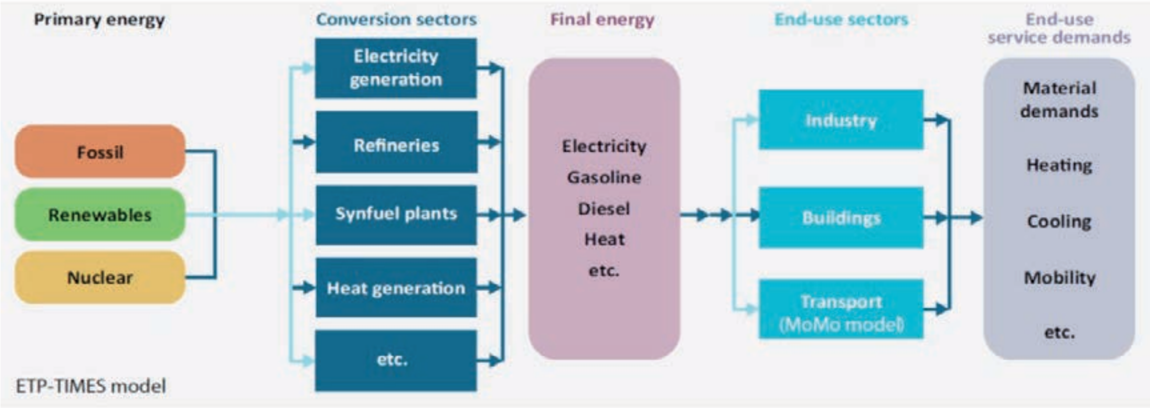
[28] See the "Technology approach" section for more information on the technologies considered in this analysis.

- energy conversion
- industry
- transport
- buildings (residential and commercial/services).

It is possible to explore outcomes that reflect variables in energy supply (using the energy conversion model) and in the three sectors that have the greatest demand and hence the largest emissions (using models for industry, transport and buildings). The following schematic illustrates the interplay of these elements in the processes by which primary energy is converted to the final energy that is useful to these demand-side sectors (Figure 55).

Figure 55. Structure of the ETP model



Note: MoMo = Mobility Model.

The ETP model enables a technology-rich, bottom-up analysis of the global energy system.

ETP–TIMES supply model

The global ETP–TIMES supply model is a bottom-up, technology-rich model that depicts a technologically detailed supply side of the energy system. It models from primary energy supply and conversion to final energy demand up to 2060. It is based on the TIMES (The Integrated MARKAL-EFOM System) model generator, which was developed by the Energy Technology Systems Analysis Programme Technology Collaboration Programme[29] of the International Energy Agency (IEA), and allows an economic representation of local, national and multiregional energy systems on a technologically detailed basis (Loulou et al., 2005).

The model covers 28 regions, representing either individual countries, such as the People's Republic of China ("China") or India, or aggregates of several countries, such as the Association of Southeast Asian Nations (ASEAN). The model regions are linked by trade in fossil fuel energy carriers (crude oil, petroleum products, coal, pipeline gas or liquefied natural gas [LNG]), biofuels (biodiesel and bioethanol) and electricity.

Starting from the current situation in the conversion sector (e.g. existing capacity stock, operating costs and conversion efficiencies), the model integrates the technical and economic characteristics of existing technologies that can be added to the energy system. The model can then determine the least-cost technology mix needed to meet the final energy demand

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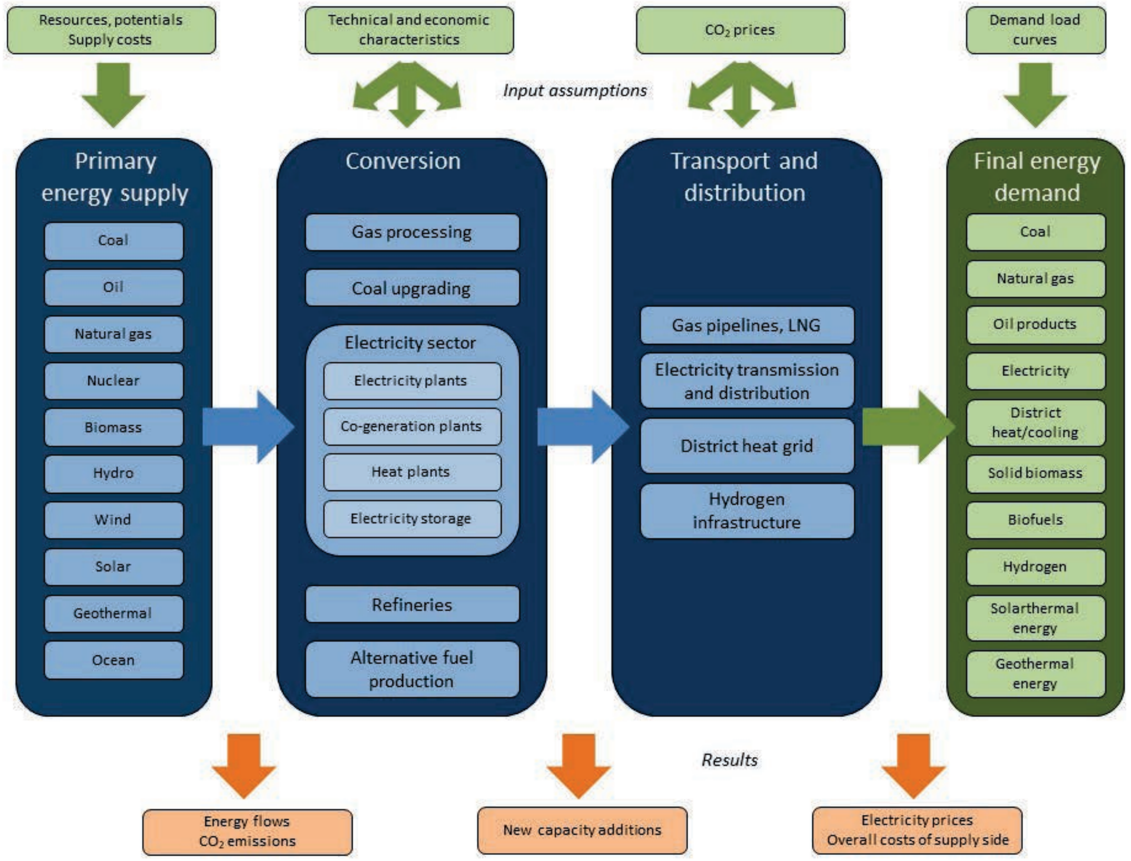
[29] For further information on the TIMES model generator, its applications and typical energy technology input data assumptions see the ETSAP website (www.iea-etsap.org).

calculated in the ETP end-use sector models for agriculture, buildings, industry and transport (Figure 56).

Figure 56. Structure of the ETP-TIMES model for the conversion sector



Notes: CO_2 = carbon dioxide; co-generation refers to the combined production of heat and power.

ETP-TIMES determines the least-cost strategy using supply-side technologies and fuels to cover the final energy demand from the end-use sector models.

Technologies are described by their technical and economic parameters such as conversion efficiencies or specific investment costs. Learning curves are used for new technologies to link future cost developments with cumulative capacity deployment. Overall, around 550 technologies are considered in the conversion sector. Electricity demand is divided into non-urban and urban. Urban is further divided into five city classes by population size to reflect local differences in the technical potential for rooftop solar photovoltaics (PVs) and municipal solid waste (IEA, 2016a; IEA, 2016b). Renewable energy sources – onshore and offshore wind, solar PVs and solar thermal electricity (STE) – are differentiated according to their potential, based on their capacity factor (in addition to offshore wind by water depth and distance to the coast) and by their distance to the city classes (five distance categories) as an approximation for the transmission costs needed to use these resources. The ETP-TIMES model also takes into account additional constraints in the energy system (e.g. emissions reduction goals). Its results provide detailed information on future energy flows and their related emissions impact, required technology additions and the overall cost of the supply-side sector.

To capture the impact on investment decisions of variations in electricity and heat demand, as well as the variation in generation from certain renewable technologies, a year is divided into four seasons. Each season is represented by a typical day, which is divided into 12 daily load segments of 2 hour durations.

For a more detailed analysis of the operational aspects of the electricity sector, the long-term ETP-TIMES supply model has been supplemented with a linear dispatch model. This model uses the outputs of the ETP-TIMES supply model to generate the electricity capacity mix for a specific model region and year. This allows for detailed analysis of an entire year with 1 hour time resolution using datasets for wind production, solar PV production and hourly electricity demand.

Given the hourly demand curve and a set of technology-specific operational constraints, the model determines the optimal hourly generation profile. To increase the flexibility of the electricity system, the linear dispatch model can invest in electricity storage or additional flexible generation technologies (e.g. gas turbines). Demand response from electricity use in the transport and buildings sectors is a further flexibility option included in the dispatch model analysis.

This linear dispatch model represents storage in terms of three steps: charge, store and discharge. The major operational constraints included in the model are capacity states, minimum generation levels and time, ramp-up and -down, minimum downtime hours, annualised plant availability, cost considerations associated with start-up and partial-load efficiency penalties, and maximum storage reservoir capacity in energy terms (megawatt hours [MWh]).

Model limitations include challenges associated with a lack of comprehensive data on storage volume (MWh) for some countries and regions. Electricity networks are not explicitly modelled, which precludes the study of the impact of spatially dependent factors, such as the aggregation of variable renewable outputs with better interconnection.

ETP-TIMES industry model

For the purposes of the industry model, the industrial sector includes International Standard Industrial Classification (ISIC) Divisions 7, 8, 10-18, 20-32 and 41-43, and Group 099, covering mining and quarrying (excluding mining and extraction of fuels), construction and manufacturing. Petrochemical feedstock use and blast furnace and coke oven energy use are also included within the boundaries of industry.

Industry is modelled using TIMES-based linear optimisation models for five energy-intensive sectors (iron and steel, chemicals and petrochemicals, cement, pulp and paper, and aluminium). These five submodels characterise the energy performance of process technologies from each of the energy-intensive subsectors, covering 39 countries and regions. Typically, raw material production is not included within the boundaries of the TIMES models, except for the iron and steel sector, in which energy use for coke ovens and blast furnaces is covered. Due to the complexity of the chemicals and petrochemicals sector, the technology detail of the submodel focuses on five products that represent about 46% of the sector's energy use:[30] ethylene; propylene; benzene, toluene and xylene (BTX); ammonia; and methanol. The remaining industrial final energy consumption is accounted for in a simulation model that estimates energy consumption based on activity level.

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[30] Including energy use as petrochemical feedstock.

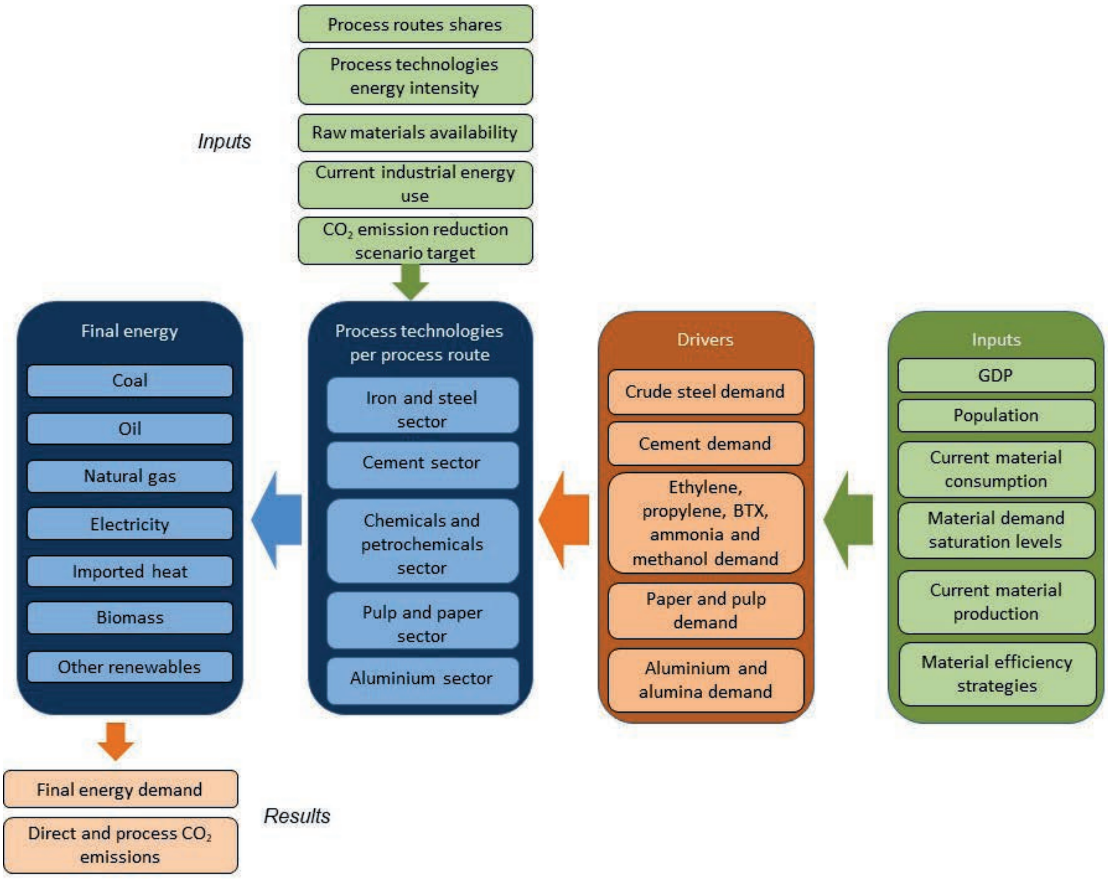
In the Reference Technology Scenario (RTS), demand for materials for the duration of the model time horizon is an exogenous input to the model. It is estimated based on country or regional-level data for gross domestic product (GDP), disposable income, short-term industrial capacity, current materials consumption, regional demand saturation levels derived from historical demand intensity curves, and resource endowments, along with some degree of improvement in recycling collection rates assuming a continuation of current trends (Figure 57). Total production is simulated by factors such as process, age structure (vintage) of plants and stock turnover rates.

In the CTS, material efficiency strategies are pursued to a moderate degree, affecting overall production levels for certain materials. Strategies pursued include considerable improvements in manufacturing yields, moderate vehicle lightweighting, limited uptake of improved buildings design and construction, and limited improvements in metals reuse. These scenarios also consider changes in materials demand due to use-phase technology shifts, including buildings lifetime extension resulting from energy retrofits and reduced vehicle use. The MEF pushes these strategies further to their reasonable limits. It has considerable additional material demand changes from the CTS, in particular due to additional vehicle lightweighting, improvements in buildings construction and design, and metals reuse. Annex III provides a detailed description of how demand for materials was derived for the CTS and MEF.

Each industry submodel is designed to account for sector-specific production routes for which relevant process technologies are modelled. Industrial energy use and technology portfolios for each country or region are characterised in the base year using relevant energy use and material production statistics for each energy-intensive industrial subsector. Changes in the technology and fuel mix, as well as efficiency improvements, are driven by exogenous assumptions on the penetration and energy performance of best available technologies (BATs), constraints on the availability of raw materials, techno-economic characteristics of the available technologies and process routes, and assumed progress on demonstrating innovative technologies at commercial scale. Thus, the results are sensitive to assumptions on how quickly physical capital is turned over, on relative costs of the various technology options and fuels, and on incentives for the use of BATs for new capacity. Fuel costs are based on outputs from the ETP conversion sector model.

The industry model allows analysis of different technology and fuel-switching pathways in the sector to meet projected material demands within a given related CO_2 emissions envelope in the modelling horizon and in least-cost fashion.

Figure 57. **Structure of ETP industry model**



Note: Refer to Annex III for further details on the methodology for materials demand and the impact of material efficiency strategies on material demand assumptions.

Based on socio-economic assumptions, historical trends, expert views and statistical information, exogenous material demand projections are used to determine the final energy consumption and direct CO_2 emissions of the sector, depending on the energy performance of process technologies and technology choice within each of the available production routes.

Global buildings sector model

The buildings sector is modelled using a global simulation stock accounting framework, split into residential and non-residential subsectors across 35 countries and regions (Figure 58). The residential subsector includes all energy-using activities in apartments and houses, including space and water heating, cooling, ventilation, lighting, and the use of appliances and other electrical plug loads. The non-residential subsector includes activities related to trade, finance, real estate, public administration, health, food and lodging, education and other commercial services. This is also commonly referred to as the commercial and public services sector. It covers energy used for space and water heating, cooling, ventilation, lighting and a range of other miscellaneous energy-consuming equipment such as commercial appliances, office equipment, cooking devices and medical equipment.

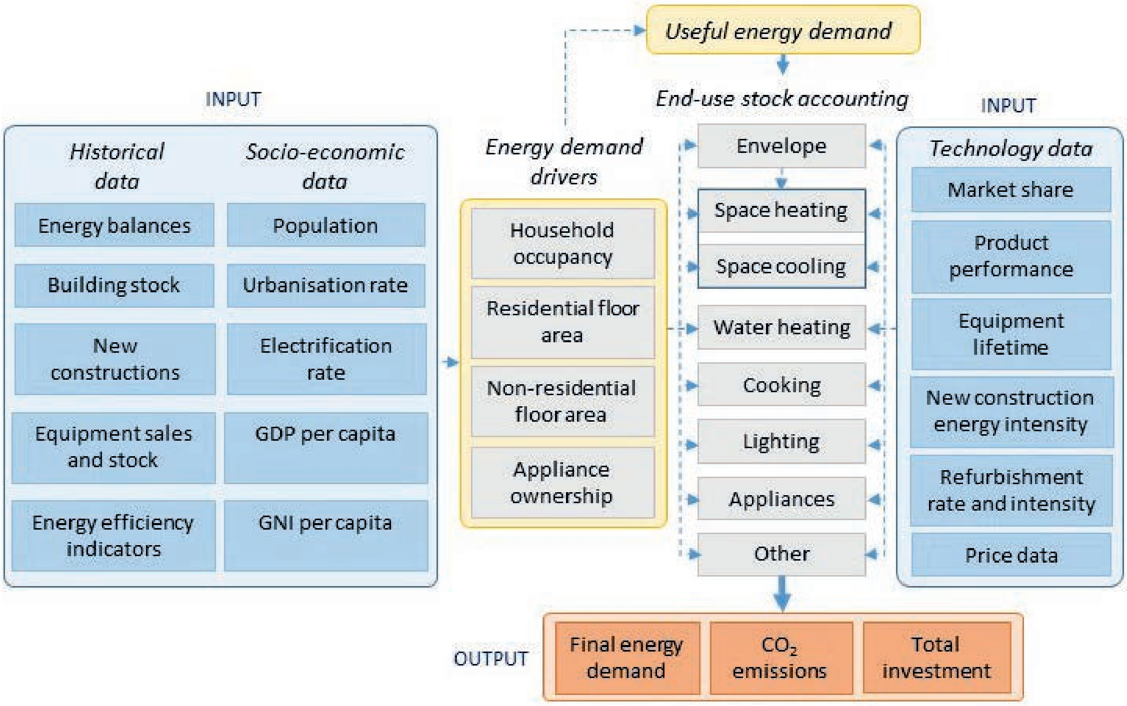
For both subsectors, the model uses socio-economic drivers, such as population, GDP, income (approximated by gross national income [GNI] per capita), urbanisation and electrification rates, to project the major buildings energy demand drivers, including residential and non-residential floor area, number of households and residential appliance ownership. As far as possible, country statistics are used for historical energy balances by end use, floor area, appliance ownership rates, and other building-related technical data and efficiency rates (e.g. technology stock and sales data). These data can be difficult to obtain across many developing countries. Therefore, in several cases, the historical driver parameters for the ETP buildings sector model have been estimated using a series of applied logistic functions relative to GDP, GNI per capita, urbanisation and electrification, or another combination of proxies as defined by multilinear regressions. Those functions are applied to individual countries, or, in cases where few data are available, to country clusters designed to be as homogeneous as possible within the cluster and as heterogeneous as possible among cluster categories. The functions differentiate the applied energy indicators by year to 2060 and across the 35 model countries and regions. The indicators are then applied within a stock accounting framework, which is distinguished by annual vintages, and the technology (or buildings stock) lifetimes are spread using a Weibull distribution.

Whenever possible, historical data and buildings sector information, such as buildings energy codes or minimum energy performance standards for end-use equipment, are applied within the model. Depending on the end use or technology, multiple categories are included (or estimated) within the model. For example, the global buildings stock is broken down into three categories, including near-zero energy buildings (nZEBs), code-compliant buildings and buildings that do not meet a code or do not have an applicable buildings energy code. Buildings end-use technologies (e.g. major household appliances) are similarly broken down into categories where applicable, such as best in class, median market performance and minimum energy performance technologies.

Using the annually differentiated stock accounting framework by country or region, historical useful energy intensity is estimated across the various buildings end uses based on assumed technology shares and efficiencies. Buildings stock characteristics (e.g. nZEB and code-compliant buildings energy intensity) are applied with heating and cooling equipment to estimate historical and then projected annual demand for space heating and cooling per unit of floor area (i.e. useful energy services delivered). The model also takes into account the ageing, refurbishment or reconstruction of buildings through degradation, improvement, renovation rates or specific lifetime distributions. For the other end uses (e.g. water heating, lighting, appliances and cooking), the useful energy demand is similarly estimated through a differentiated stock accounting framework to determine the useful (or delivered) energy service by end use. Across all end uses and countries/regions, useful energy demand can vary over time (e.g. relative to average GNI per capita growth), where some convergence (in useful energy service) is assumed across similar countries/regions, depending on the buildings ETP scenario.

For each of the derived useful energy demands, a suite of technology and fuel options are represented in the model reflecting current techno-economic characteristics (e.g. efficiencies, costs and lifetimes) as well as their assumed evolution to 2060 in the applied ETP scenario. Depending on the technology stock, as well as assumptions on the penetration and market share of new technologies in the future, the ETP buildings sector model allows exploration of strategies that meet the different useful energy demands and the quantification of the resulting developments by final energy consumption and related CO_2 emissions. Detailed annual results from the model are also applied within a logarithmic mean Divisia index analysis. This allows in-depth tracking of changes in activity, technology and energy performance over time with respect to the various scenarios.

Figure 58. Structure of the buildings sector model



Starting from socio-economic assumptions, the buildings sector model determines demand drivers and related useful energy demands, which are then applied across buildings end uses and technology choices to calculate final energy consumption across the 35 model countries and regions.

Modelling of the transport sector in the MoMo

Overview

The MoMo is a techno-economic database spreadsheet and simulation model that enables detailed projections of transport activity, vehicle activity, energy demand, and well-to-wheel CO_2 and pollutant emissions according to user-defined policy scenarios to 2060.

It comprises:

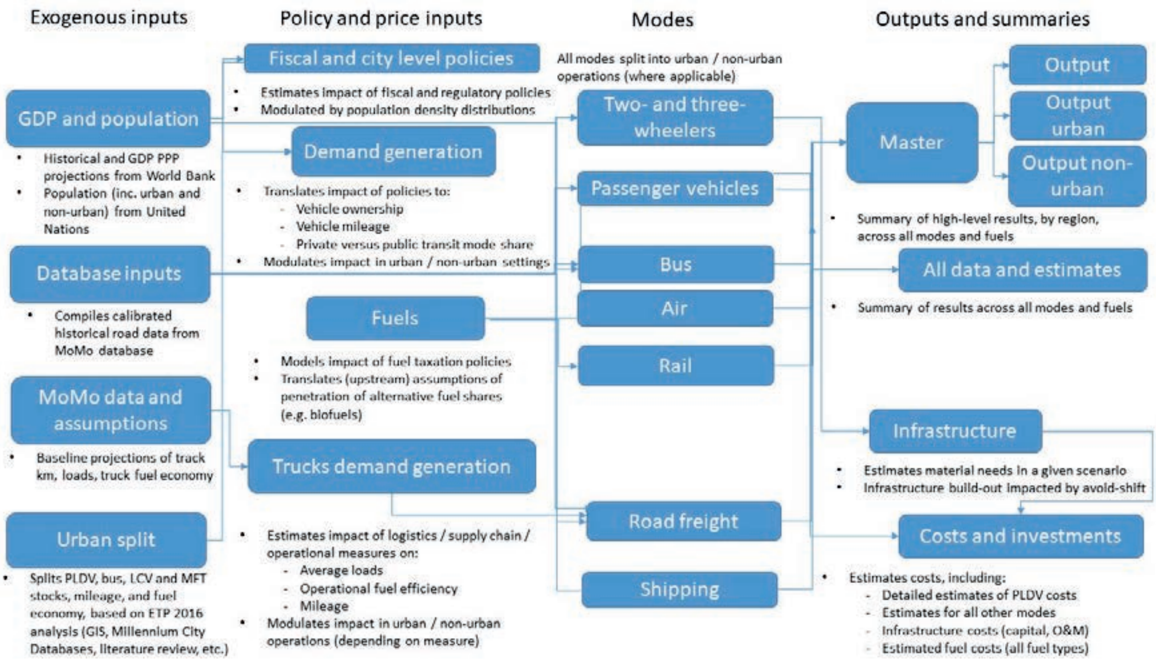
- 27 countries and regions, which are aggregated into four Organisation for Economic Co-operation and Development (OECD) regional clusters and 11 groups of non-OECD economies
- historical data from 1975 to 2017 (or 1990 to 2017 for certain countries)
- a simulation model in five-year time steps, for creating scenarios to 2060 based on "what-if" analysis and backcasting
- disaggregated urban versus non-urban vehicle stock, activity, energy use and emissions
- all major motorised transport modes (road, rail, shipping and air) providing passenger and freight services
- a wide range of powertrain technologies: internal combustion engines (including gasoline, diesel, compressed natural gas [CNG] and LNG), as well as hybrid electric and electric vehicles (including plug-in hybrid electric and battery-electric vehicles) and fuel-cell electric vehicles.

Associated fuel supply options include: gasoline and diesel, biofuels (ethanol and biodiesel via various production pathways) and synthetic alternatives to liquid fuels (coal to liquid and gas to liquid); gaseous fuels, such as natural gas (CNG and liquefied petroleum gas) and hydrogen via various production pathways; and electricity (with emissions according to the average national generation mix as modelled by the ETP-TIMES model in the relevant scenario).

The MoMo further enables estimation of scenario-based costs of vehicles, fuels and transport infrastructure, as well as the primary material inputs required for the construction of vehicles, related energy needs and the resultant CO_2 emissions.

To ease the manipulation and implementation of the modelling process, the MoMo is split into modules that can be updated and elaborated upon independently. Figure 59 shows how the modules interact with one another. By integrating assumptions on technology availability and cost in the future, the model reveals, for example, how costs could drop if technologies were deployed at a commercial scale and allows detailed bottom-up "what-if" modelling, especially for passenger light-duty vehicles (PLDVs) and trucks (IEA, 2018).

Figure 59. Structure of the MoMo



Notes: PPP = purchasing power parity, km = kilometres, LCV = light commercial vehicle, MFT = medium freight truck, GIS = geographic information system, O&M = operation and maintenance.

The MoMo covers all transport modes and includes modules on local air pollutants and the cost of fuels, vehicles and infrastructure, as well as analysis of the material needs for new vehicles.

Data sources

The MoMo modelling framework relies upon compiling and combining detailed data from various sources on vehicles in each of the countries/regions to estimate aggregate energy consumption, emissions and other energy-relevant metrics at the country/regional level.

MoMo modellers have collected historical data series from a variety of public and proprietary data sources for more than a decade. National data are gathered primarily from the following organisations: 1) national and international public institutions (e.g. the World Bank, the Asian Development Bank and Eurostat); 2) national government ministries (e.g. departments of energy and transport, and statistical bureaus); 3) federations, associations and non-governmental organisations (e.g. Japan Automobile Manufacturers Association, Korea Automobile Manufacturers Association and National Association of Automobile Manufacturers of South Africa); 4) public research institutions (e.g. from peer-reviewed papers and reports from universities and national laboratories); 5) private research institutions (e.g. International Council on Clean Transportation); and 6) private business and consultancies (e.g. IHS Automotive/Polk, Segment Y, and other major automotive market research and analysis organisations, in addition to major energy companies and automobile manufacturers).

Calibration of historical data with energy balances

The framework for estimating average and aggregate energy consumption for a given vehicle class *i* can be neatly summarised by the Activity = Share x Intensity x Fuel (ASIF) identity (Schipper, Marie-Lilliu and Gorham, 2000):

$$\boldsymbol{F} = \sum_{\boldsymbol{i}} \boldsymbol{F_i} = \boldsymbol{A} \sum_{\boldsymbol{i}} \left(\frac{\boldsymbol{A_i}}{\boldsymbol{A}}\right)\left(\frac{\boldsymbol{F_i}}{\boldsymbol{A_i}}\right) = \boldsymbol{A} \sum_{\boldsymbol{i}} \boldsymbol{S_i I_i} = \boldsymbol{F}$$

where *F* is the total fuel use (megajoules [MJ] per year); *A* is the vehicle activity (vehicle kilometres [vkm] per year]); *I* is the energy intensity (MJ/vkm); *S* is the structure (shares of vehicle activity [%]); and *i* is an index of vehicle modes and classes (MoMo vehicles belong to several modes). Vehicle activity can also be expressed as the product of vehicle stock (vehicles) and mileage (kilometre [km] per year). The energy used by each mode and vehicle class in a given year (MJ per year) can therefore be calculated as the product of three main variables: vehicle stock (vehicles), mileage (km/year) and fuel economy (MJ/vkm).

To ensure a consistent modelling approach is adopted across the modes, energy use is estimated based on stocks (via scrappage functions), utilisation (travel per vehicle), consumption (energy use per vehicle, i.e. fuel economy) and emissions (via fuel emissions factors for CO_2 and pollutants on a vehicle and well-to-wheel basis) for all modes. Final energy consumption, as estimated by the "bottom-up" approach described above, is then validated against and calibrated as necessary to IEA energy balances (IEA, 2016c).

Vehicle platform, components and technology costs

Detailed cost modelling for PLDVs accounts for initial (base year) costs, asymptotic (i.e. fully learned-out) costs and an experience parameter that defines the shape of cost reductions. These three parameters define learning functions that are based on the number of cumulative units produced world wide. Cost functions define various vehicle configurations, including vehicle component efficiency upgrades (e.g. improved tyres or air-conditioning controls), material substitution and vehicle downsizing, conventional spark and compression ignition engine improvements, conventional and plug-in hybrid powertrain configurations, batteries, electric motors and fuel cells. These configurations are added to a basic glider cost. The ratios of differences in vehicle technologies deployed in PLDVs are extrapolated to other road vehicle types (i.e. two- and three-wheelers and freight trucks).

The primary drivers of technological change in transport are assumptions on the cost evolution of the technology, and the policy framework incentivising adoption of the technology. Oil prices and the set of policies assumed can significantly alter technology penetration patterns. The model supports a comparison of marginal costs of technologies and aggregates to total cost across all modes and regions, for each scenario.

Infrastructure and fuel costs

The MoMo estimates future infrastructure costs according to scenario-based projections on modal activity and fuel use. Infrastructure cost estimates include capital costs, operations and maintenance, and reconstruction costs – split by geography into urban and non-urban regions according to the location of the investments. Fuel costs are also estimated based on scenario-specific projections of urban and non-urban consumption, and include all fuel types (fossil-derived fuels, biofuels, electricity and hydrogen).

Elasticities

The MoMo has included key elasticities from 2012. Price and income elasticities of fuel demand, for light-duty (passenger) road activity as well as road freight, based upon representative "consensus" literature values, are used to model vehicle activity and fuel consumption responses to changes in fuel prices. These fuel prices are driven by projections and policy scenarios (CO_2 or fuel taxes). Elasticities also enable vehicle ownership to vary according to fuel prices and income, as proxied by GDP per capita.

Framework assumptions

Economic activity (Table 2) and population (Table 3) are the two fundamental drivers of demand for energy services in scenarios. These are kept constant across all scenarios as a means of providing a starting point for the analysis and facilitating interpretation of the results. Under the ETP assumptions, global GDP will more than triple between 2017 and 2060; however, uncertainty around GDP growth across the scenarios is significant. CO_2 emissions in the RTS are substantially higher than the level that would be needed to keep warming with 1.5 to 2 degrees Celsius. The resulting climate change in the RTS is likely to have a profound and unpredictable impact on the potential for economic growth. This effect is not captured by ETP analysis. Moreover, the structure of the economy is likely to have non-marginal differences across scenarios, suggesting that GDP growth is unlikely to be identical even without considering the climate impact. The redistribution of financial, human and physical capital will affect the growth potential globally and on a regional scale.

Energy prices, including those of fossil fuels, are a central variable in the analysis. The continuous increase in global energy demand is translated into higher prices for energy and fuels. Rising prices are a likely consequence unless current demand trends are broken. However, the technologies and policies to reduce CO_2 emissions in the scenarios will have a considerable impact on energy demand, particularly for fossil fuels. Declining demand for oil in the CTS and MEF reduces the need to produce oil from costly fields higher up the supply curve, particularly in non-members of the Organization of the Petroleum Exporting Countries. As a result, oil prices in these scenarios are lower than in the RTS and even decline. Prices for natural gas will also be affected, directly through downward pressure on demand, and indirectly through the link to oil prices that often exists in long-term gas supply contracts.[31] Coal prices are also substantially lower owing to the large shift away from coal in the CTS and MEF.

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[31] This link is assumed to become weaker over time in the ETP analysis, as the price indexation business model is gradually phased out in international markets.

Table 2. Real GDP growth projections used in the analysis, %

Country/region	2015-20	2020-30	2030-40	2040-60	2015-60
World	3.7	3.6	3.1	2.1	2.8
OECD	2.2	1.8	1.7	1.6	1.7
Non-OECD	4.8	4.8	3.8	2.3	3.5
ASEAN	5.2	4.9	3.7	2.2	3.5
Brazil	0.9	2.7	3.0	1.7	2.1
China	6.5	5.0	3.3	1.7	3.3
European Union	2.2	1.6	1.4	1.3	1.5
India	7.4	7.3	5.2	2.8	4.8
Mexico	2.7	3.2	3.0	2.1	2.6
Russian Federation	1.3	1.9	2.1	1.2	1.5
South Africa	1.4	2.3	2.9	2.2	2.3
United States	2.2	1.8	2.0	1.9	1.9

Notes: Growth rates are compounded average annual growth rates. They are based on GDP in United States dollars in purchasing power parity constant 2015 terms.GDP is assumed to be identical across scenarios.

Sources: IEA (2016d), *World Energy Outlook*; IMF (2016), *World Economic Outlook* (database), www.imf.org/external/pubs/ft/weo/2016/01/weodata/index.aspx.

Table 3. Population projections used in the analysis (millions)

Country/region	2015	2020	2030	2040	2050	2060
World	7 348	7 761	8 515	9 172	9 733	10 184
OECD	1 275	1 310	1 360	1 395	1 413	1 420
Non-OECD	6 073	6 452	7 154	7 778	8 320	8 764
ASEAN	632	666	724	766	793	805
Brazil	206	214	225	232	233	229
China	1 379	1 407	1 424	1 401	1 349	1 274
European Union	510	514	516	513	506	495
India	1 309	1 383	1 513	1 605	1 659	1 679
Mexico	121	128	142	151	158	160
Russian Federation	144	144	141	136	133	130
South Africa	55	59	64	69	73	75
United States	322	334	357	376	392	407

Source: UNDESA (2015), *World Population Prospects: The 2015 Revision*, https://esa.un.org/unpd/wpp/.

Technology approach

In this analysis, the definition of technologies "available and in the innovation pipeline" includes those technologies that are commercially available, or at the stage of development that makes commercial-scale deployment possible within the 2020-60 scenario period, such as:

- Existing commercial BATs, for example, solar thermal and heat pumping technologies for space and water heating, light-emitting diodes (LEDs) for lighting, high-performance windows (e.g. low-emissivity and double- or triple-glazed windows), high-performance insulation, green or cool roofs, thermal energy storage, enhanced catalytic and biomass-based processes for chemical production, onshore wind, offshore wind, solar PVs, STE, hydropower, geothermal (direct, flash), nuclear power, large-scale electric heat pumps, and conventional biodiesel and bioethanol.

- Technologies in the demonstration phase (technologies that have been proven, and have sufficient techno-economic data available to be assumed to be commercially available within the time horizon of the model), for example, high-performance heat pumping technologies, high-efficacy (e.g. greater than 150 lumens/watt) LED lighting, aerosol-based whole-building envelope air sealing, advanced buildings insulation (aerogel, vacuum insulated panel and phase change materials), whole-building renovation solutions, zero-emission fuels for transport, upgraded smelt reduction and direct reduced iron, coal-fired integrated gasification combined cycle (IGCC), coal-fired IGCC with CO_2 capture, coal-fired power plants with post-combustion CO_2 capture, conventional bioethanol with CO_2 capture, advanced biodiesel, large-scale hydrogen electrolysis and hydrogen from natural gas with CO_2 capture.
- Technologies in pilot testing, for example, "smart" buildings technologies and intelligent controls, dynamic solar control, hybrid heat pumps, fuel cells and hydrogen-ready equipment, inert anodes for aluminium smelting, oxy-fuelled coal power plants with CO_2 capture, gas-fired power plants with CO_2 capture, biomass integrated gasification combined cycle (BIGCC), wave energy, tidal stream, tidal lagoon, enhanced geothermal energy systems, advanced biodiesel with CO_2 capture, hydrogen from biomass gasification and biofuels from algae.
- Technologies under development, for example, solar cooling solutions, vacuum insulated panels for refrigeration and buildings envelopes, thermoelectric cooling using heat pumps, full oxy-fuelling kilns for clinker production, BIGCC with CO_2 capture, and hydrogen from coal and biomass with CO_2 capture.
- Technologies with incremental improvements of performances compared with today's BATs (may not be available yet, but can be envisaged to be available within the time frame of scenarios), for example, high-performance appliances in buildings, improved controls of cooling and heating (smart thermostats), advanced district energy networks, low rolling resistance tyres, vehicle design improvements that reduce energy needs and energy intensity improvements towards BAT in industrial process technologies.
- Supporting infrastructure to facilitate the uptake of improved and newly demonstrated technologies, for example, low-temperature distribution, high-performance district energy networks, smart grids with intelligent demand-side response, transport and storage infrastructure to support carbon capture and storage, and electric vehicle charging infrastructure.

Some technology options are not available within the model until later time periods, depending on their current level of readiness, and some have constraints to account for process-specific limitations to deployment.

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Annex III. Material demand and efficiency modelling

Overview of material demand modelling methodology

Analysing how material demand is affected by material efficiency strategies and end-use technology shifts required building bottom-up material demand estimates for the value chains of focus. Historical data on activity levels (e.g. floor area in a given country or region) and material demand intensities (e.g. consumption of steel and cement per area of floor area) by application were compiled to calculate material demand. These estimates were verified against top-down historical estimates of material demand for those specific segments of demand, which were derived based on production and consumption statistics and on macroeconomic indicators. Future estimates of material demand were arrived at using estimates of future activity levels and scenario-based assumptions of how material intensities change in the future.

Comprehensive statistics or estimates of material demand intensities by end use and total material demand by end use do not currently exist. Therefore, the analysis relied on a variety of sources, including individual life-cycle assessment (LCA) studies and other literature providing estimates of material intensities for some regions. The bottom-up buildings construction and vehicles material demand assessment aligned sufficiently with the top-down data for incorporation into the bottom-up modelled material demand. Material intensities were also explored for infrastructure, focusing on transport and power generation. However, given that these two segments make up only a portion of the infrastructure category in top-down estimates, the infrastructure bottom-up estimates were not incorporated into the bottom-up modelled material demand estimates.

The Clean Technology Scenario (CTS) and Material Efficiency variant (MEF) total material demand curves were calculated by starting with the Reference Technology Scenario (RTS) demand curves, which were derived from gross domestic product and population estimates. Then, the differences in demand in the buildings construction and vehicles supply chains were added or subtracted from the RTS, as calculated using the described bottom-up method. For steel and aluminium, changes in manufacturing and semi-manufacturing yields and reuse rates across different applications were also accounted for in the modelled material demand curves across all demand segments (see Table 4, Table 5, Table 6 and Table 7).

Table 4. Steel manufacturing yields

	Current (%)	RTS in 2060 (%)	CTS and MEF in 2060 (%)
Semi-manufacturing yields			
Cast iron and cast steel products	100	100	100
Light and heavy sections, rails, reinforcing bars, and welded and seamless tubes	95	97-98	97-98
Wire rods	90	93	97
Hot-rolled coils (general and galvanised strips) and hot-rolled narrow strips	83-90	84-92	88-92
Cold-rolled coils (general and organic coated), electrical sheets, plates and hot-rolled bars	75-80	82-85	88-92
Cold-rolled coils (tinned and galvanised)	60-70	64-74	69-80

	Current (%)	RTS in 2060 (%)	CTS and MEF in 2060 (%)
Semi-manufacturing yields			
Product manufacturing yields			
Buildings	93	93	93
Infrastructure	95	95	95
Cars	69	69	83
Trucks	80	80	96
Ships and other transport vehicles	81	81	97
Mechanical equipment	80	80	89
Electrical equipment	87	87	96
Metal goods	77	77	91
Domestic appliances	80	80	94
Food packaging	70	70	83

Sources: Current values are based on Cullen, K., J. Allwood and M. Bambach (2012), "Mapping the global flow of steel: from steelmaking to end-use goods", https://doi.org/10.1021/es302433p. Future values informed by a combination of Cullen et al. (2012) and expert input.

Table 5. Steel reuse rates

	Current (%)	RTS in 2060 (%)	CTS in 2060 (%)	MEF in 2060 (%)
Buildings	2	4	9	13
Infrastructure	0	1	3	8
Cars	2	3	5	15
Trucks	2	5	10	30
Ships and other transport vehicles	5	12	25	50
Mechanical equipment	1	3	6	9
Electrical equipment	1	14	27	41
Metal goods	1	6	12	19
Domestic appliances	2	14	28	43
Food packaging	0	0	0	0

Notes: To account for practicality constraints and trade-offs among material efficiency strategies, reuse rates are assumed to achieve 75-85% of the technical potential outlined in Cooper and Allwood (2012) and Milford et al. (2013) by 2060. The improved reuse rates in the MEF would require targeted efforts not already occurring in the CTS, such as setting up collection and inventories and better integration throughout value chains.

Sources: All values are International Energy Agency (IEA) estimates informed by Cooper, D. and J. Allwood (2012), "Reusing steel and aluminium components at end of product life", https://doi.org/10.1021/es301093a; Milford, R.L. et al. (2013), "The role of energy and material efficiency in meeting steel industry CO_2 targets", https://doi.org/10.1021/es3031424.

Table 6. Aluminium manufacturing yields

	Current (%)	RTS in 2060 (%)	CTS and MEF in 2060 (%)
Semi-manufacturing yields			

	Current (%)	RTS in 2060 (%)	CTS and MEF in 2060 (%)
Semi-manufacturing yields			
Deoxidation aluminium, powders and pastes	100	100	100
Extrusion, wires and cables, other	76	80	88
Sheets and plates	74	77	83
Can sheets	72	76	83
Foils	63	66	72
Shape casting	50	52	57
Product manufacturing yields			
Buildings and construction	90	92	95
Transport – cars and trucks	80-84	87-89	95
Transport – aerospace	60	65	74
Packing (cans and others)	75	80	89
Machinery and equipment	75	80	89
Electrical (cables and other)	80-90	85-92	94-95
Consumer durables, destructive uses, other	80	85	94

Sources: Current values are based on Liu, G. C. Hangs and D. Muller, (2013), "Stock dynamics and emission pathways of the global aluminium cycle", https://doi.org/10.1038/nclimate1698. Future values are informed by a combination of Liu et al. (2013) and expert input.

Table 7. Aluminium reuse rates

	Current (%)	RTS in 2060 (%)	CTS in 2060 (%)	MEF in 2060 (%)
Buildings and construction	2	6	11	17
Transport – cars and trucks	2	5	10	30
Transport – aerospace	2	7	14	27
Packing (cans and others)	0	0	0	0
Machinery and equipment	1	3	6	9
Electrical (cable and other)	1	11-14	22-28	33-43
Consumer durables	2	13	25	38
Destructive uses, other	0	0	0	0

Notes: To account for practicality constraints and trade-offs among material efficiency strategies, reuse rates are assumed to achieve 75-85% of the technical potential outlined in Cooper and Allwood (2012) by 2060, with an adjustment for buildings and construction based on the steel values in Milford et al. (2013). The improved reuse rates in the MEF would require targeted efforts not already occurring in the CTS, such as setting up collection and inventories and better integration throughout value chains.

Sources: All values are International Energy Agency (IEA) estimates informed by Cooper, D. and J. Allwood (2012), "Reusing steel and aluminium components at end of product life", https://doi.org/10.1021/es301093a; Milford, R.L. et al. (2013), "The role of energy and material efficiency in meeting steel industry CO_2 targets", https://doi.org/10.1021/es3031424.

Buildings value chain assumptions and modelling methodology

Material intensities for buildings were derived from analysis of many literature estimates. Most of these estimates were LCAs for individual buildings, while a few were estimates of average material intensities for particular countries. The literature values were used to estimate average material intensities by buildings type (residential and non-residential), frame and height. Regional estimates of the proportion of each buildings frame and buildings heights were used together with the material intensities to derive regional material demand estimates.

Table 8. Assessment of steel efficiency strategy potential in the MEF

Lever	Strategy	Reduced steel use potential by 2060 relative to 2017 for one building (%)	Market share that the strategy is applied to by 2060, in benchmark region (%)
Building designs	Switch to composite frames	33	19 for residential and 24 for non-residential (of non-precast)
	Optimise steel frames	24	67 (of non-precast)
	Optimise other frames	13	67 (of non-precast)
Material properties	Use best available steel (e.g. high-strength steel)	6	67 (of non-precast)
On-site practices	Waste reduction	Market-wide steel building manufacturing losses remain at 7% to 2060	
Combination of all categories above	Precasting and prefabrication*	32 for steel frames and 18 for non-steel frames	10%
Lifetime	Lifetime extension	Annual retrofit rate of 2-3% of the buildings stock and extension of new commercial buildings lifetime to 50-70 years	
Post-use	Reuse	13% average reuse rates, relative to minimal reuse currently	
	Recycling	98% collection rate, relative to 85% currently	

* Precasting and prefabrication applies only to RCC (Reinforced Cement concrete) frames

Notes: Calculating the sector-wide cement reduction of each strategy requires multiplying the reduction potential for one building by the market share applied to for each strategy. The additivity of material efficiency strategies is specified by Figure 36, where options placed in series are additive while options placed in parallel are not. For instance, enhancing a steel frame building could either benefit from a 24% steel use reduction from enhanced buildings design, plus a 6% reduction from enhancing material properties, or from a 32% reduction from using precast. Lifetime extension impacts steel demand through reduced total new floor area.

Sources: Estimates were derived through a combination of literature review and expert opinion. Sources consulted include ArcelorMittal (n.d.), "HISTAR: Innovative high strength steels for economical steel structures", http://sections.arcelormittal.com/fileadmin/redaction/4-Library/1-Sales_programme_Brochures/Histar/Histar_EN.pdf; Axmann, G. (2003), "Steel going strong", https://www.aisc.org/modernsteel/archives/2003/january/; Carruth, M.A., J.M. Allwood and M.C. Moynihan (2011), "The technical potential for reducing metal requirements through lightweight product design", http://dx.doi.org/10.1016/j.resconrec.2011.09.018; Cooper, D.R. and J.M. Allwood (2012), "Reusing steel and aluminium components at end of product life", http://doi.org/10.1021/es301093a; Cooper, D.R. et al. (2014), "Component level strategies for exploiting the lifespan of steel in products", http://dx.doi.org/10.1016/j.resconrec.2013.11.014; Dunant, C.F. et al. (2017), "Real and perceived barriers to steel reuse across the UK construction value chain", http://doi.org/10.1016/j.resconrec.2017.07.036; Dunant, C.F. et al. (2018), "Regularity and optimisation practice in steel structural frames in real design cases", http://doi.org/10.1016/j.resconrec.2018.01.009; Milford, R.L. et al. (2013), "The role of energy and material efficiency in meeting steel industry CO_2 targets", http://doi.org/10.1021/es3031424; Pauliuk, S., T. Wang and D.B. Muller (2013), "Steel all over the world: Estimating in-use stocks of iron for 200 countries", http://dx.doi.org/10.1016/j.resconrec.2012.11.008; Schlueter, A. (2016), "3for2: Realizing spatial, material, and energy savings through integrated design", http://global.ctbuh.org/resources/papers/download/2783-3for2-realizing-spatial-material-and-energy-savings-through-integrated-design.pdf.

A combination of literature analysis and expert opinion was used to estimate the future potential for steel and cement material intensity savings from each strategy in the MEF relative to 2017 levels (Table 8 and Table 9). Reduction potentials were assumed to approach the technical potential (although they may be lower due to economic and behavioural constraints), and also took into account interactions among strategies. Strategies were applied to a large portion of the market in 2060, although they were not universally applied due to practical constraints. The benchmark market shares in the tables were applied to advanced economies, while uptake in developing and emerging economics were assumed to be 60-80% of the benchmark uptake. In the CTS, it was assumed that the material intensity reduction potential by 2060 for each strategy will be 70% of that achieved in the MEF and the market share reached will be only 20% of that in the MEF. In the RTS, material intensities remain at 2017 levels through to 2060.

Table 9. Assessment of cement efficiency strategy potential in the MEF

Lever	Strategy	Reduced cement use potential by 2060 relative to 2017 for one building (%)	Market share that the strategy is applied to by 2060, in benchmark region (%)
Building designs	Switch to composite frames	20	19 for residential and 24 for non-residential (of non-precast)
	Structural optimisation	13	50 (of non-precast)
Material properties	Use best available concrete (e.g. lower cement content)	20	50 (of non-precast)
On-site practices	Waste reduction	Market-wide cement wastage rates of 5 to 7 currently (depending on region) are reduced to 4 to 6 by 2060	
Combination of all categories above	Precasting and prefabrication*	36	10
Lifetime	Lifetime extension	Annual retrofit rate of 2-3% of the buildings stock and extension of new non-residential buildings lifetime to 50-70 years	
Post-use	Reuse of concrete elements	10	10 (assumes reuse only possible for precast buildings)

* Precasting and prefabrication applies only to RCC frames.

Notes: Calculating the sector-wide cement reduction of each strategy requires multiplying the reduction potential for one building by the market share applied to for each strategy. The additivity of material efficiency strategies is specified by Figure 36, where options placed in series are additive while options placed in parallel are not. For instance, enhancing buildings design could either benefit from a 13% cement use reduction from optimising buildings design, plus a 20% reduction from optimising material properties, plus waste reduction, or from a 36% reduction from using precast. Lifetime extension impacts cement demand through reduced total new floor area.

Sources: Estimates were derived through a combination of literature review and expert opinion. Sources consulted include Block, P. et al. (2017), "NEST HiLo: Investigating lightweight construction and adaptive energy systems", http://dx.doi.org/10.1016/j.jobe.2017.06; European Cement Research Academy (2015), "Closing the loop: What type of concrete reuse is the most sustainable option?", https://www.theconcreteinitiative.eu/images/Newsroom/Publications/2016-01-16_ECRA_TechnicalReport_ConcreteReuse.pdf; Favier, A. et al (2018), A sustainable future for the European cement and concrete industry: Technology assessment for full decarbonisation of the industry by 2050, https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf;European Climate Foundation, ETH Zurich and Ecole Polytechnique Federale de Lausanne (2018), Identification of low carbon technologies for cement and concrete industry in Europe; Huberman, N. and D. Pearlmutter (2008), "A life-cycle energy analysis of building materials in the Negev desert", https://doi.org/10.1016/j.enbuild.2007.06.002; Kapelko, A. (2006), "Possibilities of cement content reduction in concrete with admixture of superplasticiser SNF", https://doi.org/10.1080/13923730.2006.9636383; Lopez-Mesa, B. et al. (2009), "Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors", https://doi.org/10.1016/j.buildenv.2008.05.017; Miller, D. et al. (2013), "Environmental impact assessment of post tensioned and reinforced concrete slab construction", https://doi.org/10.3850/978-981-07-5354-2_St-131-407; Moussavi Nadoushani, Z.S. et al. (2015), "Effects of structural system on the life cycle carbon footprint of buildings", http://dx.doi.org/10.1016/j.enbuild.2015.05.044; MPA the Concrete Centre (2018), "Material efficiency: Design guidance for doing more with less, using concrete and masonry", https://www.concretecentre.com/Publications-Software/Publications/Material-Efficiency.aspx; Orr, J.J. et al. (2011), Concrete structures using fabric formwork, https://doi.org/10.17863/CAM.17019; Schlueter, A. (2016), "3for2: Realizing spatial, material, and energy savings through integrated design", http://global.ctbuh.org/resources/papers/download/2783-3for2-realizing-spatial-material-and-energy-savings-through-integrated-design.pdf; Scrivener, K., V. John and E. Gartner (2016), "Eco-efficient cements: Potential, economically viable solutions for a low-CO_2, cement-based materials industry", http://wedocs.unep.org/handle/20.500.11822/25281; Post-tensioning Association (2018), "Post-tensioning benefits for developers", http://www.posttensioning.co.uk/developer/; Wassermann, R., A. Katz and A. Bentur (2009), "Minimum cement content requirements: a must or a myth?", https://doi.org/ 10.1617/s11527-008-9436-0

The strategy categories in the tables encompass consideration of various specific strategies to reduce material demand. These include the following:

- optimising buildings design to reduce material needs
- switching to composite frame buildings
- reducing over-engineering/overestimation
- optimising the structure
- post-tensioning
- using fabric formwork
- choosing lateral load-resisting systems
- using hollow-core concrete
- optimising steel fibres in concrete
- using cold-formed/light-gauge steel framing
- using correct exposure class for concrete
- employing additive manufacturing
- enhancing material properties
- improving concrete packing, including by using admixtures
- using high-strength cement
- using high-strength steel
- promoting best construction practices
- reducing waste
- improving value chain management
- prefabricating/precasting
- extending buildings lifetimes
- in-depth retrofitting
- repositioning
- repurposing
- handling end of life of buildings elements
- reuse
- recycling.

Vehicles value chain assumptions and modelling methodology

Estimates of the material intensity were incorporated into the IEA Mobility Model (MoMo), a transport energy database and simulation model with full stock accounting. The reassessment of historical material trends in passenger light-duty vehicles (PLDVs) drew upon recent updates of the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) modelling tool (Argonne National Laboratory, 2017)[32] and validation against detailed material composition tracking of light-duty vehicles sold in the United States (Dai, Kelly and Elgowainy, 2016). Due to data limitations, material composition trends for other global regions were assumed to be the same as in the United States. However, sales-weighted average kerb weights

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[32] GREET material composition by vehicle part is decreased in resolution in the MoMo to the basic vehicle systems level (i.e. body, powertrain and battery).

and powertrain shares differed based on the resolution available in the IEA historical vehicle database.

Historical estimates of the material composition of light commercial vehicles (LCVs) and heavy-duty vehicles (HDVs) (medium and heavy-freight trucks, buses and minibuses) were estimated based on underlying data provided from a study for the Directorate-General Clima of the European Commission by Ricardo-AEA (Hill et al., 2015).

Keeping forward-looking transport carbon dioxide (CO_2) emissions consistent with the RTS would require that vehicle efficiency improvements occur over a sustained time period in vehicle design. Rates of vehicle efficiency progress in light-duty sales would need to match the ambition of historical best performance, even in countries where initial standards are being formulated or follow-up standards will soon be drafted. The global trend of increasing vehicle size (Global Fuel Economy Initiative, n.d.) would have to stop in the coming one to two decades, as well as the trend of compensating savings from lightweighting by adding more safety, performance and other amenities. Heavy-duty vehicle efficiency standards should be designed to promote/capture the impact of lightweighting (so that these are incentivised alongside other improvements to operational efficiency); testing regimes like those used by the People's Republic of China ("China") that simulate vehicles at maximum load provide no such incentive.

The policy stringency required in the CTS scenario is even greater. The success of emissions reduction targets in this scenario is predicated not only on fuel economy standards and vehicle purchase and usage pricing, but also by policies across the energy system, notably in electricity generation. The CTS incorporates a rapid shift to electric powertrains across all road vehicle categories, at rates intermediate between those detailed in the 2018 *Global Electric Vehicle Outlook* EV30@30 scenario and this publication's RTS (IEA, 2018).

Lightweighting was assumed to be a key strategy to achieve fuel efficiency improvements in the scenarios. Lightweighting assumptions were informed by a combination of: studies conducted by the National Highway Traffic Safety Administration and by the Environmental Protection Agency to inform the US 2017-25 fuel economy standards (EPA, 2012; Singh, 2012); literature assessments of the technical and economic potential for lightweighting (Dai, Kelly and Elgowainy, 2016; Ducker Worldwide, 2017; Kelly et al., 2015; Kelly et al., 2014; Luk et al., 2017; Modaresi et al., 2014); and consultation with experts. Following expert review of initial assumptions on the potential for maximum lightweighting in each scenario by 2030 and 2060, final assumptions were made for the maximum kerb weight reductions possible in the sales-weighted average new sales of conventional internal combustion engine (ICE) PLDVs. These "benchmark weight reductions" were assigned to the region with the highest ambition. For LCVs and HDVs, benchmark weight reductions for the RTS were set based on the lightweighting assumptions in Hill et al. (2015), which is broadly in line with the RTS scenario definition. Given the lack of studies outlining lightweighting potential in LCVs and HDVs under more ambitious policy conditions, the CTS and MEF benchmark weight reductions were set proportional to the incremental weight reduction potential relative to the RTS in PLDVs. The resulting total maximum assumed weight reductions for each vehicle category for ICEs are shown in Table 10.

Table 10. Total maximum weight reduction for ICE vehicles by vehicle type relative to 2015

Vehicle category (MoMo)	Category (external source)	2030 (%)			2060 (%)		
		RTS	CTS	MEF	RTS	CTS	MEF
PLDV	Car/sports utility vehicle*	10	15	22	22	28	40
LCV	Heavy van^{+}	8	12	18	18	23	33
Medium-freight truck	Rigid truck^{+}	12	16	22	20	24	32
Heavy-freight truck	Articulated truck^{+}	11	14	20	22	26	36
Minibus	City bus^{+}	10	13	15	19	22	24
Bus	Coach^{+}	14	19	25	20	24	31

Notes: PLDVs are split in the IEA MoMo into passenger cars and light trucks based on country-specific data availability. Kerb weights of heavy vans (Isenstadt et al., 2016) were scaled at the ratio of 3.5/5 based on the ratio of maximum gross vehicle weight to estimate material composition of LCVs.

Sources: * Argonne National Laboratory (2017b), GREET; $^{+}$ Hill, N. et al. (2015), Light weighting as a means of improving Heavy-duty Vehicles' energy efficiency and overall CO_2 emissions, https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/heavy/docs/hdv_lightweighting_en.pdf.

For vehicles with electric motors and batteries (hybrid electric vehicles, plug-in hybrid electric vehicles and battery-electric vehicles [BEVs]), the body and powertrains were assumed to be lightweighted more aggressively than in ICEs, given that lightweighting can allow for reduced batteries sizes or increased range with the same battery size. The financial incentive for more lightweighting was assumed to be stronger earlier on, and then to decline over time as battery costs fall. Thus, the analysis assumed that the combined weight reduction in the electric vehicle (EV) body and powertrain (not including the battery) is 20-25% greater than the ICE weight reduction in 2030 (depending on the scenario) and 10% greater in 2060. Battery weight was assumed to remain relatively constant over time. While battery developments after 2030 are highly uncertain, this analysis assumed that in the 2030-40 time frame, a shift from nickel-manganese-cobalt to lithium-sulphur or lithium-air chemistries will be successfully translated from the laboratory to commercial automotive applications. This will enable considerable improvements in battery density. However, the density improvements were assumed to be offset by increases in capacity, as consumers continue to value greater range, thus resulting in a relatively constant battery weight over time. In the CTS and MEF, lightweighting beyond the RTS enables a reduction in battery capacity while achieving the same range, resulting in somewhat lighter batteries.

In the MEF, all regions pursue equally ambitious material efficiency strategies and thus all achieve the maximum weight reduction. In the RTS and CTS, the benchmark region was set as the region with the strongest fuel economy and lightweighting regulations in that scenario. For PLDVs, the benchmark region was China. For LCVs and HDVs, the benchmark region was North America, where heavy-duty fuel economy regulations and testing procedures explicitly incentive lightweighting as a strategy for vehicle efficiency improvements. Weight reductions in other regions were set based on the relative ambition of their fuel economy and lightweighting regulations. To illustrate, Table 11 shows the weight reductions by region in the RTS and CTS for PLDVs.

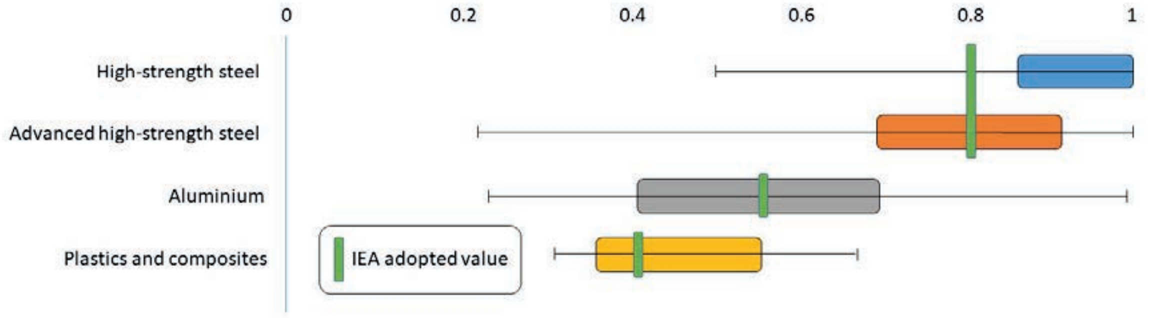
Table 11. Kerb weight reduction in PLDVs by region and scenario relative to 2015

Region	2030 (%)		2060 (%)	
	RTS	CTS	RTS	CTS
North America	8	14	20	26
OECD Europe	7	10	17	21
OECD Pacific	7	10	17	23
Eurasia	2	4	11	13
Eastern Europe	2	3	7	11
China	10	15	22	28
India	6	9	17	22
Other Asia	2	4	9	12
Middle East	4	6	15	22
Central and South America	5	9	17	22
Africa	4	8	14	22

Notes: The figures show the percentage reduction in vehicle kerb weight of new vehicle sales relative to 2015. They apply to conventional ICE PLDVs. OECD = Organisation for Economic Co-operation and Development.

Weight reductions were assumed to be achieved through a combination of part downsizing and optimisation, material substitution, and secondary weight reduction. The mass composition assumptions for the benchmark ICE passenger car were chosen based on the range of mass compositions found in the literature and to achieve the targeted weight reduction. The mass compositions for other vehicle types were set to achieve approximately the same proportion of weight reduction from each lightweighting strategy, while taking into account differences in the original mass composition of the vehicle.

Figure 60. Estimates of the MSR in vehicles



Notes: Range of MSRs of different lightweight materials reported by the US Department of Energy (EERE, 2013) and error bars representing theoretical limits as calculated by Kelly et al. (2015), as presented in Luk, J. et al. (2017). Due to data limitations, the IEA assumed a single value for high-strength steel and advanced high-strength steel. Due to uncertainty on the potential for plastics and composites, the IEA similarly assumed a single value across these options (which are introduced into vehicles from 2030 onwards in all scenarios). MSRs adopted in this study were: steel to high-strength and advanced high-strength steel: 0.80; steel to aluminium: 0.55; and steel to plastics and composites: 0.40.

Sources: Adapted with permission from Luk, J. et al., (2017), "Review of fuel saving, life cycle GHG emission, and ownership cost impacts of lightweighting vehicles with different powertrains", http://doi.org/10.1021/acs.est.7b00909. Copyright 2017 American Chemical Society. Estimates of the MSR of plastics and composites are from Kelly et al. (2015), "Impacts of vehicle weight reduction via material substitution on life-cycle greenhouse gas emissions", https://doi.org/10.1021/acs.est.5b03192.

There is considerable variability in MSR estimates found in literature.

The mass composition assumptions were also influenced by the material substitution ratio (MSR), which is the mass of lightweight material needed to replace a unit mass of conventional material. By convention, the basis for comparison for road vehicles is conventional steel or iron casting. Figure 60 reproduces a figure from Luk et al. (2017) that shows the range of MSR values technically possible, and adding to it literature values for the MSR of advanced plastics, as well as the values adopted in this study.

Transport infrastructure value chain assumptions, modelling methodology and preliminary findings

A preliminary assessment of material demand for transport infrastructure was conducted, with a focus on rail and roads. Given that transport infrastructure accounts for only a portion of the infrastructure category of top-down material demand assessments, as well as data limitations and uncertainty, infrastructure was not included in the bottom-up material demand assessment and modelling for this analysis. It remains an area for additional exploration in future analyses. This section provides an overview of the data collected and preliminary analysis.

Material intensity of transport infrastructure

Infrastructure for transport is one of the key infrastructure types (others include energy and heating, water and waste), and is thus a significant contributor to demand for materials. Transport infrastructure includes roads, rail, bridges, tunnels, pavements, car parks, shipping ports and airports. This analysis estimated the material demand from rail and road infrastructure, which constitute major demand sectors for steel and cement. The steel and cement requirements for building new infrastructure and maintenance and replacement of existing infrastructure were assessed by applying material intensities to activity data, consisting of road network data from the International Road Federation (International Road Federation, 2013), and on the joint data work between the International Railway Union and the IEA (IEA and UIC, 2017).

Rail

The IEA database of rail infrastructure splits rail into several categories, as shown in Table 12.

Table 12. Rail classification

Category	Operation	Definition
Metro	Urban	Primarily underground or secondarily elevated track
Light rail	Urban	Mostly at-grade
Conventional rail	Suburban and intercity	Suburban train journeys connecting urban centres with surrounding areas, and intercity services with long distances and maximum speeds less than 250 kilometres per hour (km/h)
High-speed rail	Intercity	Intercity rail services with long distances between stations and maximum speeds greater than 250 km/h

Material is required for the rail track and also for supporting infrastructure such as stations, tunnels and elevated track supports. The demand for materials in tonnes per kilometre (km) of rail is highly variable, and depends on the design of the particular system. This design is a function of various considerations, including the required functionality of the system, applicable design regulations, budgetary constraints, geology and geography of the area, and other economic and political factors. These factors may influence each other. For instance, a region more prone to earthquakes is likely to have regulations that require infrastructure to be built to withstand their impact.

A major determinant of the materials intensity is whether a given section of track is at-grade, elevated, underground or in a tunnel. Elevated track generally requires more material than at-grade track, while underground and tunnelled tracks require more material than at-grade and elevated tracks. Most systems are composed of a combination of these vertical alignments. A survey by the International Tunnelling Association (ITA) of 30 cities in 19 countries found that while most track in the cities surveyed was at-grade for regional metro and suburban trains and urban light-rail tramways, most track was underground for urban metro and automatic metro (Table 13) (ITA, 2004). Yet systems vary greatly around these medians. For example, the Chicago Metro system consists of only 8% underground track[33].

Table 13. Median vertical alignment by rail type found in the ITA survey of 30 rail lines

Category	At-grade (%)	Elevated (%)	Underground (%)
Regional metro and suburban trains	92	2	5
Urban metro and automatic metro	7	10	78
Urban light-rail tramways	98	2	9

Source: ITA (2004), "Underground or aboveground? Making the choice for urban mass transit systems", https://doi.org/10.1016/S0886-7798(03)00104-4.

The ITA found that decisions on vertical alignment of urban transit systems are complex. Underground systems are often chosen to gain right of way when integrating into existing urban environments, for environmental preservation, to cross natural obstacles or when necessary to deal with difficult topography. When elevated track is an option, it may be chosen over underground track due to lower upfront investment costs. At-grade systems are often suitable for regional trains and light rail, as they make use of existing rail networks or operate on existing rights of way at lower speeds than high-capacity urban metros. For intercity trains, geography is a major influence in design decisions; crossing mountain passes generally requires tunnels, while crossing bodies of water requires either bridges or tunnels.

The choice between ballasted and non-ballasted track also influences material demand. Until recently, railway track was traditionally ballasted, meaning that gravel was used as the track bed between the ground and railway sleepers. Non-ballasted track, which relies on a track bed composed of a concrete and asphalt mixture, is a more modern design. While non-ballasted track has higher upfront costs, it requires less maintenance, has longer durability and improves ride performance, particularly for high-speed rail applications. It also requires more upfront demand of energy-intensive materials – by one estimate, approximately 10% more steel and over 50% more concrete than ballasted track (Network Rail, 2009). However, given the longer service life cycle, steel and concrete use could, in some cases, be comparable or even lower for non-ballasted track.

Some of the differences in the estimated material use across rails systems likely result from varying LCA methodologies and data uncertainties. Methodological differences including

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[33] Personal communication with Mikhail Chester, associate professor in civil, environmental and sustainable engineering at Arizona State University.

choice of system boundaries could lead to different material intensity estimates across studies for the same network, or even system of track.

The result of these and other factors is a wide variability in the material demand per km of track. While literature estimates of material quantities for rail are scarce, the estimates that could be found illustrate this wide variability (see Box 7 in Chapter 6). For example, for estimates of the material requirements for high-speed rail, the project with the highest material quantity needs used eight times the amount of concrete and 20 times the amount of steel as the project with the lowest quantities. Much of the variability can be explained due to differences in vertical alignment: systems with higher proportions of underground, tunnelled or elevated line tend to have substantially larger material demand. However, other factors also have an influence, such that even systems with comparable vertical alignment can have considerable variation in material demand.

Given the absence of detailed regional or network data on the share of track that is at-grade, elevated, underground or in a tunnel, or ballasted versus non-ballasted, it is difficult to estimate with any level of accuracy or precision national average material intensities for rail. However, general trends can be discerned, such as that metro systems tend to have a higher material intensity than light rail, conventional and high-speed rail, due to the high proportion of metro track that is underground. For this analysis, material intensities were based on an average of literature estimates, after normalising for vertical alignment using a combination of the median vertical alignment for each category of rail found by the ITA (2004) and estimates of the amount of material demand used specifically in tunnelled compared to non-tunnelled track from Network Rail (2009). Concrete intensities were used to derive cement intensities, assuming an average cement mass fraction of 10%.

In addition to material demand for constructing rail lines, material demand for maintenance and reconstruction can be significant. Data for material inputs for rail maintenance are even more scarce than for construction. One study estimated the material demand over the course of a lifetime for maintenance would add up to approximately 70% of the concrete and 90% of the steel used to initially build the line (Asplan Viak AS, 2011). Another study found that 25% of the emissions over the life cycle of a streetcar were from major refurbishment and reconstruction, during a 38 year period (Makarchuk and Saxe, 2019).

Roads

The IEA database of road infrastructure splits roads into several categories, as shown in Table 14.

Table 14. Road classification

Category	Definition
Motorways	At least four lanes; 100% paved
Highways	Two to four lanes; typically 100% paved in developed economies
Secondary roads	One to two lanes; typically mostly paved
Other roads	One to two lanes; most likely among the four types to be unpaved

Notes: The International Road Federation maintains comprehensive statistics on the lengths of roads by type and the percentage of paved roads in most countries of the world. IEA estimates of total paved lane km are based on assumed allocations using the International Road Federation road database.

Source: Dulac, J. (2013), "Global land transport infrastructure requirements: estimating road and railway infrastructure capacity and costs to 2050", https://www.iea.org/publications/freepublications/publication/TransportInfrastructureInsights_FINAL_WEB.pdf; International Road Federation (2013), "World road statistics", https://worldroadstatistics.org/.

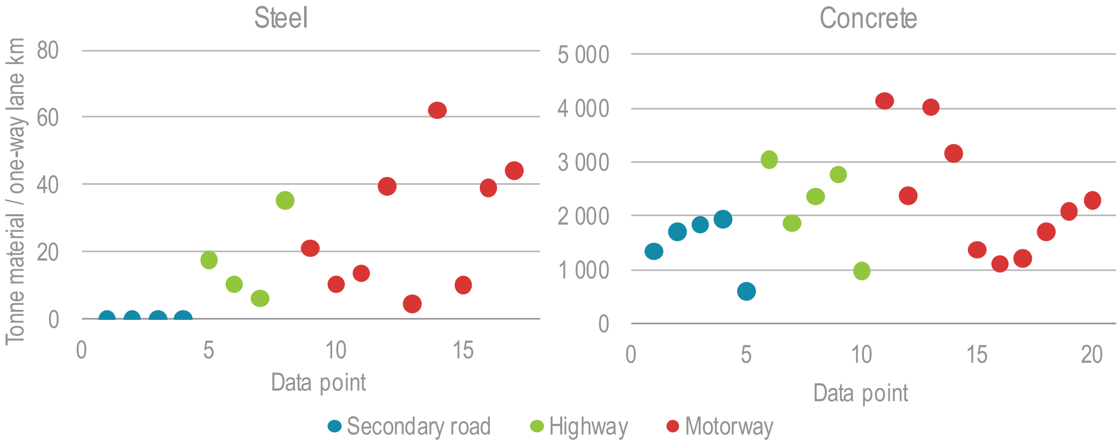
The material demand of road surfaces is influenced by numerous factors such as: design regulations; budgetary constraints; and expected volume, speed and composition of traffic on the roadway. Cement and steel reinforcement are required for concrete paved roads. Thus, a first factor in determining cement and steel demand for roads is the proportion of roads that are paved. In the IEA MoMo, estimates of paved lane km are made under assumptions of the average number of lanes per road category and allocation of paved road first to motorways, then highways, and finally to secondary and other roads (Dulac, 2013).

Out of the roads that are paved, the next critical consideration in estimating the material intensity is the share that are concrete, asphalt or composite. Official statistics on road network coverage by road surface type are scarce and region specific. Broad-based estimates suggest that over 90% of paved roads are asphalt in some regions, with the remaining 10% being concrete or composite (European Asphalt Pavement Association, 2018; Virginia Asphalt Association, 2018). A larger proportion of motorways and highways are concrete, due to the functional requirements for durability and stiffness. In the United States (where the government provides publicly available statistics on paved roads by type), in 2016, concrete and composite road surfaces accounted for 12% of paved secondary roads, 27% of highways and 47% of motorways (U.S. Federal Highway Administration, 2016). As secondary roads make up most roads (approximately 90%), 14% of total road km were concrete or composite. The decision to pave with concrete versus asphalt is largely a trade-off between the higher upfront costs of concrete surfaces and their better durability and ability to withstand heavy loads, resulting in a longer service life and lower maintenance requirements.

Within concrete roads, there is considerable variability in material intensities found in the literature estimates (as with rail, directly stated material quantities for roads are scarce in the literature) (Figure 61). Cement intensities can be derived from the concrete intensities using assumptions on the mass fraction of cement in concrete, which typically range from 7% to 15%. For this analysis, it was assumed to be 11-17% for roads, depending on the region. Some general trends can be observed. The need for highways and motorways to withstand heavy loads is reflected in their higher material requirements. The concrete intensity of motorways is generally greater than that of highways, which is greater than that of secondary roads. Highways and motorways are frequently reinforced with steel, but secondary roads tend not to be.

However, even within a given road type, there is considerable variability in material intensity. This is primarily due to road design. Differences in road design such as depth of the paved surface (overlay), lane width, and whether the road has paved shoulders and medians, as well as the mass fraction of cement in the concrete, all influence the steel and cement materials intensity (measured in kilogrammes per lane km). Such differences arise primarily from functional and economic considerations (e.g. surface performance and budgetary constraints), which are influenced by design regulations (and the degree to which these are enforced) and common practices for paving, maintenance and rehabilitation (M&R) and decommissioning. These may be influenced by weather and climate conditions in the region, as more extreme conditions tend to require more durable surfaces that are designed to withstand specific conditions (e.g. they are heat resistant or resistant to cracking during freeze-thaw cycles).

Figure 61. Material intensity estimates for concrete roads



Notes: Not all sources had material quantities for both concrete and steel. Thus the numbered data points in the steel and cement graphs do not necessarily correspond with one another.

Sources: Athena Institute (2006), "A life cycle perspective on concrete and asphalt roadways: Embodied primary energy and global warming potential", http://www.athenasmi.org/wp-content/uploads/2012/01/Athena_Update_Report_LCA_PCCP_vs_HMA_Final_Document_Sept_2006.pdf; Athena Sustainable Materials Institute (2018), Pavement LCA, http://www.athenasmi.org/our-software-data/pavement-lca/; Loijos, A., N. Santero and J. Ochsendorf (2013), "Life cycle climate impacts of the US concrete pavement network", http://dx.doi.org/10.1016/j.resconrec.2012.12.014; Miatto, A. et al. (2017), "Modeling material flows and stocks of the road network in the United States 1905-2015", https://doi.org/10.1016/j.resconrec.2017.08.024; Santero, N., A Loijos and J. Ochsendorf (2013), "Greenhouse gas emissions reduction opportunities for concrete pavements", https://doi.org/10.1111/jiec.12053; Spielmann, M. et al. (2007), Transport Services – Ecoinvent report No. 14; TERI (2012), "Life cycle analysis of transport modes, volume I", Treloar, G.J., P.E.D. Love and R.H. Crawford (2004), "Hybrid life-cycle inventory for road construction and use", http://dx.doi.org/10.1061/(ASCE)0733-9364(2004)130:1(43); Weiland, C. and S. Muench (2010), Life-cycle assessment of reconstruction options for interstate highway pavement in Seattle, Washington, https://doi.org/10.3141/2170-03; Zapata, P. and J.A. Gambatese (2005), "Energy consumption of asphalt and reinforced concrete pavement materials and construction", https://doi.org/10.1061/(ASCE)1076-0342(2005)11:1(9).

There is considerable variability in the material intensity of concrete roads.

The effects of climate change will lead to design challenges in the 21st century that will differ from those of the 20th century. Additionally, with rapid development in digital technologies leading to more frequent changes in how infrastructure is used and maintained, and with a need to transition from infrastructure design and planning that enables rapid development to designs that acknowledge natural resource and energy constraints, infrastructure will need to be designed to be more flexible and resilient (Box 10).

Box 10. Infrastructure needs for the next century

As infrastructure ages, the ways that it can most efficiently provide necessary services in a world of rapid and continuing urbanisation, digitalisation and population growth require careful evaluation. This is particularly true in the face of uncertain climate effects that are increasingly likely to compromise the lifetime and reliability of certain infrastructures. In developed countries, physical infrastructure systems in transportation, water treatment and delivery, and in power generation, transmission and distribution, have been built over recent decades. These systems have reached a state of maturity – they are either not expanding or are expanding at much slower rates than previously – without having changed much, other than in the integration of digital technologies to monitor and optimise their operations. The expansion of roads and car parks in the United States provides a stark example of the ways that infrastructure has been built to support technological, institutional and social forces that dominated through most of the 20th century (Pollard, 2003; Shoup, 1997).

In a context where the technologies and patterns of service provision change only gradually (as with cars over the past half century), long-lived infrastructure can serve its purpose. But in an era where autonomous and shared vehicles may transform urban landscapes (see Box 6 in Chapter 6), the design and capacity of roads to serve passenger and freight mobility needs versus other infrastructure (e.g. rail transport or walking and cycling ways) need to be reconsidered. The impact of mobility services on urban form will depend on the ability to plan for, anticipate and manage the infrastructure and also the regulatory and pricing context of new technologies and business models.

Chester and Allenby (2018) enumerated multiple interdependent challenges facing infrastructure design in the present era. Focusing on the United States, they cited examples of how infrastructure is insufficiently flexible for future uses. In the United States, in particular, physical infrastructure suffers from lack of funding. It is also prone to the effects of changing natural systems, including the climate. When funds are invested in new infrastructure, there is often a mismatch between design principles and the social and environmental purposes for which it is being built. This disconnect is often exacerbated by policies, financing and codes that were established to protect incumbent technologies. In the face of the challenges of designing future infrastructures, Chester and Allenby (2018) argued that engineers will need to play a new role in a reconceived infrastructure that moves, "from the purely physical, to a system that includes institutional components and knowledge as integral parts". Examples of such novel systems include intermittent renewable electricity generation, microgrids and EV charging infrastructure.

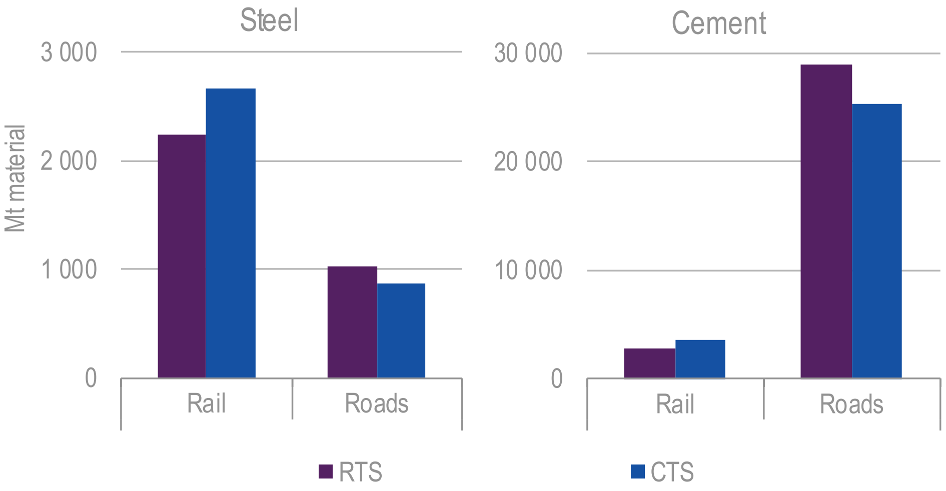
In the developing and emerging world, old cities are being retrofitted and new cities built without incorporating state-of-the-art understanding of the principles, designs and technologies for reducing CO_2 emissions (Chester et al., 2014). By some estimates, about one-half of the world's urban landscape that will be in place in 2030 is yet to be built (Seto and Christensen, 2013). Designing flexible infrastructure capable of enabling dynamic evolution of low-carbon societal and economic development patterns will require a systems-level view. This must move beyond vehicle powertrain shifts, power mix changes and end-use appliance efficiencies. It should instead incorporate an understanding of the interdependencies among infrastructures and the technologies they support (e.g. roads, petrol stations, cars and trucks), a recognition of "lock-in" (e.g. density impact on modal shares), and of the social and institutional frameworks that build and maintain infrastructure.

Institutional structures have historically focused on rapid development. Realigning them to focus on sustainability, equity and transparency will be a key challenge in the coming decades (Chester et al., 2014). A further priority will be "coupled strategies" that reduce CO_2 emissions while building resilience to changing climatic conditions. Institutions will need to accommodate the different rates of progress across different types of technology. For instance, power supply infrastructure, buildings and roads endure over many decades, the vehicle fleet turns over in about a decade, but information and communication technology (ICT) is evolving each year. The integration and impact on infrastructure of emerging ICT-enabled technologies (e.g. automated vehicles and EVs, smart applications and variable renewable energy) on patterns of usage, energy consumption and emissions, is a challenge facing cities across the world (Chester et al., 2014).

Material use in transport infrastructure in the RTS and CTS

The collected material intensity data were applied to future projections of road and rail build-out, derived from the IEA MoMo. These estimates were not included in the overall modelling, due to irreducible data uncertainties (stemming from the estimation of total paved lane km for roads and from the highly variable and context-dependant steel and cement intensity for all categories of roads and rail infrastructures) and difficulty in validating the bottom-up estimates through comparison to top-down material demand estimates (given that transport infrastructure accounts for only a portion of top-down infrastructure estimates). However, preliminary steel and cement demand estimates are presented here, and may be expanded upon through future analyses. Cumulative demand for materials from 2017 to 2060 for rail infrastructure is greater in the CTS than the RTS, while demand is lower for road infrastructure (Figure 62). For steel, the effect of increased demand for rail infrastructure outweighs the decline for roads, such that cumulative demand for combined rail and road infrastructure in the CTS is 8% higher than in the RTS. For cement, the opposite is true, resulting in a 9% lower combined cement demand.

Figure 62. Global cumulative steel and cement demand for roads and rail to 2060



Notes: Estimates of steel and cement use in road and rail infrastructure are subject to considerable data uncertainty. Reducing this uncertainty, for instance by referring to country-specific design studies and regulations, and by using new data sources and estimation sources (e.g. satellite data estimates of global paved road coverage), are an ongoing area of research. Mt = million tonnes.

Higher build-out of rail infrastructures in the CTS translates to greater demand for steel and cement for rail, while reduced road building leads to lower material demand for roads.

While build-out of rail infrastructure will increase steel and cement demand, and therefore production emissions, an LCA is needed to determine whether shifts in transport activity offset these emissions, leading to a net reduction in CO_2 emissions. Many studies in the literature analyse the conditions under which modal shift leads to reductions in life-cycle energy consumption and CO_2 emissions. Chester and Cano (2016) assessed the life-cycle emissions per passenger km travelled for the Expo light rail in Los Angeles (United States) compared to car travel. They found that within 14 years of the beginning of operation of the line, it would "pay back" the CO_2 emissions from constructing the line in reduced emissions from vehicle travel, resulting in a net savings in emissions for its use after the 14 year payback period. Saxe et al. (2017) estimated that the Sheppard subway line in Toronto (Canada) would pay back the emissions from building it 11 years after beginning operation. These types of LCA can be sensitive to the assumptions involved, including changes in ridership (the number of passengers using a public transport service) and what type of vehicle would be replaced by transit use. However, they suggest that within a time frame of one to two decades, upfront CO_2 emissions incurred from material production and construction to enable lower-emission modes of transport typically pay off and result in net emissions reduction.

Material efficiency strategies for transport infrastructure

Material demand for transport infrastructure was not evaluated for the MEF. Nonetheless, there is likely some potential to apply material efficiency strategies to transport infrastructure that would put a downward pressure on demand relative to the CTS. For example, switching from prescriptive to performance-based standards for road construction could prevent building roads with more steel and cement than needed to perform the required function. Milford et al. (2013) estimated that the lifetime of rail tracks could be doubled through reuse of steel in secondary routes, using higher-strength steels and restoration.

However, the potential to reduce material use in infrastructure may be more limited than the potential in other areas such as buildings. Infrastructure is required to handle substantial stress, such as weight of rail carriages and trucks. In many cases, the infrastructure is highly exposed to weather events and climatic fluctuations. These factors may also limit end-of-life material efficiency opportunities, for instance with the reuse of steel. Some elements of transport infrastructure such as bridges and certain rail lines may be subject to considerable corrosion and fatigue damage from use, making their reuse not possible. Cooper and Allwood (2012) estimated a technical potential of only 11% reuse of steel in infrastructure, in contrast to 38% for steel in buildings, given the considerable corrosion and fatigue damage that some elements of transport infrastructure are subjected to, making their reuse not possible. Furthermore, there may be trade-offs between upfront emissions from material used to construct infrastructure and the life-cycle emissions impact. Building more durable infrastructure may reduce future material needs to repair and rebuild. In the case of roads, design choices can also influence emissions from the vehicles that use them.

The interactions among vehicle design, road traffic and surface design (so-called "road vehicle interactions") are complex but important. The energy and CO_2 emissions incurred by material used in infrastructure must be considered in light of the potential for well-designed and properly maintained infrastructure to improve the operational efficiency (and hence reduce fuel use) of the vehicles using it. In particular, energy use and emissions incurred by well-designed and maintained roads and railways are generally paid back over a period of months to years (on heavily trafficked roads) or years to decades (on less utilised roads or rail). This payback tends to be faster and particularly robust in cases where vehicles use ICEs and rely on fossil fuels (oil products and natural gas). In cases where lower-carbon electricity powers vehicles, the energy and CO_2 trade-offs between infrastructure investment and efficiency may become less clear cut, although it might still make sense to invest in higher materials intensity road infrastructure for other reasons (e.g. to improve the efficiency of EVs, thereby reducing the need for larger batteries).

The ability to model the impact of surface on vehicle efficiency has been one of the main recent methodological improvements in road surface LCA. This has led to new insights: on an old debate related to the environmental performance of concrete versus asphalt surfaces; on scheduling M&R; and on how algorithms and big data could help inform more optimal balancing of budgetary constraints, surface performance and environmental impact (Box 11). Finally, more-efficiently executed or less-frequent M&R needs can also reduce vehicle emissions that occur from traffic back-ups and idling during M&R events.

The impact of vehicles on roads should also be considered. Road infrastructure (roads, bridges and tunnels) is built to accommodate certain car and truck traffic profiles specific to routes and localities. Lightweighting is not only among the most promising strategies for reducing vehicle fuel consumption, but also can translate to reduced road damage. The relationship between road degradation and vehicle weight follows a fourth power law, and so the largest reduction in road damage can be realised by reducing the load borne by each axel for HDVs.

Box 11. Road surfaces for climate: where the rubber meets the road

In developed countries where road infrastructure networks have already been built, typically more than 90% of road investments go to M&R. Strategic allocation of funding can ensure that limited budgets are used to maximum effect. Budgetary constraints and technical considerations, rather than environmental performance (or LCA-informed assessment of the energy and CO_2 emissions impact) currently determine road surface management regimes (Torres-Machi et al., 2017).

To move to a regime where the environmental impact of surface design, construction and M&R is considered together with technical and economic criteria, three steps are needed. First, policies (e.g. designs, regulations or performance-based standards) and assessment tools and guidelines that rely on the latest LCA must be set up. Next, LCA methods must be developed and refined. It is imperative that studies consider all phases associated with road usages – including materials, construction, use, M&R and end of life – and that they acknowledge case-specific content and data uncertainty. Finally, policy best practices must be disseminated across countries and jurisdictions.

Development of data tools and methods has made it possible to assess the energy and emissions impact of two phases of surfaces (use and M&R), with increasing precision and accuracy. Surface-vehicle interactions have been shown to account for a high share of both effects. This is not surprising: the rolling resistance impact of surface roughness, texture and deflection can account for 15-50% of total vehicle fuel consumption, depending primarily on vehicle speed (Beuving et al., 2004). Studies have shown that reducing rolling resistance by 10% leads to fuel economy gains of 1-2% (Evans et al., 2009; National Research Council of The National Academies, 2006).

Data-driven M&R can be used to identify stretches of heavily utilised highways requiring resurfacing, thereby targeting limited budgets for maximum impact. Surface M&R can translate into savings on time scales of weeks to months, compared to many other policy and technology measures to improve the efficiency of road vehicles operations, which can take years or decades to realise.

On highways with high utilisation, timely M&R of surfaces results in improvements in real-world fuel economy of around 2.5%. This may be even greater than the gains achieved through fuel economy standards (Wang et al., 2012). Wang et al. (2012) also found that for the California road network, the energy and CO_2 emissions incurred in M&R were offset by fuel economy improvements of vehicles utilising road stretches within a single year, and at most within 2 years. These results were robust to surface materials, regardless of whether asphalt surfaces were overlaid with common hot-mix asphalts or concrete surfaces were restored via replacing slabs and full-lane diamond grinding. On less-frequently driven stretches of road, the quality and methods of M&R were the critical variables that could determine whether they result in a net reduction in energy use and emissions from a life-cycle perspective (Wang et al., 2012). This suggests that performance-based certification standards or project evaluation may help to ensure that rehabilitation furthers emissions and sustainability goals.

Surface effects on vehicle rolling resistance are primarily a function of roughness and macrotexture, though stiffness and, for asphalt, viscoelastic properties also have an impact that is difficult to model. Roughness is commonly measured with the international roughness index. Macrotexture is measured by the mean profile depth for asphalt or mean texture depth for concrete. Due to the viscoelastic properties, the energy lost by deflection on asphalt surfaces can be much higher than on stiffer concrete surfaces, particularly for heavy trucks. While advocates of concrete surface cite this design feature and others argue that concrete surfaces are superior to asphalt ones, considerations of cost, durability, degradation and recyclability must also be assessed when new roads are built. While many LCA literature studies explore the comparative merits of asphalt versus concrete surfaces, data uncertainty, methodological differences, and variability among usages and contexts have impeded efforts to designate a clear winner between the two in terms of energy use and CO_2 emissions impact (Inyim et al., 2016).

By considering the above metrics, together with daily vehicle traffic counts, road type and vehicle mix, road maintenance agencies can develop relatively cheap "trigger" guidelines to prioritise which road stretches should receive M&R to minimise CO_2 emissions (Wang, Harvey and Kendall, 2014).

Other approaches to rank road surface stretches for M&R rely on big data analytics. Louhghalam, Akbarian and Ulm (2017) integrated surface-vehicle interaction models with road network databases. By exploring the spatial and temporal variability in the potential for CO_2 emissions reduction across the state of Virginia's road network, they found that the spatial distribution of emissions attributable to poor road maintenance followed a power law (Zipf's law). This meant that a small share of highly utilised but rough roads could be identified where M&R can have a maximal impact. Other studies have developed algorithms that optimise across multiple criteria (Santos, Ferreira and Flintsch, 2017), for instance by maximising long-term network-level technical and environmental performance subject to budgetary constraints (Torres-Machi et al., 2017), or minimising costs subject to CO_2 emissions reduction targets (Lee, Madanat and Reger, 2016). In the future, these methods may be supplemented by low-cost sensors and remote sensing (Chester et al., 2014).

Data and dissemination of best practices can be expected to reduce the life-cycle impact and improve the sustainability of surface design, M&R and end-of-life treatment. For asphalt surfaces, a recycling-based M&R strategy with hot-mix asphalt and using about 30% reclaimed asphalt surface materials tends to perform well in terms of energy use and emissions, and also in cost and performance metrics (Santos, Flintsch and Ferreira, 2017). However, best practices tend to be subject to geographic and climate constraints, as well as to design requirements, as shown by a study of the life-cycle energy and emissions impact of asphalt recycling in Sweden (Miliutenko, Björklund and Carlsson, 2013). Better guidelines can inform all of these practices, provided these considerations are clearly communicated.

The potential to save material in transport infrastructures through strategies such as reducing over-engineering and materials optimisation is therefore lower than in the buildings sector. Current material intensities may be appropriate for meeting performance, durability, efficiency and safety requirements. Some regions might find it to be in their long-term economic and environmental interest to resort to more material-intensive road surface strategies, for instance by building surface overlays at greater than current depths, or by building higher shares of concrete highways.

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Annex IV. Transport policies assumptions and impact on activity levels

Policies that seek to improve the energy efficiency and reduce the emissions of transport typically target various strategies to reduce operational fuel use while providing the same level of service. This approach is understandable and effective. Fuel consumed by cars, trucks, ships and aircraft accounts for the most visible energy security, emissions and environmental impact of transport (including emissions of local air pollutants with the consequent health impact). It also accounts for most of the carbon dioxide (CO_2) and pollutant emissions associated with transport from a life-cycle perspective. In this context, the most broadly applied regulatory and fiscal measures to reduce externalities make good pragmatic sense as measures to achieve societal and environmental goals. These measures include the following:

- vehicle efficiency (or fuel economy) standards
- fuel quality regulations (fuels of a certain minimum quality are required for vehicle emissions control technologies to function properly)
- other fiscal and regulatory policies to promote more-efficient vehicles and alternative fuels and powertrains (e.g. electric vehicles).

However, other policies and metrics that are less prominent are also crucial to reduce the energy, emissions and materials intensity of transport. Policy measures that address systemic inefficiencies across transport services are best encapsulated by the "avoid, shift and improve" paradigm. Smart urban planning can avoid the need to rely on motorised vehicles through mixed-use and transit-oriented development and by planning multicentric cities. Together with densification, these measures can reduce the annual distances travelled by road vehicles. Infrastructure planning and policies that promote convenient, accessible, reliable and attractive public transport, as well as walking and cycling alternatives to cars, can similarly shift transport activity to lower energy and emissions intensity modes. Similar shifts can be realised in freight.

For vehicles and infrastructure, the energy and emissions benefits of the avoid, shift and improve paradigm in transport tend to lead to emissions and energy use reductions in terms of final energy or direct (exhaust-pipe) CO_2 emissions, and also from a life-cycle perspective. The upfront energy and emissions incurred from investments in public and non-motorised transport **infrastructure** are typically quickly paid back through reduced activity – and hence lower fuel use and emissions – in high-intensity modes such as road and aviation. On the **vehicles** side, energy-efficient and low-emissions powertrains (e.g. electric vehicles) tend to incur higher energy use and emissions in vehicle (and battery) production and recycling as a trade-off for lower operational emissions intensity. A comprehensive view can inform the degree to which investments in more energy- and emissions-intensive material use pay for themselves in operational fuel and energy savings. It is hence a useful basis for analysing the trade-offs between materials and production-phase impact and operational (use-phase) impact.

The Clean Technology Scenario (CTS) incorporates policy levers that change the structure and nature of transport demand. A portfolio of national and city-level policies promotes all three key policy levers (avoid, shift and improve). Some of the main policy elements are[34]:

- taxation of transport fuels (including biofuels and electricity), based on their well-to-wheel greenhouse gas emissions

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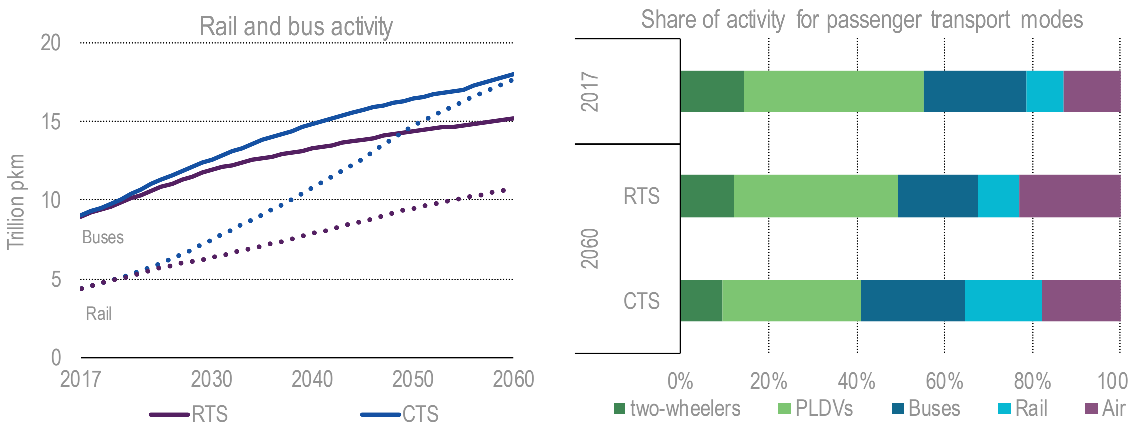
[34] For details on the full suite of policies, their regional stringency and roll-out over time, see Chapter 5 of the 2016 and 2017 *Energy Technology Perspectives* (IEA, 2016, 2017).

- taxation of vehicle purchase and usage including differentiated taxation (rebates), as well as annual insurance and registration charges
- city-level travel demand management measures such as congestion pricing, parking pricing and low-emission zones.

In addition to a more rapid diversification of powertrains, primarily to electric drive (plug-in hybrid and battery-electric vehicles), the result of these policies is a reduction and substitution of road vehicle activity. This translates into lower vehicle stocks in the CTS. The substitution of road vehicle activity for other modes is shown in Figure 63. In the CTS, buses, trains and two-wheelers provide many of the same services provided by cars and trucks in the Reference Technology Scenario (RTS). This has implications on the build-out of transport infrastructure and the material composition of the road vehicle fleet.

Figure 63. Effects of avoid-shift policies in transport



Notes: Avoid-shift policies are needed to mitigate a growing modal share of passenger light-duty vehicles (PLDVs) and especially passenger aviation. pkm = passenger kilometre.

Avoid-shift policies promote modal shifts in the CTS, resulting in a reduction in vehicle use and road infrastructure and an increase in rail.

In the CTS, the reduction in vehicle activity translates into reduced road building. The shift to rail activity requires more infrastructure building, for urban (metro or light rail) and for intercity (including high-speed) rail modes.[35] Most of the recent historical growth in road and rail infrastructure has been in developing and emerging economies. This trend is expected to continue over the coming half century. However, specific development and sustainability policies can have a determinant impact on the degree of expected growth. In advanced economies, strategies and policies to diversify mobility away from roads could lead to strategic abandonment of rarely utilised or redundant paved roads, as well as reallocation of urban paved areas (including roads and parking) to alternative uses (e.g. parks, pedestrian and cycling paths). In emerging economies, the growing demand for private vehicles, and hence the volume of road building needed to accommodate it, can be mitigated through policies to shift travel to rail (and bus). Strategic development of high-speed rail can globally dampen demand for

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[35] The fundamental assumption for road utilisation is that current levels of congestion are maintained in the future. For rail activity, it is assumed that track utilisation converges to high levels of utilisation (downward in the case of modes with very high utilisation, such as the metro in the People's Republic of China, and upward in the case of modes with lower utilisation, such as intercity passenger rail in North America).

passenger aviation and long-distance car trips. Cities in the developing and emerging world, many of which have yet to be built, could lock in lower-carbon mobility patterns early by developing metro and light rail. The potential for urban rail to substitute for car travel is more limited, but nevertheless exists in cities in advanced economies.

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Abbreviations, acronyms, units of measure and regional definitions

Abbreviations and acronyms

ASEAN	Association for Southeast Asian Nations
AV	autonomous vehicle
BAT	best available technology
BEV	battery-electric vehicle
BIGCC	biomass integrated gasification combined cycle
BTX	benzene, toluene and xylene
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CNG	compressed natural gas
CO_2	carbon dioxide
CTS	Clean Technology Scenario
deQo	database of embodied Quantity outputs
DRC	Democratic Republic of the Congo
ETP	Energy Technology and Policy
ETP	*Energy Technology Perspectives*
EUR	euro
EV	electric vehicle
GDP	gross domestic product
GNI	gross national income
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
HEV	hybrid electric vehicle
HDV	heavy-duty vehicle
ICE	internal combustion engine
ICT	information and communication technology
IEA	International Energy Agency

IGCC	integrated gasification combined cycle
ITA	International Tunnelling Association
LCA	life-cycle assessment
LCV	light commercial vehicle
LED	light-emitting diode
LNG	liquefied natural gas
MEF	Material Efficiency variant
MoMo	Mobility Model
M&R	maintenance and rehabilitation
MSR	material substitution ratio
NCA	nickel cobalt aluminium oxide
NMC	nickel-manganese-cobalt oxide
nZEB	near-zero energy building
OECD	Organisation for Economic Co-operation and Development
OPC	ordinary Portland cement
PLDV	passenger light-duty vehicle
ProSUM	Prospecting Secondary raw materials in the Urban mine and Mining wastes
PV	photovoltaic
RCC	reinforced cement concrete
RTS	Reference Technology Scenario
STE	solar thermal electricity
SUV	sports utility vehicle
TIMES	The Integrated MARKAL-EFOM System
USD	United States dollar

Units of measure

°C	degree Celsius
EJ	exajoule
gCO_2/kWh	grammes of carbon dioxide per kilowatt hour

GJ	gigajoule
Gt	gigatonne
$GtCO_2$	gigatonne of carbon dioxide
kg	kilogramme
km	kilometre
km/h	kilometre per hour
kt	kilotonne
MJ	megajoule
Mt	million tonne
$MtCO_2$	million tonne of carbon dioxide
MWh	megawatt hour
m^2	square metre
pkm	passenger kilometre
t	tonne
tCO_2	tonne of carbon dioxide
TWh	terawatt hour
vkm	vehicle kilometre

Regional definitions

North America: Canada, Mexico and United States

Central and South America: Argentina, Bolivarian Republic of Venezuela, Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Plurinational State of Bolivia, Suriname, Trinidad and Tobago, Uruguay, and other countries and territories.

Europe: European Union (Austria, Belgium, Bulgaria, Croatia, Cyprus[36], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain,

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[36] Note by Turkey
The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".
Note by all the European Union Member States of the OECD and the European Union
The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

Sweden and United Kingdom), Albania, Belarus, Bosnia and Herzegovina, Former Yugoslav Republic of Macedonia, Gibraltar, Iceland, Israel, Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Turkey and Ukraine.

Africa: Algeria, Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Democratic Republic of the Congo, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe, and other countries and territories.

Middle East: Bahrain, Iraq, Islamic Republic of Iran, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates and Yemen.

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Table of contents

List of figures

List of boxes

List of tables

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