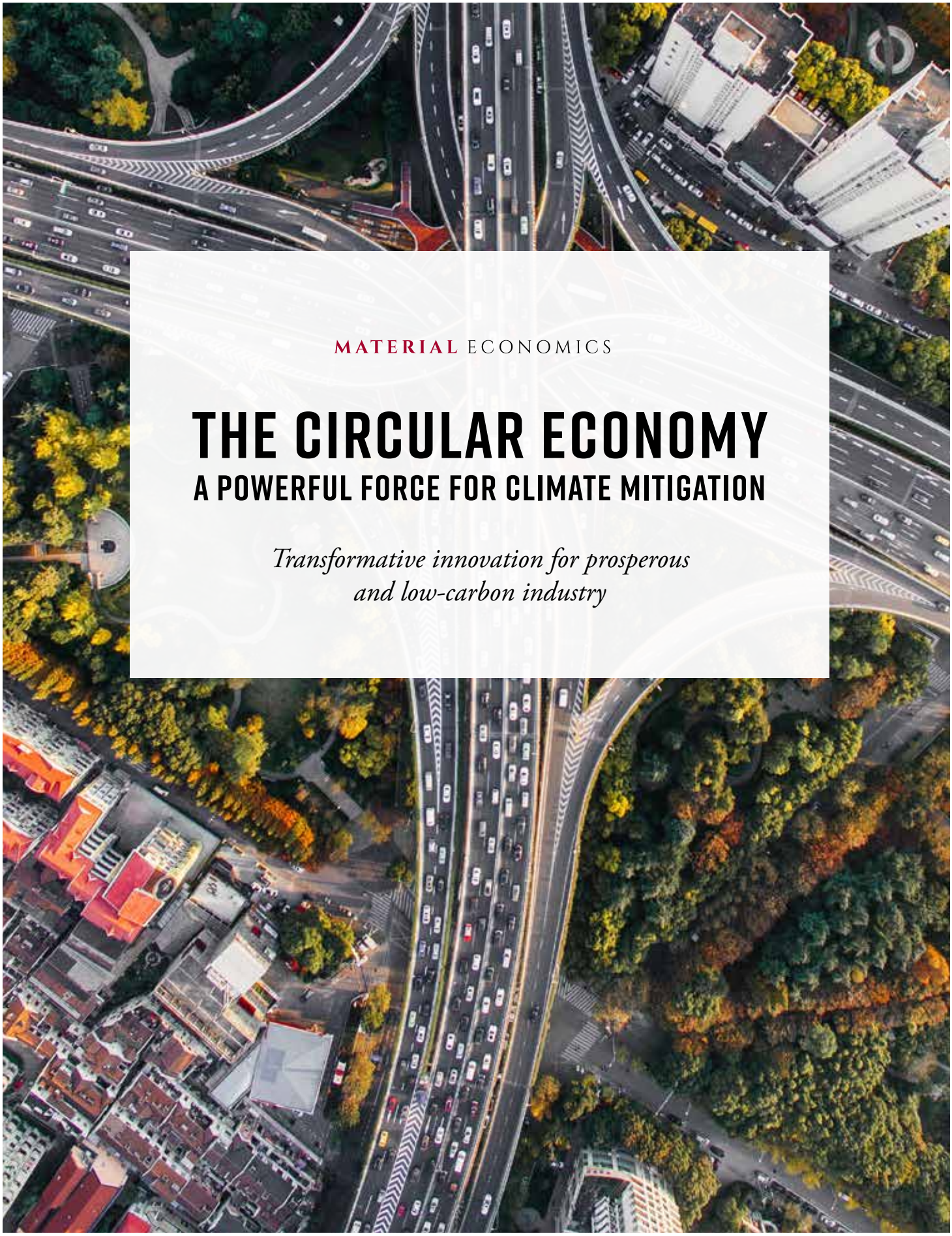

MATERIAL ECONOMICS

THE CIRCULAR ECONOMY

A POWERFUL FORCE FOR CLIMATE MITIGATION

Transformative innovation for prosperous and low-carbon industry

SITRA · European Climate Foundation · Climate-KIC (Climate-KIC is supported by the EIT, a body of the European Union) · Energy Transitions Commission · Ellen MacArthur Foundation · MAVA Fondation pour la Nature · ClimateWorks Foundation

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PREFACE

There is intense debate about how to close the gap between current climate policy and the long-term goal of the Paris Agreement: an economy with net zero emissions. Within Europe, policy discussions and proposed 'roadmaps' to date have focused mainly on increasing energy efficiency and deploying low-carbon energy sources. Both are crucial, but when it comes to industry, a major source of emissions, they offer only a partial solution. Additional strategies are needed to address the substantial process emissions from the production of materials such as steel, cement, plastics and aluminium.

Most discussion has focussed on the *supply* side: the need to develop and deploy new industrial production processes, turn to non-fossil feedstock and fuels, and use carbon capture and storage to offset any remaining emissions. What is mostly missing from climate and industrial debates is a discussion of the *demand* side: Can we make better use of the materials already produced, and so reduce our need for new production?

The concept of the 'circular economy' offers precisely this opportunity, through strategies such as recirculating a larger share of materials, reducing waste in production, lightweighting products and structures, extending the lifetimes of products, and deploying new business models based around sharing of cars, buildings, and more.

This report takes a first step towards quantifying the potential for circular economy opportunities to reduce greenhouse gas emissions. It examines the key materials flows and value chains, identifies relevant circular economy approaches, and explores their cost-effectiveness. It also considers barriers that might stand in the way of achieving a more circular economy, and policies and initiatives that could overcome them.

To our knowledge, this is the first attempt to quantitatively address this issue across materials and value chains, and for the entire EU economy. As with any first effort, there are many uncertainties, and further analysis will be needed. Still, our analysis shows that the potential for emissions abatement is substantial, and in many cases can be economically attractive. Indeed, we believe that 'materials efficiency' deserves to be a priority in discussions of industrial decarbonisation, just as energy efficiency is a priority in discussions of transforming the energy system. A more circular economy can reduce CO_2 emissions, reduce the scale of the challenge of decarbonising materials production, and contain the cost of achieving an industrial base compatible with a low-carbon economy.

This project has been carried out by Material Economics, with the support of Climate-KIC, ClimateWorks, Ellen MacArthur Foundation, Energy Transitions Commission, European Climate Foundation, MAVA Foundation, and SITRA. The Steering Group has comprised Mari Pantsar (SITRA), Janez Potočnik (International Resource Panel), Martin Porter (European Climate Foundation), Adair Turner (Energy Transitions Commission), Jocelyn Blériot (Ellen MacArthur Foundation), Christoph Wolff and Simon Wolf (European Climate Foundation) and Anders Wijkman (Climate-KIC). Research guidance have been provided by Dr Jonathan Cullen and Prof. Frank Geels. The project team has included Anna Teiwik, Cornelia Jönsson, Stina Klingvall, and Unn Hellberg. Material Economics is extremely grateful for all the contributions of these organisations and individuals, as well as many other researchers, policymakers, and business representatives who have contributed their knowledge and insight to this project. Partner organisations and their constituencies do not necessarily endorse all findings or conclusions in this report. All remaining errors and omissions are of course the responsibility of the authors.

Per-Anders Enkvist

Per Klevnäs

EXECUTIVE SUMMARY

Industrial CO_2 emissions are a major concern as Europe tries to achieve the deep emission reductions required for its climate commitments. In the European Commission's 'Roadmap 2050', one-quarter of the CO_2 emissions remaining mid-century were from industry, especially from heavy industry producing basic materials. With more ambitious targets after the Paris Agreement, the EU must now articulate how to combine net-zero emissions with a prosperous industrial base.

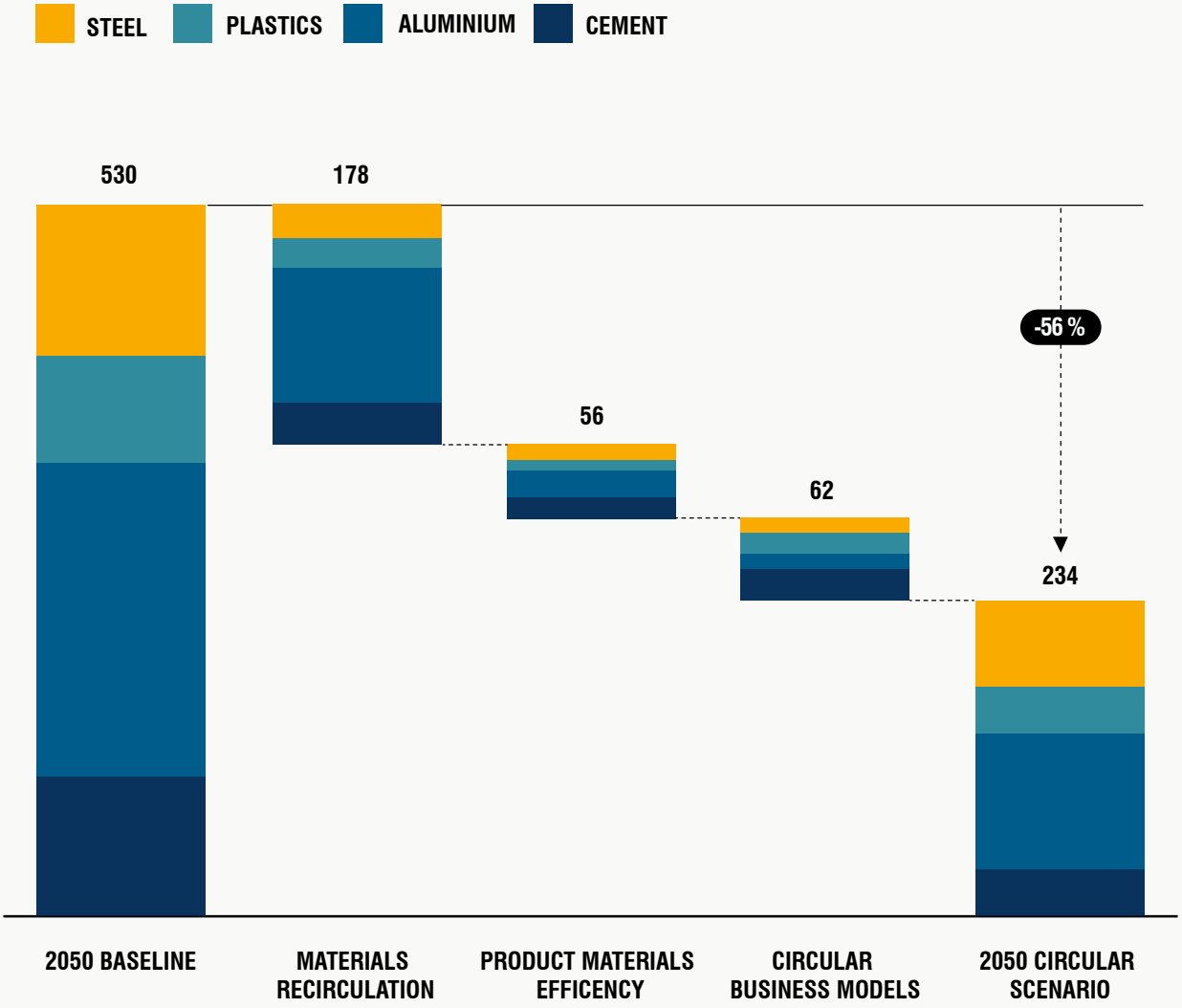
So far, discussions of industry emissions have focussed on the supply side: reducing the emissions from the production of steel, cement, chemicals, etc. Far less attention has been given to the demand side: how a more circular economy could reduce emissions through better use and reuse of the materials that already exist in the economy. This study aims to bridge that gap. It explores a broad range of opportunities for the four largest materials in terms of emissions (steel, plastics, aluminium and cement) and two large use segments for these materials (passenger cars and buildings).

The key conclusion is that a more circular economy can make deep cuts to emissions from heavy industry: in an ambitious scenario, as much as 296 million tonnes CO_2 per year in the EU by 2050, out of 530 in total – and some 3.6 billion tonnes per year globally. Demand-side measures thus can take us more than halfway to net-zero emissions from EU industry, and hold as much promise as those on the supply side. Moreover, they are often economically attractive.

Opportunities for more productive use of materials therefore deserve a central place in EU climate policy. Much like improving energy efficiency is central to the EU's efforts to achieve a low-carbon energy system, a more circular economy will be key to developing European industry while cutting its CO_2 emissions. As industry associations and the European Commission consider new mid-century 'roadmaps' for industry, they should include circular economy measures for cost-effective ways to achieve deep emissions cuts.

A MORE CIRCULAR ECONOMY CAN CUT EMISSIONS FROM HEAVY INDUSTRY BY 56% BY 2050

EU EMISSIONS REDUCTIONS POTENTIAL FROM A MORE CIRCULAR ECONOMY, 2050
MILLION TONNES OF CARBON DIOXIDE PER YEAR



Demand-side opportunities could reduce EU industrial emissions by almost 300 Mt per year by 2050, or 56 %, with attractive economics. These abatement opportunities fall into three major categories:

A. Materials recirculation opportunities (178 Mt per year by 2050). The EU economy is accumulating large stocks of metals and plastics, and by 2050 could meet a large share of its need for these materials by recirculating what has already been produced: 75% of steel, 50% of aluminium, and 56% of plastics (cement is less amenable to recycling, although it is possible to reuse some unreacted cement). Recirculating materials cuts CO_2 emissions and requires much less energy than new production does. However, current practice is not set up to facilitate these high recycling rates. An influx of new materials is required both to replace metals and plastics that are lost, and to compensate for downgrading of quality. In some cases, metals are mixed or downgraded because materials specialisation requires it, but there also are many cases where this could be avoided or much reduced. For steel, the key is to ensure much cleaner scrap flows that allow for high-quality secondary steel, and less pollution of steel with copper; for aluminium, smaller losses and less mixing of different alloys will be crucial. Mixing and downgrading effects are particularly serious problems for plastics, making a large share of used plastics literally worthless. This study shows how 56% of plastics could be mechanically recycled, with a focus on the five main types of plastic that account for 70% of volumes. The aim must be to move these to a tipping point where recycling is economically viable, driven by the inherent material value. For this, as with steel and aluminium, product design and end-of-life disassembly need to change to enable high-value recovery.

B. Product materials efficiency (56 Mt per year by 2050). These opportunities have in common that they reduce the total materials input to key products. One strategy is to reduce the amount of materials that are lost in production: for example, half the aluminium produced each year does not reach the final product, but becomes scrap, while some 15% of building materials are wasted in construction. Another opportunity is to use more advanced materials and construction techniques, such as high-strength steel that can cut materials use by 30%. There also are opportunities to reduce over-specification, such as the near 100% overuse of steel in buildings relative to what is strictly required to meet design specifications. Further gains can be achieved by tailoring products better to specific uses; for example, to the extent that fleets of shared cars can replace individual ownership (see below), many of the cars needed will be smaller, just big enough for a one- or two-passenger trip in the city. Companies already have incentives to use these strategies to some extent, but some opportunities are missed through split incentives in complex supply chains. Many measures will become much more economic with greater digitalisation in the mobility and buildings value chains and other technological development now underway.

C. New circular business models in mobility and buildings, notably through sharing (62 Mt per year by 2050). This opportunity pivots on making much greater use of vehicles and buildings, which together represent a majority of European demand for steel, cement and aluminium. Currently, the utilisation of many of these assets is very low: about 2% for the average European car, and about 40% for European offices, even during office hours. Sharing enables much more intensive use. For vehicles, this in turn means that higher upfront costs of electric drivetrains, more advanced automation technology, or higher-performance materials can be paid back over many more miles. In addition, professionally managed fleets of such higher-value cars are more economical to maintain, reuse, remanufacture and recycle. Vehicle lifetimes, on a per-kilometre basis, can thus increase drastically. The result is a self-reinforcing loop of incentives for higher utilisation, lower-carbon energy, and less materials use. In a circular scenario, the materials input to mobility falls by 75%. It also brings many other benefits, including a much lower total cost of travel. Sharing models are taking root by themselves, but much more could be done to accelerate their growth, and to find ways to resolve the concerns that have arisen with some early iterations of such business models.

Many of these abatement opportunities are economically attractive on their own terms, provided that we are willing to organise the mobility and real estate sectors somewhat differently in the future. Many others cost less than 50 EUR per tonne CO_2 avoided, less than most other ways to reduce these emissions, including supply-side measures for industry. Circularity is strongly aligned with the digitalisation trend that is sweeping across industry; for example, digitalisation means it is ever cheaper to keep track of complex supply chains and material flows, optimise sharing business models, and automate materials handling in construction. A more circular economy would have many other benefits as well, such as reduced geopolitical risks, local job creation, lower air pollution, and reduced water use. They therefore can contribute to several of the Sustainable Development Goals.

A more circular economy is indispensable for meeting global material needs without exceeding the available carbon budget. The Intergovernmental Panel on Climate Change has estimated a remaining 'carbon budget' for this century of around 800 billion tonnes (Gt) CO_2. This is the amount of emissions that can be emitted until 2100 for a good chance of keeping warming below 2°C – with still less for the 'well below 2°C' target set by the Paris Agreement. This study estimates that, on current trends, materials production alone would result in more than 900 Gt of emissions. Energy efficiency and low carbon energy will help, but do not resolve this dilemma: emissions add up to 650 Gt even with rapid adoption. This is because so much carbon is either built into the products themselves and then released at their end of life (plastics), or is inherent to the process chemistry of production (steel, cement). For context, note that 2°C scenarios typically 'allocate' about 300 Gt CO_2 to these sectors for the total world economy.

Options to get to 300 Gt include a) aggressive scale-up of carbon capture and storage; b) the rapid introduction of radical process changes that are currently in early development stages; and c) reducing demand for primary materials through the range of circularity measures discussed above. This report argues that it is almost impossible to achieve the cut to 300 Gt without a major use of category c) – hence our assertion that a low-carbon economy must be much more circular than today's. While this study has focussed on Europe, an extrapolation to other world regions suggests that the measures identified could contribute 3.6 Gt CO_2 per year to global efforts to cut greenhouse gas emissions by 2050. The claim on the carbon budget could be reduced by 333 Gt by 2100. In this setting, the additional supply-side measures required start to look manageable, and a well-below 2 °C objective within reach.

Achieving these opportunities is doable and requires 'energy efficiency-type' interventions. Many of the abatement opportunities identified are low-cost or even profitable, but are held back by multiple barriers. For example, product manufacturers lack incentives to enable high-value recycling several steps later in the value chain, and many externality advantages of sharing business models are not accounted for. A higher carbon price would help on the margin, but capturing a large share of the opportunities will require addressing those barriers directly. We estimate that up to 70–80% of the abatement opportunities are additional to ones already addressed by existing climate policy approaches. The situation resembles that for energy efficiency, where careful analysis of cost-effective potentials and barriers has motivated a range of interventions, from aggregate efficiency targets to product standards and labelling schemes. Many of the circularity measures are similarly cost-effective, or could be once scaled-up, but require that barriers are overcome. The next task is to explore which policy instruments would be most effective in pursuing different opportunities.

The priority now should be to firmly embed circular economy measures in the low-carbon agenda. This study is an early quantitative investigation into the low-carbon benefits of the circular economy. Much more work is required, but we hope this report nonetheless shows the potential available for European industry. The most urgent priority now is to build a solid knowledge base – and then to incorporate circular economy opportunities alongside low-carbon energy supply, electrification of transport and heat, and energy efficiency as a core part of the transition to a low-carbon economy. A more circular economy could play a key role in helping Europe and the world to meet our climate targets.

1. THE CLIMATE POTENTIAL OF A CIRCULAR ECONOMY

Industrial CO_2 emissions are a major concern as Europe tries to achieve the deep emission reductions required for its climate commitments. In the European Commission's 'Roadmap 2050', one quarter of CO_2 emissions remaining mid-century were from industry, and especially from heavy industry producing basic materials. With more ambitious targets after the Paris Agreement, the EU must now articulate how to combine net-zero emissions with a prosperous industrial base. Without strong action, emissions from the global production of basic materials alone risk exceeding the available 'carbon budget'.

This study shows how a more circular economy can make deep cuts to emissions from heavy industry: in an ambitious scenario, as much as 296 million tonnes CO_2 per year in the EU by 2050, out of 530 Mt in total – and some 3.6 billion tonnes per year globally. Demand-side measures thus hold as much promise as ones on the supply side. They are all but indispensable for the joint objectives of economic development and action on climate change. Moreover, they are often economically attractive.

Opportunities for more productive use of materials therefore deserve a central place in EU climate policy. Much like improving energy efficiency is central to the EU's efforts to achieve a low-carbon energy system, a more circular economy will be key to developing European industry while cutting its CO_2 emissions. As industry associations and the European Commission consider new 'roadmaps' for industry mid-century, they should include circular economy measures for cost-effective ways to achieve deep emissions cuts.

1.1 MATERIALS & GHG EMISSIONS – WHY A 2°C ECONOMY MUST BE CIRCULAR

Industry is a vital part of any modern economy. As countries develop and their economies grow, they build up an ever-larger stock of basic industrial commodities and materials such as steel, cement, aluminium, and plastics to underpin infrastructure, transport systems, buildings and factories, and to produce and package consumer goods. Materials are the heart of maintaining a high standard of living. A healthy industrial sector is also widely seen as crucial for economic competitiveness.

Yet industry is also a major source of greenhouse gas emissions: 40% of total emissions in 2014, and growing[1]. To achieve the Paris Agreement's long-term goal of a global economy with zero net GHG emissions, we need to sharply reduce industrial emissions. The challenge for policy-makers – and for industry – is how to curb emissions while continuing to meet our economies' material needs.

Zero-carbon energy is a crucial part of the answer, but it is not enough. This is because so much carbon is either built into the products themselves and then released at their end of life (plastics), or is core to the process chemistry of their production (steel, cement). The demand side – making more of the materials we have already produced – will therefore be key to a materials sector in a low-carbon economy. The good news is that there is large potential. Our analysis shows that circular approaches can reduce CO_2 emissions from materials production in the EU by 56% by 2050. For the EU, this represents a major opportunity to both narrow the emissions gap, and reassert itself as a trailblazer and global leader in industry.

GLOBAL MATERIALS DEMAND IS SET TO INCREASE 2- TO 4-FOLD AS THE WORLD ECONOMY GROWS

Global heavy industry is growing fast. Steel production grew by 40% over the last 10 years, with nearly 95% of this growth in China alone. Cement tripled in just a decade and global plastics demand is doubling about every 20 years. Given the importance of these materials in modern economies, it is no surprise that economic development around the world has kept increasing demand for these commodities. That growth is set to continue. Large parts of the world are still at the initial stages of urbanisation and industrialisation. For example, the stock of steel in industrialised countries is typically 10-14 tonnes per capita, but in non-OECD countries, the average per capita stock is just 2 tonnes[2]. Similar gaps exist with other materials.

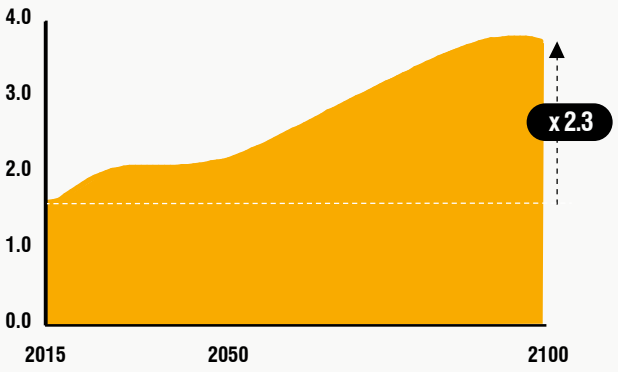
To investigate how future materials demand could influence CO_2 emissions, this study focusses on four materials that, together, account for 75% of direct CO_2 emissions from industry: steel, cement, aluminium and plastics.[3] In each case, we developed a detailed scenario, based on long-term population and economic development, and using the state-of-the art approaches in published literature to examine how much of these four materials would be needed in different world regions if they develop similarly to today's OECD economies.

The results of this analysis are striking: As shown in Exhibit 1.1, steel and cement consumption could roughly double, aluminium triple, and plastics quadruple by the end of the century. Precisely how far and how fast demand would increase is uncertain, of course, but our findings are in line with other existing research.[4] The core message is clear: in a business-as-usual development, primary materials demand would rise rapidly and continue to do so for many decades.

Exhibit 1.1

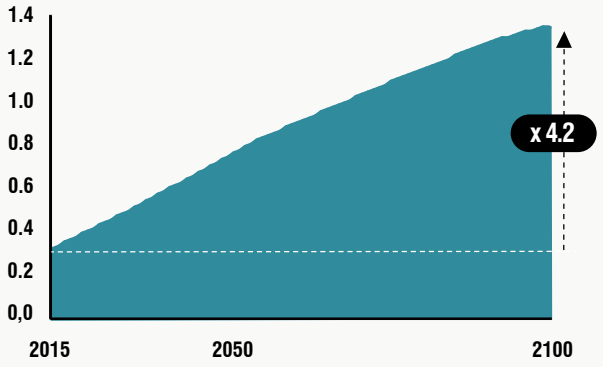
WITH CURRENT PATTERNS OF MATERIALS USE, GLOBAL DEMAND FOR KEY MATERIALS WILL INCREASE 2- TO 4-FOLD

STEEL
Gt STEEL PER YEAR



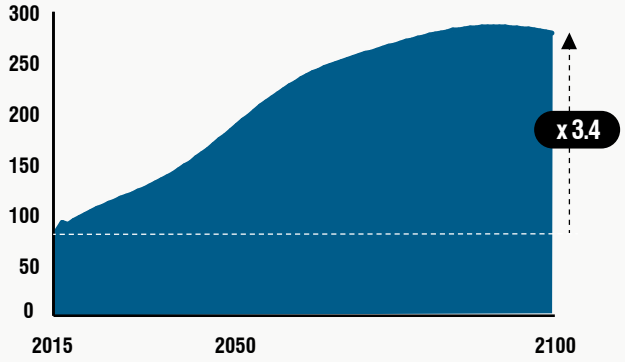
Steel is used in construction and infrastructure, transportation, industrial machinery, and consumer products. Global steel production now stands at 1.6 billion tonnes per year, having grown by 40% in the decade to 2015. China alone accounted for nearly 95% of this growth. Historically, steel stocks have tended to grow fast once countries reached incomes of around 5000 USD/person, then tapered off at higher income levels, at 12–15 tonnes per person. Our scenario derives the demand resulting if all world regions were to follow this pattern, with convergence to OECD levels of steel stocks of 13 t per capita.

PLASTICS
Gt PLASTICS PER YEAR



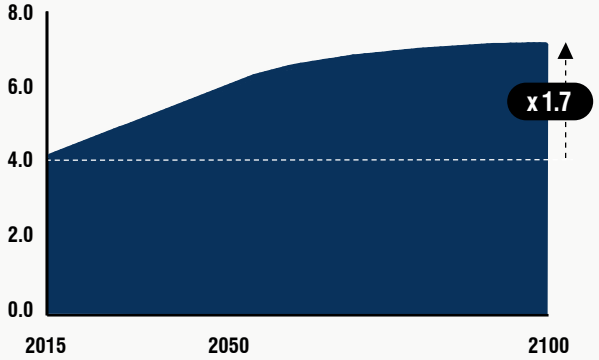
Plastics production has grown by 50% in the past decade, to just under 350 million tonnes per year. In advanced economies, packaging is a major use, followed by construction and automotive. In Europe, current annual use of plastics is about 100 kg/person, while North America is at about 140 kg/person. Our scenario illustrates the outcome if all world regions converge to 120 kg/person.

ALUMINIUM
Mt ALUMINIUM PER YEAR



Aluminium is used in packaging, buildings, automobiles and other sectors Global production of primary aluminium now stands at around 60 million tonnes per year, with an additional 30 million tonnes of remelted aluminium. Stocks have been growing strongly in all advanced economies, though they vary greatly: from 600 kg per person in the United States, to 200–500 kg per person in European countries. Our scenario assumes global convergence to 400 kg.

CEMENT
Gt CEMENT PER YEAR



Global cement production has tripled in just a decade and currently stands at just over 4 billion tonnes per year. Cement production is closely related to construction activity and the build-out of infrastructure. Historically, it has peaked and then declined as GDP per capita grows, but with big variations: China used more cement in three years than the United States did in an entire century. Existing scenarios reflect these uncertainties, with some suggesting minimal further growth, and others predicting an explosion. Our scenario is in the middle, anticipating cement demand of just over 7 billion tonnes per year by 2100.

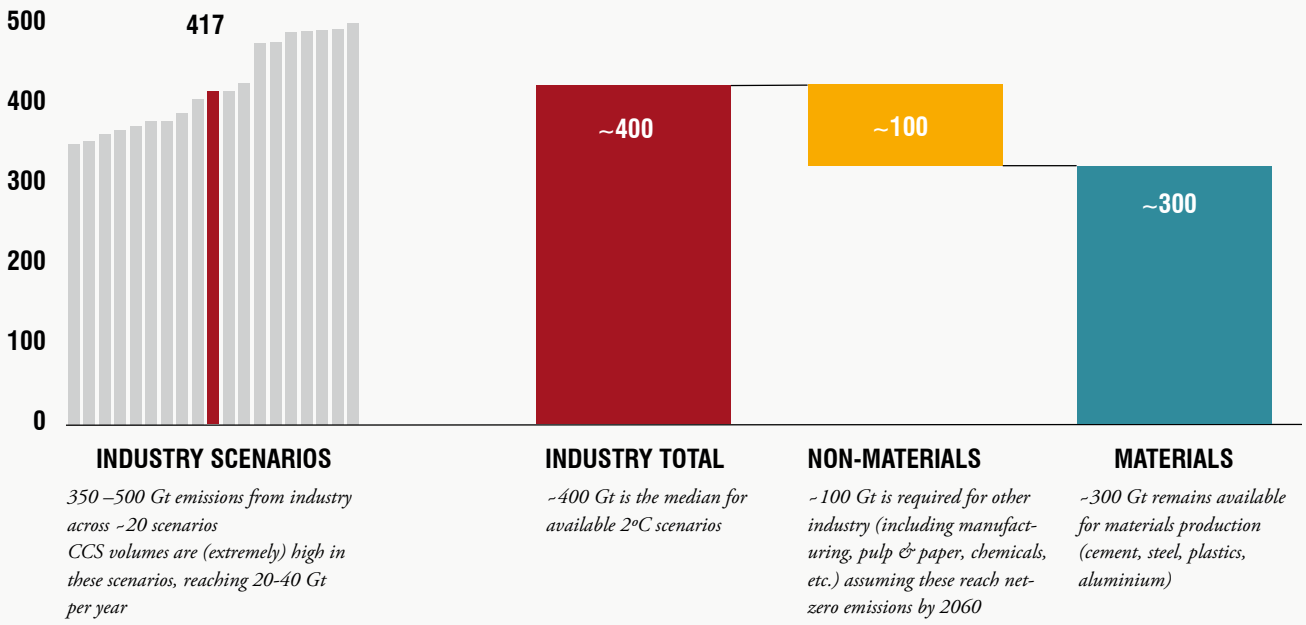
GROWTH IN MATERIALS USE RISKS EXHAUSTING THE CARBON BUDGET AND IMPERIL CLIMATE OBJECTIVES

Given the large emissions from heavy industry, the rise in materials use has major implications for CO_2 emissions. Looking ahead, rapidly increasing materials production therefore risk laying significant claim to the available 'CO_2 budget' – i.e., the total amount of CO_2 that can be emitted until 2100, while limiting the increase in global temperatures to a given target (see box below). For a 2°C scenario, the remaining budget for emissions is around 800 billion tonnes (Gt) of CO_2 until 2100, and still less for a 'well-below' 2°C or 1.5°C target as envisaged in the Paris Agreement.[5] This budget must cover all major emissions from energy and industry: not just materials production, but also power generation, transportation, heating, appliances, manufacturing and more. In fact, the amount 'allocated' for production of the four materials is no more than about 300 Gt CO_2, as shown in Exhibit 1.2.[6]

Exhibit 1.2

EXISTING SCENARIOS IMPLY THAT AT MOST 300 Gt OF THE REMAINING CARBON BUDGET COULD BE ALLOCATED TO THE PRODUCTION OF MATERIALS

CUMULATIVE INDUSTRY CO_2 EMISSIONS IN 2ºC SCENARIOS, 2015 – 2100
Gt CO_2



NOTE: INDUSTRY SCENARIOS THAT MEET 2°C TARGET WITH >2/3 PROBABILITY AND WHICH REPORT INDUSTRIAL EMISSIONS
SOURCE: MATERIAL ECONOMICS ANALYSIS OF IPCC AR5 DATABASE.[7]

CLIMATE TARGETS AND CARBON BUDGETS

Greenhouse gases accumulate in the atmosphere, and as concentrations increase, they cause warming and disrupt the climate. Scientists have estimated roughly what temperature increase is associated with different CO_2 concentrations, as well as the amount of CO_2 emissions that would result in those concentrations, after accounting for natural carbon sinks and, in some scenarios, future 'negative emissions' due to carbon capture and storage (CCS) or other measures.

Subtract emissions to date, and the result is a 'carbon budget' for any given climate target – that is, how much can be emitted between now and the year 2100 if we are to keep warming below 2°C, for instance.

Several variables can affect the budget, including the target itself, the probability of achieving it (66% vs. 50%), the use of 'negative emissions', and the period covered by emissions to date. Sector-specific budgets also reflect judgements about the share of remaining emissions that should be allocated to each sector.

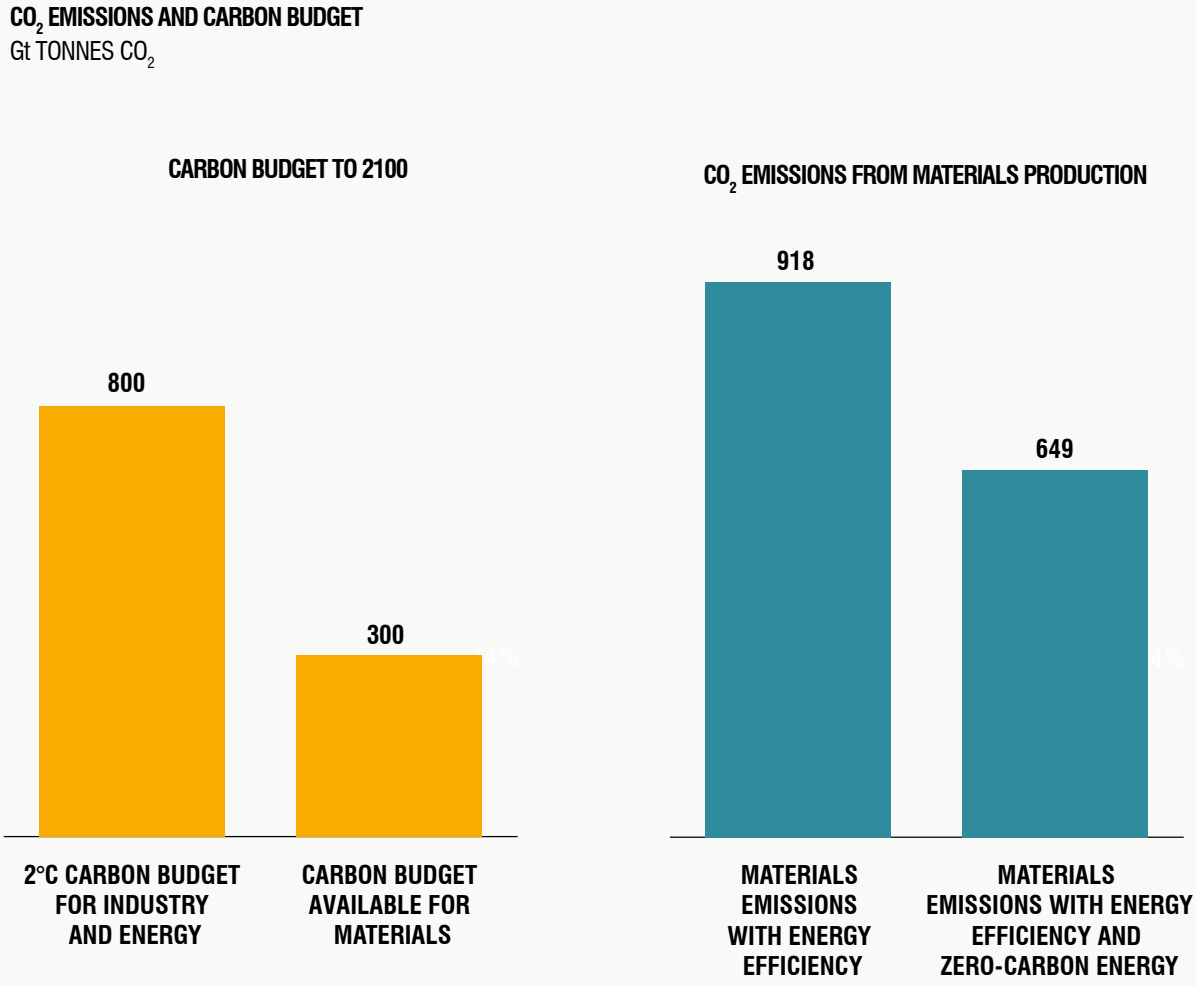
In our analysis, we use scenarios with at least 66% change of meeting a 2°C objective, which are those closest to the Paris Agreement's objective of limiting global warming to 'well below' 2°C.

Our projections of materials demand, however, imply far larger emissions, as much as 918 Gt CO_2. This is true even though we assume in our calculations that the 'best available technique' is rapidly adopted to improve energy and process efficiencies, and that current practices for materials recycling continues (for example, even in the baseline scenario, the emissions per tonne of steel falls by 40%, mostly because there is much more scrap-based steel production). Still, current processes are intrinsically very carbon-intensive, resulting in large emissions.

To take this one step further, we also investigate how far it would help to switch the energy inputs to production to low-carbon sources.[8] Even if this was completed by 2050, some 649 Gt of CO_2 emissions would result by 2100, more than twice the amount that would put materials production on a path consistent with climate objectives (Exhibit 1.3). As shown in Exhibit 1.4, the reason for the continued high emissions is that a large share result not from fuel combustion, but from chemical processes in the production of materials. Decarbonising energy is therefore not enough.

Exhibit 1.3

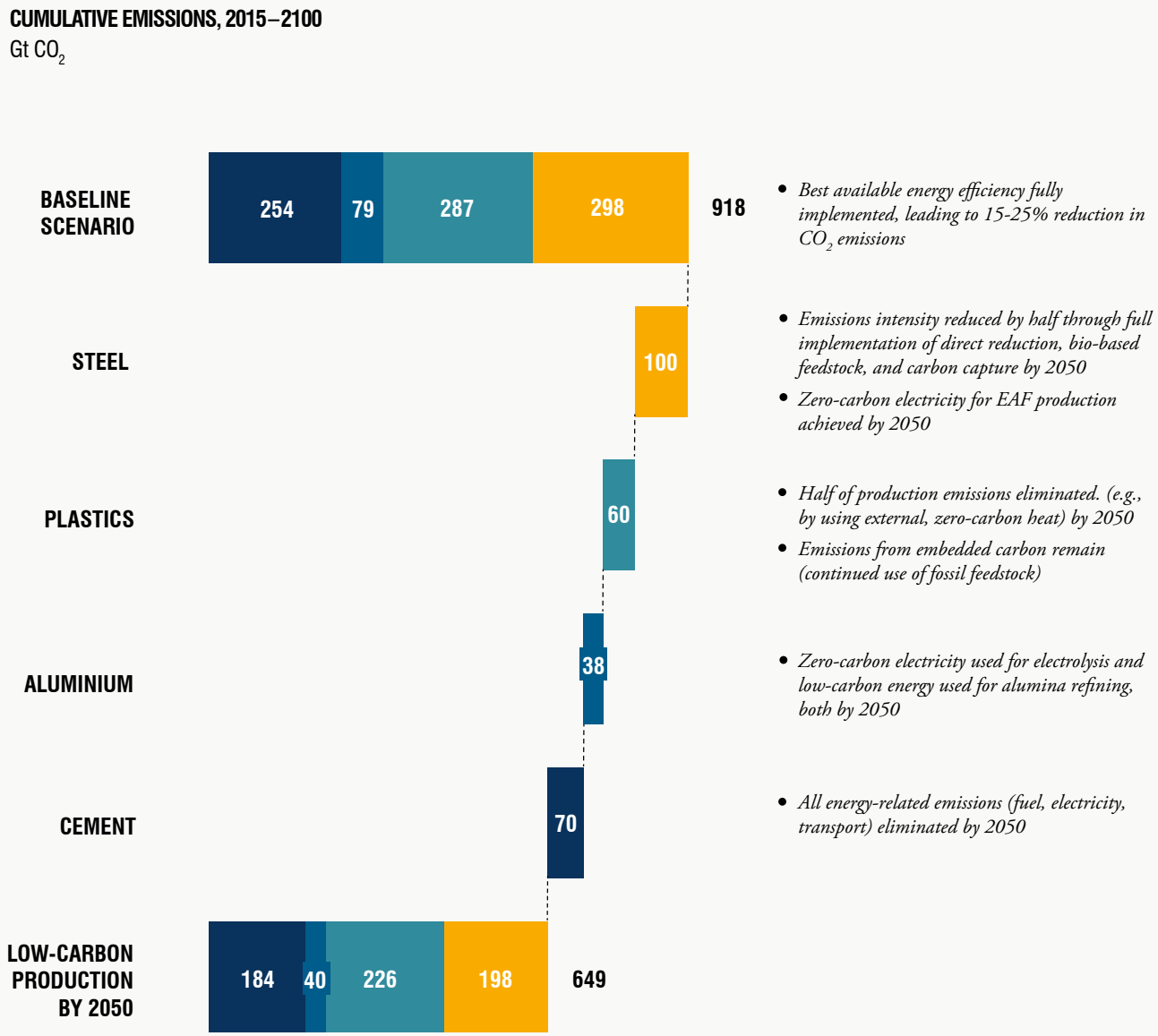
MATERIALS PRODUCTION ALONE RISKS EXCEEDING THE TOTAL REMAINING CARBON BUDGET FOR A 2°C SCENARIO



SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT. MULTIPLE SOURCES, SEE ENDNOTES.[9]

Exhibit 1.4

LOW-CARBON ENERGY IS NOT ENOUGH: EVEN WITH 100% LOW-CARBON ENERGY BY 2050, EMISSIONS FAR EXCEED THE AVAILABLE CARBON BUDGET



NOTE: PLASTICS EMISSIONS INCLUDE EMISSIONS FROM PRODUCTION AS WELL AS EMBEDDED EMISSIONS, SEE ENDNOTES.[10]
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SUBSEQUENT CHAPTERS OF THIS REPORT.

A MORE CIRCULAR ECONOMY IS INDISPENSABLE FOR CLIMATE TARGETS

Given that low-carbon energy will not solve the problem of CO_2 emissions from materials, other measures are needed. On the supply side, a broad range of options have been proposed, from hydrogen-based steelmaking to new routes for plastics synthesis, but all are at early stages of development. Another option that is often discussed is to deploy carbon capture and storage (CCS) – which also lags far behind the levels of deployment required for a 2°C scenario.[11] Both will likely be needed to bring industry in line with the goal of net-zero emissions, but they will not suffice.

Given the scale of the challenge of low-carbon production, it is high time that climate policy looks not just at how materials are produced, but at ways to reduce demand for new materials. In the sections that follow, we show how a more circular economy could mean we get much more out of the materials we already have, making it possible to meet the needs of a modern economy with significantly lower levels of new primary materials production.

Demand- and supply-side strategies can also be mutually reinforcing, as is widely recognised in discussions of energy transitions. All low-carbon scenarios foresee a step-change in efficiency, so that essential services such as mobility, thermal comfort, or mechanical power can be achieved with much lower levels of energy input. Across 2°C scenarios, energy efficiency improvements account for some 40% of the emissions reductions. Reducing total energy demand also makes it easier to grow low-carbon energy sources to fully meet global needs, and to keep costs manageable.

The same happens with industry in a more circular economy. The strategies we explore in this report effectively increase the 'materials efficiency' of the economy, reducing the amount of new materials required. This narrows the emissions gap that needs to be closed through supply-side measures, buying time and reducing the need to deploy the most expensive technologies. Circular approaches already require some energy input, but less than new materials production, and they shift emissions away from hard-to-abate, costly industrial processes, towards activities that are much easier to decarbonise. Notably, unlike today's primary materials production, much of the circular economy can be powered by low-carbon electricity.

Circular economy strategies also have multiple 'co-benefits' beside CO_2 reductions. By reducing the need for industrial processes associated with substantial air pollution, for example (e.g. steel production using coal), they can reduce disease and mortality.[12] By reducing the need for mining, they reduce soil and water pollution as well as the destruction of ecosystems. By reducing the amount of plastic left to decay in landfills and in waterways, they avoid poisoning wildlife and, through the food chain, humans. Many strategies would also create new jobs close to where materials are used, and some would make key services, such as transportation, more accessible and affordable. Thus, along with climate targets, a more circular economy would also make several Sustainable Development Goals more achievable.

Put together, these arguments make a compelling case for the circular economy not just as one option to consider in the quest to meet climate targets, but as an invaluable part of the transformation we need for a prosperous and sustainable future.

In the section that follows, we explore the potential for CO_2 emission reductions. Then, in Section 3, we examine the economics of a more circular economy. We focus both analyses on the EU, an advanced economy with ambitious climate targets and a strong record in pioneering low-carbon technologies. The EU could spearhead many of these strategies and reap the benefits while showing the rest of the world how they, too, can reduce industrial emissions without compromising on economic development.

Many strategies *would also create new jobs close to where materials are used, and some would make key services, such as transportation, more accessible and affordable.*

1.2 A MORE CIRCULAR ECONOMY CAN CUT 2050 EMISSIONS FROM HEAVY INDUSTRY BY 56%

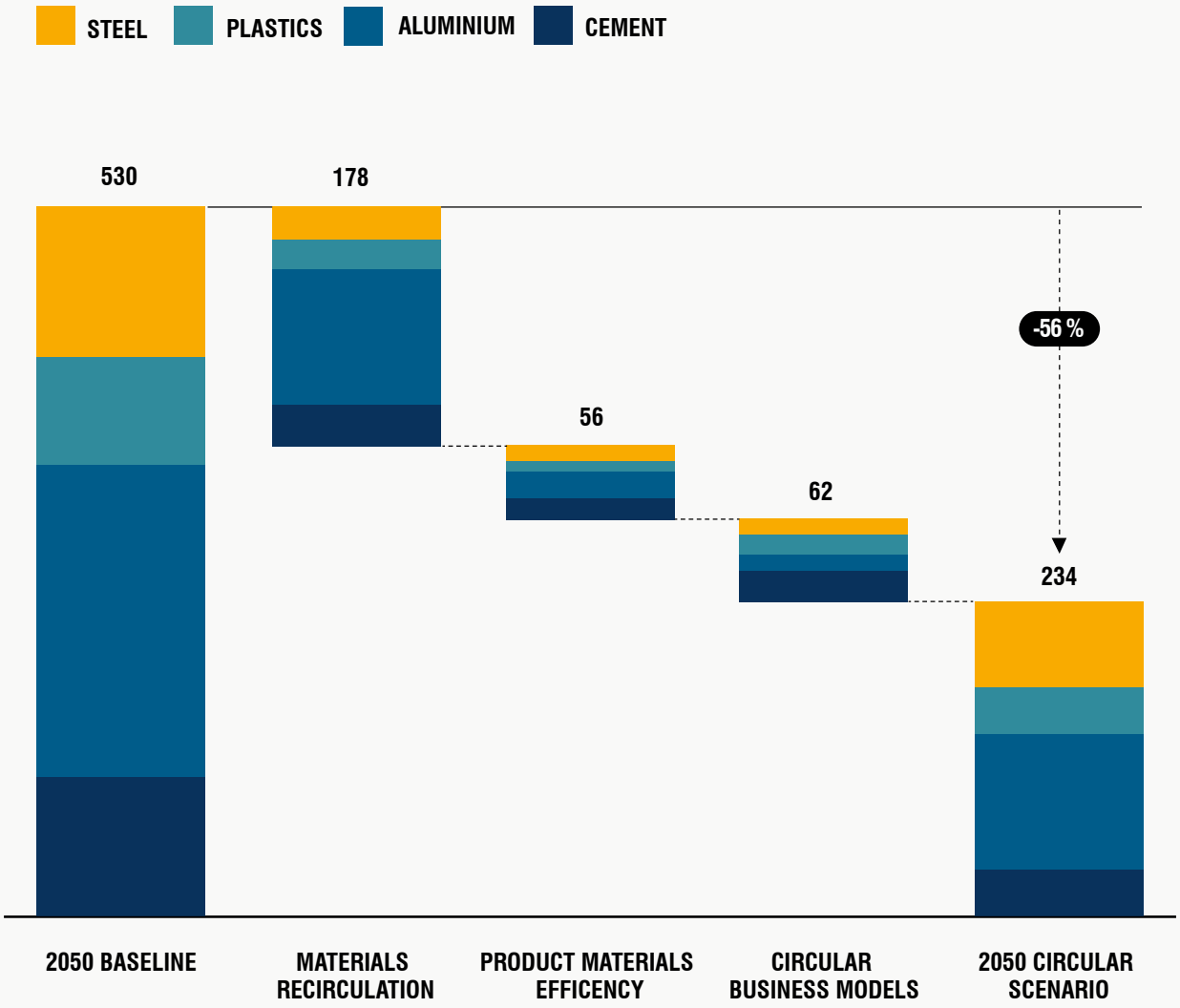
To quantify the potential of a more circular economy to reduce industrial GHG emissions, we conducted an in-depth study of steel, plastics, aluminium and cement in the European Union, as well as two key supply chains – passenger cars and buildings. As we describe in detail below, we found that a more circular economy could reduce emissions from the production of these four materials by more than half: set against emissions of 530 Mt CO_2 per year, the circular economy abatement potential we identify is almost 296 Mt CO_2 per year by 2050 (Exhibit 1.5).

Mobilising this potential would make an indispensable contribution to the EU's climate commitment. Meeting targets under the Paris Agreement requires near-zero net emissions in the EU around mid-century or before – leaving no or little room for residual emissions from industry. Yet existing analyses do not articulate how this would be achieved for heavy industry. For example, the European Commission's 2011 'Roadmap 2050' foresaw emissions reductions from all of industry of 259 Mt CO_2, while leaving 170 Mt CO_2 in place, even with assumptions of very large volumes of CCS[13]. Sector roadmaps from steel, cement and chemical industry associations left 300 Mt CO_2 in place, even after abatement of 150 Mt CO_2 through CCS[14]. The European Commission is expected to produce a new mid-century roadmap in 2019. Our analysis suggests that demand-side strategies should have a central place in net-zero scenarios for European industry.

Exhibit 1.5

CIRCULAR OPPORTUNITIES CAN CUT 2050 EMISSIONS FROM STEEL, PLASTICS, ALUMINIUM AND CEMENT BY 56%

EU EMISSIONS REDUCTIONS POTENTIAL FROM A MORE CIRCULAR ECONOMY, 2050
Mt OF CARBON DIOXIDE PER YEAR



WITHOUT DEEP TRANSFORMATION, EMISSIONS WOULD AMOUNT TO 530 Mt CO_2 IN 2050

In order to gauge the potential impact of a more circular economy on industrial emissions, we looked more closely at each of the four materials and the two value chains. Exhibit 1.6 provides an overview. Cars and buildings account 60-70% of steel, cement and aluminium use, and some 30% of plastics. Conversely, steel, cement, aluminium and plastics account for 85% of the materials CO_2 footprint of buildings and passenger cars.

Exhibit 1.6

STUDY SCOPE: FOUR MATERIALS AND TWO VALUE CHAINS THAT TOGETHER ACCOUNT FOR MOST OF INDUSTRIAL CO_2 EMISSIONS

FOUR KEY MATERIALS CATEGORIES

STEEL

- *Used across economy in construction, transportation, industrial machinery, and consumer products*
- *40% of demand is served by secondary production in the EU, but the industry still releases some 230 CO_2 Mt per year*

PLASTICS

- *In advanced economies, packaging is a major use, followed by construction and automotive*
- *100 kg/capita is consumed annually in Europe, of which secondary plastics only represent 10% of demand*
- *130 Mt CO_2 are released annually from European production*

ALUMINIUM

- *Key uses include buildings, automotive, electrical machinery and packaging*
- *The EU imports 40% of its aluminum, sometimes from locations with very high CO_2 intensity of production*
- *In total, the CO_2 footprint of EU demand is around 80 Mt annually*

CEMENT

- *Used for construction of buildings and infrastructure*
- *Production is primarily local due to high availability of raw materials and high cost of transportation*
- *CO_2 emissions are more than 110 Mt per year, of which 55% are due to the process chemistry rather than energy*

66%

OF INDUSTRIAL CO_2 EMISSIONS

TWO KEY VALUE CHAINS AND PRODUCT CATEGORIES

CARS/MOBILITY

- *Automotive sector uses 20% of steel, 10% of plastics and 20% of aluminium*
- *CO_2 emissions from materials in passenger cars sold in the EU are around 50 Mt per year*
- *Embodied emissions in materials are becoming a larger share of total CO_2 footprint*

BUILDINGS/SHELTER

- *Buildings account for 33% of steel, 20% of plastics, 25% of aluminium and 65% of cement*
- *The CO_2 footprint of building materials in the EU is 250 Mt per year*
- *Embodied carbon is 10-20% of EU buildings' CO_2 footprint today, but already 50% in countries with low-carbon energy*

~50%

PASSENGER CARS AND BUILDINGS JOINTLY ACCOUNT FOR ALMOST HALF OF EMISSIONS FROM STEEL, PLASTICS, ALUMINIUM AND CEMENT

SOURCE: SEE SUBSEQUENT CHAPTERS OF THIS REPORT.

Steel, cement, aluminium and plastics account ***for 85% of the materials*** *CO_2 footprint of buildings and passenger cars.*

Total emissions from the production of the four materials for EU consumption amounts to 564 Mt CO_2.[15] The baseline scenario sees a varied development of demand: steel demand falls slightly, as the total steel stock saturates, whereas cement use stays constant, and plastics and aluminium use grows somewhat. The current production processes and practices continue to be used, so that plastics production is fossil-fuel based, cement is based on clinker production from limestone, and primary steel continues to use basic oxygen furnaces based on coal. However, trends towards lower emissions also continue: the efficiency of the processes improves by 10-20% through the rapid adoption of best available production techniques; materials use becomes more circular even in the baseline scenario; and the energy system is assumed to be decarbonising, so that emissions from EU electricity fall to near-zero levels, in line with the 2011 European Commission Roadmap 2050. Nonetheless, there is only a small net decrease in industrial emissions by 2050, to 530 Mt CO_2 (Exhibit 1.7).

The largest net growth in emissions in our baseline scenario occurs in plastics. This is only partly because consumption increases, but more because plastics contains substantial embedded carbon in the material itself, which is released as CO_2 when plastics are incinerated. Today, when plastics are burned instead of other fossil fuels, the net increase in emissions is relatively small. That would change dramatically in a decarbonised energy system, where the alternative would be zero-carbon energy sources. Thus, a continuation of the current shift towards burning plastics would result in substantial additional emissions in 2050. Accounting for those emissions as well as modest consumption growth, annual emissions from plastics are as high as 233 Mt CO_2. Clearly, the incineration of fossil-based plastics cannot continue in a low-carbon economy.

In the steel sector, on the other hand, emissions decline even in the baseline scenario. This is due to several factors: reduction in demand for steel as the EU steel stock stabilises, a gradual and substantial shift toward more secondary and less primary production, and the decarbonisation of electricity inputs to secondary steel production. The EU steel sector thus is already on a path to a more circular economy that would significantly reduce emissions reductions – but as we discuss below, there is potential to go much further than is possible with current practice.

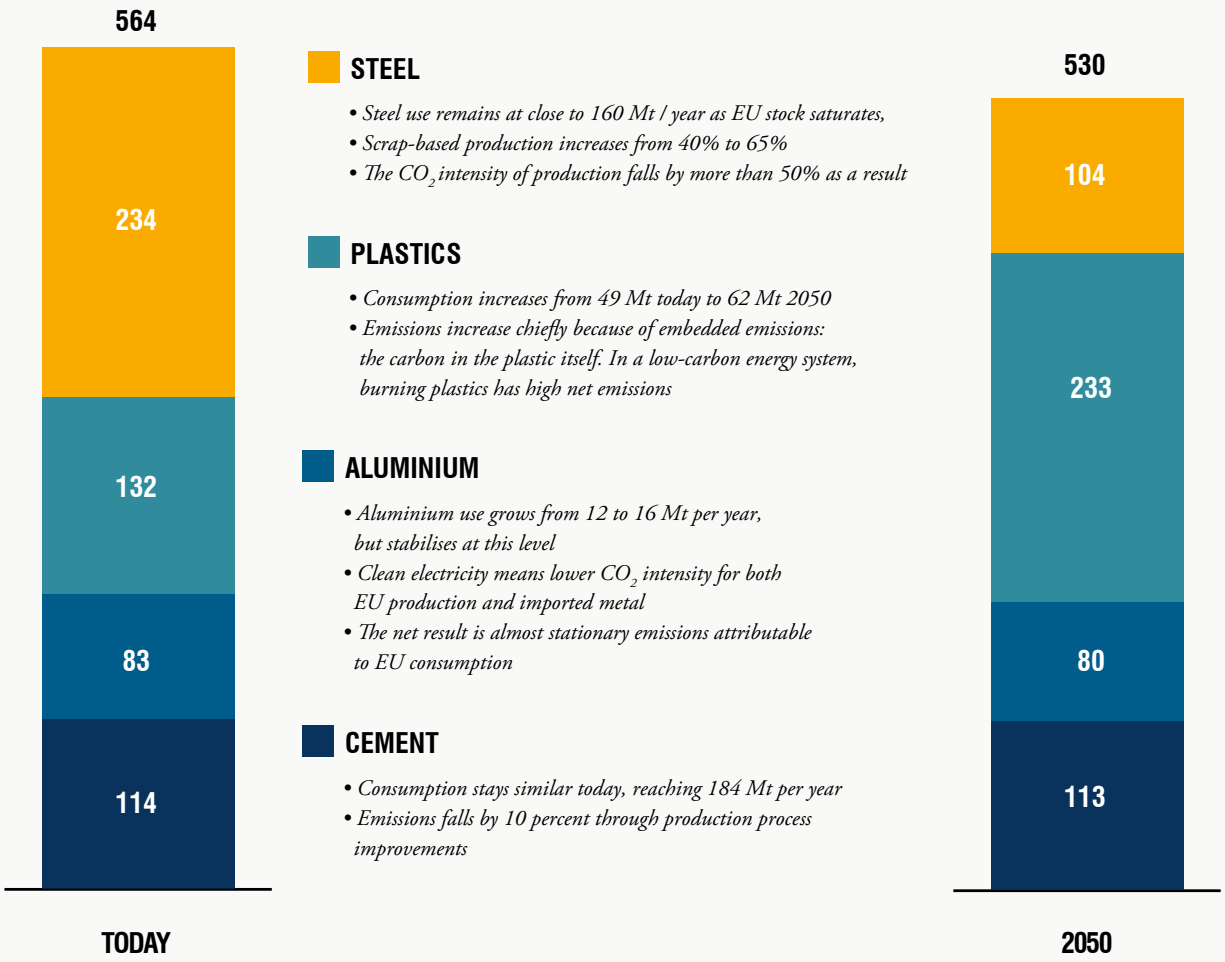
For aluminium, the combination of a higher share scrap-based production and the decarbonisation of electricity production more than offset the growth in emissions that would otherwise occur as the volume of aluminium increases. For cement, the baseline scenario shows a very small decline in emissions, as improvements in process efficiency slightly outstrip growth in demand.

The bottom line is that despite increased recycling, especially of steel, and the transformation of EU energy supply, emissions from materials production in 2050 would be largely similar to today. Achieving the much-larger reductions needed for a low-carbon economy will thus require strategies to reduce demand, even as new technologies are deployed to reduce industrial process emissions as well.

Exhibit 1.7

WITHOUT DEMAND-SIDE MEASURES, EU EMISSIONS FROM MATERIALS PRODUCTION BARELY DECLINE BY 2050

MATERIALS PRODUCTION EMISSIONS, 2015 AND 2050
Mt OF CARBON DIOXIDE PER YEAR, EU



STEEL

- *Steel use remains at close to 160 Mt / year as EU stock saturates,*
- *Scrap-based production increases from 40% to 65%*
- *The CO_2 intensity of production falls by more than 50% as a result*

PLASTICS

- *Consumption increases from 49 Mt today to 62 Mt 2050*
- *Emissions increase chiefly because of embedded emissions: the carbon in the plastic itself. In a low-carbon energy system, burning plastics has high net emissions*

ALUMINIUM

- *Aluminium use grows from 12 to 16 Mt per year, but stabilises at this level*
- *Clean electricity means lower CO_2 intensity for both EU production and imported metal*
- *The net result is almost stationary emissions attributable to EU consumption*

CEMENT

- *Consumption stays similar today, reaching 184 Mt per year*
- *Emissions falls by 10 percent through production process improvements*

SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT.

THREE CIRCULAR STRATEGIES WORK TOGETHER TO CUT EU INDUSTRIAL EMISSIONS

The demand-side potential includes a range of strategies. We include under the umbrella of 'circular economy' any opportunity to provide the same economic service with less primary material. In this section, we explore the potential associated with each of three categories of measures, which are further summarised in Exhibit 1.8.

- **Materials recirculation** opportunities provide more than half of the abatement potential, at 178 Mt CO_2 per year, by increasing the share of materials needs that are met by using recycled rather than primary materials. This means increasing both the volume and the quality of secondary materials.
- **More material-efficient products** jointly make up opportunities with 56 Mt CO_2 of abatement potential. These opportunities have in common that they reduce the total materials input required to produce a given product or structure, through lightweighting, reduced waste, high-strength materials, and other strategies.
- **New circular business models** could reduce emissions by 62 Mt CO_2. The main lever here is a large increase in the materials productivity of both mobility and buildings: increasing the benefits derived from each building or vehicle through shared use and measures to prolong their lifetime.

Exhibit 1.8

THREE CIRCULAR ECONOMY STRATEGIES MAKE BETTER USE OF MATERIALS AND PRODUCTS TO REDUCE GHG EMISSIONS

Materials recirculation *opportunities provide more than half of the abatement potential.*

1. MATERIALS RECIRCULATION STRATEGIES COULD CURB EMISSIONS BY 178 Mt CO_2 PER YEAR

From a circular economy perspective, Europe is a treasure trove of recyclable materials – those that have already been discarded, as well as millions of tonnes more that will become available as buildings, vehicles and products are taken out of service in the future. As shown in Exhibit 1.9, producing secondary materials through recycling results in far lower emissions per tonne than producing primary materials. Thus, every piece of scrap holds the promise of CO_2 savings. Across materials, realising the potential requires creating robust systems for collection, avoid contamination by additives or mixing of different qualities of materials, and producing materials of sufficient quality to serve as genuine substitutes for the corresponding primary material. However, the scope for increasing the reuse of different materials varies significantly:

- **Steel:** Current EU steel production is more than 60% based on primary production, i.e. produced from iron ore. However, a detailed analysis of steel stock evolution and scrap flows suggests that, in decades to come, the EU will approach the point where the need to maintain a near-constant stock of steel can be served to a large extent by recirculating steel that has already been produced. Doing so will require reducing losses of steel, changing how steel scrap is handled and traded, and avoiding contamination of the steel stock with copper, as we discuss below. The CO_2 prize is substantial, as recycled steel can cut emissions by 90% if using largely decarbonised electricity.

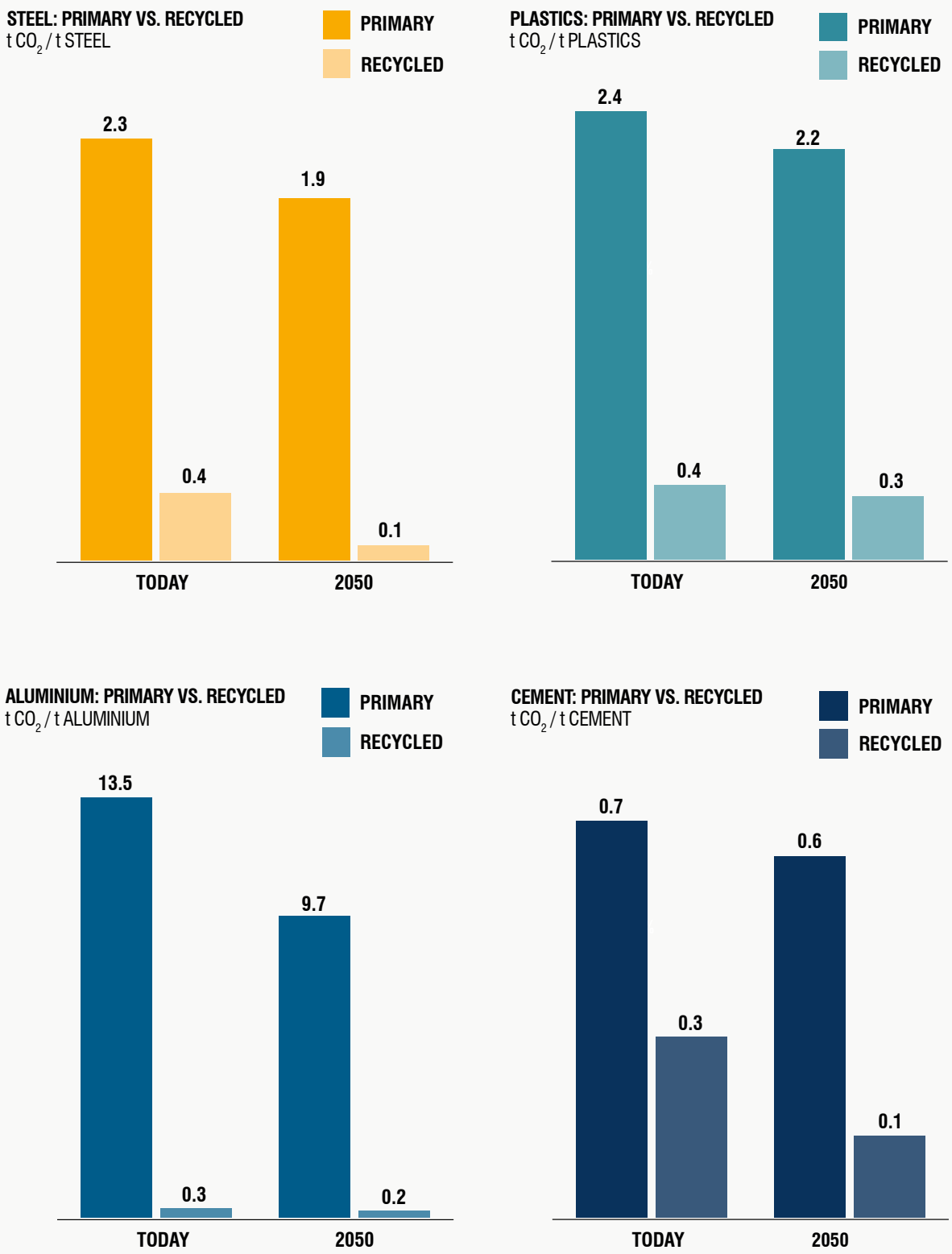
- **Plastics:** The largest potential to improve circularity is in plastics, where recycling rates today are low (recycled volumes are just 10% of plastics in the market), and CO_2 gains would be substantial. A detailed assessment of plastics categories and uses identifies opportunities to greatly increase recycling levels, especially for the biggest five plastic types that make up 70% of demand. More than half of plastics volumes could be recycled mechanically, and a further 11% through chemical recycling approaches.

- **Aluminium:** It is less certain to what extent the stock of aluminium will stabilise, but the amount of post-consumer scrap available will nonetheless increase. By 2050 potentially, post-consumer scrap generated in Europe could amount to as much as 75% of the production required to meet European demand. The opportunity is to enable the continued use of this scrap in a wide range of applications, so that it can replace a greater share of primary metals production.

- **Cement:** Cement cannot be recycled in the conventional sense, though structural elements can be reused. In addition, as we explain below, approaches are under development to recover unreacted cement from concrete, which can then be recycled into new concrete production.

Exhibit 1.9

MATERIALS RECYCLING CUTS CO_2 EMISSIONS FROM MATERIALS SIGNIFICANTLY



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SUBSEQUENT CHAPTERS OF THIS REPORT.

2. MORE MATERIAL-EFFICIENT PRODUCTS CAN CUT EMISSIONS BY 56 Mt CO_2 PER YEAR

The amount of materials required also can be reduced substantially through a range of approaches. One is to reduce the amount of materials that are discarded as scrap or waste in the manufacturing or construction process. For example, some 15% of buildings materials are wasted in construction, a share that can be reduced substantially through best practice. Another strategy is to use more advanced materials and construction techniques. High-strength steel, for instance, has the potential to cut materials use by 30–40% in a range of applications, from heavy machinery to buildings and furniture. It also is possible to save materials by reducing over-specification; by one estimate, as much as 50% of steel used in buildings is in excess to what is strictly required to meet structural needs. Finally, lightweighting of products can also be achieved by tailoring individual products better to specific uses; for example, while cars built for individual ownership typically need to be able to carry at least four passengers and some baggage, cars built for a shared fleet could vary in size, with many just big enough for a one- or two-passenger trip in the city.

3. NEW CIRCULAR BUSINESS MODELS IN MOBILITY AND BUILDINGS CAN REDUCE EMISSIONS BY 62 Mt CO_2 PER YEAR

The third pillar of the abatement potential is opportunities that increase the utilisation and prolong the lifetime of materials-intensive assets in the economy. In both cases, the same initial materials input can then provide a much larger amount of use benefits, whether passenger travel, or effective occupied square metres. The opportunity is most significant for personal vehicles; as we describe below, a system of fleet-managed, shared vehicles could require just 25% of the materials inputs of today's system of individually owned cars.

Fully achieving the potential gains in this category would require deep changes in how we deliver services and goods, which in turn would drive major changes in how vehicles and buildings are initially built and maintained. But the rewards would be substantial. As we elaborate below, there are major opportunities to boost productivity and achieve significant co-benefits for the environment, public health, and quality of life.

In practice, these broad strategies translate into a wide range of measures: from changes to product design and materials choice, to improved technology, larger scale in secondary materials industries, and even extensive changes in the value chains and organisation of mobility and buildings.

* * *

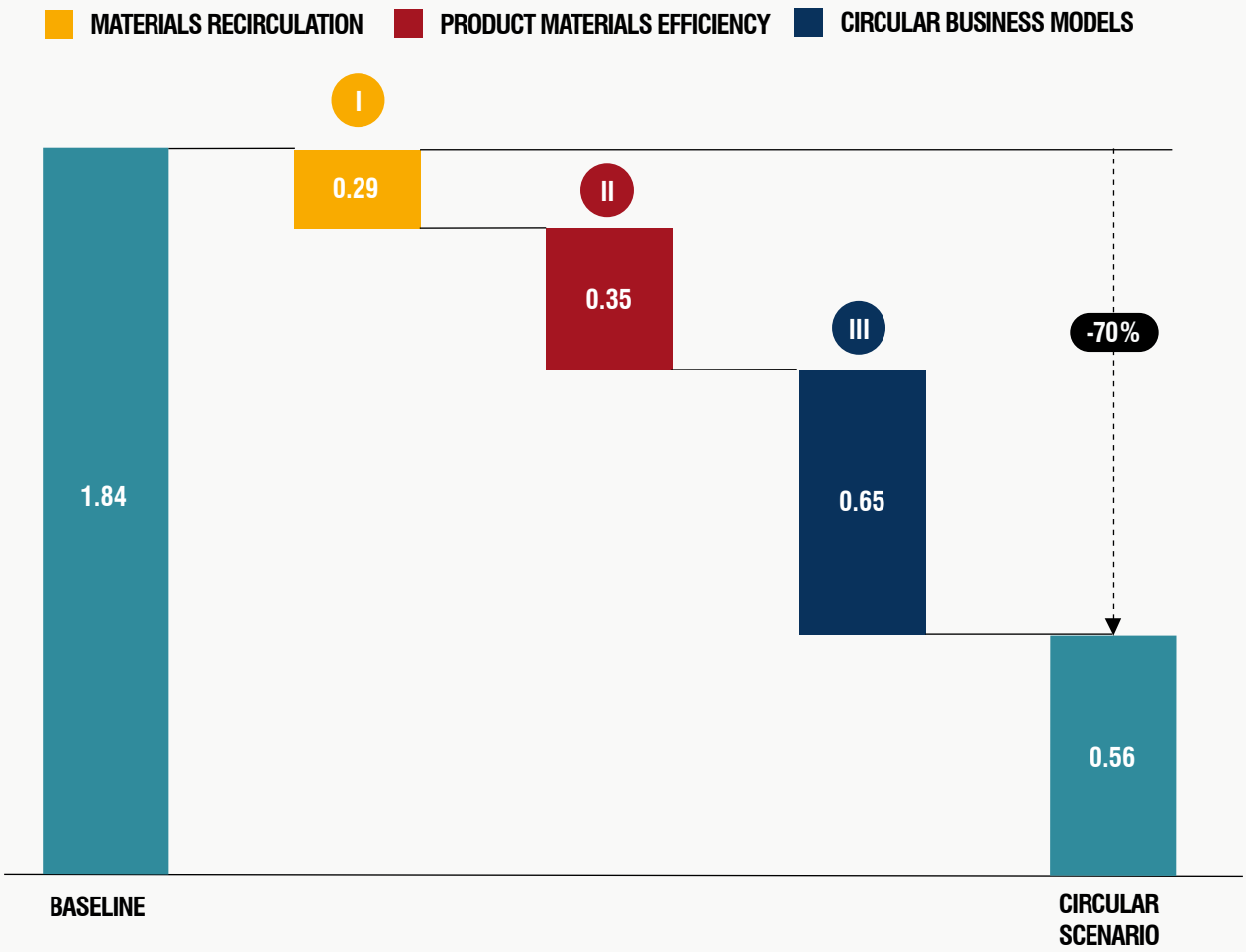
The benefits of circular approaches are strengthened by the fact that many of these measures work well together. For example, reducing the materials intensity of buildings and vehicles reduces the total steel stock needed, which secondary steel production needs to grow less to meet the demand. Likewise, new business models that boost the value realised from each product can drastically improve the economics of measures to make products more materials-efficient. Cumulatively, these opportunities can result in a step change in resource efficiency.

Tracing one material in one value chain makes clear the extent the opportunity. For example, circular strategies could jointly cut the amount of primary steel required to serve mobility needs by 70% (Exhibit 1.10). Put differently, the productivity of materials use has increased so that each tonne of steel supports more than three times as much transportation.

Exhibit 1.10

CIRCULAR MEASURES CAN REDUCE THE PRIMARY STEEL REQUIRED TO SUPPORT MOBILITY BY 70 PERCENT

PRIMARY STEEL USED FOR MOBILITY SERVICES
TONNE PRIMARY STEEL PER MILLION PASSENGER KILOMETRE



A circular scenario results in mobility services being provided with much less primary steel used per unit, through:

I MATERIALS RECIRCULATION
already is a major part of steelmaking, with secondary (recycled) steel making up around one-third of current global production. Still, there is much potential to increase recycling by improving collection rates, avoiding contamination with copper, reducing losses during remelting, and avoiding downgrading. Together, these measures could reduce the need for global primary steel production by another 14% by 2050, and as much as 80% in a more mature economy such as the EU.

II MORE MATERIAL -EFFICIENT PRODUCTS
can reduce steel requirements by some 30%. The first step is to reduce process losses; up to half of steel now ends up as process scrap rather than in the final product. A second step is to make cars in a much wider range of sizes, and to use more advanced materials that may cost more, but pay off when vehicles are used more intensively.

III IMPROVED PRODUCTIVITY OF USE
has particularly large potential for vehicles. Today's passenger cars use only 2% of their capacity, because they are parked most of the time and often carry only one or two people when used. Replacing a large share of personal vehicles with a system of fleet-managed, shared vehicles would mean that cars could not only be used more intensively, but such use would make a range of strategies feasible that extend their lifetimes. These include more durable design and higher-value materials, a greater share of intrinsically more durable electric vehicles, predictive and fleet-managed maintenance, and modular design for reuse and remanufacturing. The combination of sharing and longer lifetimes could almost halve the amount of materials needed per passenger-kilometre travelled.

NOTE: ANALYSIS IS BASED ON GLOBAL STEEL PRODUCTION.

DEMAND- AND SUPPLY-SIDE MEASURES ARE BOTH REQUIRED FOR DEEP DECARBONISATION OF INDUSTRY

The emissions reductions described above are net reductions, accounting for the inputs required to implement relevant measures, including transportation and electricity. The numbers highlight another advantage of these approaches: they can benefit from synergies with the decarbonisation of transport and electricity systems. The overall resource requirements also are modest when compared with the requirements for supply-side abatement – for example, the energy requirements are much lower per tonne material produced. The intrinsic higher resource efficiency of a more circular economy therefore pays off not only in reduced demand for primary raw materials, but also in terms of inputs for low-carbon energy, putting less strain on other aspects of the overall transition to a low-carbon economy.

Yet nothing in this report should be taken to mean that circular economy approaches should replace supply-side measures. Both are needed if Europe is to decarbonise its industry. Exhibit 1.11 shows the potential for demand-side emissions reductions combined with the potential on the supply side. Total 2050 baseline demand across steel, plastics, aluminium and cement is over 400 Mt per year, of which almost 300 Mt are primary materials. As noted earlier, even assuming the use of the best available technologies, energy efficiency improvements, the use of low-carbon energy, and circularity consistent with current trends, total emissions from the production of these materials would be 530 Mt CO_2 per year, barely changed from today.

The demand-side measures explored in this report would reduce primary materials needs by 173 Mt per year, and associated emissions by 296 Mt CO_2. If emissions are to be reduced by an illustrative 90%, that would still leave about 209 Mt CO_2 of emissions to abate. Supply-side measures are crucial to closing that gap.

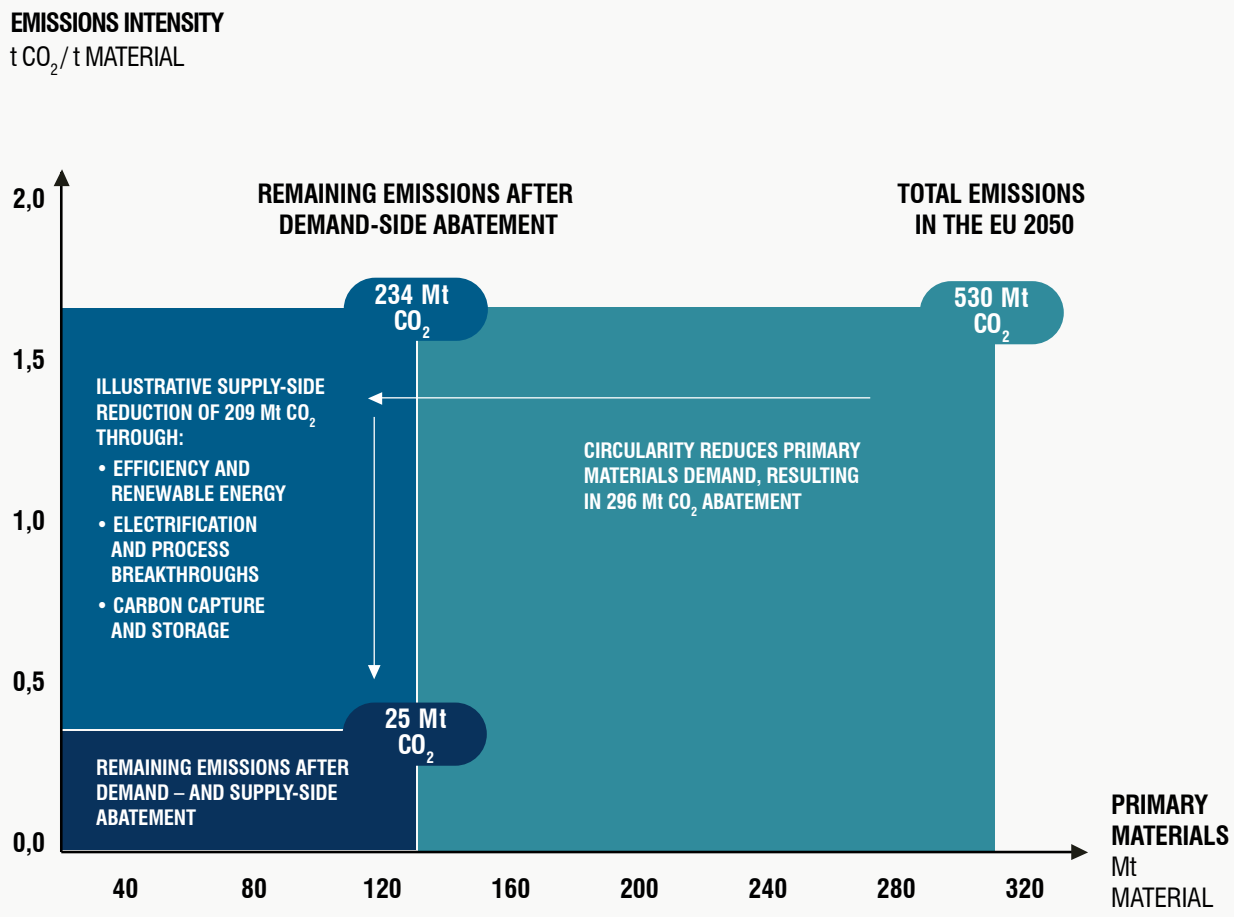
Sharply reducing emissions from materials production would require fundamental changes to industrial processes. Examples include replacing coal with hydrogen as an input to primary steel production, the synthesis of plastics from non-fossil feedstock (e.g. bioplastics), and novel cements. While there are promising options under exploration, they are at low technological readiness, and far from commercial use. Developing and deploying them is a major undertaking, with uncertainty both about which options will prove successful, and how long they will take to scale up. Additional CO_2 reductions may be possible through further energy efficiency improvements, wider use of renewable energy and electrification as well.

The other main option is to capture CO_2 from existing processes. This is being trialled at some industrial sites, but is still at demonstration phase. After more than a decade of active development, CCS still faces large challenges, including a lack of viable storage sites for CO_2, and the cost and logistics of fitting a large number of dispersed industrial sites with CCS technology.

Overall, circular economy opportunities thus substantially reduce the scale of supply-side abatement required, potentially providing the majority of the emissions reductions required for EU 2050 targets.

Exhibit 1.11

THE ROLE OF DEMAND- AND SUPPLY-SIDE MEASURES IN DECARBONISING EMISSIONS FROM MATERIALS PRODUCTION



GLOBALLY, A MORE CIRCULAR ECONOMY COULD AVOID 3.6 Gt CO_2 PER YEAR BY 2050

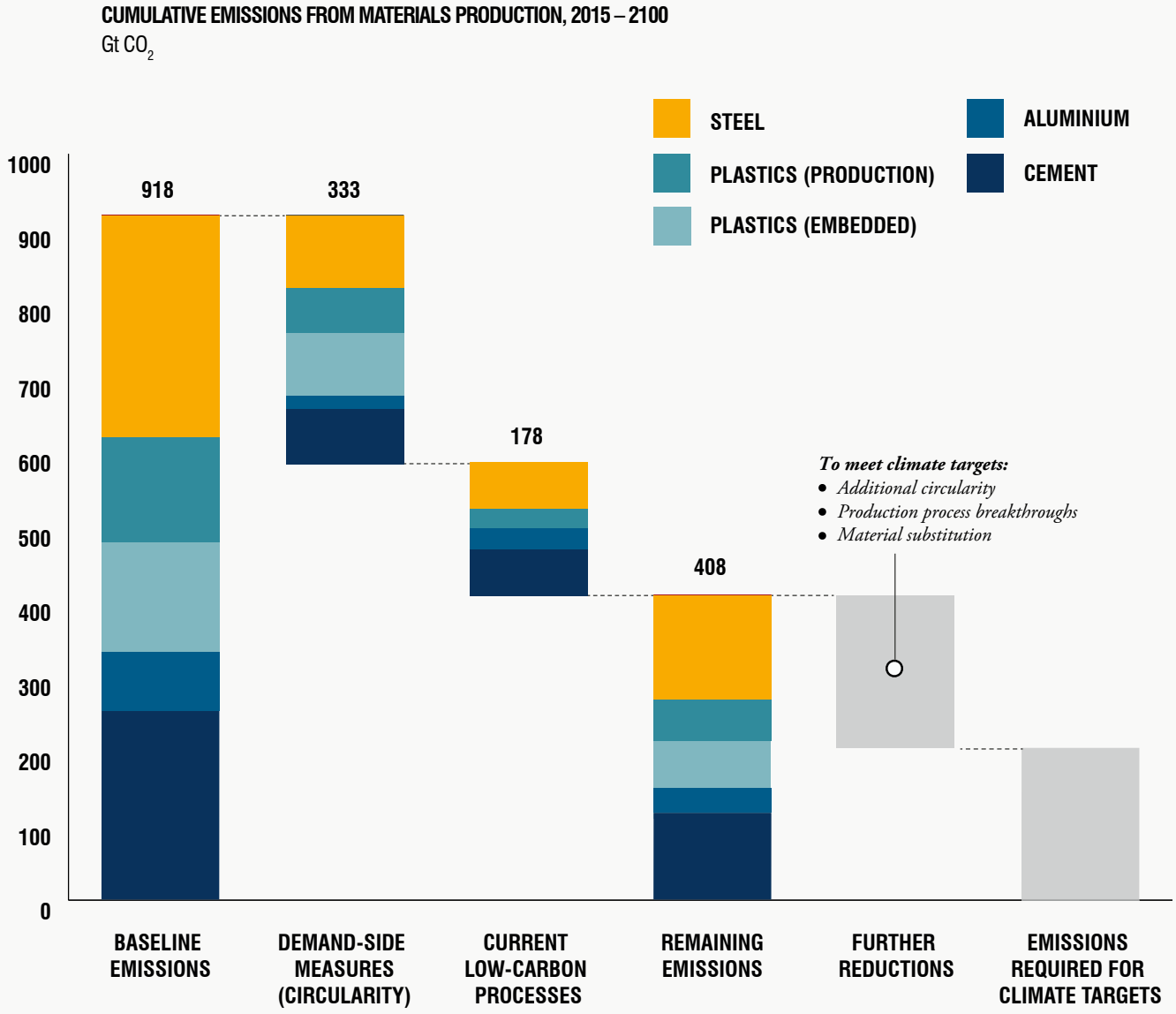
The EU is well positioned to pioneer many circular economy principles, especially those focused on materials recirculation. It helps to have large stocks of materials already available for recycling. Although there is potential for recycling also in developing countries, it is smaller when much of production goes towards building up the total stock.

Strategies focused on materials efficiency and productivity of use, on the other hand, could benefit developing countries at least as much as the EU. Instead of replicating the inefficiencies of the mobility and buildings systems of today's OECD economies, these countries can 'leapfrog' to more efficient technologies and business models. Making construction more materials-efficient, for example, is crucial for countries that are rapidly expanding their built area.

Altogether, we estimate the global abatement potential from circular measures at 3.6 billion tonnes of CO_2 per year by 2050, or nearly 45% of baseline emissions (increasing to 60% later in the century). This development course is one much more consistent with climate objectives; in terms of cumulative emissions to 2100, a more circular economy could cut 333 out of the 918 billion tonnes of CO_2 in the baseline scenario (Exhibit 1.12). Rapidly adopting current low-carbon technologies could cut another 178 billion tonnes, so that just over 400 billion tonnes remain. To meet climate objectives, emissions would need to fall still further – through additional circular economy measures beyond those investigated in this study, materials substitution, and the development and gradual adoption of even lower-carbon production processes than those available today.

Exhibit 1.12

A MORE CIRCULAR ECONOMY COULD CUT GLOBAL EMISSIONS BY MORE THAN 300 BILLION TONNES TO 2100



1.3 MANY CIRCULAR ECONOMY STRATEGIES ARE ECONOMICALLY ATTRACTIVE

In Section 2, we showed the substantial potential for circular economy strategies to reduce industrial emissions. The obvious next question is, are they cost-effective? In this section, we quantify the cost of different circular economy options; Exhibit 1.13 summarises our findings in a cost curve. One axis shows the abatement potential available, divided into groups of measures that add up to 296 Mt CO_2.[16] The other axis shows the estimated cost of each measure, expressed in EUR per tonne of CO_2 avoided.

It is striking how economically attractive many measures appear to be, with low and even negative costs. Many measures are economically attractive, if barriers to their implementation can be overcome; many others have a cost of no more than 50 EUR/t CO_2, less than many other ways to reduce emissions (including many supply-side opportunities for industrial emissions). We caution that this cost curve is indicative, with many uncertainties, and must be followed up with deeper analysis to improve the estimates. Nonetheless, the results show a clear potential for circular economy strategies to make very cost-effective contributions to a low-carbon economy. Moreover, ex-ante analyses of this kind often fail to capture many of the technological developments that will become available. In subsequent chapters of the report, we provide more details about the numbers underlying our analysis.

Some care is required in interpreting a cost curve of this type. While a negative cost shows that a measure can 'pay for itself' when viewed from a societal perspective, that does not mean that it will be implemented without policy action. If measures that have net benefits remain, it is because there are barriers or market failures that prevent their implementation. In such situations, the market will not act by itself, even if prices are favourable; policy interventions will be needed to overcome the barriers.

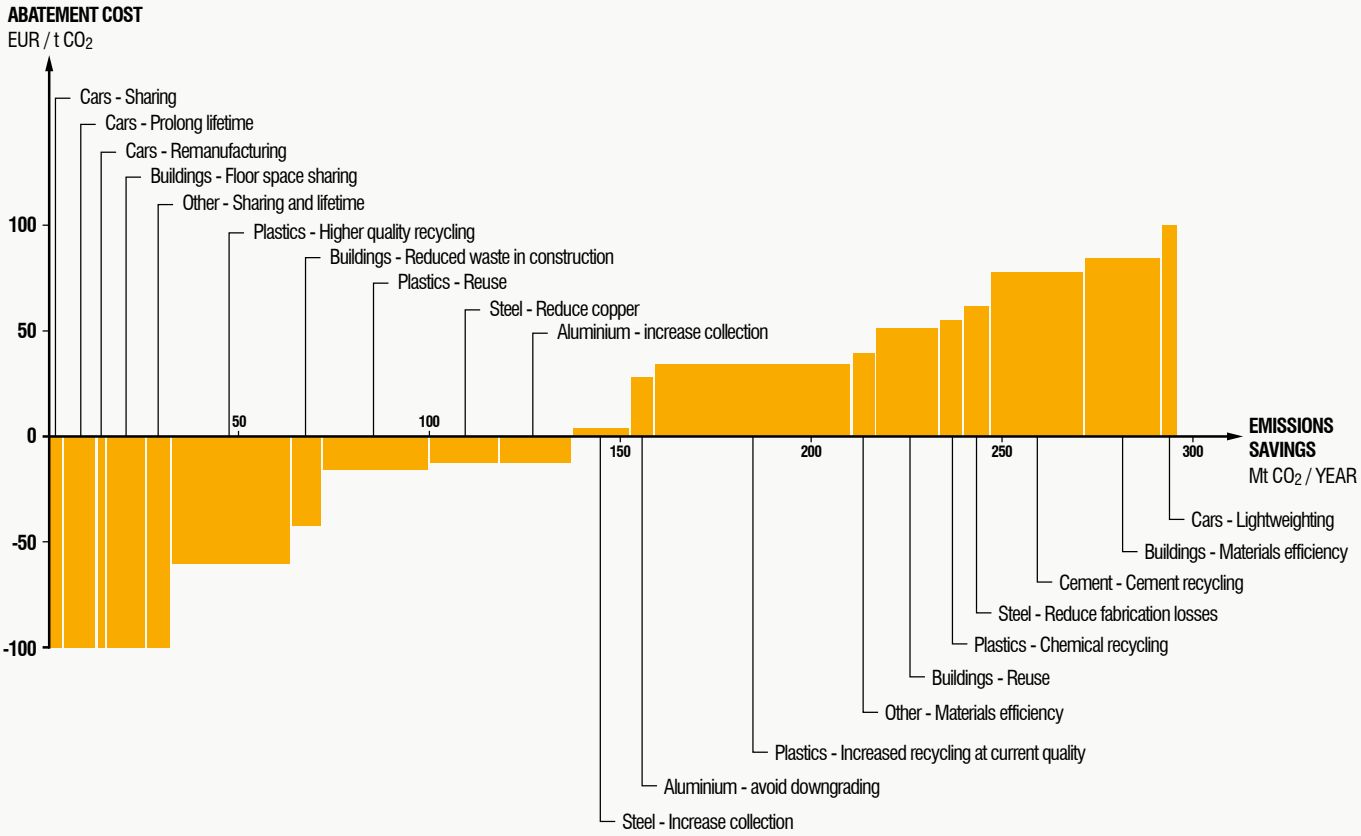
Some negative cost measures may also require systemic shifts in a value chain or sector. Car-sharing is a case in point; shared fleets of cars could lower costs significantly relative to individual ownership, but this would require a large-scale shift towards a different innovation focus and overall system for how to serve mobility. Realising the potential CO_2 and economic benefits therefore requires large-scale and systemic shifts, not just incremental change. A similar argument applies to high-value plastics recycling: negative costs are not available today, but depend on a combination of technical progress, change in the way that plastic is used in products and handled at end-of-life, and large scale in recycling activities.

To further understand the economic significance of different measures, it helps to distinguish the costs and benefits that arise in each category, see following sections.

Exhibit 1.13

A COST CURVE FOR CIRCULAR ECONOMY MEASURES TO REDUCE EU CO_2 EMISSIONS

ABATEMENT POTENTIAL AND COST FOR CIRCULAR ECONOMY LEVERS, 2050
Mt CO_2 PER YEAR; EUR PER t CO_2 ABATED



HOW TO READ THE CO_2 ABATEMENT COST CURVE

The CO_2 abatement cost curve summarises the opportunities to reduce CO_2 emissions through circular economy opportunities. The width of each bar represents the CO_2 potential of that opportunity to reduce CO_2 emissions in 2050, relative to a baseline scenario. It accounts for overlaps and interactions that arise when all the opportunities are pursued simultaneously.

The height of each bar represents the average cost of avoiding 1 tonne of CO_2 emissions by 2050 through that opportunity. In several cases, the cost is a weighted average across several sub-opportunities. All costs are in 2015 real Euros. The cost of abatement is calculated from a societal perspective (excluding taxes and subsidies), but does not account for reduced externalities or other benefits associated with the opportunities. The opportunities are ordered left to right with the lowest-cost abatement opportunities to the right and highest to the left. Both volume and cost estimates are of course uncertain in such a long timeframe

I. MATERIALS RECIRCULATION CAN BUILD ON HIGH-VALUE PRODUCTION OF RECYCLED MATERIALS

The economic attractiveness of materials recirculation depends in large measure on the capacity to retain the material value over the use cycle. Substantial values are created when materials are initially produced. If these can be retained and recovered, the CO_2 benefits of avoided primary production can be coupled to the industrial opportunity of preserving the intrinsic value of the secondary materials. This is why already, 83% of steel and 77% of aluminium is recycled. The CO_2 and other resource benefits in turn depends on the ability to produce high-quality secondary materials that are capable of substituting for primary materials.

For further recycling to be economically attractive, it is necessary to either reduce the cost of collection and secondary materials production, or to increase the value of the material produced. A key finding of our analysis is that the scope for high-quality secondary materials production is far from exhausted, for two main reasons:

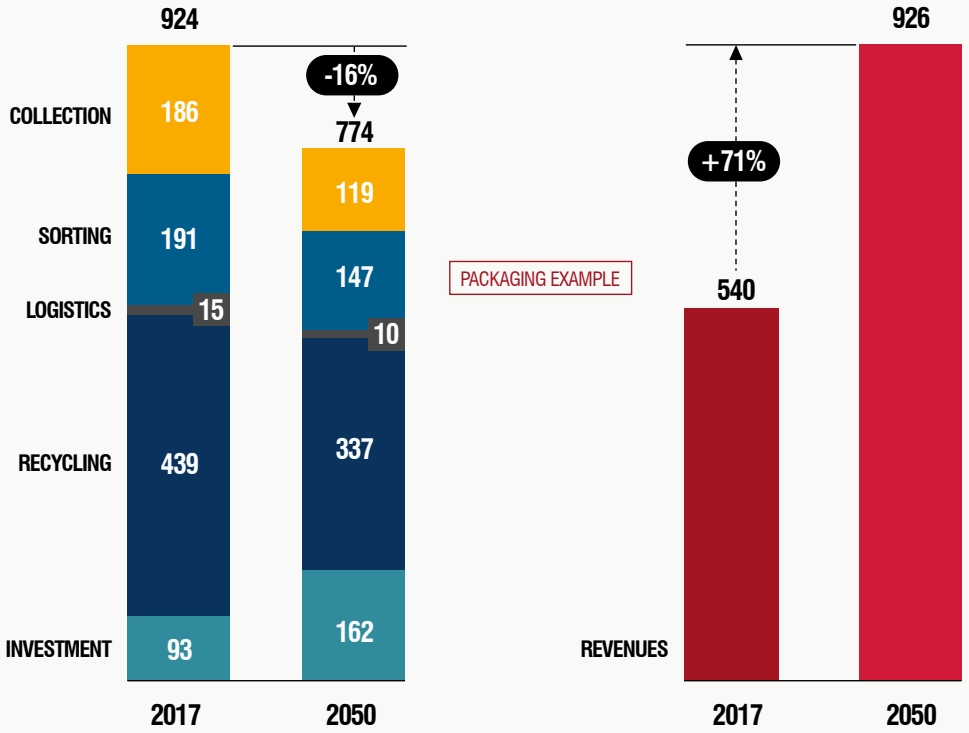
First, there are numerous barriers and market failures that now hinder what would otherwise be cost-effective materials recovery and secondary materials production. One major problem is that current processes for product design and dismantling, from cars to buildings and packaging, lead to significant materials degradation. Even minor modifications could capture large additional values.

Second, technology continues to improve, making circular economy measures more viable – through everything from advanced sensors, to automation, to information technology and mobile apps. The costs of technology also continue to decline, to the point that the value of the materials to be recovered would more than offset the cost of implementing the necessary tools.

Plastics recycling offers a particularly instructive example of the dynamic. Aging, additives, contamination, mixing of different plastic types and other factors conspire to hold back this market. As a result, recycling often results in low-value secondary materials produced at relatively high cost. In CO_2 terms, abatement costs are around 50–100 EUR per tonne CO_2. Even though plastics recycling rates as high as 30% are reported in the EU, the actual volume of secondary materials in the market is only 10%. As illustrated in Exhibit 1.14, a range of measures to improve the collection and processing of plastics for recycling could transform the economics. Once we have a system that retains substantial value, recycling plastics can become profitable, and take off on a larger scale. Our analysis suggests that this is feasible for the top five plastic types.

Exhibit 1.14

PLASTICS RECYCLING CAN BE MADE ECONOMICALLY VIABLE THROUGH A RANGE OF MEASURES



- ***Cleaner flows*** *from materials choices and product design optimised for recycling*
- ***Increased scale*** *reduces unit cost*
- ***Specialisation*** *and regional integration of markets*
- ***Technological improvement*** *boosts efficiency but* ***requires higher investment***
- ***Reduced risk*** *from regulations and market uncertainty*

- ***Increased yields*** *give larger revenues per tonne treated plastic (better technology, cleaner inflows)*
- ***Higher quality*** *enables pricing closer to virgin materials (additional sorting, improved technology, cleaner flows and optimised products)*
- ***Raised cost of virgin materials*** *improves willingness to pay for secondary products*
- ***Better functioning markets*** *reduce current commercial risk to buyers*

DEEP TRANSFORMATION THROUGH COORDINATED AND SUSTAINED ACTION ACROSS THE VALUE CHAIN

SOURCE: SEE CHAPTER 3.

2. MAJOR VALUE CHAINS COULD REDUCE THE AMOUNT OF MATERIALS REQUIRED FOR PRODUCTS

Measures aimed at using materials more efficiently cover a wide gamut and can vary significantly in the trade-offs between reduced materials use and other costs. What all these have in common is that they reduce materials use by changing production processes or product design – encompassing measures such as reduced process scrap in manufacturing, reduced materials waste in construction, more materials-efficient production techniques such as customised structural elements in buildings, and the use of high-strength materials.

The financial benefit is primarily the avoided cost of materials. The costs of the measures, on the other hand, can include factors such as larger inventories, smaller scale of operation, higher labour cost, or slower production. Interviews with market actors suggest that the balance between these two depends strongly on specific circumstances, and we therefore have been cautious with cost estimates in the above abatement cost curve. On the other hand, several companies indicated in interviews that they have found low-hanging fruit that enabled substantial materials savings without large costs.

For all the caveats, there are four broad trends that support a move to greater cost-effectiveness in improving materials efficiency:

- **Technical advances** can drastically lower the cost of reducing waste in production. A prominent example is 'additive' manufacturing methods such as 3D printing, which can almost eliminate production scrap. Another is advances in building information management systems, which mark and track construction materials much more closely, and have shown significant potential for reducing waste of materials in the construction phase.
- **Increased automation** can reduce the trade-off between materials efficiency and labour cost. This often is the limiting factor today; for example, a major reason for over-specification of steel in buildings is the additional labour cost of using more custom-made components. With automation of more of the construction process, this trade-off could be reduced.
- **Increased utilisation and lifetime** – as part of sharing models of mobility and buildings use – can justified the use of lighter but more costly materials, by spreading their cost over a much more extensive period of use.
- **Reducing the need for spare capacity** – a real possibility with new business models – would address a major driver of materials use today. Personal vehicles are a good example. Although most people rarely use every seat in their car, few would want to own a car that can only carry one or two people. However, in a system of shared fleets of cars, such vehicles would be more economically viable. A fleet could have some larger cars, and others designed for one- or two-person trips. In that context, 'lightweighting' could be achieved at scale at low or even negative costs simply by making smaller cars.

None of this means that increased materials efficiency will necessarily happen by itself. The materials footprint of products and structures often is low on the agenda today. But it shows that important CO_2 gains could be available without incurring very high costs.

*Steel use in buildings is **almost 50% higher** than what is strictly required to meet design specifications.*

3. NEW CIRCULAR BUSINESS MODELS COULD YIELD MAJOR PRODUCTIVITY GAINS AND CO-BENEFITS

Some of the most economically attractive options are to be found in circularity strategies that focus on using products more efficiently. Several of these measures would reduce CO_2 emissions at a significant net profit. This is because they involve making large systemic improvements to boost productivity in the value chains for mobility and for buildings.

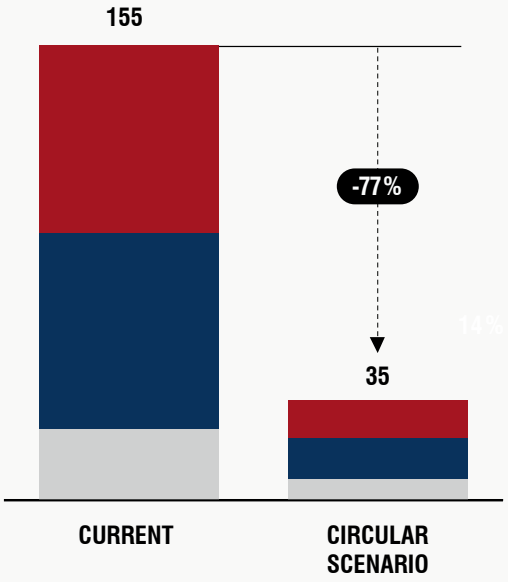
Today, large transaction costs undermine the economic efficiency with which we use key assets. The average European car is used at 2% of its capacity, and even during business hours, the average European office space is only used at about 40% of capacity. In contrast, a system of shared vehicles, designed to be optimised for intensive use and with much longer lifetimes, would spread the cost of cars over a much greater number of kilometres – with much lower costs as a result. Similar approaches could be taken to use buildings (and individual spaces within them) more efficiently, and to extend lifetimes (of whole buildings or parts) so that future construction activity could be reduced.

As we discuss below, the real issue with such system shifts is not whether they would be more productive and lower-cost – they undoubtedly would, as shown in Exhibit 1.15. Moreover, they could have substantial co-benefits, from lower pollution to reduced traffic congestion. However, they would constitute a major shift in how mobility and buildings use are organised. What the abatement cost analysis shows is that these shifts would make a major contribution towards a low-carbon transition, while also offering economic advantages.

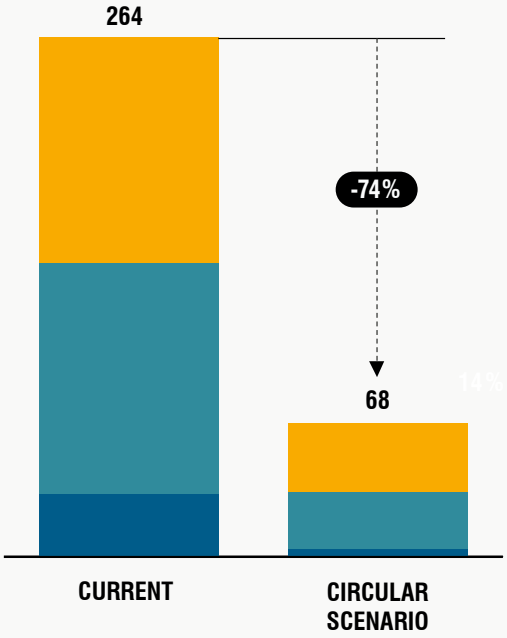
Exhibit 1.15

A SYSTEMIC SHIFT TOWARDS CIRCULARITY IS A MAJOR PRODUCTIVITY OPPORTUNITY – BOTH FOR INDIVIDUAL USERS AND SOCIETY

COST OF PASSENGER TRANSPORT
EUR PER 1000 PASSENGER KILOMETRES



CO-BENEFITS FROM A SHIFT TOWARDS SHARED CARS
EUR PER 1000 PASSENGER KILOMETRES



- COST FOR MATERIALS, MANUFACTURING AND DISTRIBUTION
- COST OF DRIVING, INCLUDING FUEL, INSURANCE, PARKING ETC.
- COST FOR MAINTENANCE
- COST OF SOCIETY, INCLUDING INFRASTRUCTURE, PARKING AND LAND
- COST FOR CONGESTION
- OTHER EXTERNALITIES, INCLUDING ACCIDENTS, NOISE AND AIR POLLUTION

- ***Shared car fleets and higher utilisation per car*** *lower cost per kilometre*
- ***Larger share of secondary materials and components*** *reduces cost for materials*
- ***Shared cars that are to a larger extent electric, autonomous and of smaller average size*** *reduce cost of materials and cost of driving*
- ***Longer car lifetime*** *reduces costs per kilometre, while more durable materials, autonomous cars etc. also have negative impact on cost savings*

- ***Fewer cars*** *due to higher occupancy per car result in improved air quality and reduce noise level and congestion*
- ***Autonomous cars*** *are safer, reduce need for signs, lanes and other infrastructure and can optimise trafic flows*
- ***More electric vehicles*** *reduce noise level and have positive impact on air quality, especially when shitfing towards renewable energy sources*

1.4 SEIZING THE OPPORTUNITY WILL REQUIRE LEADERSHIP AND CONCERTED ACTION

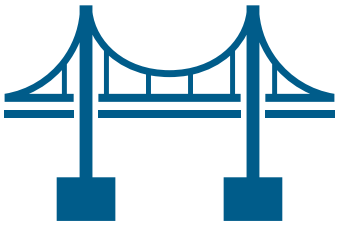
A key take-away from our analysis is that the potential of circular economy measures can only be realised if policy-makers and businesses actively pursue these opportunities. In this section, we lay out a broad implementation agenda. We start by describing in more detail what the concrete mitigation and industrial opportunity is in each materials category and value chain, summarised in Exhibit 1.16. We then turn to a discussion of the feasibility of different measures, barriers that need to be overcome, and key policy interventions needed.

Exhibit 1.16

ABATEMENT OPPORTUNITIES ACROSS MATERIALS AND KEY MEASURES

	ABATEMENT OPPORTUNITY	KEY MEASURES AND ENABLERS	CO_2 ABATEMENT
STEEL	**As the EU steel stock** saturates, there is potential to meet demand to a large extent through secondary steel production. In combination with low-carbon electricity, this makes possible deep cuts to emissions	**Enable high-quality** secondary production through more advanced scrap markets **Avoiding contamination** of steel by copper **Increase collection** of post consumer scrap **Reduce fabrication scrap**	41 Mt
PLASTICS	**Plastics recycling** is very low, despite high technical potential. Secondary plastics production driven by intrinsic materials value could see more than half of total plastics recycled	**Product design** that facilitates recycling **Large-scale** and specialised recycling operations and regional integration of markets **Technology** development for sorting, automation, and chemical recycling	117 Mt
ALUMINIUM	**Aluminium recycling** can be increased further by reducing losses of aluminium, process scrap, and by avoiding the downgrading of aluminium through the mixing of different qualities of metal	**Reduce collection losses** **Increase alloy separation** in scrap recycling to avoid downgrading and thereby increase the usefulness of secondary aluminium **Reduce scrap** forming during production	26 Mt
CEMENT	**Cement recycling** is at an early stage, but both re-grinding and re-use of building structural segments are now being trialled	**Increased development** of smart crushers and increased use of recovered concrete in construction **Development of local markets** for re-use of structural segments	25 Mt
PASSENGER CARS	**Materials in cars** have the potential to be more efficiently used when cars are shared and more intensively used	**Increased lifetime** and more durable materials will be keys to the economic logic of the sharing model **Vehicle size customized** for the number of people riding saves materials as cars can be smaller	19 Mt
BUILDINGS	**Material use for buildings** can decrease by 30% as they are used more efficiently	**Material savings** during construction by reduction of waste **Through engineering** for light weighting can less material be used **Development of local** markets for re-use of building components **Increased sharing** of space to reduce total floor space	55 Mt
OTHERS	**Similar CO_2 abatement** opportunities for other product groups, such as rest of transportation, machinery etc.	**Light weighting** to reduce materials per product **Development of local** markets for re-use of building components **Prolonged lifetime** Leasing models to increase utilisation	13 Mt

UNDERSTANDING THE OPPORTUNITIES AND BARRIERS ACROSS MATERIALS AND VALUE CHAINS



STEEL

The CO_2 abatement potential for steel use arises from the possibility that future EU steel needs could be met to a large extent by recycling existing steel. Current practice is not set up for this possibility, but instead requires a substantial share of primary production – both to replace steel that is lost at various points in the use cycle, and to compensate for downgrading of steel quality. By addressing these issues, the EU could transition to a much more circular steel system by 2050, replacing 30 Mt of today's 92 Mt of primary steel production by secondary production, and reducing emissions by 57 Mt CO_2 per year by mid-century.

Achieving this would require a major reconfiguration of EU steel production. The current industry reflects a long legacy of building up a substantial steel stock – i.e., the total amount of steel in use in the economy at any one time. This has required constant additions of new, primary metal. Primary production now accounts for nearly 60% of production, and the large majority of the sector's CO_2 emissions of around 230 Mt per year.

These parameters may change in decades ahead. The growth in the total stock is slowing and may well saturate in the next decades. At this point, demand is concentrated on producing steel to replace annual stock turnover of 2–3%. A detailed analysis of available steel stocks and flows suggests that the volume of scrap available will approach total steel requirements, likely by the 2030s. This is a major shift, with the prospect that, for the first time, an industrial economy could meet its steel requirements largely by recirculating the stock it has already built up. Given the much lower CO_2 emissions from secondary steel production, this also could drastically reduce CO_2 emissions from steel production.

Building such a circular system would require three main actions. First, current losses of steel need to be reduced by higher collection of process scrap and scrap from end-of-life products. Second, secondary steel production needs to improve to match the quality of primary steel. Today, secondary steel is disproportionately used for relatively basic construction steels, while for more demanding uses, primary metal is typically used. If secondary production is to serve also more demanding product groups, a more developed market is required, matching scrap inputs to secondary steelmaking with the needs and tolerances of high-quality steel production. This is doable, as demonstrated by several producers who rely on a combination of good control of scrap supplies and advanced metallurgy to make some of the highest-quality steels in the world – entirely from scrap. It also would create new sources of value and business opportunity in a more advanced scrap market.

Third, it is crucial to address the problem of copper pollution. Copper often enters steel scrap at the point of recycling, as products containing both steel and copper are dismantled. When cars are scrapped, for example, it is common for the steel to have more than 0.4% of copper content even after basic processing. This reduces the quality and potential uses of the secondary steel. Even levels of 0.2–0.3%, which are seen in several EU countries, lower the value of the steel. Moreover, once mixed in, copper cannot be separated from the steel with any commercially viable technique. To keep the quality of the steel stock, processes must be improved to dismantle products more carefully at end of life, to sort better, and to separate high-copper scrap from purer varieties. Design improvements can also make it easier to avoid cross-contamination of materials during recycling.

PLASTICS

Most plastics can be recycled and used multiple times, but as noted above, actual volumes of secondary plastics production amount to just 10% of total demand in the EU. A detailed assessment of plastic types and use categories suggests that 56% of plastic volumes could be mechanically recycled or reused, with the recovered material value paying for much of the cost. Another 11% could be recouped through chemical recycling techniques (such as pyrolysis and depolymerisation). Together, these measures would reduce emissions from 233 to 144 Mt CO_2 per year, compared with producing new plastics and incinerating them at end-of-life.

Indeed, plastics offer the greatest untapped potential identified in our analysis. It arises both because of the low starting point for recycling, and because the contribution of plastics to CO_2 emissions will grow drastically over time. Right now, the main alternative to recycling is incineration of plastics for energy recovery – essentially, using them as a fossil fuel, and in the process releasing as much CO_2 as was created when the plastics were first produced. Today the net emissions from incinerating plastics are rarely noted and arguably modest, as another fossil fuel would likely be used instead. By mid-century, however, heat and electricity production in a low-carbon EU would need to be largely emissions free. At this point, using plastics for energy production becomes a major source of fossil CO_2 emissions. Recycling helps avoid that problem.

To achieve recycling of 56% of plastics volumes (rather than the 10% we see today) will require change throughout the value chain. Above all, the potential for high-quality recycling must be built into the design of the main product groups. Better design can make it easier to separate different types of plastic, for example, and make used plastics easier to clean. This represents a major change from today's practice, where plastics recycling has sprung mostly from a waste handling logic, with little or no adaptation 'upstream'. In tandem, secondary plastics production must transition from today's fragmented and small-scale activity to large-scale operations that can reap substantial benefits of scale and enable specialisation. Finally, major investments are needed to accelerate the development of technologies to mark different plastic types, automate sorting and processing, and recycle plastics chemically.

Although these changes can seem daunting given today's low starting point, much can be gained by first focusing on three key product categories – packaging, automotive and buildings – and on the five plastic types that jointly represent more than 70% of plastics use. Over time, successful approaches can be rolled out more broadly to fully realise the potential for cost savings and CO_2 reductions.

Moreover, achieving this would have significant economic value: our analysis suggests that concurrent improvements in product design and materials choice; increased scale in collection and recycling, and improvement in underlying technologies jointly can substantially improve the economics of recycling. Much of it could be driven by underlying value of the material, or else have a low cost of abatement compared to many other measures to reduce CO_2. In tandem, a secondary plastics industry of this scale would have revenues of some 30 billion per year.

ALUMINIUM

The resource gains from recycling are particularly large in the case of aluminium, as remelting existing metal requires just 5% of the energy of new production. Moreover, the EU imports about one-third of its aluminium, much of it produced with coal-fired electricity and carrying a CO_2 footprint as high as 18 tonnes CO_2 per tonne of aluminium – almost nine times more than one tonne of primary steel.[17] Recycling aluminium can reduce CO_2 emissions by as much as 98% relative to this.

Reducing the need for primary aluminium, particularly imports, could thus yield significant energy savings and CO_2 reductions. We estimate that improvement on current practice could avoid 3-5 Mt per year of primary aluminium production that otherwise would be required to serve European demand by 2050, or 40-60% of the total. The CO_2 avoided could amount to 30-50 Mt CO_2 per year.

Two changes to current practice will be necessary for this. A first step is to reduce losses, which now amount to almost 30%. This requires higher collection and better end-of-life treatment for a range of products, alongside design of those products so that aluminium can be recovered.

It also will be necessary to improve recycling practice, as current methods result in irreversible downgrading that in time will become an obstacle to recycling. Specifically, today's aluminium recycling is an 'open loop': after first use, a variety of specialised aluminium alloys are often mixed together and used to produce cast aluminium. However, the recycled material has limited uses; most aluminium products need to be made from metal with much more tightly controlled alloy content. Over the next decades, a continuation of downgrading of aluminium therefore threatens to undermine recycling. This is even more so as cast aluminium is used primarily in components of internal combustion engine drivetrains of cars. As global markets shift more and more to electric vehicles, demand for cast aluminium could fall, even as more and more aluminium is alloyed to the point where it has no other uses than to make cast products.

In decades to come, continued aluminium recycling will thus require that additional flows of aluminium are kept in 'closed loops', so that metal can be recycled and used for the same purpose repeatedly, similar to current practice for beverage cans. As with steel, a continued circular system for aluminium would require product design that enables separation of individual qualities, more developed dismantling of products at end-of-life, advanced sorting technology, and additional deposit schemes.

Overall, aluminium therefore is yet another example of how a future circular system will require change of current practice, with large CO_2 benefits as a result. This also creates new opportunities for value creation, in preserving and monetising the inherent value in secondary materials.

PASSENGER CARS

As noted above, passenger cars offer a major opportunity to provide the same service with much lower materials requirements. We find that in a system where professionally managed, shared vehicle fleets meet two-thirds of travel demand, materials requirements could fall by as much as 75%, reducing annual CO_2 emissions associated with materials production by 43 Mt by 2050.

Today's cars are optimised for the use pattern associated with ownership by individual households. The result is overcapacity of individual vehicles (five-seat cars used mostly for one-passenger trips), and vehicles that are stationary 95% of the time. Vehicle design therefore also is optimised for this structure of use and ownership.

A car system built around professionally managed fleets of shared cars would change many of the underlying incentives. Sharing enables much more intensive use of each vehicle. Once the use of these fleets achieves sufficient scale, there will be enormous incentives for changes to the design of vehicles and for innovation. Higher utilisation justifies much more investment in upfront costs, from the higher cost of electric-vehicle drivetrains, to more advanced automation technology, or higher-performance materials. Professionally managed fleets in turn also enable much greater control over vehicle maintenance, parts inventory, reuse of components, and remanufacture. Sharing of vehicles also makes possible a much closer match of vehicle size to the needs of individual trips, thus reducing the average size of vehicles substantially.

These factors combined can reduce materials requirements dramatically. The average car would be smaller, far more durable, and better maintained. The initial design and materials choices would be optimised for much more intensive use. Combined with an electric drivetrain, the effective lifetime therefore could more than double. Lightweighting techniques that use advanced materials would be far more economic than when applied to a personal car. The same is true of using automation to reduce accident risk, and applying more advanced manufacturing methods such as 3D printing to reduce materials losses at the production stage.

Although we describe this primarily in terms of materials requirements, the main motivation for such a system is the much wider productivity opportunity that it represents. As noted above, we calculate that the cost per passenger-kilometre could be as much as 77% lower. Major externalities also could be reduced by three-quarters, including major costs from factors such as traffic congestion, air pollution and collisions. Although the pace of change will depend on many factors, not least travellers' expectations and norms about car ownerships, the analysis makes plain that the incentives are very strong.

BUILDINGS AND CEMENT

The EU buildings sectors uses as much as 1.6 billion tonnes (Gt) of materials per year, a number that is likely to grow as the total stock is slowly expanding, and a wave of post-war buildings will require substantial renovation or replacement in decades ahead. The CO_2 footprint is significant, and in the EU countries that have gone furthest in improving energy efficiency and decarbonising heat, the construction phase now accounts for as much as half of the lifetime CO_2 footprint of a building (with the use-phase the remaining half).[18] By 2050, we estimate that just cement, steel, aluminium and plastic used for construction would result in emissions of 230 Mt CO_2 if they were made with today's production processes. Demand-side measures could reduce this by 80 Mt CO_2 per year, or 30%.

The abatement potential springs from addressing significant underlying inefficiencies in the construction value chain. The building sector is characterised by multiple stakeholders with diverse interests and contract structures from design, through to construction and use. These result in deeply split incentives; for example, a common situation is that the client pays for materials, whereas the builder can only improve profit by reducing labour costs – skewing incentives strongly against strategies to reduce materials use. The rate of innovation and knowledge diffusion also is slow, as a result of high industry fragmentation, high workforce turnover, a project-based business, and low investment and R&D in a cyclical and volatile business. One marker of the inefficiencies is stagnant labour productivity, with no growth over the past 15 years (even as manufacturing productivity increased by a third).

Unsurprisingly, these features also translate to significant structural overuse and waste of materials. For example, an estimated 50% of steel used in buildings is in excess of what is needed to achieve the desired structural properties.[19] In some segments, utilisation of building space is very low; for example, some 60% of European office space is unoccupied even during working hours. Between 10–15% of delivered materials are not employed in actual construction process but wasted. Buildings often are demolished wholesale, even when structural elements (accounting for 85% of the GHG footprint of materials) have long remaining technical lifetime.

Key opportunities to reduce emissions include:[20]

- **Design for longevity and disassembly:** Much of the abatement potential lies beyond 2050 but requires action today to avoid saddling future generations with unnecessary construction needs.
- **Floor space sharing:** Sharing principles include communal space-sharing in residential settings, co-working offices, etc.
- **Reuse of existing buildings:** adaptive reuse (i.e. reuse of the building structure for a new purpose, e.g. office building becoming residential building), relocation of buildings (reuse of structure on a new site) and reuse of building components can save up to 70% of materials that otherwise would go to waste.
- **Materials efficiency:** reducing materials needed per building through new materials choices, new design of building components, less over-design, and new construction techniques.
- **Reduced waste in construction:** waste during construction can be reduced by 5–10% of total materials through increased standardization, improved planning and appropriate storage and transportation.
- **Cement recycling and reuse:** there is some potential both to reprocess concrete to recover some unreacted cement, and to directly reuse structural elements. Scaling these would depend on highly developed, local markets.

In many cases, these strategies are underused today not because they are inherently expensive, but because a range of barriers and split incentives prevent their deployment. This resembles the situation for energy efficiency in buildings, where the solution often has been to mandate minimum energy efficiency standards to capture potential that is cost-effective. In other cases, the business case does not stack up today, but could improve with new technology. The clearest examples are improved materials efficiency and reduced waste in construction, both of which are limited today by the concern to reduce labour cost. Digitalisation of materials management and automation of construction could significantly reduce the cost of techniques to reduce materials use.

OTHER VALUE CHAINS

Passenger cars and buildings jointly account for just under half of emissions from cement, steel, plastics and aluminium. However, many of the underlying principles also apply to other products, including heavy-goods vehicles, machinery in agriculture and industry, packaging, some infrastructure, and several consumer goods categories. The potential in these sectors is likely to be lower than the 75% reduction in the case of passenger cars, but a conservative analysis suggests that some 13 Mt CO_2 of additional abatement would be available in the EU through a range of circular economy strategies across additional transport, consumer goods, and infrastructure and construction value chains.

A NEW POLICY AGENDA TO REALISE THE OPPORTUNITIES

The opportunities explored above, cumulatively, would significantly reduce CO_2 emissions from industry. Moreover, as shown in Section 3, many of the options are economically attractive, powered by the inherently higher productivity of shared mobility systems and the savings from reduced waste and avoided materials costs. Yet it is also clear that multiple barriers stand in the way. Some, such as the problem of copper contamination of steel, will require sector-specific measures and specialised technologies; others, such as high-value plastics recycling, require much more alignment of incentives along value chains, from the initial design of a product to its end-of-life treatment.

Energy efficiency again offers a helpful example. As the barriers that hinder progress have been recognised, policy-makers have adopted a wide range of interventions to capture cost-effective potential – from aggregate targets, through to quota systems, financing mechanisms, subsidies, and detailed product-level standards and labelling schemes. Similarly, multi-faceted approaches will be needed to promote circularity.

Circular economy policy will require action across waste, transportation, and the built environment, as well as infrastructure, industrial and innovation policy. Some will cover familiar ground – such as effective waste management – but some will push policy-makers into unfamiliar realms and require learning and ingenuity. Along with EU-level policies, these measures will require national implementation as well as attention by cities and regional authorities.

As with other climate policy challenges, a concerted effort is needed to understand potentials, identify and test new approaches, recognise and avoid unintended consequences and undue costs, and coordinate efforts. The agenda may seem daunting at first, but in many cases, policy-makers can build on frameworks already in place.

Our analysis did not investigate the merits of specific policy instruments, so we do not offer specific recommendations. However, we sketch below the elements of this policy agenda at a high level, recognising that much more investigation is required to elaborate concrete policy proposals. Four broad approaches are needed:

1. Set the direction and recognise the potential of the circular economy as a major contributor to climate targets.

2. Create enablers: from publicly funded research, to infrastructure, to regulatory frameworks.

3. Level the playing field, to remove incentives to waste and improve the financial case for investment in circular economy measures.

4. Take government action across a range of areas, especially where government already is a major actor shaping outcomes.

Exhibit 1.17

ELEMENTS OF A POLICY AGENDA: EXAMPLES OF POTENTIAL MEASURES TO INVESTIGATE

	1. SET THE DIRECTION	2. CREATE ENABLERS	3. LEVEL THE PLAYING FIELD	4. TAKE GOVERNMENT ACTION
MATERIALS RECIRCULATION	• *Targets for high value recycling* • *Improved transparency and statistics for waste and recycling*	• *Support for innovation and technology development* • *Standards for secondary materials* • *Waste regulations and landfill bans* • *Regulation of long-term destructive practices (e.g. copper, additives)*	• *Carbon pricing* • *Extended producer responsibility* • *Quotas or other support for demand* • *Improved end-of-life handling (e.g. shredding, demolition)* • *Product design (e.g. Ecodesign directive)*	• *Public procurement* • *Waste regulation systems*
PRODUCT MATERIALS EFFICIENCY	• *Targets for efficient materials use and re-use in key sectors* • *Materials passports and documentation*	• *Information systems and platforms (e.g. BIM)* • *Labelling schemes for materials efficiency in construction etc.* • *Fund innovation and technology development*	• *Waste charges* • *Support for design for disassembly*	• *Stimulate re-use and recycling markets* • *Require high materials efficiency (re-use, design for disassembly, etc.) in public procurement*
CIRCULAR BUSINESS MODELS	• *Improved evidence base and conviction about benefits of shared mobility and buildings* • *Endorse shared mobility systems as target vision*	• *Create supportive city regulations (e.g. parking for shared cars)* • *Revise barriers in existing regulations (e.g., insurance)* • *Adapt data regulations to support in new business models*	• *Pricing or regulation of congestion, air pollution and other externalities* • *Include efficient materials use or labelling in building standards*	• *City plans for longevity and adaptability of buildings* • *Integrate car sharing with public transport systems*

1. SET THE DIRECTION

The potential of circular economy measures to contribute to climate targets is far from recognised in current climate or industrial policy. Climate action plans at international, national, or city level make no or little reference to this agenda. Thus, as a first step, there is a need to focus the attention of policy-makers, civil society, researchers and business leaders. Policy can help by clarifying the intention to incorporate circularity among other aspects of EU climate and industrial policy.

The EU's '20-20-20' 2020 targets for emissions reductions, renewable energy and energy efficiency provide inspiration in this regard. Although some criticise the mixing of many targets, the long-term commitment has also been a significant catalyst in changing expectations about the direction of the energy system. At the time of the targets' introduction in 2009, there was considerable doubt and disagreement about whether renewable energy would be a major factor in the energy system over the next decade. The targets agreed by EU Member States coordinated efforts to ensure that it would be, and made a major contribution towards channelling the investment, supply-chain industrialisation, and innovation that, in turn, helped drive down costs. Today, many assessments indicate that a largely renewable energy-based electricity system is not just feasible, but potentially available at a cost similar to one run on fossil fuels. A strong political signal was part of what made that possible.

The circular economy needs a similar articulation of ambitions. From a CO_2 perspective, the key aim is to develop business models and industry structures that enable us to maintain our modern economy and living standards with much lower levels of primary materials production. That, in turn, requires a) secondary materials production, b) improved materials efficiency in major product groups, and c) increased lifetime and sharing of materials-intensive capital assets in the economy. Setting targets for these would be a good starting point for the EU.

In parallel, policy-makers can help ensure that they are moving in the right direction by kick-starting a major knowledge effort on the circular economy. Hundreds of times more research has been done on energy efficiency than on the efficiency of materials use. We need new knowledge to ensure that long-term policy is based on a much fuller understanding of the potential, the barriers, and the economics of circular economy measures.

2. CREATE ENABLERS

The circular economy will be built mainly by the private sector: the companies that produce major materials, the manufacturers, construction firms and consumer goods sellers who put the materials to use, and waste management and recycling firms. The crucial role of the public sector in this context is to facilitate and encourage private action.

One key way to do this is to stimulate innovation. Technological advances are making circularity measures more viable than ever before. Opportunities to capture value abound: from platforms for car-sharing, to autonomous vehicles, to sensor and sorting technology for scrap metals, tracking of materials inflows to buildings, chemical marking of plastics types for easy sorting, automation of construction processes, automated disassembly of complex products, chemical recycling technologies, methods to remove copper from steel, etc. EU companies that seize these opportunities could position themselves as future global leaders. Private actors may not yet be ready to make major investments in these innovations, however. The public sector can step up the pace by funding R&D and early deployment.

Regulations may also need to be adapted or introduced to enable circular economy opportunities. As ever, regulatory approaches must be weighed carefully, to balance different objectives. Areas of waste regulations to consider include how to handle current incentives for incineration of waste; the impact of additives and toxicity on plastics recycling; 'end-of-waste' policy that can result in obstacles to the trade of secondary materials; and how to ensure clarity about ownership of and access to end-of-life materials. Standards can offer another area of development, and especially to encourage European or international standards for secondary materials.

Other regulatory areas to investigate include measures to increase transparency and reporting. For example, would it be warranted to introduce reporting and tracking of materials efficiency metrics or the materials content of buildings, much like energy performance or safety standards are today? Or would the impact be limited, and costs large? Several reports on the circular economy have also proposed that the EU expand its Ecodesign directive to consider materials more systematically, whereas others have considered this too intrusive an approach.

Policy also has strong influence on many of the enablers for new business models based on sharing vehicles or buildings. These often are data-intensive, and sound approaches to data protection and cybersecurity can be a major factor in their long-term viability. Likewise, infrastructure and local policies (from parking rates, to congestion charges and city planning) strongly influence mobility choices, as can public regulations that influences insurance, liability laws, etc.

3. LEVEL THE PLAYING FIELD

To a great extent, market conditions today are skewed in favour of waste and against materials efficiency and reuse. To improve the business case for more circular business models, the financial incentives will need to change.

The fact that so many negative-cost opportunities have yet to be seized suggests that carbon prices and related tools will not be enough. Many of the relevant materials are internationally traded commodities, making it difficult for the EU to unilaterally introduce carbon prices at the levels required for deep cuts to emissions – whether on the supply or the demand side. But even high carbon prices may not suffice, because many of the barriers are non-financial. Existing regulations also steer key sectors such as buildings and waste management in ways that may encourage or discourage circularity. Thus, while a carbon price can help, policy-makers will need to do much more to unleash the full potential.

A major issue is how best to provide incentives to manufacturers to account for the impact of materials and design choices on component and materials values at the product's end of life. To date, the main approach has been 'extended producer responsibility', but in practice its implementation provides little incentive to modify product design. The externality therefore remains largely in place, and it should be a priority to consider creative approaches for how it can be addressed.

This report has not evaluated which way would be the most promising way forward, and therefore does not provide specific recommendations. To give a flavour of the options that have been proposed, one possibility is that new marking and sensor technology could enable systems that create more individual product responsibility incentives. If recycling companies can distinguish products from different manufacturers, they could then also in principle pay different amounts, depending on how adapted the products are for reuse or materials recovery. Another idea that has been floated is to introduce a system of charges or subsidies that mimics differentiated producer charges, depending on the costs that different design choices impose at end of life. If workable, these solutions could avoid some of the risks with more direct regulation of products, but they also carry their own complexities.

A second approach is to create demand for recycled materials or materials-efficient products. The 'pledging' initiative in the Commission's Plastics Strategy, where companies commit to using recycled plastics, is one attempt to create a basis for investment in additional recycling capacity to create high-quality secondary plastics. Research has identified a quota system for recycled content as a possible option, similar to quotas for renewable energy and energy efficiency. Another proposal is to support nascent markets directly (e.g. reused structural building segments, recycled cement, recycled plastics), through subsidy schemes or other mechanisms. Although these different options show the range of available possible instruments, significant additional investigation would be required to evaluate first whether such stimulation of demand is warranted, and if so which options are best suited for different markets and specific situations.

Policy intervention may also be required to limit 'rebound' effects that can arise from increased efficiency. Rebound arises when the savings from increased efficiency lead to increased consumption. This is well known in energy efficiency policy, but has been explored less for materials. An example would be the possibility that much lower cost of transportation in a shared car system leads to increased travel and reduced public transit use – already a challenge in some cities. Another risk is that the availability of inexpensive recycled materials (particularly if they are of low quality) will lead to increased consumption. Policy interventions can reduce rebound effects, even if they cannot be fully avoided.

4. TAKE GOVERNMENT ACTION

Finally, government can also be a principal actor to enable the transition to more circular outcomes. The public sector is both a major provider and user of mobility services, owner or operator of much of the built environment, and buyer of a range of materials-intensive products. That means governments are well positioned to push the market towards a more circular economy through their own investments and purchases.

Government also already is a major shaper of outcomes for transport systems and the built environment, particularly through decisions taken at the city level. One priority is to ensure public transport systems are integrated with shared car systems. City planning also influences the nature of buildings. As the potential for reduced materials use shows, issues such as materials efficiency and flexibility in the building stock are strong contenders to be considered alongside more traditional issues such as the density of occupation, social issues, etc.

Public procurement is another area open for consideration. Starting to incorporate recycled content and materials efficiency into purchasing decisions could help boost nascent markets. As with other proposals discussed here, further evaluation is required.

* * *

A common concern about the transition to a more circular economy is that it requires 'systemic' change, which is seen as difficult if not infeasible. It is true – realising the full potential described in this report would require transformative change. But what is most exciting about this opportunity is that smaller, manageable policy packages, combined with an ambitious vision for the future and strong political will, could unleash a wave of innovation and new investment that pays off for generations.

2. STEEL

TOWARDS A CIRCULAR STEEL SYSTEM

Steel offers particular promise for a circular economy. Already today, one-third of the steel we use comes from recycled metal, and the analysis presented here shows that within five decades, secondary steel could meet nearly half the world's steel needs. In fact, even with rapid global economic growth, future growth in steel demand could be met largely by reusing steel, with primary steel production held steady. The climate benefits would be significant: that level of recycling would cut the average CO_2 emissions per tonne of steel produced by 60%, reducing overall emissions from steelmaking by nearly 4 billion tonnes of CO_2 per year by the end of the century.

For the EU, the opportunity is even more immediate. Europe already has a large stock of steel, near the saturation point. Our analysis shows that if downgrading of steel is avoided, secondary steel production could meet as much as 85% of the EU's steel needs by 2050. That would be a remarkable achievement: for the first time, a major industrialised economy could meet its needs for a fundamental material almost entirely through recycling. CO_2 emissions from steelmaking would drop by 80% from current levels if low-carbon electricity is used. Thus, the EU would approach a CO_2-free steel sector in Europe – a global first.

Realising this opportunity will require significant changes to minimise losses in volume and quality from one use cycle to the next. The contamination of steel with copper could pose particular challenges. EU secondary steel production would also have to be restructured, while continued primary production would be more focussed on exports. However, the industry already faces major challenges: global over-capacity, flagging profitability, high CO_2 emissions, and the threat of tariffs. A circular steel economy offers a promising path forward by boosting productivity and making the EU a pioneer and leader in the technologies of the future.

Available scrap could cover ***85% of EU steel*** *needs by 2050.*

2.1 UNDERSTANDING FUTURE STEEL NEEDS

Steel is used across all areas of a modern, industrial economy. About half the steel produced today is used in construction and infrastructure; another 16–17% each in transportation and machinery and electrical equipment, and the remaining 15% in a variety of metal products and appliances.[1] With few exceptions, the benefits from steel derive from the total amount of steel available, and the services this steel stock enables: shelter/buildings, infrastructure, mobility, urban development, industrial production, and more. Steel flows, such as annual production, have little benefit except by enabling societies to develop and maintain this stock.

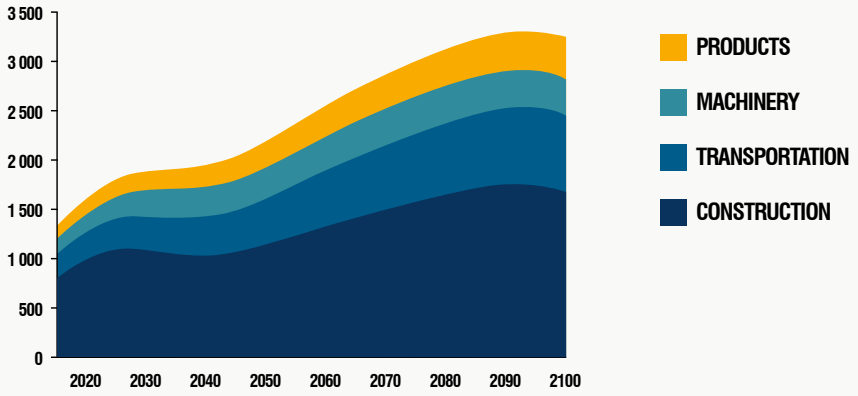
The analysis presented in this chapter focuses on the EU, but to understand the developments in one region, one needs to also take a global view. There is significant international trade in raw materials, steel products and scrap, and steel firms operate across borders. Global growth in steelmaking today is driven mainly by developing and emerging economies, as they build up their stock of steel: the total amount of steel available in the economy. In mature economies such as the U.S. and EU, this stands at about 11–14 tonnes per person[2], and steel demand is already driven largely by the need to replace older products or structures. In much of the world, however, there is still a large unmet demand for steel, with stocks ranging from about 5 tonnes per capita in China, to barely 1 tonne in much of Africa and India.[3]

We estimated future demand for steel by quantifying the production levels needed to enable the entire world to gradually transition to per-capita steel stocks similar to those in OECD countries, following similar patterns of use (see Exhibit 2.1 for an explanation of our methodology).[4] Steel production would have to rise steadily, to 2.5 times the current level. CO_2 emissions levels increase less, in part because production technology improves but mostly because there is a shift towards more recycled steel even in a baseline scenario. These are not best understood as forecasts, but as an illustration of what would be required if the current pattern of steel use in mature economies were adopted globally. As we discuss elsewhere in this report, this may not be necessary: steel needs could fall sharply if we could make do with less steel to provide the same mobility, shelter, or other services. Also, as we elaborate below, it is possible to reduce losses and increase the share of recycled steel beyond such a 'business as usual' development. On both counts, there is significant potential to reduce the need for primary steel production, and therefore also CO_2 emissions.

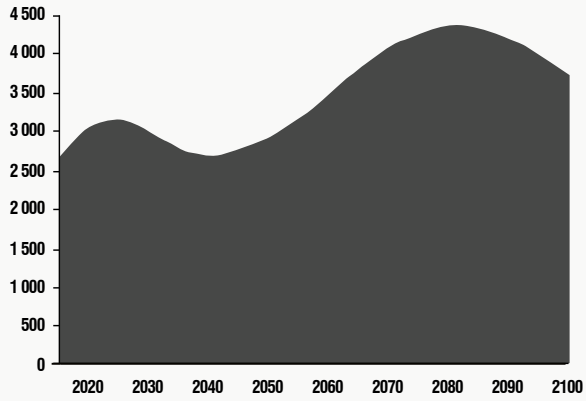
Exhibit 2.1

BASELINE PROJECTIONS FOR STEEL DEMAND, EMISSIONS, AND PRODUCTION

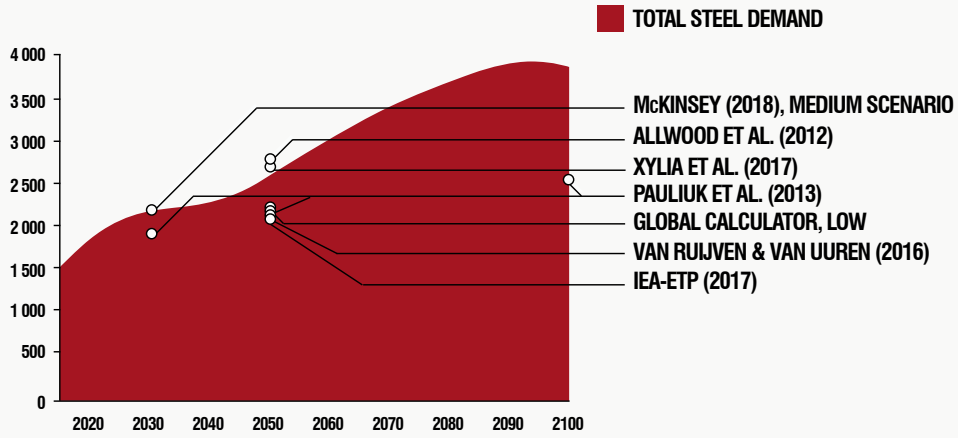
DEMAND BY PRODUCT GROUP
Mt STEEL PER YEAR, 2015-2100, GLOBAL



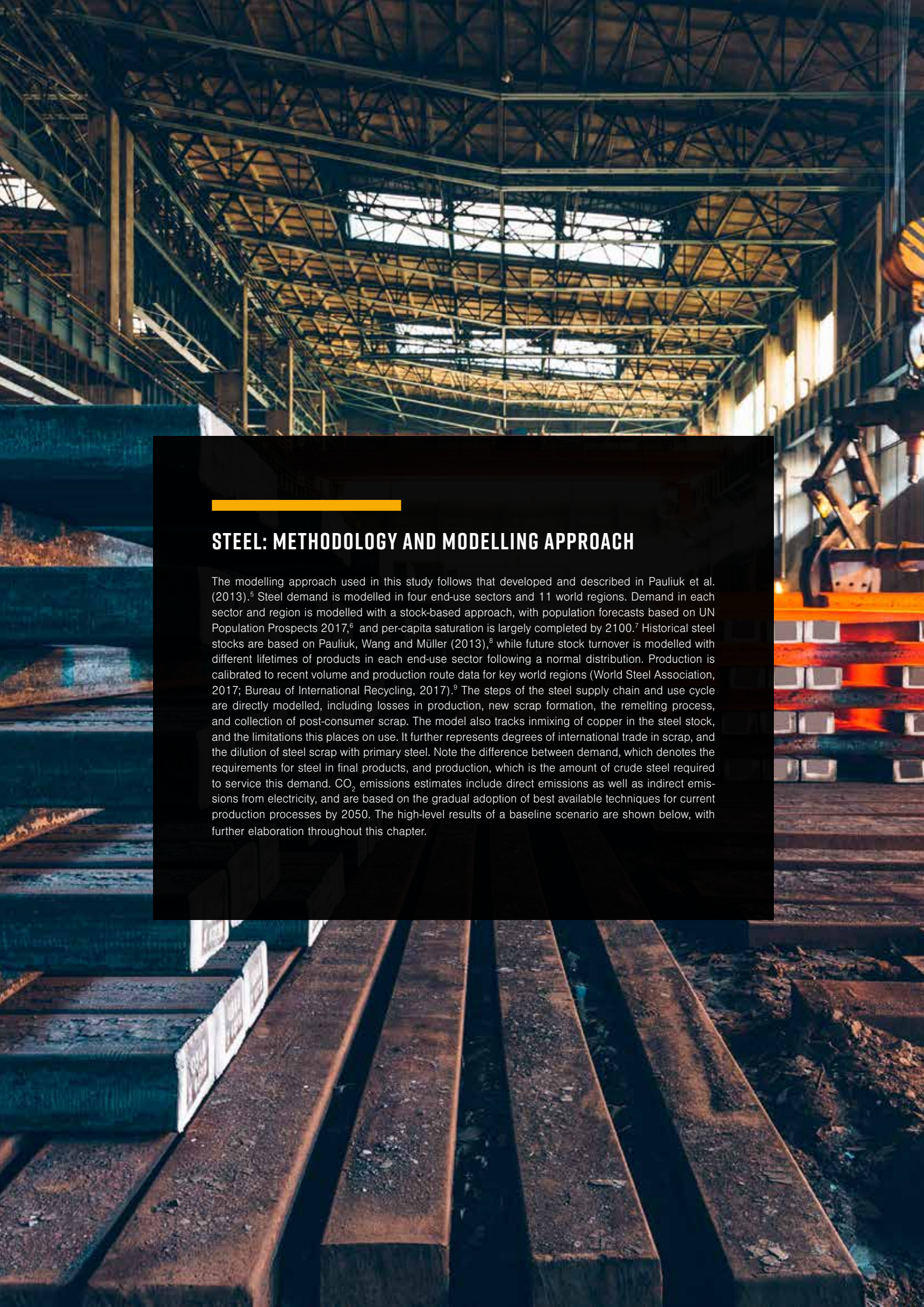
CO_2 EMISSIONS
Mt CO_2 PER YEAR, 2015-2100, GLOBAL



PRODUCTION PER ROUTE
Mt STEEL PER YEAR, 2015-2100, GLOBAL



SOURCE: PRODUCTION PROJECTIONS FROM MULTIPLE SOURCES.[10]



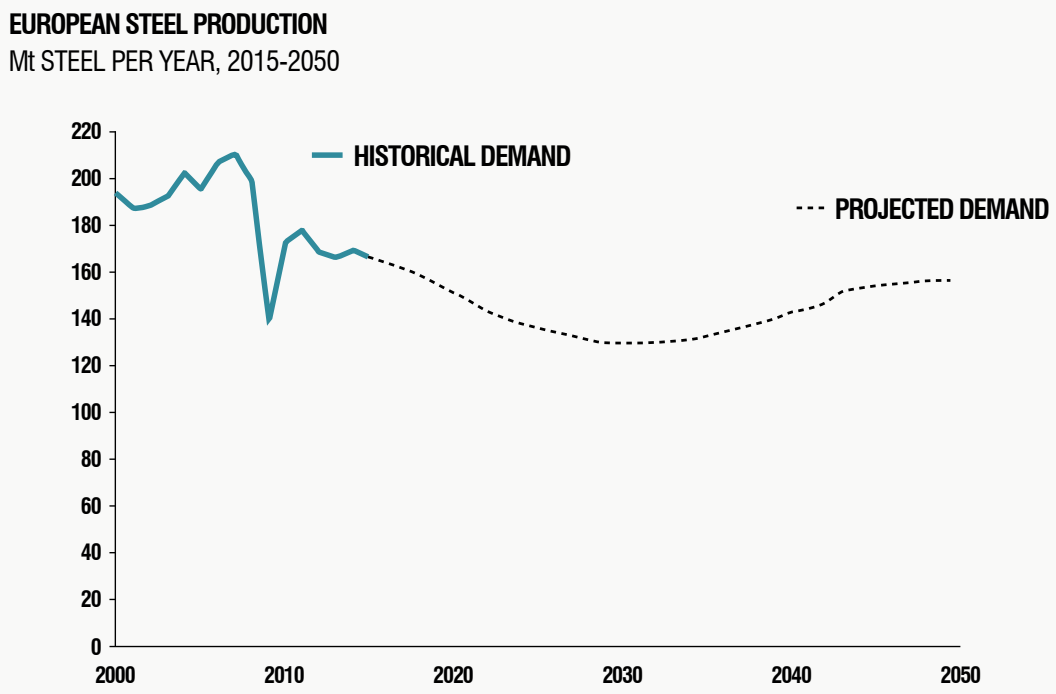
STEEL: METHODOLOGY AND MODELLING APPROACH

The modelling approach used in this study follows that developed and described in Pauliuk et al. (2013).[5] Steel demand is modelled in four end-use sectors and 11 world regions. Demand in each sector and region is modelled with a stock-based approach, with population forecasts based on UN Population Prospects 2017,[6] and per-capita saturation is largely completed by 2100.[7] Historical steel stocks are based on Pauliuk, Wang and Müller (2013),[8] while future stock turnover is modelled with different lifetimes of products in each end-use sector following a normal distribution. Production is calibrated to recent volume and production route data for key world regions (World Steel Association, 2017; Bureau of International Recycling, 2017).[9] The steps of the steel supply chain and use cycle are directly modelled, including losses in production, new scrap formation, the remelting process, and collection of post-consumer scrap. The model also tracks inmixing of copper in the steel stock, and the limitations this places on use. It further represents degrees of international trade in scrap, and the dilution of steel scrap with primary steel. Note the difference between demand, which denotes the requirements for steel in final products, and production, which is the amount of crude steel required to service this demand. CO_2 emissions estimates include direct emissions as well as indirect emissions from electricity, and are based on the gradual adoption of best available techniques for current production processes by 2050. The high-level results of a baseline scenario are shown below, with further elaboration throughout this chapter.

A closer look at the EU highlights the importance of saturation (Exhibit 2.2). The EU steel stock already approaches 12 tonnes per person, and the population level is flattening and expected to decrease. Once a saturation point is reached, EU steel demand would be driven almost entirely by the need to replace products and structures as they reach the end of their life, about 2–3% of the total stock each year. In this scenario, EU demand would fall at first, then stabilise at replacement levels of around 150 million tonnes per year. Production by the EU steel industry could of course still increase, but would have to be driven by increasing exports. As we discuss below, the stabilisation of demand even as stocks accumulate would enable Europe to rely much more heavily on recycling to meet its own steel needs.

Exhibit 2.2

EU STEEL DEMAND CAN STABILISE AS THE STOCK SATURATES



NOTE: THE FIGURE DEPICTS THE PRODUCTION OF CRUDE STEEL REQUIRED TO SERVICE EU DEMAND
SOURCE: PROJECTED DEMAND MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT; HISTORICAL PRODUCTION BASED ON WORLD STEEL ASSOCIATION (2017).[11]

2.2 CO_2 EMISSIONS FROM STEEL PRODUCTION AND USE

The need for much more steel in the future presents a dilemma for climate objectives, as the production of steel results in large emissions of CO_2. Most steel production in Europe and globally is primary production, converting iron ore to steel through the basic oxygen furnace (BOF) route. This emits, on average, just over 2 tonnes of CO_2 per tonne of steel produced.[12] Doubling primary steel production would thus double a major CO_2 source.

However, as the global steel stock grows, so does the opportunity to use remelted end-of-life steel as an alternative to primary production. Secondary steel is made in electric arc furnaces (EAF), with one-fifth the CO_2 emissions of primary steelmaking even when much of the electricity comes from fossil fuels. If power from renewable sources is used in EAF, secondary steel can be decarbonised almost entirely. A more circular steel flow therefore both is inherently far less emissions-intensive, and easier to decarbonise through the use of renewable energy; it is one of many examples in this report of how greater circularity moves the emissions from 'hard to abate' sources and towards ones with much more established ways to cut emissions.

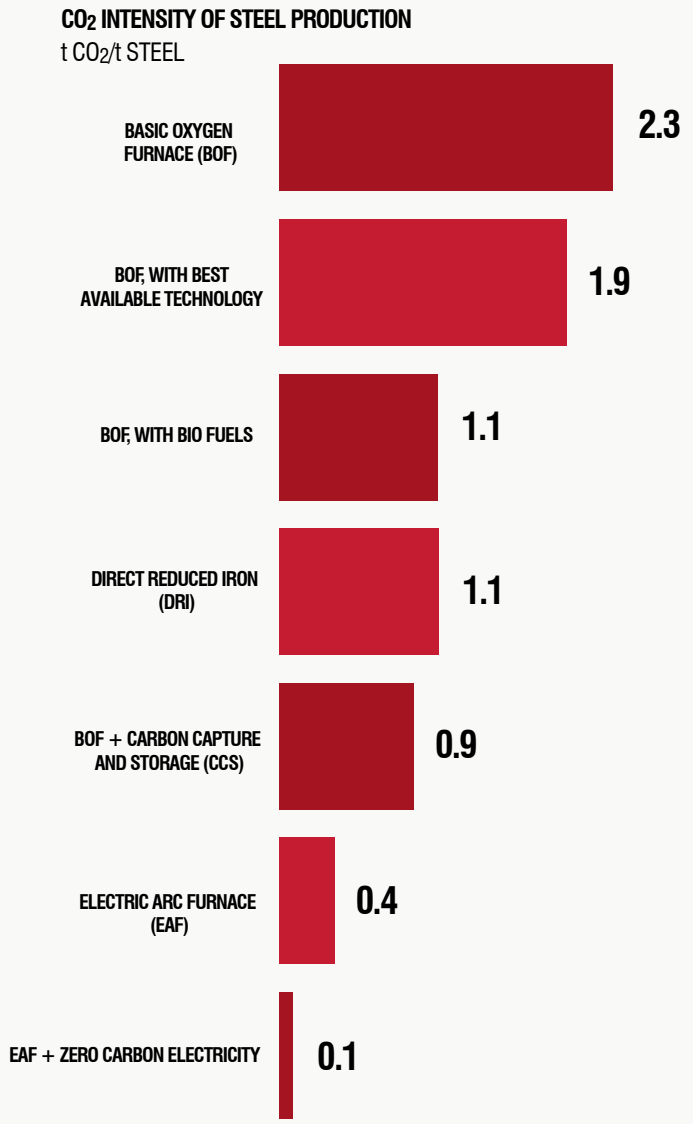
In contrast, clean power does not help much to reduce CO_2 emissions from primary steelmaking. Most of the CO_2 from primary steel production results from the chemical process in which iron ore is reduced, not from the energy used for heat. Unlike in power production or heating, it therefore is not possible to use renewable energy directly. Established options can reduce emissions by around half. For deeper emissions cuts, it would be necessary to use methods of steel production that are still under development (Exhibit 2.3).

To quantify the climate impact of continued heavy reliance on primary steelmaking and plausible scenarios for technological improvements, we constructed two scenarios for how to meet projected demand growth:

- **Baseline scenario:** This sees continued reliance on the BOF route for primary steel production, but with best available technology rapidly adopted. Steel recycling continues with the same collection rates, loss levels and practices as today.
- **Low-carbon process**: For illustration, we also show what the gradual adoption of currently proven abatement technologies in steel production would entail, so that the CO_2 intensity of primary steel production falls by half by 2050.[14]

Exhibit 2.3

STEEL RECYCLING HAS SIGNIFICANTLY LOWER EMISSIONS THAN OTHER AVAILABLE OPTIONS FOR STEEL PRODUCTION



BASIC OXYGEN FURNACE (BOF)

The large majority of current steel production uses coal to reduce iron ore and produce steel in integrated steelworks.

INCREASED PROCESS EFFICIENCY

An estimated 15% process efficiency improvement is possible within the current BOF process.

BIO-BASED INPUTS

Bio-based fuels can substitute for some of the coal input, with emissions reductions of around 50%.

DIRECT REDUCED IRON (DRI)

This route uses natural gas to reduce iron ore, which almost halves emissions. DRI accounts for 5% of current world production.

CARBON CAPTURE AND STORAGE (CCS)

Capturing the CO_2 from the blast furnace of an integrated steel plant can reduce overall emissions by 60%.

ELECTRIC ARC FURNACE (EAF)

The main route for secondary steel uses electricity to melt steel scrap and / or direct reduced iron, with only small onsite emissions.

ZERO-CARBON ELECTRICITY (EAF):

By using zero-carbon electricity, nearly all the emissions from steelmaking can be eliminated.

SOURCE: MATERIAL ECONOMICS ANALYSIS OF MULTIPLE SOURCES.[13]

There are good and bad news in this scenario (Exhibit 2.4). The good news is that even current practices would enable a much higher share of recycled steel in the future, as the amount of available scrap grows over time (see next section). EAF production could thus grow from 26% today, to 36% by 2050. This alone would reduce the CO_2 intensity of steel by one third compared with the current situation. We are thus already set to reap some of the climate benefits of increased circularity of steel use.

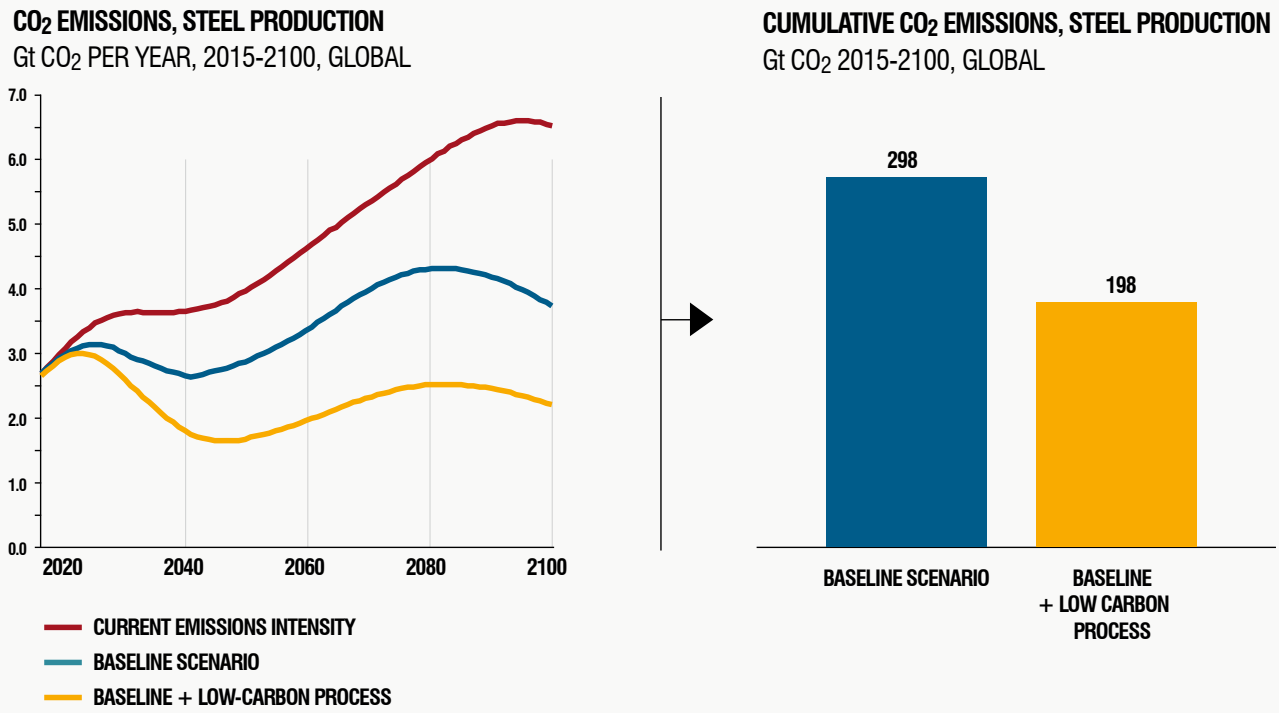
The bad news is that this leaves much of the potential for demand-side improvements on the table, through a combination of steel losses and downgrading. CO_2 emissions would therefore be higher than they need to be. As we detail in subsequent sections, improving practices could raise the share of scrap-based steelmaking to almost half by 2050, further reducing emissions by several hundred million tonnes of CO_2 per year.

The other piece of bad news is that emissions remain far higher than required to meet climate objectives. Cumulative emissions from steelmaking reach 298 billion tonnes (Gt) CO_2 by 2100. Yet as noted in Chapter 1, to stay within a carbon budget consistent with the commitments of the Paris Agreement, emissions from *all* materials production could not exceed 300 Gt CO_2. Established supply-side measures in the low-carbon scenario help, but even if those technologies were fully rolled out by 2050, as in our 'low-carbon production' scenario, cumulative emissions would still reach 198 Gt CO_2.

The main conclusion from this analysis is that demand-side measures are crucial to meeting climate objectives. Achieving deep cuts on the supply side alone would require extraordinarily rapid, global implementation of processes for steelmaking that are still unproven at scale. This is not to say that developing and deploying these technologies should not be a priority: they are necessary to handle the primary production that will still be necessary. But demand-side action is urgently needed as well, both because of the emissions reductions they provide, and because they reduce the challenge on the supply-side significantly by reducing the volume of primary steel required.

Exhibit 2.4

A BASELINE SCENARIO SEES LARGE REDUCTIONS IN THE CO_2 INTENSITY OF PRODUCTION, BUT LARGE EMISSIONS REMAIN



Even in a growing world, *recycling of steel could meet most of the growth in future global demand.*

2.3 REALISING THE POTENTIAL FOR CIRCULARITY IN THE STEEL SECTOR

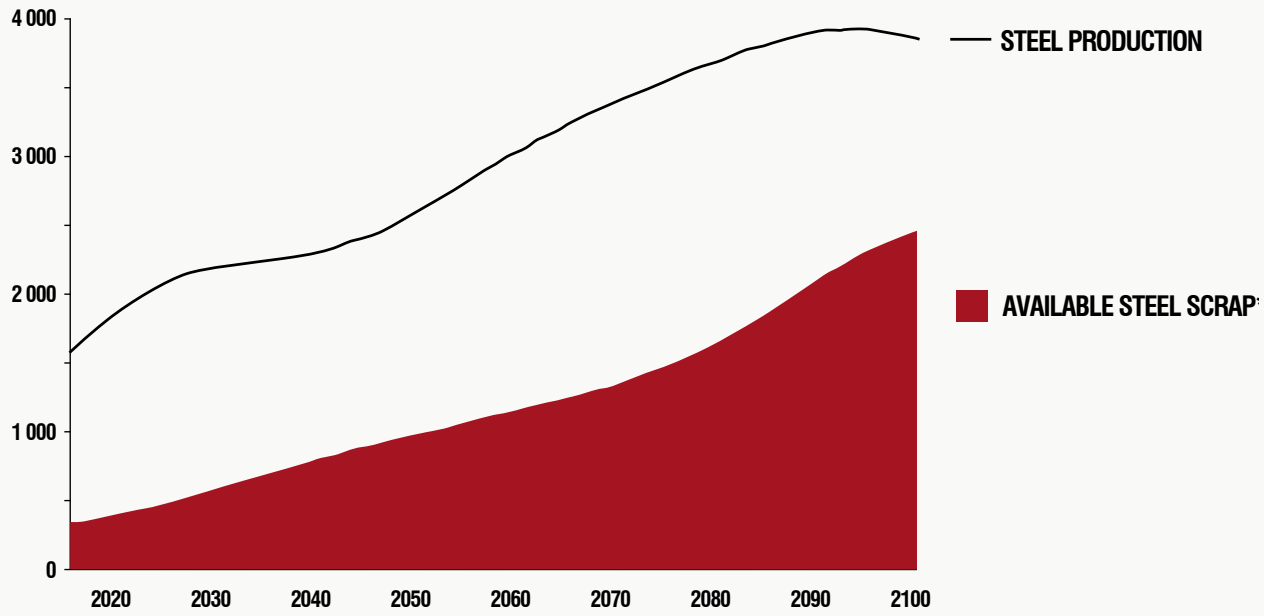
The steel sector has a head start in the circular economy, especially in mature markets such as Europe – but as steel stocks saturate, there is significant potential to scale up recycling and minimise demand for virgin steel. Already, EU steel demand is driven mainly by the need to replace products and structures at the end of their useful life. As the total steel stock saturates, the resulting scrap can be re-melted to provide an ever larger share of the flow of steel required.

We modelled the amount of scrap available worldwide, with striking results: In principle, the scrap available around the world would be sufficient to meet most of future growth in steel demand with secondary steel (Exhibit 2.5). Primary production is still required, but only for net additions to the steel stock in rapidly growing countries. For economic and environmental reasons, it makes sense to seize this opportunity – and that means making it a priority to adopt the practices required to enable future recycling: from collection at end-of-life, to keeping steel stocks pure from contaminants that could otherwise limit the uses of recycled steel.

Exhibit 2.5

EVEN IN A GROWING WORLD, RECYCLING OF STEEL COULD MEET MOST OF THE GROWTH IN FUTURE DEMAND

GLOBAL STEEL PRODUCTION AND AVAILABLE STEEL SCRAP
Mt STEEL PER YEAR, 2015-2100



The results are still more striking for the EU (Exhibit 2.6). Europe already produces around 100 Mt of scrap every year. In 2016, EAF plants in the EU produced some 65 Mt of steel, while 18 Mt of scrap was exported, and the remainder used in integrated steel plants.[15] Looking ahead, the amount of available scrap will increase, and we estimated that by mid-century, the amount of available scrap covers 80% of EU steel requirements.

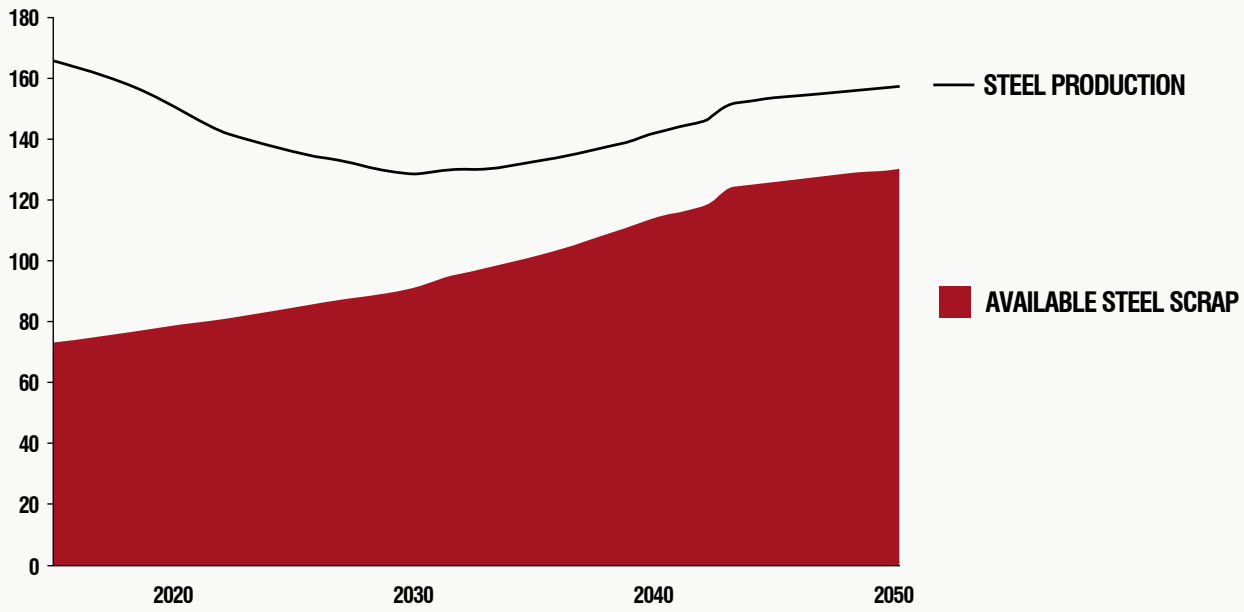
Both globally and in Europe, then, the future of steel could be much more circular than it is. However, reaping the full benefits will require significant changes in how steel flows are handled. There are three key issues, which we discuss next:

- **Reducing the losses** of steel throughout the use cycle;
- **Preventing downcycling** and enabling the production of high-quality secondary steel; and
- **Reducing the contamination** of steel – especially by copper.

Exhibit 2.6

SCRAP AVAILABILITY IN EUROPE RAPIDLY APPROACHES THE LEVEL OF DEMAND

STEEL PRODUCTION TO MEET EU DEMAND AND AVAILABLE STEEL SCRAP
Mt STEEL PER YEAR, 2015-2050



NOTE: EXCLUDING SCRAP EXPORTED OR USED IN INTEGRATED STEELMAKING.

REDUCING LOSSES OF STEEL

Steel has a high recycling rate: around 83% of end-of-life steel is collected for recycling[16], and in some countries, this reaches 90%.[17] Still, overall losses are large (Exhibit 2.7). We calculate that almost 150 Mt steel are lost each year – an amount close to the EU's annual production. The cost of producing new steel to replace these losses is on the order of 70 billion EUR, while the CO_2 emissions resulting from replacing them are more than 320 Mt CO_2 per year.

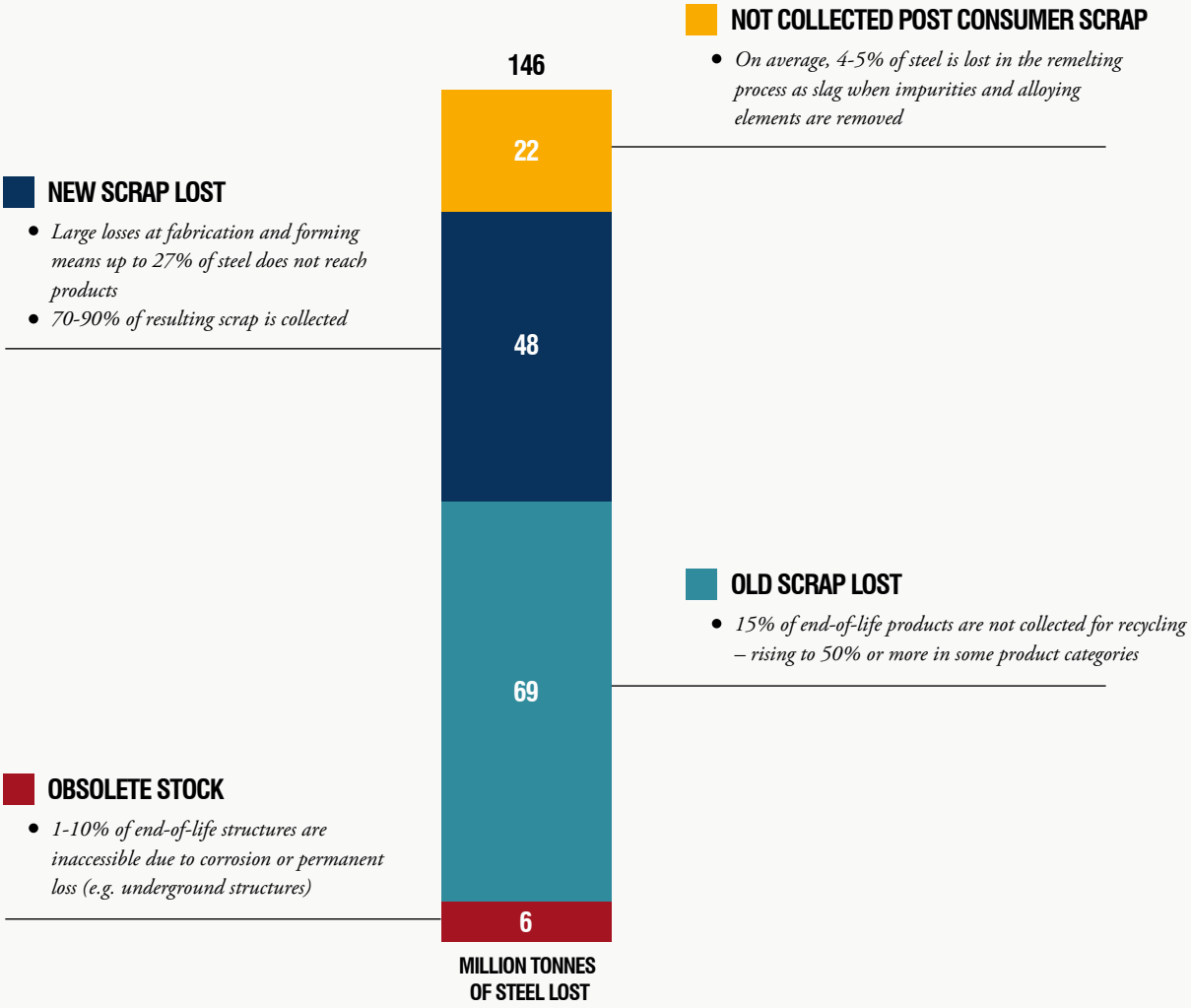
Losses in the steel system occur in four main categories:

- **Obsolete stock and inaccessible scrap:** Some steel structures are simply abandoned and not scrapped. Examples are submarine or underground pipes, or abandoned buildings or structures. In some categories, the share of end-of-life steel that is not collected can reach 10%.
- **Low scrap collection rates:** While overall collection rates are relatively high, they are low for some product groups and regions – as low as 50% for some consumer products[18], and for production scrap (new scrap), just 70%.[19]
- **New scrap:** For certain product groups, such as automobiles, only 50% of the steel used actually makes it into products. The remainder becomes scrap at the forming or fabrication stage. Overall, some 25–30% of steel becomes new scrap.[20] This means that more steel needs to be produced and circulating at any given point. It also leads to additional losses, as noted above.
- **Remelting losses:** Remelting of steel is highly optimised to maximise yields, but losses nonetheless reach an estimated 4–5%.[21] One factor that increases losses is the need to remove substances (mainly trace or alloying metals) that would otherwise affect steel purity and quality (slagging). Slagging losses could be reduced with input materials that better matched the desired output.

Exhibit 2.7

ALMOST 150 MILLION TONNES OF STEEL ARE LOST ANNUALLY

LOSSES IN STEEL PRODUCTION
Mt STEEL 2015



DOWNCYCLING TO CONSTRUCTION STEEL

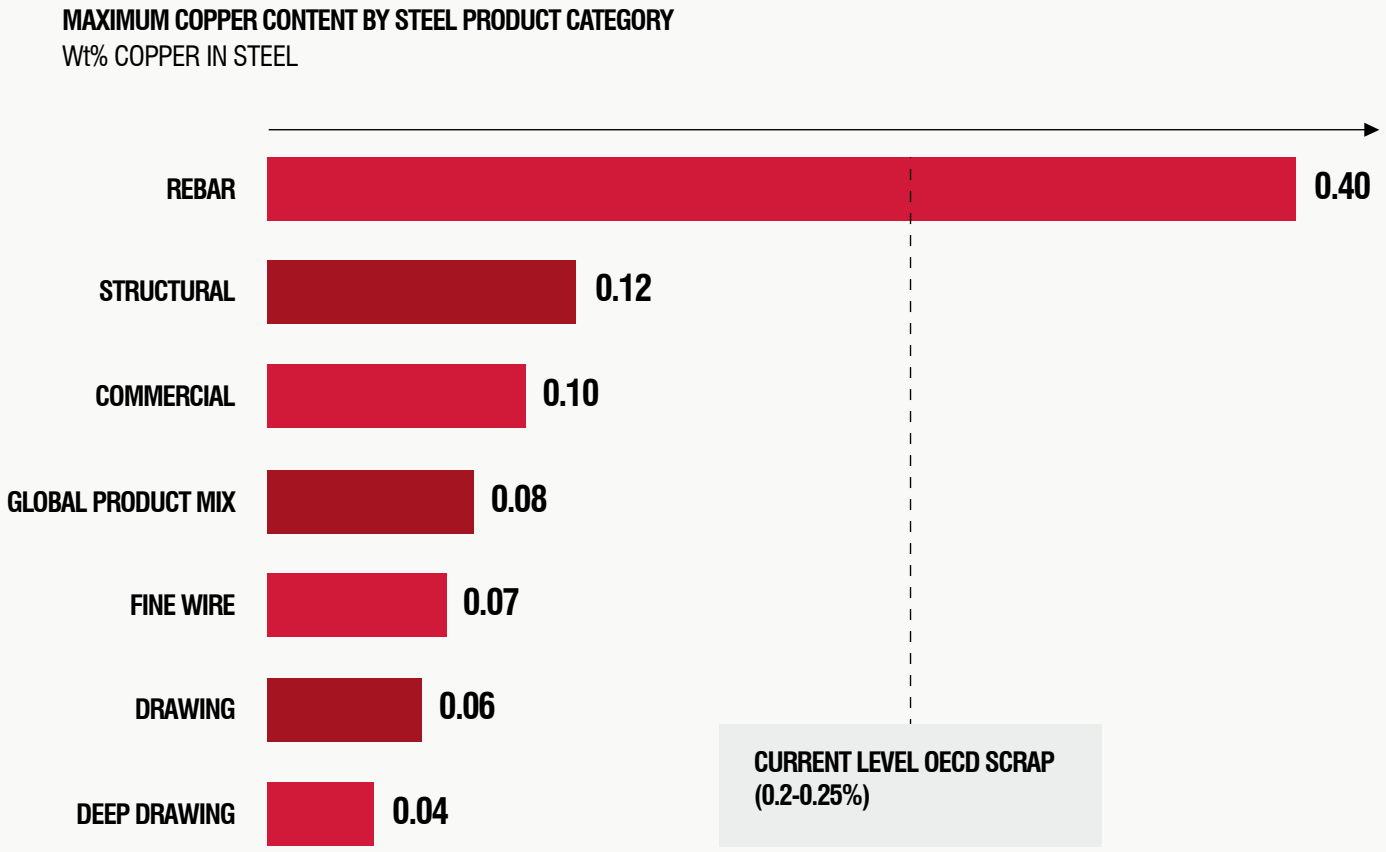
Steel comes in many different grades and qualities, and many products require precise control over the purity of the inputs and other elements of the production process. This can be a challenge for secondary steelmaking. Scrap with very different content often is mixed together in today's supply chains, making it harder to precisely control the inputs to production. This results in downcycling of steel.[22] For example, by one estimate, only around 8% of the steel originally used in cars maintains sufficient quality to be used for the same purpose again.[23]

Today, this is handled by using secondary steel primarily for relatively basic construction steels (rebar, but also structural elements). These can tolerate both a less precise composition and a higher share of 'tramp elements' – i.e., substances that are not desired. However, as we show below, there are limits to downcycling as a strategy in a world with higher shares of secondary steel. Eventually, high shares can only be achieved if secondary steel production can also produce other, high-quality products, meeting the needs of all sectors of the economy, including more demanding applications.

There is no fundamental reason that this could not be achieved. There are several secondary steelmakers that already manage to produce very high-quality and even specialty steels from scrap today. This requires a tightly controlled supply of scrap – keeping different qualities apart, matching input content to product requirements, and removing undesired elements – as well as advanced metallurgy. Replicating this across the EU and global economy would require a much more sophisticated handling of end-of-life steel.

Exhibit 2.8

COPPER LEVELS IN STEEL SCRAP ALREADY EXCEED TOLERANCES FOR MANY IMPORTANT PRODUCTS



SOURCE: MATERIAL ECONOMICS ANALYSIS; DAEHN ET AL. (2017).[28]

COPPER CONTAMINATION – A POTENTIAL MAJOR CONSTRAINT ON FUTURE SECONDARY STEEL

A particularly important aspect of downgrading is the contamination of steel with copper. Even low levels of copper drastically affect the quality of steel. At a share of 0.15% or less, steel becomes unusable for important product groups (Exhibit 2.8).[24] The copper content of OECD scrap is around 0.2–0.25%, a level that exceeds the requirements for many product categories except rebar.[25] Moreover, unlike many other elements, copper cannot be removed from the steel.[26] In effect, the addition of copper results in the permanent and long-term downgrading of the steel stock. The addition of copper and other elements also increases the energy required to produce secondary steel, in some cases by as much as 40%.[27]

Copper is added to steel primarily at the point of recycling, as products containing both steel and copper are dismantled.[29] Examples include components such as electrical motors or cables with magnetic parts, or entire products with high joint iron and copper content. End-of-life vehicles are a major source, as cars can have a copper content of 0.5% or more and often are shredded after at most basic dismantling.[30] Even to make rebar, fresh primary steel or less contaminated scrap must therefore be added. With more advanced handling of cars, such as automated or manual dismantling, the copper mixing can be reduced.

Today, the copper problem is managed in part through dilution, either with scrap containing lower levels of copper, or with fresh primary steel. Downcycling also helps manage the problem: copper contamination is a major reason why secondary steel tends to be used for construction steels, which can tolerate higher levels.

Nonetheless, this creates major challenges as copper continues to accumulate, and as the share of scrap-based production increases. As we show below, continuing today's practice would put a major obstacle in the way of a more circular steel economy, with significant increases in CO_2 emissions as a result.

2.4 A CIRCULAR SCENARIO FOR STEEL IN 2050

To explore the benefits of a more circular steel system, we constructed a scenario for the steel sector in which all three issues discussed above are addressed:

1. Reduce the losses of steel;

2. Enable the use of secondary steel across a wider range of product groups globally; and

3. Reduce and eventually eliminate the problem of copper contamination.

Globally, we find that this 'materials circularity' scenario cuts CO_2 emissions significantly (Exhibit 2.9): by 590 Mt CO_2 per year (20%) by 2050, and as much as 1.1 Gt CO_2 per year (29%) towards the end of the century. By any measure, demand-side measures for steel are a major contributor to the objective of making materials use consistent with climate objectives.

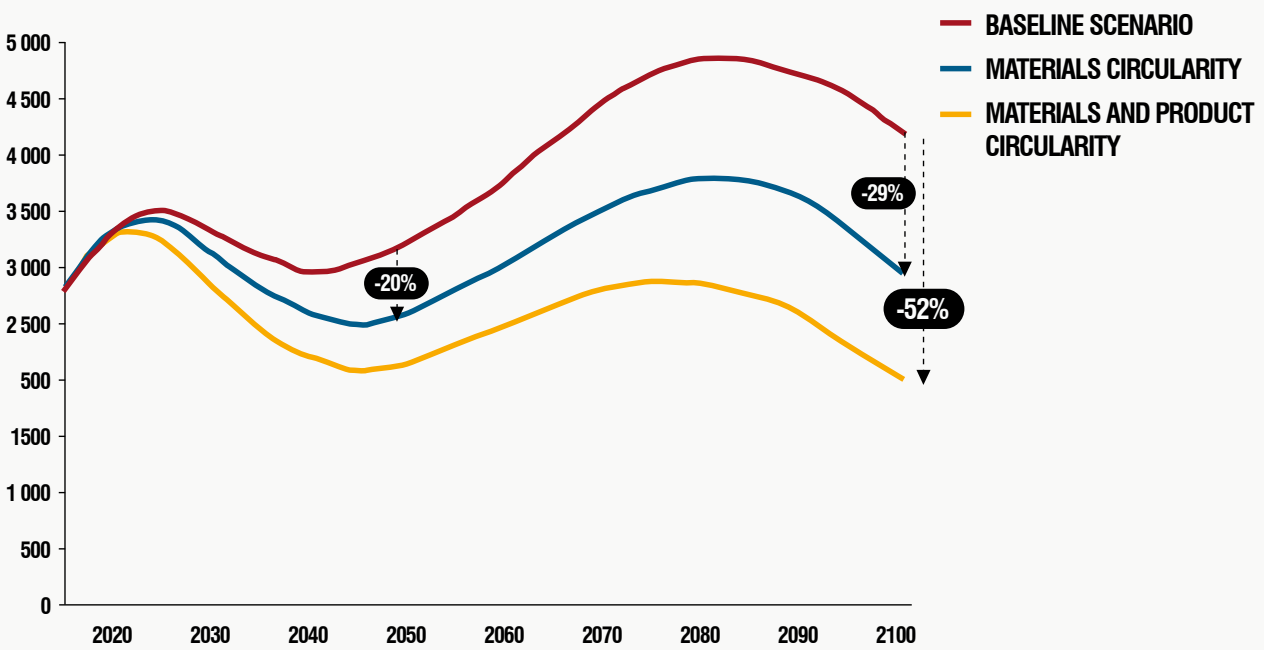
As explored elsewhere in this report, it is also possible to implement circular economy principles at the product level – through longer lifetimes, more intensive use, light-weighting, and other strategies. In a 'materials and product circularity' scenario that captures some of the opportunities in transport and buildings, the emissions reductions are still larger: as much as 52% of the emissions in 2100 are eliminated, and emissions fall in absolute terms compared with current levels.

The materials circularity scenario also sees a different profile of steel production vs. the baseline. Instead of rising to 2.2 Gt per year, primary production is never higher than 1.6 Gt. Secondary steel takes a majority role by mid-century, and nearly all growth in steel demand can thus be met through recycling.

Exhibit 2.9

A CIRCULAR SCENARIO WITH REDUCED LOSSES AND TECHNOLOGY IMPROVEMENTS HAS LARGE POTENTIAL TO REDUCE EMISSIONS

CO_2 EMISSIONS FROM GLOBAL STEEL PRODUCTION
Mt CO_2 PER YEAR, 2015-2100



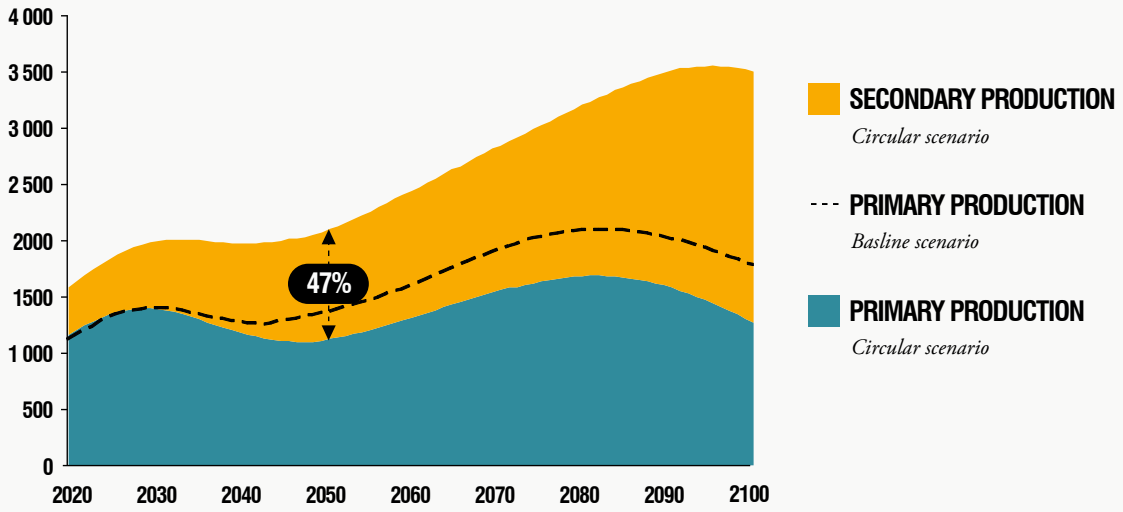
This scenario implies a major reconfiguration of global steel production, from an overwhelming emphasis on primary production, and towards a circular steel system. In fact, if the potential for circularity is realised, there might be no need to add further primary steelmaking capacity beyond the 2020s, except to replace obsolete plants (there already is very large overcapacity in steelmaking).[31] This is a major break with the past. Even in the last decades, two-thirds of new global demand has been met by building new capacity for primary steelmaking (notably, as demand has grown at unprecedented pace in China).[32] By contrast, in a circular scenario, the analysis suggest that all the blast furnaces required globally could be built by the 2020s.

Another major reconfiguration is in regional patterns of steel production and trade. The above scenario depends on reducing the contamination of steel with copper. With current practice, this would require significant scale-up of trade between regions. For dilution to be feasible, steel scrap with high copper content would need to be mixed with new primary steel produced in countries with fast-growing demand. However, this is not a viable approach as the problem grows, as perfectly mixing all available scrap and primary steel globally to keep average copper content down is unrealistic. At a minimum, it is at odds with historical patterns for steel, where most industrialised regions have aimed to meet most of their steel needs via domestic production.

Exhibit 2.10

A CIRCULAR SCENARIO HAS LARGE IMPACT ON PRIMARY STEEL PRODUCTION GLOBALLY

GLOBAL STEEL PRODUCTION BY ROUTE
Mt STEEL PER YEAR, 2015-2100



EU CO_2 EMISSIONS AND PRODUCTION

Turning to the EU, even more is at stake by improving circularity (Exhibit 2.11). As noted, the region is transition to a situation where available scrap could meet a much higher share of demand. The scenario below shows the production profile resulting if the EU were to use all domestically available scrap to meet its own demand. In principle, primary steel production could then decline steeply, falling to just 15% of current levels by the 2050s. However, this would require that the circularity levers be successfully implemented, so that nearly all available scrap is utilised, high-quality steel production from scrap is feasible, and copper contamination is resolved. If current practices were maintained instead, the EU could not use its own scrap to meet demand, as it would not hold the quality required for major product groups. Instead, some of the high-copper scrap would need to be exported, and ultimately diluted with primary steel in other markets. Meanwhile, primary production of around 50 Mt would be required to dilute remaining scrap in the EU.

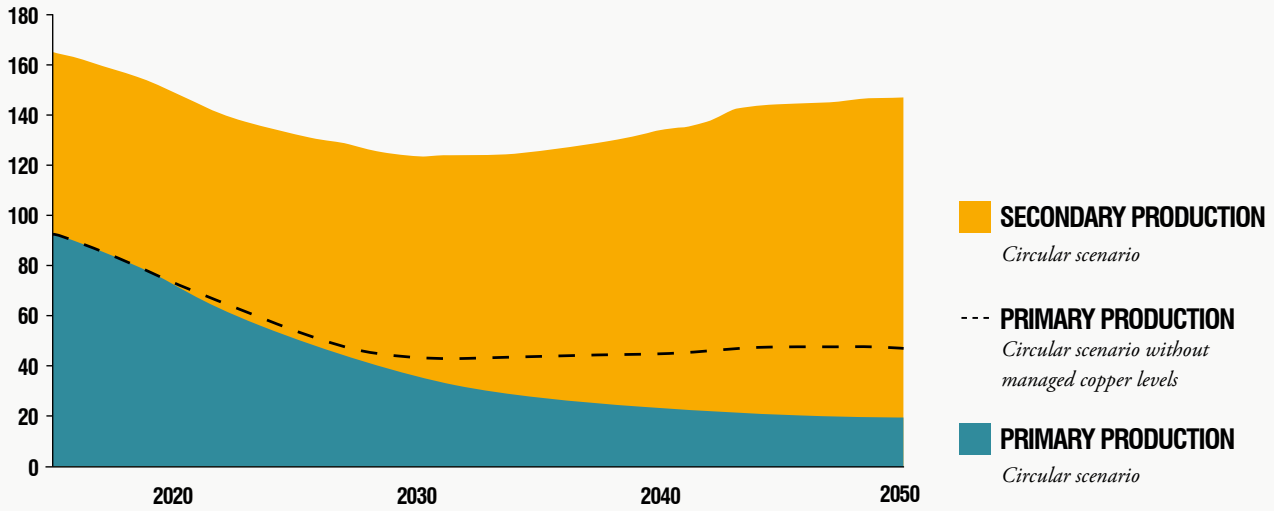
This development would also have a major impact on emissions within the EU. In a reference case, emissions remain at 104 Mt CO_2 per year in 2050, as primary steel production continues to serve 30% of EU demand. In a circular scenario, by contrast, emissions could fall by half, to 47 Mt per year.[33]

This depicts the potential to meet demand using scrap-based steelmaking. The actual production profile

Exhibit 2.11

IMPROVED CIRCULARITY COULD SIGNIFICANTLY REDUCE THE NEED FOR PRIMARY STEEL PRODUCTION TO SERVE EU DEMAND

EUROPEAN STEEL PRODUCTION BY ROUTE
Mt STEEL PER YEAR, 2015-2050



of the future EU steel industry is a much more complex question. For a start, it would of course be possible to produce steel for export, in which case additional primary production would be required. As another option, it would be possible to export ever larger amounts of scrap (already, some 18% of scrap is exported, as noted above), and continue primary steel production to meet some share of domestic demand. Either way, however, stabilisation of the EU steel stock will likely bring significant structural change to the industry, and a much smaller future role for blast furnaces.

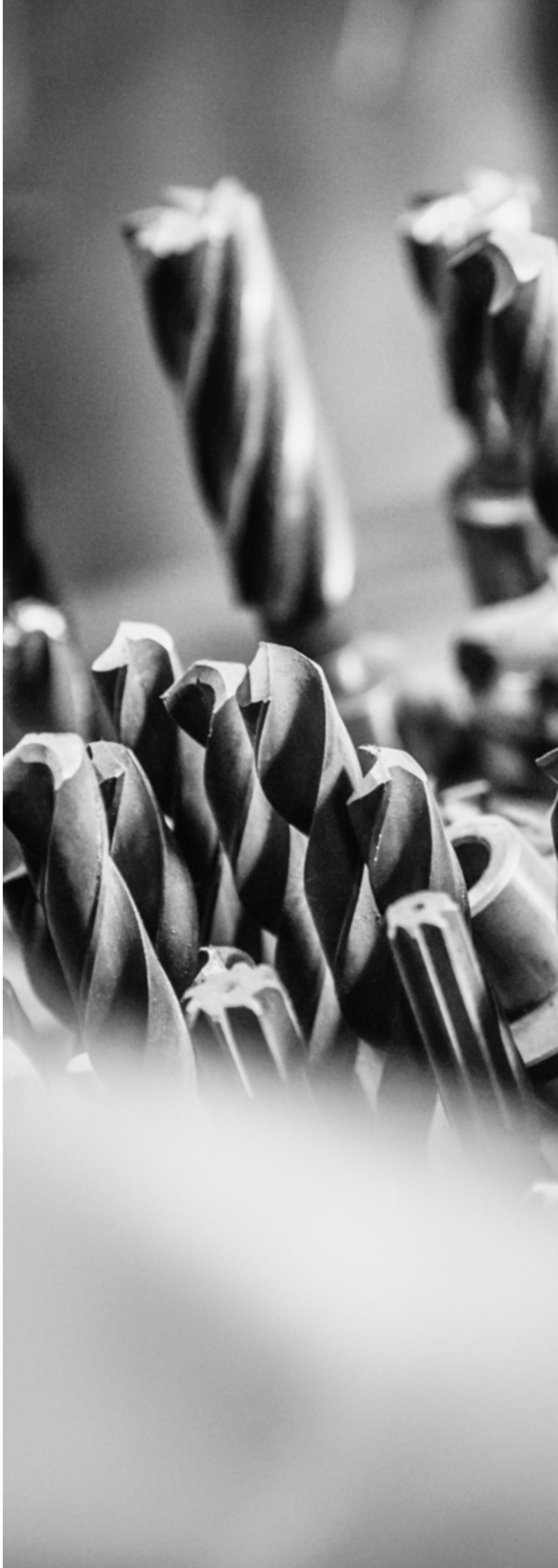
Nonetheless, the analysis shows that a nearly fully circular steel economy is possible within the EU, with large resulting reductions in CO_2. This alone is a remarkable prospect. To achieve that, a number of enablers need to be put in place, as we discuss below.

A CIRCULAR SCENARIO CAN SUPPORT SUPPLY-SIDE ABATEMENT

For clarity, the above numbers compare emissions reductions when primary steel is still largely produced through the BOF route. However, a more circular scenario can also support efforts to decarbonise primary steel production.

Reducing emissions from primary steel production faces significant challenges. First, as noted in section 2.2, though there are established technologies that could halve emissions, they are a long way from being deployed at scale, while truly deep cuts in emissions would depend on rapid deployment of breakthrough process innovations that are still at the research and development stage. This creates a significant and uncertain innovation challenge – and it would also require existing steelmaking facilities to be replaced before the end of their useful life, at a high capital cost.

In that context, demand-side measures are not only valuable on their own right, but also to buy time and take the pressure off – much like energy efficiency does on low-carbon energy supply. Circularity is thus an integral part of any deep mitigation scenario. As noted, in the long run, ensuring effective recycling globally could avoid the need to produce – and decarbonise – nearly 600 Mt of primary steel production per year, rising to 1,000 Mt with products circularity.



2.5 HOW TO GET THERE – MEASURES TO PROMOTE CIRCULARITY IN STEEL

The different circularity strategies are closely interrelated and would need to be pursued simultaneously. Copper contamination becomes a much bigger concern as secondary steel is used for a wider range of purposes, including the most demanding uses that require very high quality. Similarly, unless copper is addressed, measures to reduce losses or prevent downcycling are limited in how much they can displace primary production. As noted earlier, without solving the copper problem, the world as a whole would need to produce additional, "excess" primary steel just to dilute the contaminated steel stock. By 2050, primary steel demand for that purpose alone could amount to as much as 100–150 Mt per year. In fact, unless the copper problem is solved, other circularity measures such as increased collection and reduced losses rapidly run into a limit.

MEASURES TO REDUCE LOSSES

To arrive at the circular scenario, as little steel as possible can be lost in production and collection. To minimise losses, measures need to be taken in three main areas.

First, systems to collect end-of-use products need to be set up more widely and expand their capacity and accuracy as volumes of steel scrap grow. New initiatives and incentives will be needed to encourage consumers to recycle their products and to ensure that iron and steel products are separated when buildings are demolished.

The forming of new scrap could be reduced with closer-to-shape semi-finished products and with designs that consider the production process and aim to minimise new scrap. New technologies that leave much less production scrap, such as 3-D printing and powder metallurgy, could be adopted far more widely.[34] In addition, the quality of the collected new scrap could be improved through increased sorting. The advantage of new scrap over post-consumer scrap is known alloy content and clean streams of carbon steel. Efforts should be made to keep alloys separated to be able to utilise the properties of the scrap after remelting.

Reducing remelting losses will be challenging as more scrap enters the system. One way of reducing losses is to limit the mixing of alloys prior to melting to minimise impurities, as the process for removing undesired elements also leads to higher losses of iron. Better sorting can also reduce energy requirements of the EAF process by as much as 30%.[35] With a better alloy sorting system, alloying elements would not have to be removed, and instead their properties could be valuable for a new batch of steel being produced.

AVOIDING DOWNGRADING THROUGH A MORE SOPHISTICATED MARKET FOR STEEL SCRAP

Alloy-to-alloy sorting is another key component to avoid downgrading. If the contents of steel used for secondary production are known, steel scrap can be mixed much more closely to correspond to end products. The technologies required to achieve this are under rapid development. For example, laser-induced breakdown spectroscopy technologies are improving and falling in cost fast, making it possible to quickly determine the content of alloys. When the content is known, a much more differentiated marketplace can be created so that steel manufacturers can specify and obtain the scrap required also for exacting products.

FOUR WAYS OUT OF COPPER CONTAMINATION

Copper's effect on steel has been known for a long time, but the problem has so far been relatively easy to handle, because secondary steel demand was limited. Looking ahead, four key strategies need to be implemented:

- **Improved separation at end of life:** The first step is to avoid adding high-copper scrap to otherwise clean flows, as is often done today to dispose of flows such as copper-alloyed steel or some vehicle scrap. Beyond this, it will be necessary to increase the separation of copper and steel in the recycling process. This already happens to some extent, but practices vary widely, and the extent of sorting fluctuates with the copper price, since removing copper can be costly, manual work. To avoid the cost of manual labour, more technologies for automated sorting are being developed. More closed-loop recycling would also be necessary to keep some scrap flows very pure and enable the use of scrap in especially copper-sensitive applications.

- **Product design for reduced contamination:** The design of products can also improve the sorting process. Design principles for recycling and for disassembly could facilitate the removal of copper components by make them easier to see and to access and remove. Material substitution is sometimes an option, such as replacing copper cables and wires with optic fibre or aluminium equivalents.

- **Metallurgy to increase copper tolerance:** Production processes can be designed to be more tolerant to copper by avoiding the temperature interval where copper causes problems.[36] Although not in itself a long-term solution, this mitigates the problem.

- **Separation of copper from steel:** There currently is no commercially viable method for removing copper from steel once it has been added. Some assessments have been pessimistic that this will ever be viable.[37] Nonetheless, some research is ongoing into methods such as sulphide slagging, vacuum distillation and the use of O_2/CL_2 gas.[38]

What will it take for these measures to take root? Arguably, current markets are poorly equipped to really account for the long-term impact of current practices on the long-term quality of the global steel stock. It may therefore be necessary to consider regulation as the route to address copper pollution before it becomes a significant problem for future steel recycling.

3. PLASTICS

FINDING A PLACE WITHIN A LOW-CARBON ECONOMY

Plastics are light, versatile, and cheap materials with a wide range of uses, and in the EU we now use 100 kg of plastics per person and year. Yet the use of plastics also leads to emissions of carbon dioxide (CO_2): both in production and because fossil carbon is a major building block of all plastics. On current course, emissions would nearly double by 2050 in a baseline scenario with today's recycling rates, to more than 200 million tonnes of CO_2 per year – far exceeding levels compatible with the EU's commitments under the Paris Agreement. Given their ubiquitous role in our society, finding a way to make plastics compatible with a low-carbon economy is an urgent agenda.

Recycling can offer a large part of the answer to this. Most plastics are recyclable, and recycling saves 90% of the CO_2 emissions arising from new production. In a detailed assessment of plastics types, flows, and uses we find that a combination of re-use and recycling could provide 60% of plastics demand by 2050, cutting CO_2 emissions by half. To make this economically attractive, the key is to focus on systems that enable high quality recycling and preserve the value of plastics upon recycling. This requires a large-scale and regionally integrated secondary plastics industry, technology development, and above all changes to product design: our use of plastics must have recycling in mind from first use.

This amounts to an ambitious transformation. Achieving circular plastics use will require integration along value chains, and concerted effort to overcome a range of barriers. Yet much can be achieved by focussing on what matters most: the five largest plastics types, and their uses in packaging, automotive, and construction applications. By starting now, we could supply more than half our plastics needs through recycling by 2050.

***More than half** of plastics needs could be supplied through recycling by 2050.*

3.1 UNDERSTANDING FUTURE PLASTICS USE

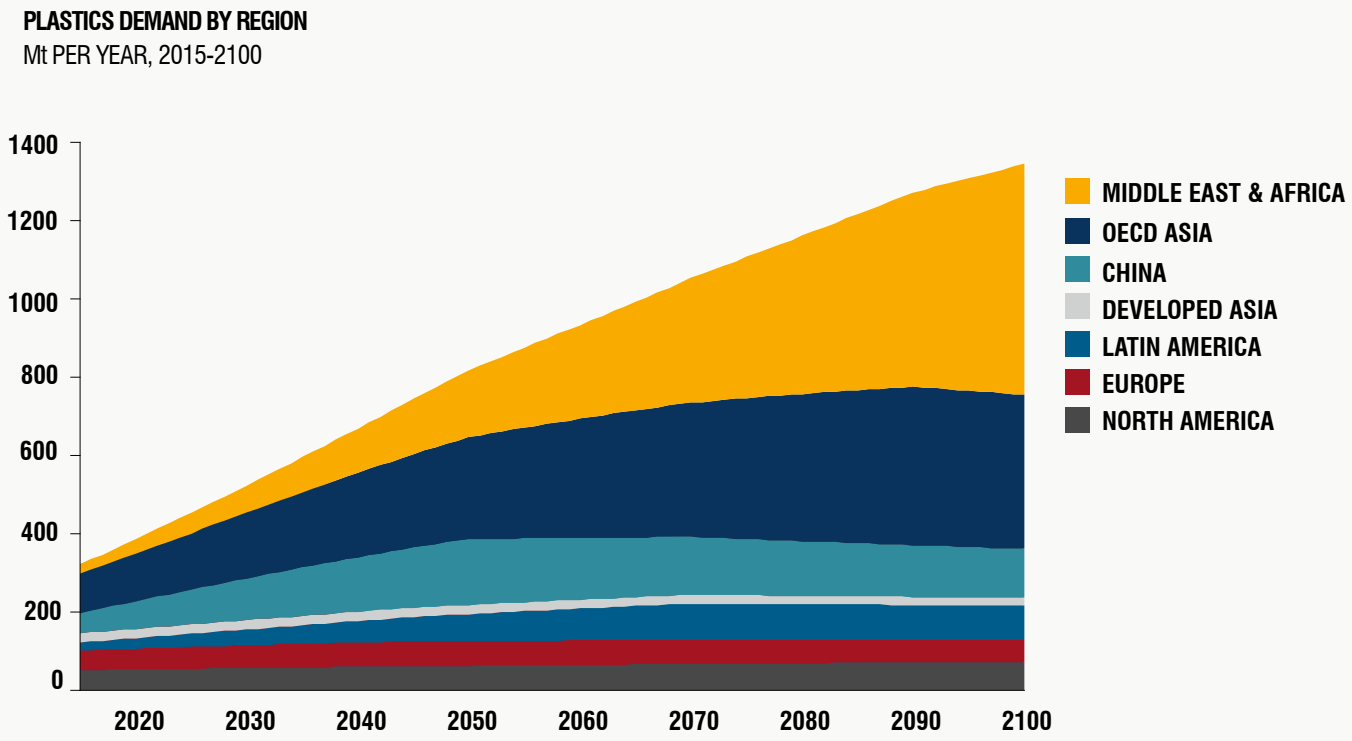
Plastics are versatile, durable and low-cost materials that are used widely across modern economies. More than 30 types of plastics are in common use, with different properties and applications in numerous sectors. Since the 1950s, global plastics production has risen dramatically, reaching more than 320 million tonnes in 2015 and now growing by about 10 million tonnes per year. In the EU, we now use 100 kg of plastics per person per year.

Global growth is set to continue. Plastics consumption increases as economies develop and begin using them in a range of products and consumer goods. Our analysis suggests that by 2050, global plastics production would double to over 800 million tonnes per year (Exhibit 3.1). If made with today's fossil feedstock, global plastics production would then require 900 Mt of oil per year, more than the European Union uses today, and 23% of total global oil use in a 2 °C scenario.[1] By the end of the century, plastics consumption would need to rise further, to 1345 million tonnes per year – more than four times today's levels.[1] By any measure, plastics therefore are a major determinant of future fossil fuel use – and hence also of carbon dioxide (CO_2) emissions, as we discuss below.

In Europe, a mature market, plastics demand actually declined with the economic downturn, and although it has since rebounded, with a growth of about 1% per year, production is no higher than in 2000. Still, the EU uses 49 million tonnes of plastics per year – about 100 kg per person. With a continued shift to lighter materials and packaging, increased use of plastics in automotive applications, and increased demand for insulation to improve buildings' energy efficiency, we project that EU plastics demand will grow to 62 million tonnes per year by 2050.

Exhibit 3.1

PLASTICS DEMAND WILL INCREASE SIGNIFICANTLY



3.2 CO_2 EMISSIONS FROM PLASTICS PRODUCTION AND USE

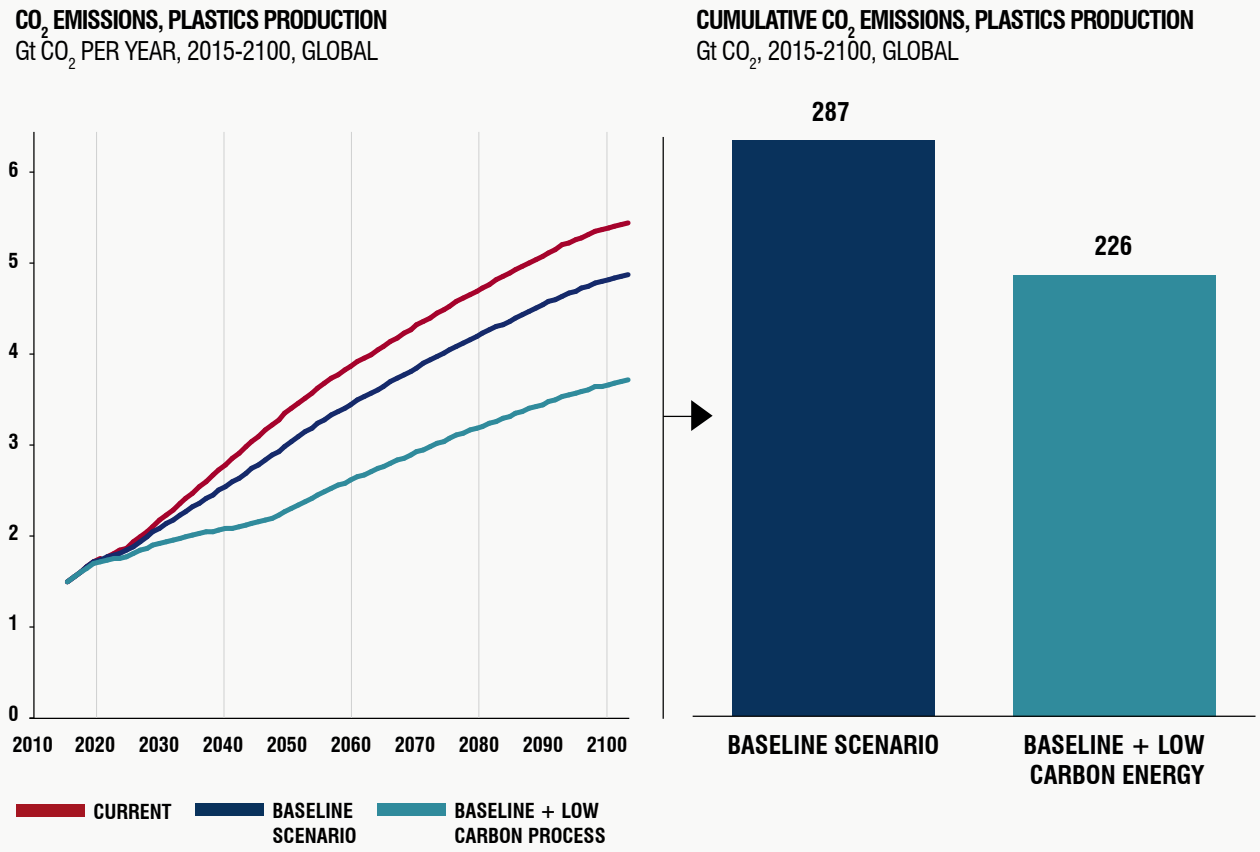
Finding a way to sustainable use of plastics has many dimensions. Plastics make up a large and growing share of solid waste around the world.[2] Marine plastic pollution is a large and growing problem.[3] Waste also decays into microplastics that pollute the entire food chain.[4] In addition, growing plastics use will be a major contributor to CO_2 emissions.

On average, each tonne of plastics produced results in 2.5 tonnes of CO_2 emissions from the production process alone.[5] In addition, carbon embedded in the material corresponds to another 2.7 tonnes of CO_2. When this carbon is released depends on how plastics are treated at end of life. In landfills (or if plastics are released into the environment), that process occurs slowly, as plastics take a very long time to break down. However, in the EU, where policy-makers aim to eliminate the landfilling of plastics, plastics that are not recycled are increasingly incinerated for energy generation, which leads to the immediate release of all embedded carbon as CO_2.

At the global level, current scenarios and roadmaps for a 2°C economy tend to overlook plastics. Their production makes up just 2% of CO_2 emissions from industry and energy, and embedded emissions often are not attributed to materials in emissions inventories, but just classified as emissions from waste. However, if plastics demand continues to grow as projected, and a larger share of landfilling is replaced with incineration, cumulative CO_2 emissions associated with plastics could grow very large. We calculate that the combined emissions from plastics production and embedded carbon would be as much as 287 billion tonnes by 2100 (Exhibit 3.2). This corresponds to more than a third of the whole carbon budget for a 2°C economy. Addressing CO_2 emissions from plastics is crucial for a successful low-carbon transition.

Exhibit 3.2

PLASTICS ALONE RISK EXCEEDING THE CARBON BUDGET QUOTA AVAILABLE FOR INDUSTRIAL EMISSIONS



SOURCE: MATERIAL ECONOMICS MODELLING.

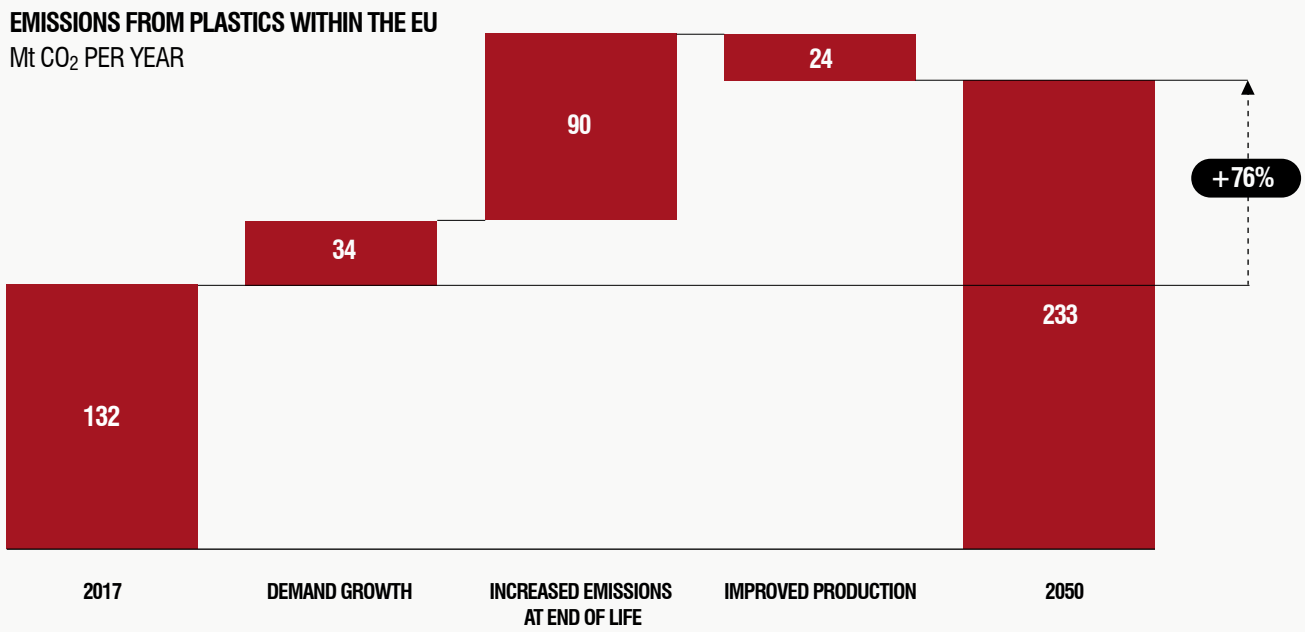
In the context of Europe's climate targets, plastics must be addressed to reach commitments under the Paris Agreement: today's emissions of 132 Mt CO_2 per year otherwise risk growing to 233 Mt, an increase of 76% (Exhibit 3.3). Today's emissions are dominated by production emissions, and end-of-life treatment adds little to this (arguably, the net emissions from incinerating plastics are low when the alternative would be to burn other fossil fuels with a similar CO_2 intensity). However, this picture changes by 2050. First, demand grows, adding 34 Mt CO_2. More than that, the emissions from end-of-life treatment increase by 90 Mt CO_2, even if today's recycling rates are maintained. This is both because the current trend of increased incineration would continue, and because, as the energy sector is decarbonised, instead of replacing fossil fuels, plastics burnt to produce energy would replace cleaner alternatives, increasing emissions. Even with a 15% reduction in the emissions from plastics production, CO_2 emissions from plastics increase to 233 Mt CO_2 per year, an amount exceeding even the total emissions implied by the Paris Agreement commitments.[6]

There are a variety of strategies that can reduce CO_2 emissions from plastics (Exhibit 3.4). Emissions from production can be reduced both by improving energy efficiency, and by adding external, low-carbon energy. However, this leaves embedded emissions in place, and even if 57% of production emissions were eliminated, the total emissions are 3.7 t CO_2 per tonne plastics. Mechanical recycling – the cleaning, re-melting, and upgrading of used plastics materials – produces less than 20% of the CO_2 emissions associated with making new plastics – even if the transportation, heat and electricity used are not yet decarbonised.[7] However, when recycling results in downgrading of plastics quality, the net emissions are higher, as it may not replace new primary plastics on a one-to-one basis. Even so, total emissions of 1.4 t CO_2 per tonne plastic are far lower than those from new production. Moreover, the emissions from mechanical recycling can be all but eliminated – provided the transportation and energy inputs used are low-carbon, and high-quality plastics are produced, capable of displacing new plastics use on a one-to-one basis.

For plastics that cannot be mechanically recycled, there are a variety of chemical recycling approaches, whereby plastics are broken down into smaller constituents that can be reassembled to new materials, chemicals, or fuels. Chemical recycling involves some loss of carbon as CO_2, but the CO_2 savings can be as much as 75% with technologies now under development.

Exhibit 3.3

NET CO_2 EMISSIONS FROM PLASTICS IN THE EU COULD GROW BY 76% BY 2050

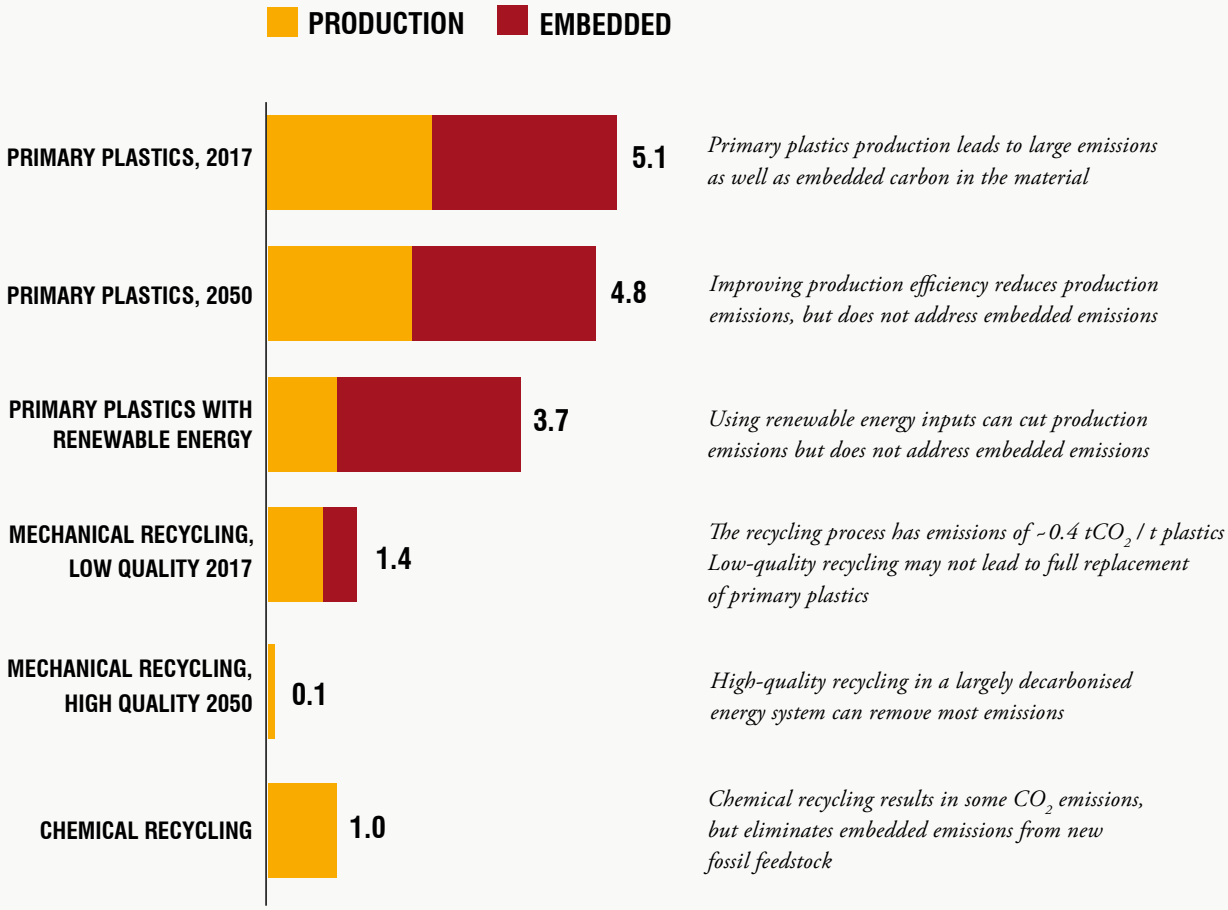


SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT.

Exhibit 3.4

PLASTICS RECYCLING HAS SIGNIFICANTLY LOWER CO_2 EMISSIONS THAN OTHER OPTIONS FOR PLASTICS PRODUCTION

EMISSIONS INTENSITY OF PLASTICS PRODUCTION
TONNES CO_2 EMISSIONS PER TONNE PLASTICS PRODUCED



SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES.[8]

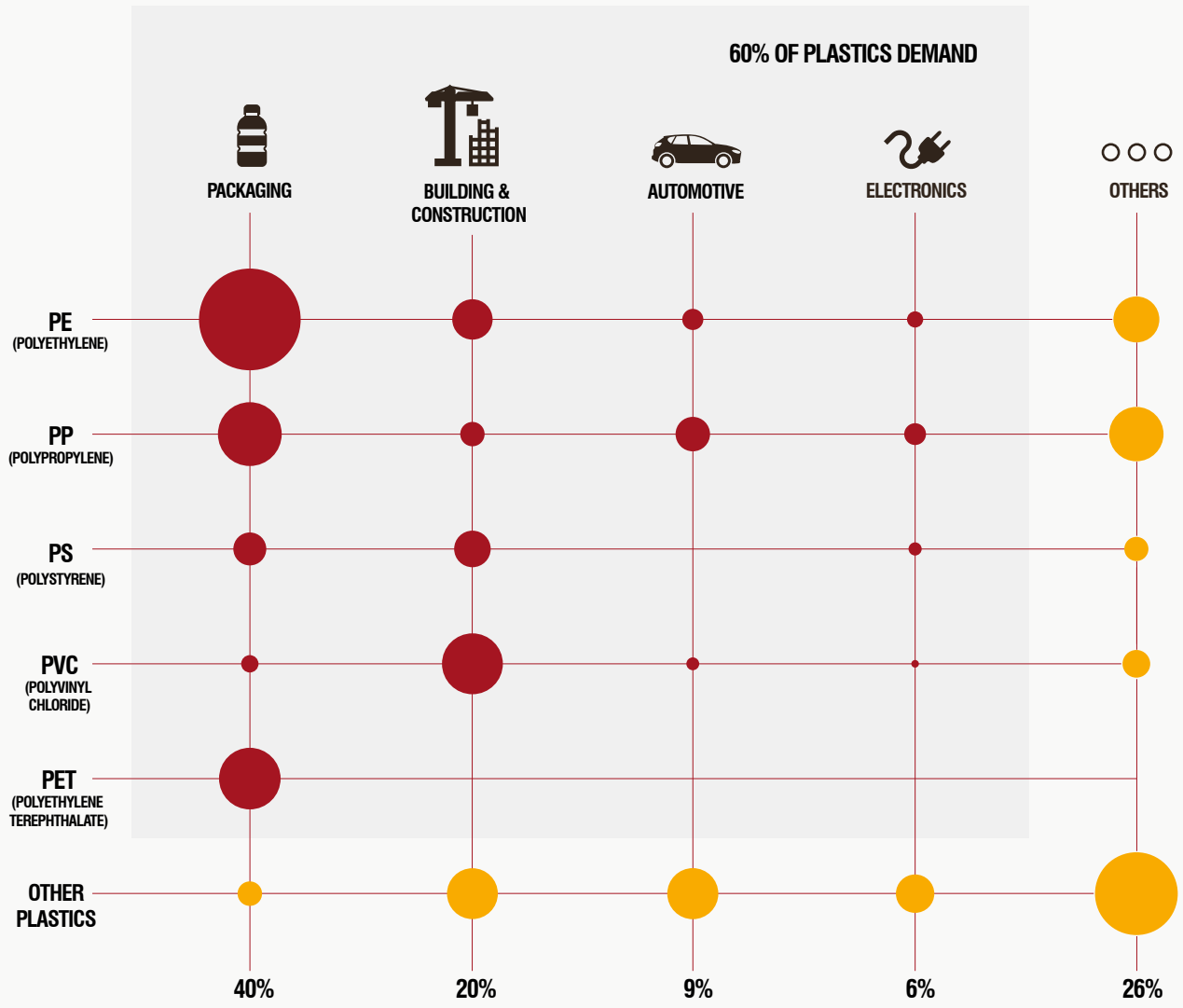
3.3 REALISING THE POTENTIAL FOR CIRCULARITY IN THE PLASTICS SECTOR

The good news is that there is significant untapped potential to recirculate plastics. More than 30 types of plastics are in common use, with different properties and applications in numerous sectors. However, much of the volume of plastics can be addressed by focussing on the largest flows (Exhibit 3.5). Four main value chains account for three-quarters of EU plastics use: packaging (40%), buildings and construction (20%), automobiles (9%) and electronics (6%). In addition, five big plastics types account for more than 70% of use, and all can be recycled mechanically.[9] That means that although the plastics industry is very complex, a circularity strategy that started with just those four value chains and five plastics types could address 60% of total plastics volumes.

Exhibit 3.5

FIVE PLASTIC TYPES IN FOUR VALUE CHAINS REPRESENT 60% OF DEMAND

SHARE OF EUROPEAN PLASTICS DEMAND (49MT)
%, 2015

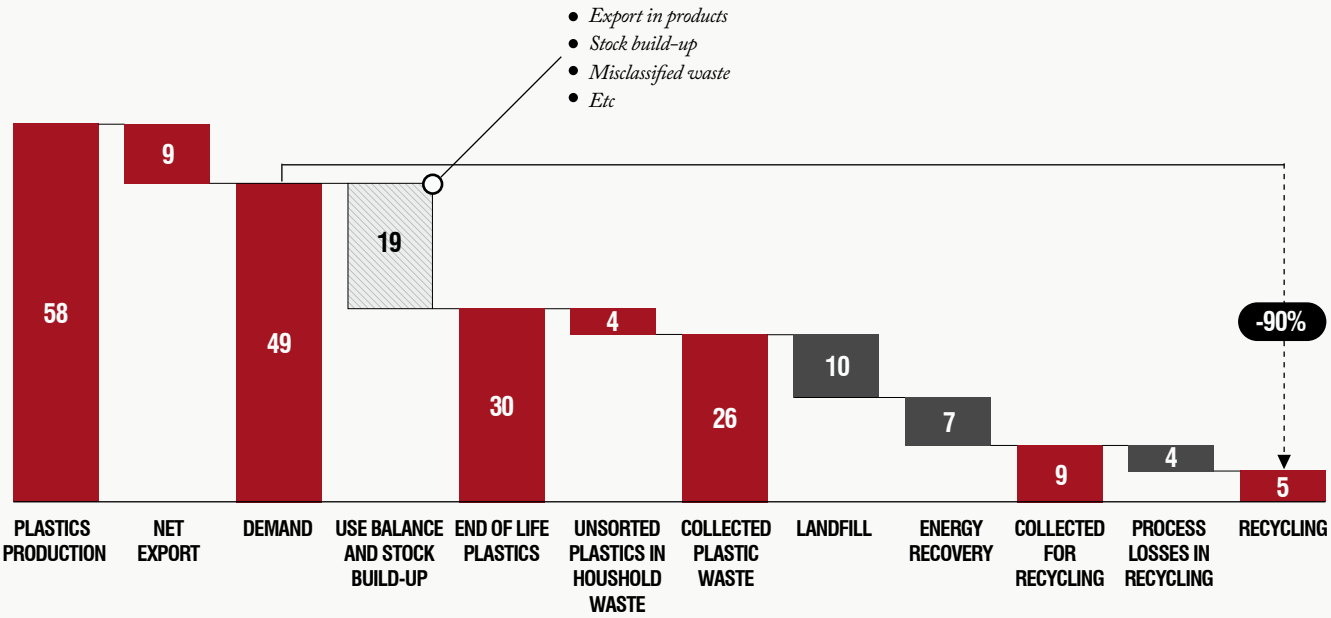


SOURCE: PLASTICS EUROPE (2018B).[10]

Exhibit 3.6

CURRENT RECYCLED VOLUMES ARE ~10% OF DEMAND – FAR LOWER THAN THE ~30% CITED IN OFFICIAL STATISTICS

PLASTIC VOLUMES IN EUROPE, 2015
Mt PER YEAR



SOURCE: PLASTICS EUROPE (2018B), DELOITTE AND PLASTICS RECYCLERS EUROPE (2015).[14]

Even though most plastics thus are recyclable, actual effective plastics recycling rates in the EU are very low. It is often said that more than 30% of plastics are recycled in Europe[11], but that is an incomplete figure (Exhibit 3.6). It refers to volumes collected for recycling, rather than actual recycled volumes, and collected volumes as a share of identified plastics waste rather than total plastics consumed. Total reported plastics waste in 2015 was 30 million tonnes, but as noted above, actual demand was 49 million tonnes. One reason is misclassification; for instance, in Sweden, a study found that only 50% of plastics waste, identified through a detailed mapping, was reported as waste in official statistics.[12] Another is that some of the plastics used are added to the stock (e.g., in buildings or long-lived products). In addition, because plastics streams for recycling are highly contaminated and mixed, only some 60 percent of the volume sent for recycling is actually reprocessed into new materials.[13] Actual EU secondary plastics production as a share of demand is therefore closer to 10% than 30%.

From a technical standpoint, three main factors inhibit the production of high-quality secondary plastics:

- **Mixed and contaminated flows.** High-quality recycling requires that plastics are separated into streams of single plastics types, separated from other matter. This is hindered by today's product design and collection systems, which mix or fuse different types of plastics, add other materials such as paper or metal, require costly sorting, and may make separation impossible.
- **Additives.** Plastics often contain additives, from colourants, to stabilisers, to flame retardants. These are difficult to trace or to remove, and can contaminate plastics or make them unsafe or impossible to use in new products.
- **Contamination.** Plastics may also be contaminated by the substances they held, leading to stains or smells that lower quality, or adding harmful chemicals that prevent recycling entirely. Some contaminants, such as medical waste, require plastics to be incinerated.

The fundamental reasons are not just technical, however, but arise from a combination of policy, market, and industry features throughout the whole value chain of plastics use (Exhibit 3.7). We start from a position where plastics recycling is an extension of end-of-life and waste policy, and need to move towards one where recycling is the intended destination for plastics used in products.[15]

1. Raw materials production – get the prices right. EU CO_2 prices for plastics production are significantly lower than either estimates of the social cost of carbon, or the implicit CO_2 prices in other climate policy (such as subsidies for renewable energy). There are many reasons for this, including the disadvantages of imposing costs on EU industry without corresponding measures in other geographies. The result is that primary plastics are cheaper than they would be if the negative environmental consequences of their use were accounted for. For illustration, with a CO_2 price of 50 EUR per tonne CO_2, the full CO_2 cost (included embedded emissions) would be 20% of the price of primary plastics, a price increase that would significantly improve the economics of recycling.

2. Product design – address externalities for recycling: Many plastic items are designed in ways that make recycling difficult or impossible. Different plastics may be used and fused together; plastics may be dyed (black plastics are difficult to recycle, and colours reduce the quality and commercial value of recycled plastics); there may also be additives that cannot be easily removed, as well as adhesives. All these factors reduce the value that can be recovered, but producers do not bear any of the cost. This is a major, unrecognised market failure, as there is no realistic mechanism for a secondary materials industry to coordinate with those upstream in the value chain to induce the changes that would retain more material value.[16]

3. Collection – target the right quantities. Plastics management policies today target collection rates, not actual production of high-quality secondary materials. The resulting collection systems are far from optimised for the recycling process. The result is additional costs of recycling, with low outputs and low revenues for the recycling industry. Future targets should instead focus on maximising the output of value retention – which requires a combination of high collection rates, minimal loss of materials, and high-quality outputs that are real substitutes for primary plastics.

4. End-of-life treatment – prevent downgrading and loss of materials. The dismantling of products at their end of life often takes little account of the implications for secondary materials production. For example, the shredding of cars results in plastics that are too mixed and contaminated to recycle (and in some cases, even to incinerate safely). Similarly, when buildings are demolished, plastics often are not recycled (with the exception of PVC recycling in some EU countries).

5. Recycling – create investment certainty and higher yields: As noted above, more than 40% of the plastics collected for recycling in the EU are never actually turned into secondary materials. The materials may not be easily recyclable, or they may be degraded or contaminated, making them unusable – or only usable for very low-value secondary materials. As important is to enable investment in the capacity for high-quality recycling. This is held back by uncertain ownership of, and access to, end-of-use plastics in many EU countries.[17] Large scale is crucial to cost efficiency in recycling. Recycling processes are often locally managed or inconsistent across different localities, making it difficult to achieve sufficient scale. Waste regulations sometimes inhibit trade in used plastics across borders, preventing the emergence of a regionally integrated market.

6. Secondary materials market – create demand pull and high quality: Due to the problems noted above, as well as a lack of quality standards for secondary plastics, most secondary plastics are perceived to be of low quality, with limited uses. They therefore often trade at a discount, with average prices as low as 50% of corresponding primary plastics in some categories – a major source of value destruction. Recycled plastics thus end up in lower-value applications such as flower pots, traffic cones or garbage bags. The combination of high cost and low quality also has resulted in limited demand for secondary plastics. There is a chicken-and-egg dynamic at work, where a fragmented and small-scale recycling industry cannot produce the consistent quality and volumes required for large-scale use, even as lack of demand holds back the investment that would enable such production in the first place.

The key lesson from this diagnosis is that barriers are found throughout the entire value chain. The remedy therefore must also address all of these, not just focus on more ambitious targets for collection. Plastics recycling needs to become a major secondary materials industry, rather than an extension of waste handling systems. This also suggests the agenda for improvement: consciously designing products for recycling and thus enabling a large-scale secondary materials industry.

Exhibit 3.7

IMPROVING PLASTICS RECYCLING WILL REQUIRE TRANSFORMATION ACROSS THE ENTIRE VALUE CHAIN

	FROM	TO
1. RAW MATERIAL	**VIRGIN PLASTICS** do not carry cost of externalities	**VIRGIN PLASTICS** carry cost for embodied carbon (other externalities likely via regulation)
2. PRODUCT	**PRODUCT DESIGN** does not bear costs for downstream externalities and costs	**MATERIALS AND DESIGN** choices to make reuse and recycling the intended destination at end of life
3. COLLECTION	**POLICY AND SYSTEMS** focus on collection volumes – similar to other 'waste' flows	**FOCUS ON ENABLING** raw materials flows for secondary materials production
4. END-OF-LIFE	**END-OF-LIFE TREATMENT** and dismantling without focus on retaining material value	**PRODUCTS DESIGNED** for disassembly and dismantled to retain secondary material value
5. SECONDARY MATERIAL PRODUCTION	**LOW-QUALITY** inputs and investment uncertainty results in low yields and small-scale, fragmented industry	**LARGE-SCALE INDUSTRY** with high-quality outputs with high retained value and the ability to replace primary materials one-to-one
6. MARKET FOR RECYCLED MATERIAL	**INCENTIVES** focused on supply into recycling process	**RELIABLE PRODUCTS** and demand-side incentives create market certainty and stimulate investment in capacity

3.4 A CIRCULAR SCENARIO FOR EU PLASTICS USE IN 2050

To estimate the CO_2 emission reduction potential from a more circular plastics system, we constructed a scenario for 2050 that captures the potential for plastics recycling much more fully. As noted above, in the baseline scenario, production of plastics for EU use and associated end-of-life treatment would produce 233 Mt of CO_2 emissions in 2050. This includes emissions from production and disposal, and assumes all plastics are incinerated, with no carbon capture and storage (Exhibit 3.8). In a circular scenario, emissions are reduced by nearly 50% by making reuse and recycling the standard for end-of-life plastics. To reach climate objectives, these emissions would need to be reduced further, through additional recycling, substitution with other materials, use of renewable energy in production, replacement of fossil feedstock with bio-based alternatives or chemicals synthesised from (non-fossil) CO_2, and other production process innovation.

Exhibit 3.9 shows the different components of a circular scenario for EU plastics, all of them contributing to significant reuse of end-of-life plastics and substitution of primary plastics with secondary materials. Key features of this scenario include:

- **Increase the collection rate** for mechanical recycling to 73%. The rate varies by value chain and plastics type, but is underpinned by collection up to 85% of the five largest plastic types. Collection rate remains as low as 30% for other, smaller-scale plastics, which although often very valuable, often also entails small volumes that make the economics of recycling difficult. The non-collected portion of 27% also includes a large share of thermosets, which can be chemically but not mechanically recycled.
- **Significant yield improvements** in sorting and recycling to 76%: The share of plastics that are collected for recycling but not turned into secondary materials falls from more than 40% today to 24%. Combined with a 73% collection rate, this means that the output from re-use recycling is 56% of total end-of-life plastics volumes.
- **Chemical recycling of 25%** of remaining flows. This focuses on the remaining 44% of plastics that are difficult to handle through mechanical recycling. Thus, 11% of total end-of-life plastics are chemically recycled.

Exhibit 3.8

IMPLEMENTING A CIRCULAR PLASTICS SCENARIO CAN REDUCE 2050 EMISSIONS BY 50%

PLASTICS PRODUCTION EMISSIONS
Mt CO_2, EUROPE, 2050

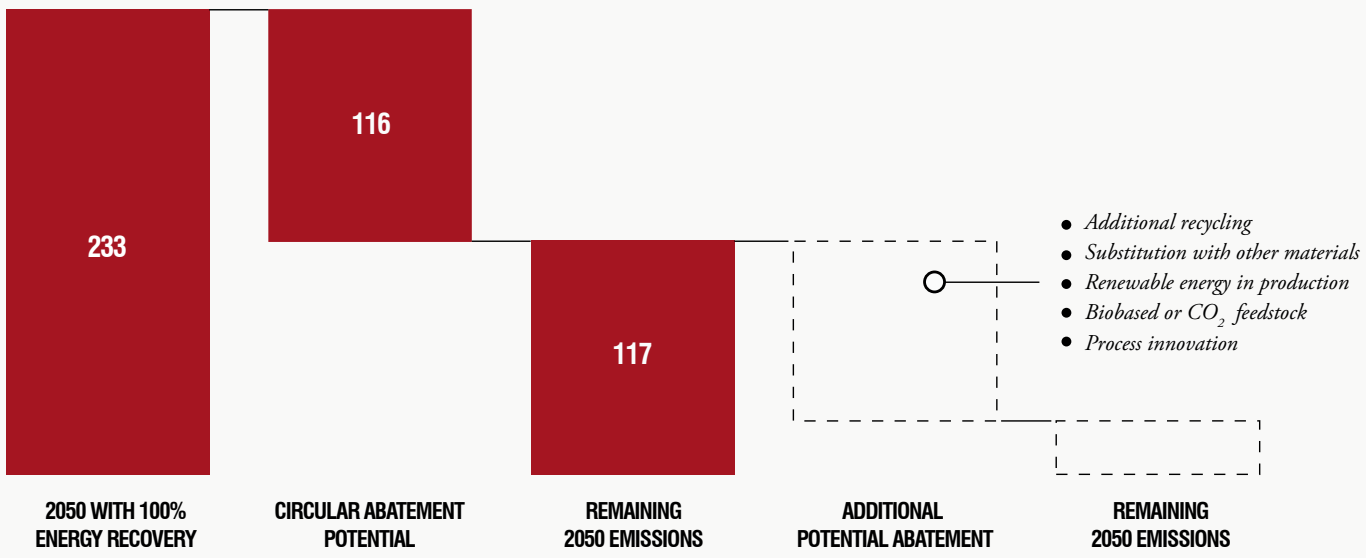
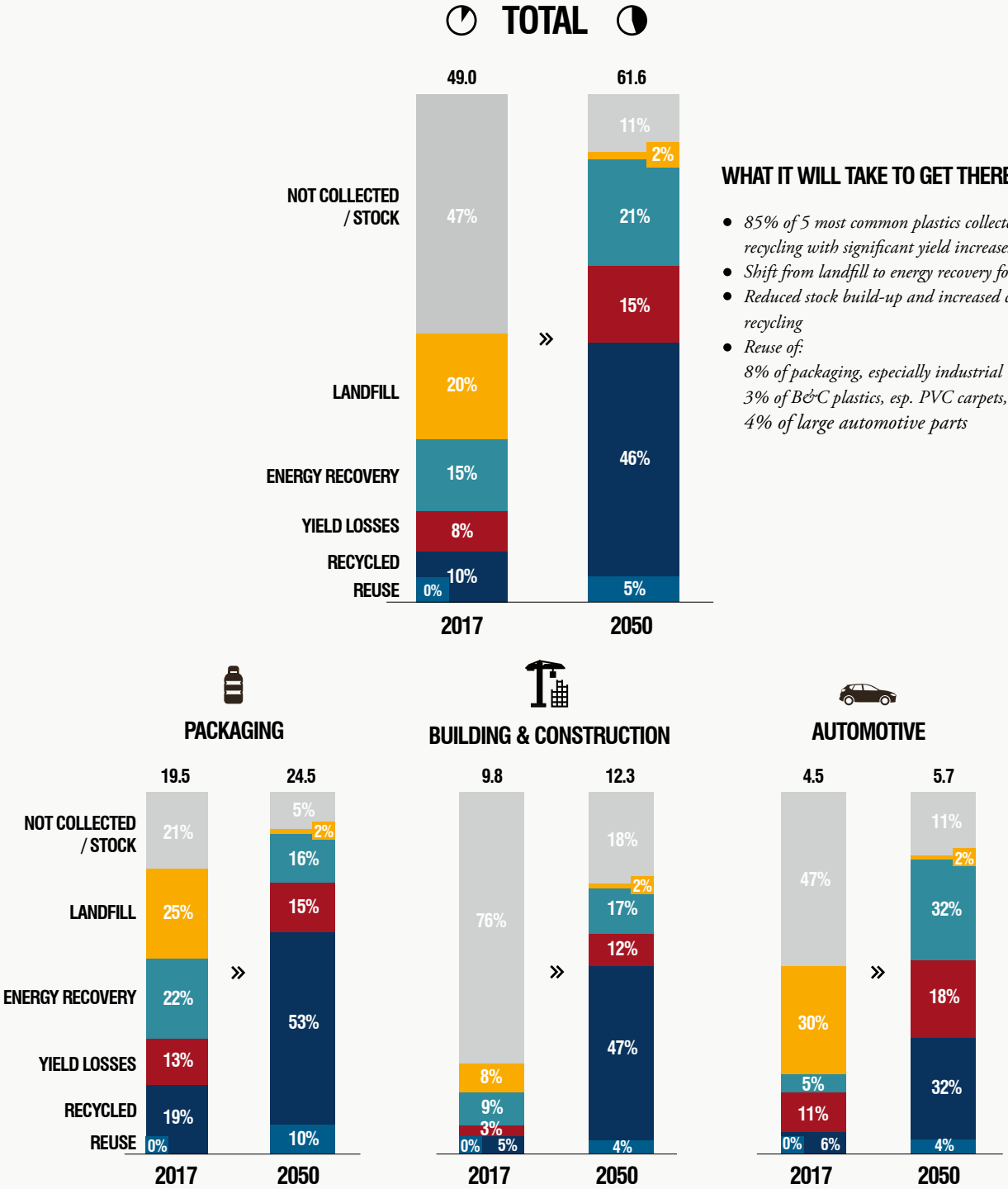


Exhibit 3.9

AN AMBITIOUS CIRCULAR SCENARIO FOR PLASTICS IN 2050

TREATMENT OF END OF USE PLASTICS, 2017 AND 2050
MILLION TONNES; % OF PLASTIC DEMAND



WHAT IT WILL TAKE TO GET THERE

- *85% of 5 most common plastics collected for recycling with significant yield increases (90% yield)*
- *Shift from landfill to energy recovery for non-recycled*
- *Reduced stock build-up and increased collection for recycling*
- *Reuse of:*
  8% of packaging, especially industrial
  3% of B&C plastics, esp. PVC carpets, pipes etc.
  4% of large automotive parts

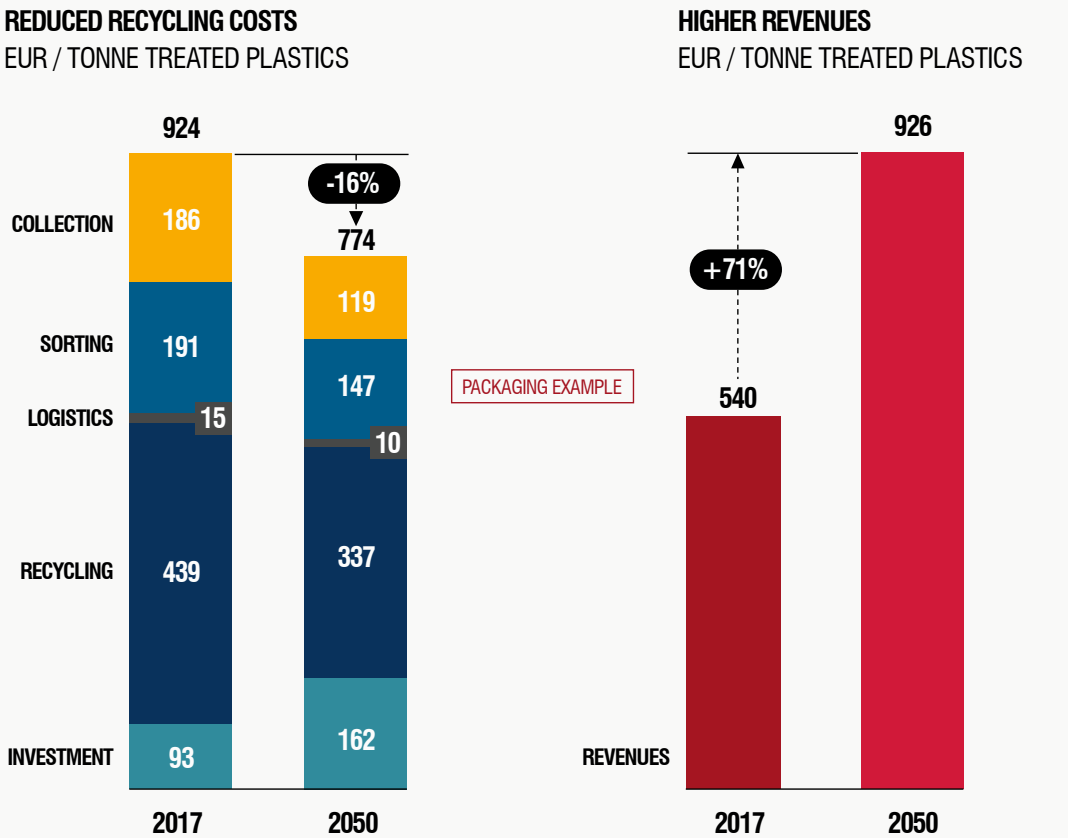
SOURCE: DELOITTE AND PLASTICS RECYCLERS EUROPE (2015), PLASTICS EUROPE (2018B).[18]

Overall, this is a highly ambitious scenario. Realising the circular scenario described above will require transforming the system to address barriers across the value chain. This may seem daunting, but the prize would be worth it: in the circular scenario, the reuse and recycling of secondary plastics creates revenues of 27 billion EUR per year. Plastics could then move a good way towards where steel or aluminium are today, with recycling driven by the value of secondary materials.

A deepdive into the economics of recycling gives an indication of how costs and revenues would have to shift. Today, costs often exceed the available revenues from often low-quality secondary plastics output. Exhibit 3.10 shows a case study example for plastic packaging. Our analysis suggests that costs can be reduced by 16% by creating cleaner flows from materials choices and product design optimised for recycling; increasing the scale

Exhibit 3.10

RECYCLING IS FINANCIALLY CHALLENGING TODAY BUT CAN BE MADE ECONOMICALLY ATTRACTIVE



- ***Cleaner flows*** *from materials choices and product design optimised for recycling*
- ***Increased scale*** *reduces unit cost*
- ***Specialisation*** *and regional integration of markets*
- ***Technological improvement*** *boosts efficiency but* ***requires higher investment***
- ***Reduced risk*** *from regulations and market uncertainty*

- ***Increased yields*** *give larger revenues per tonne treated plastic (better technology, cleaner inflows)*
- ***Higher quality*** *enables pricing closer to virgin materials (additional sorting, improved technology, cleaner flows and optimised products)*
- ***Raised cost of virgin materials*** *improves willingness to pay for secondary products*
- ***Better functioning markets*** *reduce current commercial risk to buyers*

DEEP TRANSFORMATION THROUGH COORDINATED AND SUSTAINED ACTION ACROSS THE VALUE CHAIN

of recycling; creating more specialised but also regionally integrated recycling; adopting new technologies; and reducing risks due to regulations and market uncertainty. At the same time, revenues can be increased by as much as 71%, through increased yields, which give higher revenues per tonne of treated plastic (better technology, cleaner inflows); higher quality, which enables pricing closer to virgin materials (an average of 70% of virgin prices in our scenario); higher costs for virgin materials, which improve buyers' willingness to pay for recycled materials; and better-functioning markets that reduce current commercial risk to buyers, thus incentivising the use of secondary plastics and investments in recycling capacity and innovation.

Alongside all of these, strong technology development provides a significant boost. Recycling is strongly synergistic with digitalisation, which is rapidly reducing the cost of marking of different materials and products, use of sensor technology, and automation of dismantling and sorting – all of which will be fundamental to achieve more cost-effective plastics recycling. This requires increased capex, but this is more than offset by the higher revenues available from higher-quality outputs.

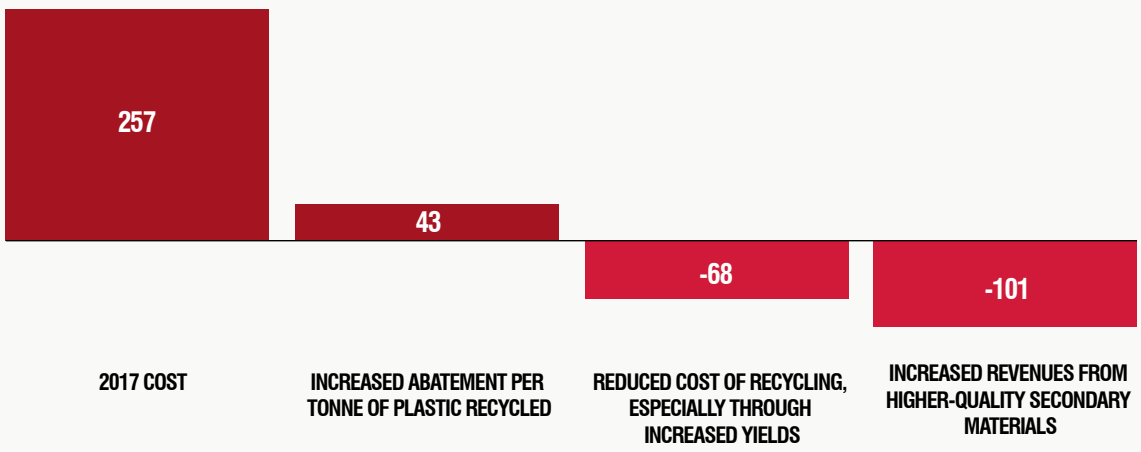
Achieving this transformation holds the promise of an industry driven by the intrinsic value of plastics.[19] From a climate perspective, adopting those measures could also make the difference between plastics recycling being a costly abatement option, or an economically attractive one. Today, recycling is expensive seen from a pure CO_2 perspective (although it can have other benefits). With the transformation described above, this changes by 2050. Exhibit 3.11 shows a particularly striking example, with today's high abatement cost for packaging. By 2050, the net CO_2 abatement per tonne of recycled plastic goes up (for the reasons described in section 3.2), while the net cost of recycling pivots to a net benefit. The abatement cost is therefore negative, meaning that the transformed recycling system can not only cut CO_2, but also create a net financial gain.

These cost estimates need careful interpretation. First, the negative cost does not mean that large profits will accrue to recycling industries. Rather, the benefit will be distributed across the value chain, including through changed prices for end-of-life plastics and for secondary plastics. Second, achieving this cost depends on the full transformation described above. It is not something one actor can create on its own.

Exhibit 3.11

REDUCING ABATEMENT COST REQUIRES HIGHER NET ABATEMENT, IMPROVED YIELDS AND HIGHER QUALITY

ABATEMENT COST (PACKAGING EXAMPLE)
EUR PER TON ABATED CO_2



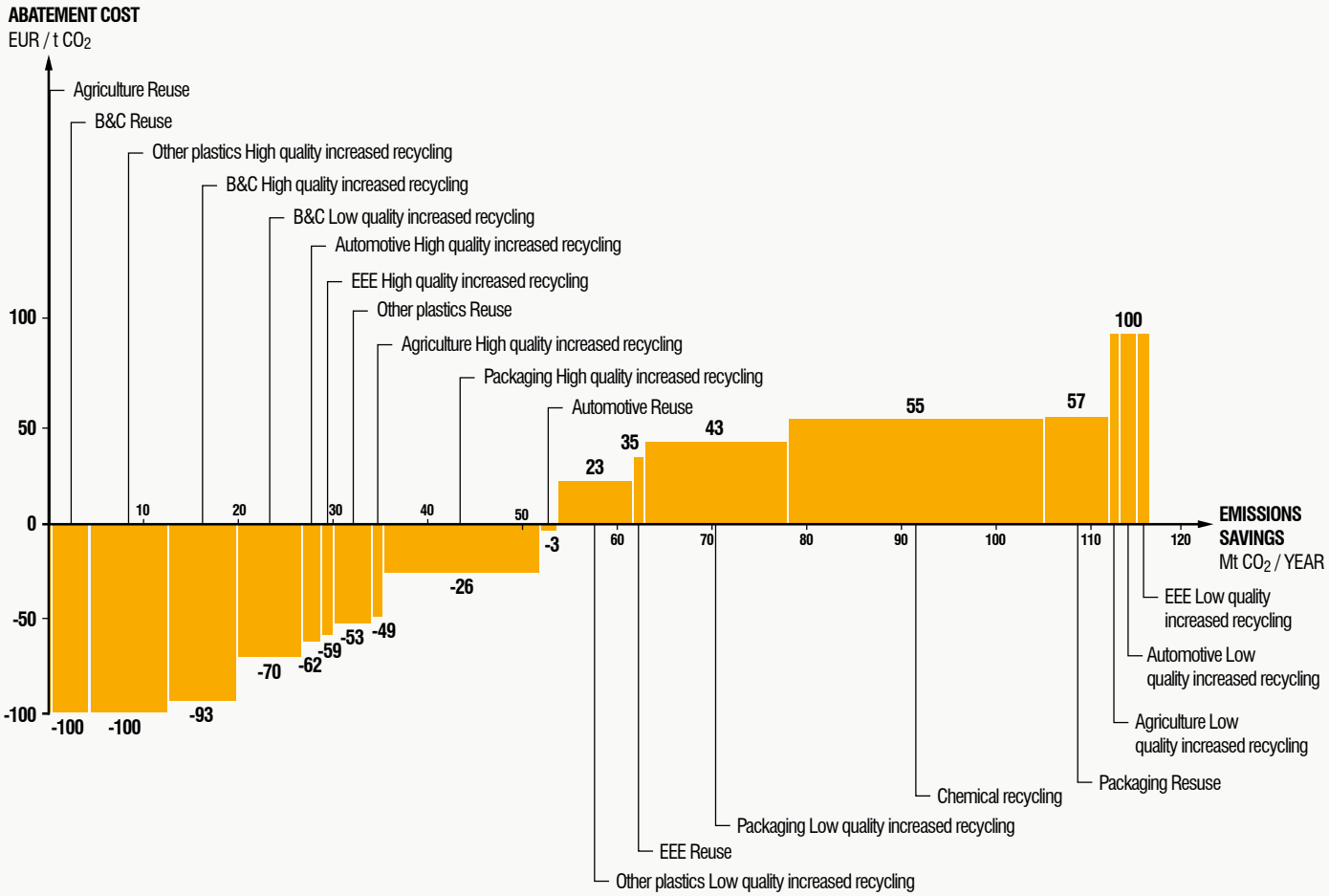
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

Performing the above analysis for all segments and for different qualities of plastics flows, it is possible to create a cost curve for CO_2 reductions through plastics recycling (Exhibit 3.12). The horizontal axis shows the total abatement potential, which sums to the 116 Mt CO_2 per year, described above. The costs are estimated similarly to that described for the packaging example described above. There are of course many uncertainties in project technology developments, the feasible quality of secondary plastics, and other factors leading to 2050. Also, although we have attempted to account for the increased cost of adapting products for recycling, the actual cost will not be known until incentives to do so are created. As with other areas where incentives have been lacking to date, there is likely to be significant low-hanging fruit, but there will also be instances where adapting for recyclability would create significant compromises with function, or impose costs. For all these reasons, these costs are exploratory and indicative. Nonetheless, the analysis shows that plastics recycling can not only be a substantial abatement opportunity in terms of volume, but also has the potential to be economically attractive compared to much else that needs to happen to put the EU on a low-carbon pathway.

Exhibit 3.12

WITH CHANGES THROUGHOUT THE VALUE CHAIN, RECYCLING COULD BE A HIGHLY COST-EFFECTIVE FORM OF CO_2 ABATEMENT BY 2050

PLASTIC COST CURVE 2050 POTENTIAL
EUR PER ABATED t CO_2, EUROPE, 2050



NOTE: BUILDINGS AND CONSTRUCTION (B&C), ELECTRICAL AND ELECTRONIC EQUIPMENT (EEE).

COMPLEMENTING STRATEGIES TO FURTHER REDUCE EMISSIONS

Even ambitious recycling as described above would leave half of emissions in place. These arise from a variety of sources, which also suggest ways to reduce them (Exhibit 3.13).

Even with ambitious mechanical and chemical recycling, a small share of plastics will be difficult to collect and treat. There are also substantial yield losses from plastics that are collected for recycling, but which do not become secondary materials. In both cases, primary plastics must be produced to replace the material lost. In addition, the recycling processes also result in some CO_2. Both losses and direct CO_2 emissions are particularly large for chemical recycling, and an innovation priority therefore must be to find more effective processes with a higher yield, including by introducing external, renewable energy to generate the heat necessary.

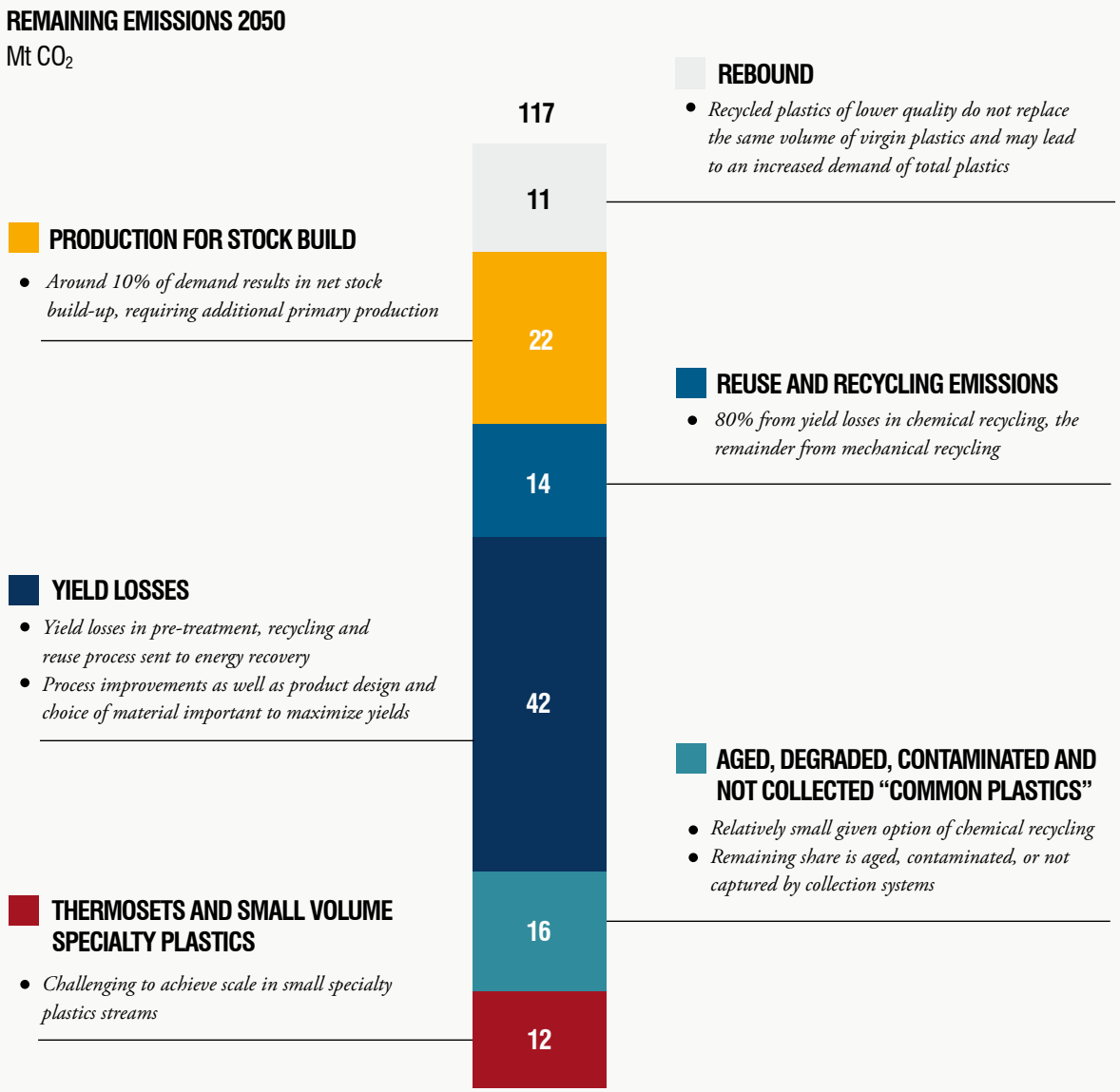
There are also emissions from the production of primary plastics required to add to the total stock of plastics in the economy. How much will be required is very uncertain – it is possible that the total stock will saturate, removing much of these emissions. Finally, we have allowed for some rebound effects: an increase in plastics consumption due to the increased supply of some relatively lower-quality recycled materials. This can be reduced by improving quality further, or if the amount of lower-quality plastics could be absorbed by existing demand pools.

To further reduce emissions, a combination of additional strategies will be necessary:

- **Substitution with other materials.** The scenario here is based on continued growth in plastics use. However, there are other options, including substituting to other materials that either can be more easily recycled, or ones that are based on bio-feedstock.
- **Use of renewable energy in production.** As noted above, adding external renewable energy to the plastics production process can reduce emissions to some degree. With further process innovation, it is possible that even more of the production emissions could be abated. As noted, however, this does not address the fossil carbon in the feedstock.
- **Non-fossil feedstock.** Replacing fossil fuels with other feedstocks could address a large share of both production and embedded emissions. Bio-based feedstocks have been mooted as one alternative, although the volumes of biomass required would be large. Another option would be to use either CO_2 or carbon-monoxide as feedstock.[20] However, these would have to come from non-fossil sources if total emissions are to be brought to net-zero. Using such routes also would have large resource requirements, especially for renewable electricity.

Exhibit 3.13

DEEPER TRANSFORMATION AND INNOVATION IS REQUIRED TO REDUCE THE REMAINING 65% OF EMISSIONS



3.5 HOW TO GET THERE – MEASURES TO PROMOTE PLASTICS RECYCLING

As noted above, current policies are focused mainly on waste management, with increasing pressure on recyclers to maximise collection volumes. The recent EU Plastics Strategy sought to complement this, including to introduce measures in other parts in the value chain.

We propose that the bedrock of a future sustainable plastics system – and secondary plastics industry – must be to enable high value of secondary plastics. Exhibit 3.14 illustrates examples of policy areas that could support or accelerate a transition. The full change described above will take time – possibly measured in decades – so it is important to start on this path as soon as possible.

This report has not evaluated individual policy proposals, and is in no position to make specific proposals for policies. However, a number of high-level principles can guide policy-makers as they approach this area.

First, changes must occur simultaneously across the entire value chain: primary production, product design, recycling infrastructure and business models, the market for secondary plastic, and legacy waste handling regulations and systems. One route to this could be further industry integration, perhaps of primary and secondary materials production. However, it is also possible that a range of barriers – rooted in the economics of incomplete contracts and transaction costs – will continue to prevent market actors from achieving this outcome. If so, policy will have an important coordinating role.

Second, a starting point for policy must be to analyse and correct for current externalities. One of these is the lack of a price on emitting CO_2, to reflect either the social cost of carbon, or the prices that will eventually be required across the economy to reach climate targets. More broadly, low taxes on resources and pollution relative to those on the inputs to recycling (notably, labour and transport fuels) reduce incentives for recycling. A second is to recognise and address the heavy externalities that product design choices impose on recycling. This is a new agenda, and there is an urgent need to evaluate the costs and benefits of different options to address it – whether the gradual introduction of product regulation, voluntary agreements, standards, industry design protocols, financial incentives, or in other ways.

Third, policy-makers need to consider the nature of barriers to demand for secondary plastics. Engagements with a range of companies for this study suggest that there is significant latent demand from companies that increasingly seek to use secondary materials, but with undeveloped markets, this cannot support the necessary investment in recycling infrastructure. The 'pledging' mechanism in the Plastics Strategy sought to address this. If policy-makers discover that more far-reaching intervention is warranted, options to evaluate could include quotas for recycled plastics in selected product categories, financial instruments linked to the use of secondary materials, and market creation through public procurement.

Fourth, waste collection systems and practices for handling end-of-life products need to be revisited to account for their impact on high-value recycling. Today's collection systems are fragmented, with patchy coverage of plastics streams and end-use segments. Much of infrastructure is optimised to meet policy targets that are not necessarily conducive to actual production of high-quality secondary materials. Another area to investigate are the practices for dismantling end-of-life products, notably the demolition of buildings and shredding and mixing of materials from end-of-life vehicles.

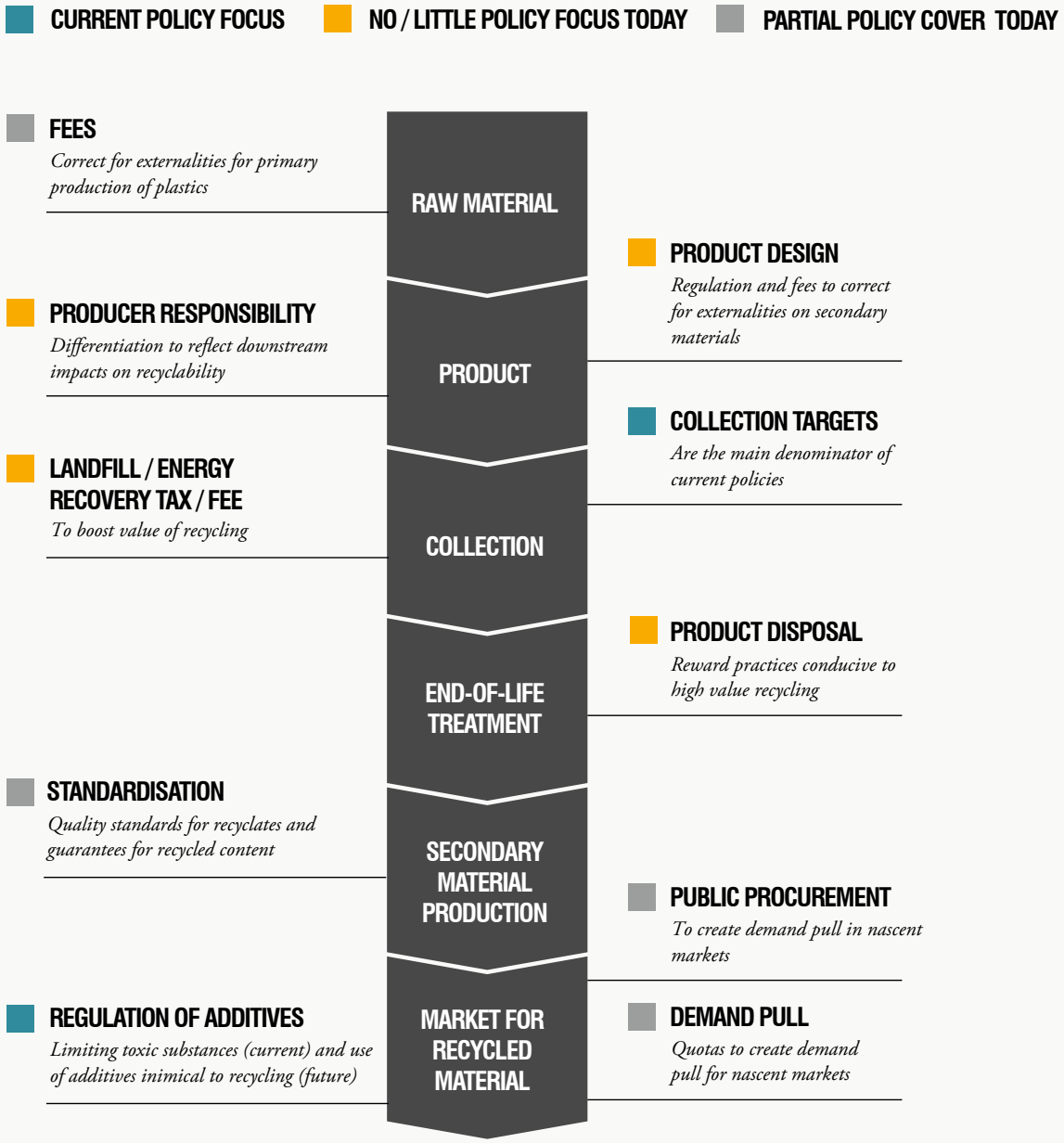
Fifth, waste regulations may also need updating. Large-scale use of secondary plastics requires that markets operate at a scale and to the standards of global value chains for raw materials. By contrast, current regulations often treat recycling as an off-shoot of local, small-scale waste handling. Key issues to consider include restrictions on trade across borders, lack of clarity about ownership and access to plastics flows, and the resulting investment uncertainty. As with other policy areas, changes would need to be evaluated for their impact on other objectives, notably that of ensuring safe waste handling.

Finally, governments need to kick-start innovation. Recycling is undergoing a quiet technology revolution. Technology is already improving fast, with recent plants significantly more capable than ones available only a few years ago. Digitisation is a major force to harness, with applications across marking, remote sensors, real-term tracking, and automation. In parallel, there is a need for materials development, notably to find long-term solutions for plastics that are hard to recycle, such as engineering plastics and thermosets. Policy can support these agendas both through fundamental research, development, and demonstration, and by supporting new technology deployment – analogous to the approach taken to renewable energy technologies or other long-term key solutions to climate mitigation.

Exhibit 3.14

CURRENT POLICIES COVER ONLY PARTS OF THE RANGE OF BARRIERS TO HIGH-VALUE PLASTICS RECYCLING

EXAMPLES OF POLICIES – ALL WOULD NEED CAREFUL EVALUATION



4. ALUMINIUM

REALISING THE POTENTIAL FOR RECYCLING

Aluminium is a heavily used material for which the potential for circularity is growing fast. Even with rapid demand growth, the potential for aluminium recycling is increasing: By 2050, the share of reused material could, in principle, double – even as total aluminium use grows strongly. In the EU, there will be enough end-of-life aluminium to serve more than half of demand by mid-century. Moreover, the resource gains from circularity are particularly large with aluminium, as remelting existing metal requires just 5% of the energy of new production, sharply reducing CO_2 emissions.

Capturing this opportunity, however, requires significant changes. A first step is to reduce losses of aluminium in each use cycle, which now amount to 25–30%. This requires better end-of-life treatment and collection for a range of products, as well as product designs that facilitate the recovery of aluminium. End-of-life aluminium will also need to be handled differently. Today much of it is 'downcycled' into a mix of different alloys that can only be used for a small share of aluminium demand. If this were to continue, there would eventually be 'excess scrap', even as demand for new aluminium kept growing. A shift to electric vehicles will exacerbate this problem by further reducing demand for the cast aluminium components that absorb most of the recycled aluminium today.

A more circular scenario for aluminium requires reducing losses when products are first manufactured, and better separating and sorting end-of-life aluminium. This would have significant climate benefits. Globally, CO_2 emissions could be reduced by 300 Mt per year in 2050, and in Europe, by close to 30 Mt. The latter represents 36% of emissions from meeting EU aluminium demand in a baseline scenario.

Overall, aluminium therefore is yet another example of large CO_2 benefits from enabling a more circular system. This also opens up new opportunities for value creation, in preserving and monetising the inherent value in secondary materials.

*Globally, CO_2 emissions could be **reduced by 300 Mt** per year in 2050.*

4.1 UNDERSTANDING FUTURE ALUMINIUM NEEDS

Aluminium is a relatively young, but versatile material with multiple and ever-increasing uses in packaging, buildings, automotive and other sectors. No other metal except for steel is more widely used around the world. Production of aluminium from ore ('primary aluminium') now stands at just under 60 million tonnes per year, and it continues to grow.

In recent years, growth in aluminium production and use has been dominated by developing countries. China in particular has been a major driver of aluminium demand, accounting for more than 70% of the increase in production in the past decade. As a result, 55% of primary aluminium production is now in China.

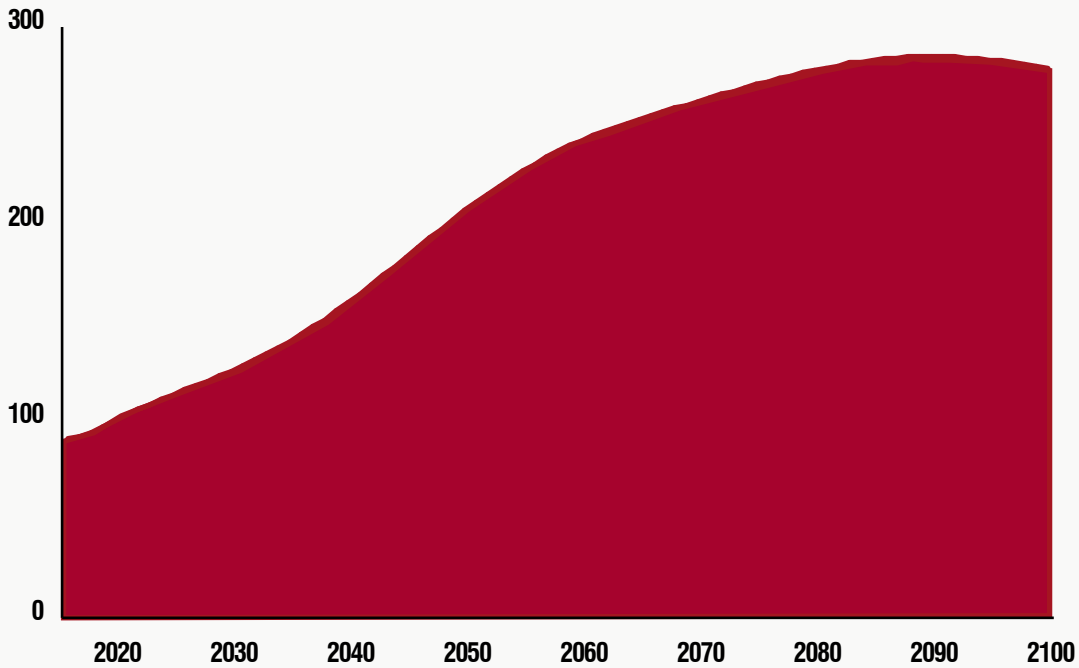
The analysis we present in this chapter focuses on the EU, but the global context is crucial because aluminium is a global commodity. Raw materials, aluminium and scrap metal are all traded internationally, and the EU imports a significant share of the aluminium it uses. Thus, any effort to develop a more circular aluminium economy needs to take global trade into account.

Like other metals use, the benefits from aluminium depend on the available stock: the total amount of metal embodied in structures and products such as cars, buildings or machinery. Demand for aluminium derives from the need to build up and maintain this stock – which is still growing in all world regions.[1] To meet future needs, the global stock per capita would need to increase by 350% (see Exhibit 4.1 for an explanation of our methodology). To keep up, aluminium production would have to increase rapidly. By 2050, our scenario shows global aluminium production would more than double from current levels.

Exhibit 4.1

GLOBAL DEMAND FOR ALUMINIUM PROJECTED IF BY 2100, ALUMINIUM STOCKS WORLDWIDE MATCHED THOSE IN OECD COUNTRIES TODAY

GLOBAL ALUMINIUM PRODUCTION
Mt ALUMINIUM PER YEAR, 2016–2100



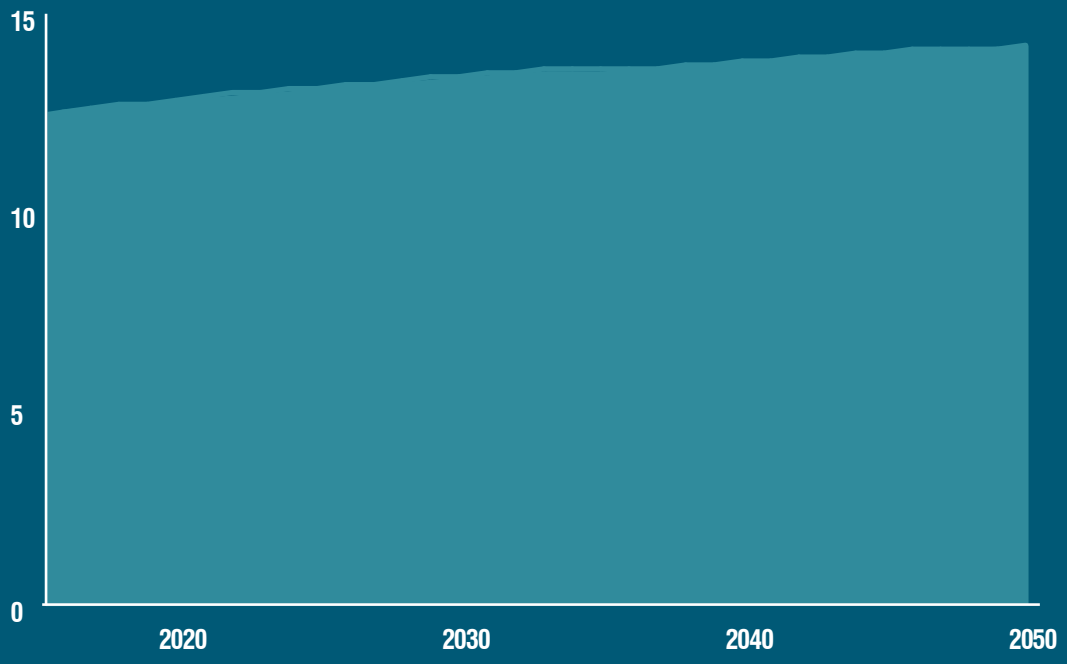
SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT.

The modelling of future demand follows the methodology described in Liu, Bangs, and Müller (2013).[2] Demand is modelled for six end-use sectors (consumer durables, construction, electrical equipment, machinery, transport and other) and five world regions (Europe, North America, Japan, China and Rest of World). Demand in each sector and region is modelled with a stock-based approach, with population forecasts based on UN Population Prospects 2017.[3] Per-capita saturation at around 425-475 kg per person, depending on the region, follows projected GDP develoments and is completed in all regions by 2100. In addition, the scenario includes a bottom-up model of the evolution of vehicle production, including the shares of electrical and internal combustion engine vehicles, and the assumed aluminium content in these categories. Historical aluminium stocks are based on the data described in Bertram et al. (2017)[4], while the split of stocks between end-use sectors is based on Liu and Müller (2013).[5] Future stock turnover is modelled with different lifetimes of products in each end-use sector following a normal distribution. The steps of the aluminium supply chain and use cycle are directly modelled, including losses in production, new scrap formation, and collection of post-consumer scrap. Losses and other parameters are calibrated so production and shares of products match those in data published by World Aluminium (2018a)[6], and also based on various estimates in the literature. The model also tracks separate flows of casting alloys vs. wrought aluminium. It further represents degrees of international trade in scrap, and the dilution of casting aluminium with other scrap or with primary metal. CO_2 emissions estimates include emissions from alumina refining, aluminium smelting, and casting, but do not include other sources sometimes included in full life-cycle assessments (such as the emissions from the production of anodes, the transportation or raw materials or products, or the mining of bauxite). Both direct emissions from fuel use and indirect emissions from electricity production are included. In keeping with the approach used elsewhere in this study, the baseline scenario includes the gradual decarbonisation of the energy system, as described elsewhere in the text, and by 2100, both alumina refining and electricity production are therefore assumed to be fully CO_2-free. The resulting global production of aluminium is shown on the previous page, with further results elaborated throughout the chapter.

Exhibit 4.2

EU ALUMINIUM DEMAND GROWS ONLY SLOWLY TO 2050

ALUMINIUM PRODUCTION REQUIRED TO MEET EU DEMAND
Mt ALUMINIUM PER YEAR, 2016–2050



NOTE: THE FIGURE DEPICTS THE PRODUCTION OF ALUMINIUM REQUIRED TO SERVE EU DEMAND, NOT PRODUCTION IN THE EU.
SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT.

Within the EU, future demand growth will depend strongly on when saturation is reached, and at what level. Although aluminium stocks vary significantly by country, the current average is 250 kg per person. Our scenario assumes that aluminium stocks continue to grow until they reach 450 kg per person by mid-century, an 80% increase. Thereafter, demand would be driven not by a further increase in the total stock of aluminium, but by the need to replace products at end of their life.

However, this does not mean that *production* would need to grow much. Today, the production required to serve EU demand amounts to just over 13 million tonnes per year of combined primary and secondary (i.e. recycled) aluminium, but this already includes continued additions to the stock.[7] Achieving the 80% increase in stock by 2050 would require only a slight increase, to 14 million tonnes per year (Exhibit 4.2).[8]

Several things are notable about this projection. First, in keeping with our focus on the demand side, it covers only the aluminium production required to meet demand for aluminium within the EU. Europe also manufactures and exports a wide range of products containing aluminium – for example, it exports cars containing some 800,000 tonnes of aluminium each year.[9] In principle, European aluminium production could therefore grow faster than demand for aluminium in the EU, driven by exports of either aluminium or aluminium-containing products.

Second, the level of demand depends on when the stock will saturate. As noted, the above profile achieves an 80% increase in the stock by 2050. With still higher levels, demand would have to be higher. However, there also are strong reasons why continued growth in the aluminium stock beyond these levels might not be necessary. As the analysis in Chapter 5 sets out, demand for materials from the automotive sector could be as much as 75% lower in a future shared mobility system than in today's system of individually owned cars. Chapter 6 shows that materials use in buildings also could be reduced significantly. These two sectors account for half of aluminium demand. Moreover, as we discuss in Section 4.4, this does not in fact significantly affect our findings; achieving a more circular use of aluminium remains important even with higher growth.

Finally, it is important to distinguish where aluminium is used from where it is produced. The aluminium used for manufacturing in the EU has a variety of sources; a third is imported. In that regard, aluminium differs from the other materials investigated in this report, which the EU produces more or less in the same amounts as it uses domestically. In addition, the EU imports half of the alumina used (alumina is the intermedia product in producing aluminium metal from bauxite ore).

4.2 CO_2 EMISSIONS FROM ALUMINIUM PRODUCTION AND USE

Primary production of aluminium requires very large amounts of energy. The smelting of aluminium uses 13–15 MWh per tonne of metal produced. Multiply that by the almost 60 million tonnes of aluminium now produced around the world, and the electricity usage amounts to as much as 5% of global electricity production – roughly what is used for household lighting around world.[10] When using fossil fuels for electricity production, large amounts of CO_2 emissions result. In addition, greenhouse gas emissions arise from the production of alumina, and there are further emissions associated with the smelting process and with casting the metal into ingots.

Adding these up, emissions from aluminium production can vary significantly. The key determinant is whether the electricity is low-carbon. Globally, 60% of aluminium today is produced using coal-fired electricity,[11] which results in emissions per tonne of aluminium produced of as much as 18 tonnes CO_2. For comparison, this is more than 7 times the emissions associated with producing one tonne of primary steel.

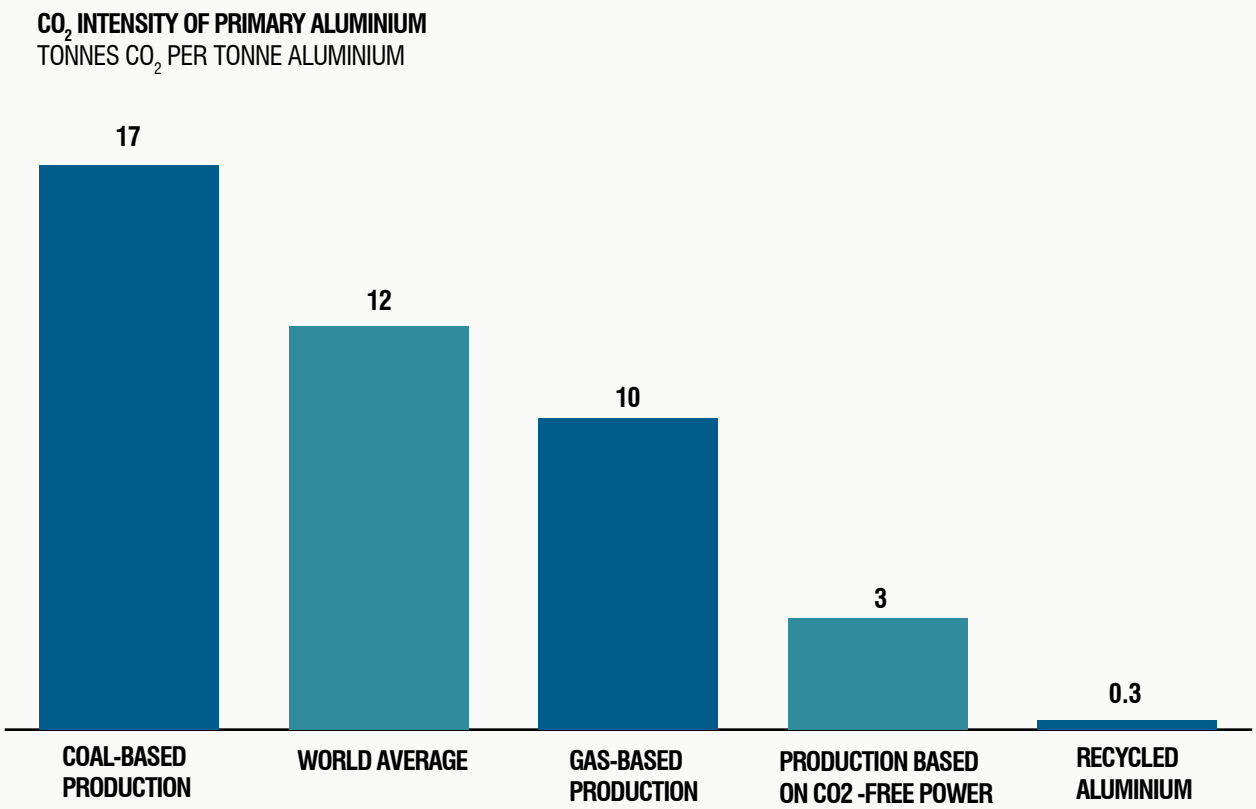
Unlike with steel production, however, emissions from aluminium production can be reduced dramatically by using low-carbon power. With a decarbonised electricity supply, emissions from primary aluminium production are reduced to just over 3 tonnes CO_2 per tonne. Indeed, a majority of the aluminium produced in Europe is relatively low-carbon, because it is made with hydro- and nuclear power.[12]

Yet as dramatically as low-carbon electricity can lower emissions from aluminium production, recycling aluminium still has even lower emissions, because remelting requires just 5% of the energy of primary production. This results in emissions savings of up to 98% (Exhibit 4.3).

Accounting for both direct emissions and indirect emissions, aluminium production emits some 800 Mt CO2 per hear (Exhibit 4.4).[14] If global electricity production was decarbonised to meet climate targets, CO_2 emissions from aluminium production would increase far less dramatically

Exhibit 4.3

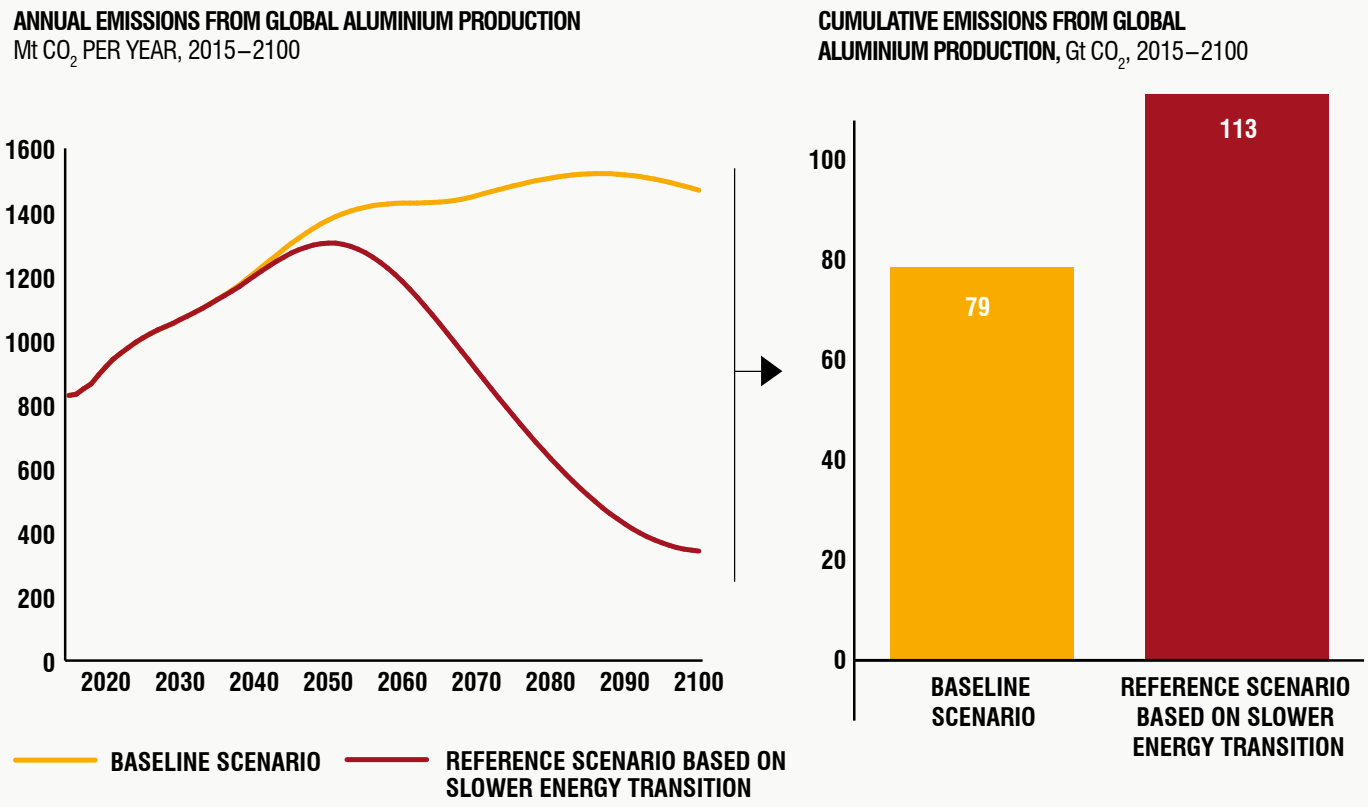
RECYCLED ALUMINIUM HAS FAR LOWER EMISSIONS THAN NEW PRIMARY PRODUCTION



SOURCE: MATERIAL ECONOMICS CALCULATIONS BASED ON MULTIPLE SOURCES. [13]

Exhibit 4.4

LOW-CARBON ELECTRICITY CAN DRAMATICALLY CUT EMISSIONS FROM ALUMINIUM BUT CUMULATIVE EMISSIONS TO 2100 NONETHELESS ARE LARGE



SOURCE: INTERNATIONAL ENERGY AGENCY (2017); MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT.[16]

than demand for the metal, and starting in mid-century, they would actually decline.[15] In a more typical 'reference' scenario, however, where electricity production is decarbonised much more slowly than the goals of the Paris Agreement would imply, emissions from aluminium production would gradually rise to 1.5 billion tonnes of CO_2 per year. Cumulative emissions (which are what matters most for the climate) would be about 80–110 Gt CO_2, or 27–37% of the 300 Gt carbon budget available for all of industry in a low-carbon scenario. Note that the 'reference' scenario is shown for illustration of the impact of a slow energy transition on emissions only; it is not used for any evaluation of the benefits of greater circularity described in this report.

As this shows, even if emissions from aluminium were sharply reduced by changing production technologies[17], there is much value in also reducing the amount of primary aluminium required to meet economic needs. To put this in perspective, if primary aluminium production grows as rapidly as our analysis suggests, fully decarbonising aluminium smelting through low-carbon power would require an additional 1,335 TWh per year of zero-carbon electricity in 2050 – almost as much electricity as India uses today. Demand-side measures are therefore crucial to reduce the claim that aluminium makes on clean energy, and thus reduce the cost and increase the feasibility of decarbonising the industry.

The good news is that there is significant potential to improve on current practices, to enable a larger share of production through recycling and thus reduce the need for future primary aluminium production even in a world with strongly growing demand.

4.3 REALISING THE POTENTIAL FOR CIRCULARITY IN THE ALUMINIUM SECTOR

The core of the circular economy opportunity for aluminium is to make the best use possible of metal that has already been produced. This requires minimising the losses of aluminium, and ensuring that secondary production (i.e., recycling) can meet as much of aluminium needs as possible.

The potential for more circular aluminium will grow in the future (Exhibit 4.5). Today, aluminium recycled from end-of-life products covers just 20% of total global demand. By 2050, however, this share will almost double, even as overall demand for aluminium more than doubles. Half the growth in demand could thus be met by recycling. In Europe, secondary production could be still more important, as the total metal available for recycling would grow from 27% today, to 55% in 2050.

Both globally and in Europe, then, recycling could be a major part of supplying future aluminium needs – with major savings of energy and CO_2 emissions. However, there is a long way from available scrap to production of high-quality, secondary aluminium that can be used across applications. There are two key issues:

- **Reducing the losses** of aluminium throughout the use cycle; and
- **Preventing downcycling** and enabling the production of high-quality secondary aluminium.

REDUCING LOSSES OF ALUMINIUM

For many consumers, aluminium is a prime example of effective recycling. For decades now, many countries have run successful aluminium recycling programmes, and even if many other items are discarded, beverage cans are carefully collected and reused. This system for recycling beverage cans is particularly effective, and in general, aluminium scrap collection rates are relatively high. Globally, 77% of aluminium from end-of-life products is collected for recycling, though the rate varies significantly across regions and product groups.[18] Still, this means 23% of end-of-life aluminium goes to waste.

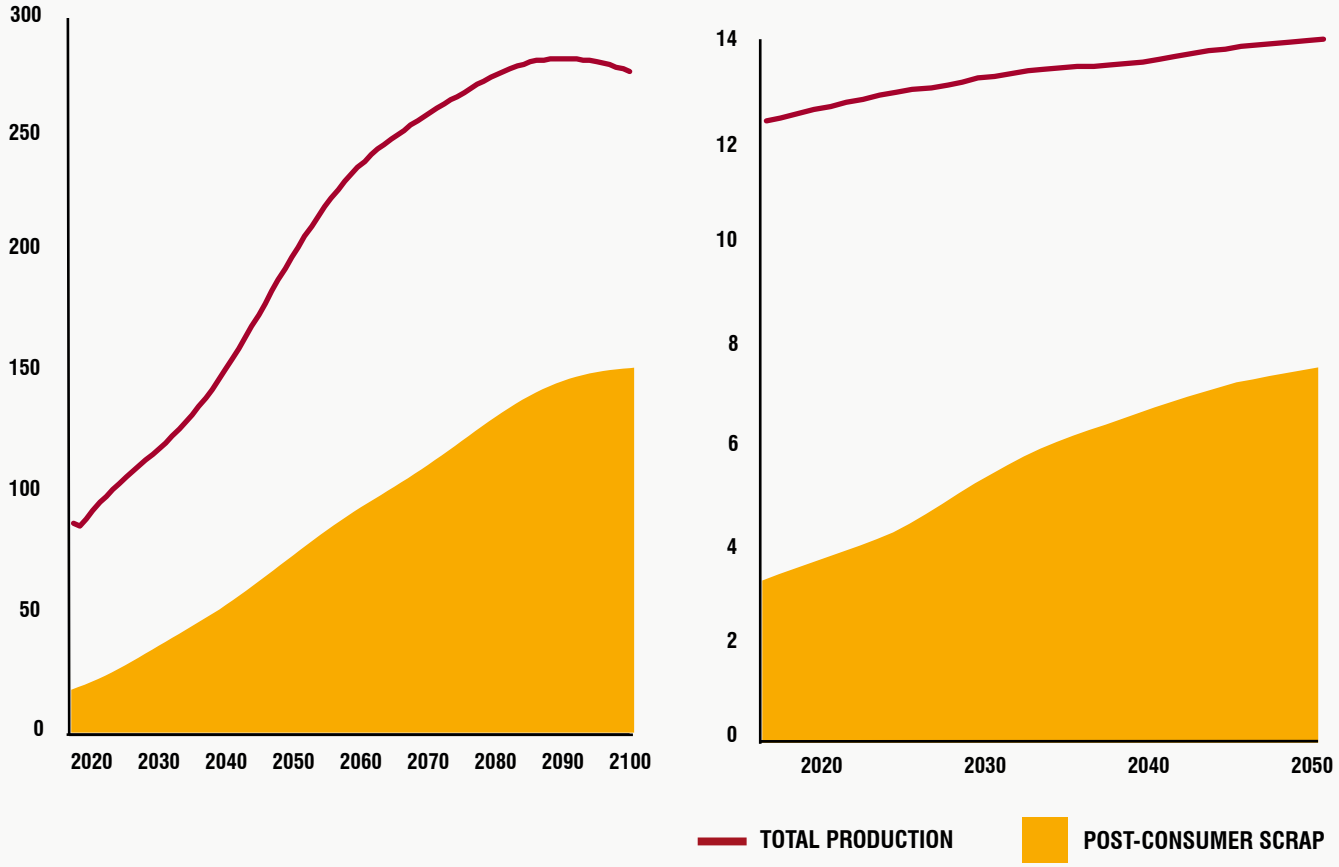
In addition, large amounts of scrap aluminium are created during the casting, fabrication or manufacturing processes – around 35% of the material ends up not in products, but as 'new scrap'.[19] While almost all this new scrap is collected, some 2% is not returned for remelting or refining.[20] In addition, for the 98% that is reused, some 2–3% is lost during processing, remelting and refining.[21] All of this contributes to higher overall losses of aluminium.

Altogether, in each use cycle, 25–30% of aluminium is lost. To counter this, the single most important measure is to increase collection rates of post-consumer scrap, although reducing the amount of new scrap created is also helpful.

Exhibit 4.5

POST-CONSUMER SCRAP COULD MEET A LARGE SHARE OF FUTURE GROWTH IN GLOBAL ALUMINIUM DEMAND

AVAILABLE ALUMINIUM POST-CONSUMER SCRAP COMPARED TO TOTAL PRODUCTION



NOTE: 'AVAILABLE SCRAP' REFERS TO THE AMOUNT OF POST-CONSUMER SCRAP THAT WOULD BE COLLECTED WITH CURRENT PRACTICES.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT

DOWNCYCLING OF ALUMINIUM TO CAST PRODUCTS

Although aluminium can be remelted indefinitely, there are three factors that greatly complicate secondary aluminium production:

- **Aluminium is rarely** used in its pure form, but typically alloyed with a range of other elements to attain the desired properties. Those properties often depend on keeping alloying composition within a tight range, so even small deviations can undermine the quality for a specific purpose (Exhibit 4.6).
- **There are many dozens** of different alloys in major use, but a key divide is that wrought alloys contain much smaller quantities of alloying elements than do casting alloys.[22] Wrought alloys with lower alloying content can generally be recycled into casting alloys, but this is a one-way street, and wrought products cannot be created from aluminium that has once been a casting alloy.
- **Finally, a major difference** from steel is that most alloying elements cannot realistically be removed once they have been added.[23]

Exhibit 4.6

ALUMINIUM NEEDS TO BE COMBINED WITH ALLOYING ELEMENTS TO PRECISE SPECIFICATIONS

PURE ALUMINIUM	BEVERAGE CAN	AIRPLANE	ENGINE BLOCK
• LOW DENSITY • HIGH CONDUCTIVITY • CORROSION RESISTANT • SOFT	LID: 2,6 % MG 0,25 % CR CONTAINER: 1,2 % MN 1 % MG	2 % CU 3 % MG 6 % ZN	17 % SI 5 % CU 0,5 % MG 1 % ZN

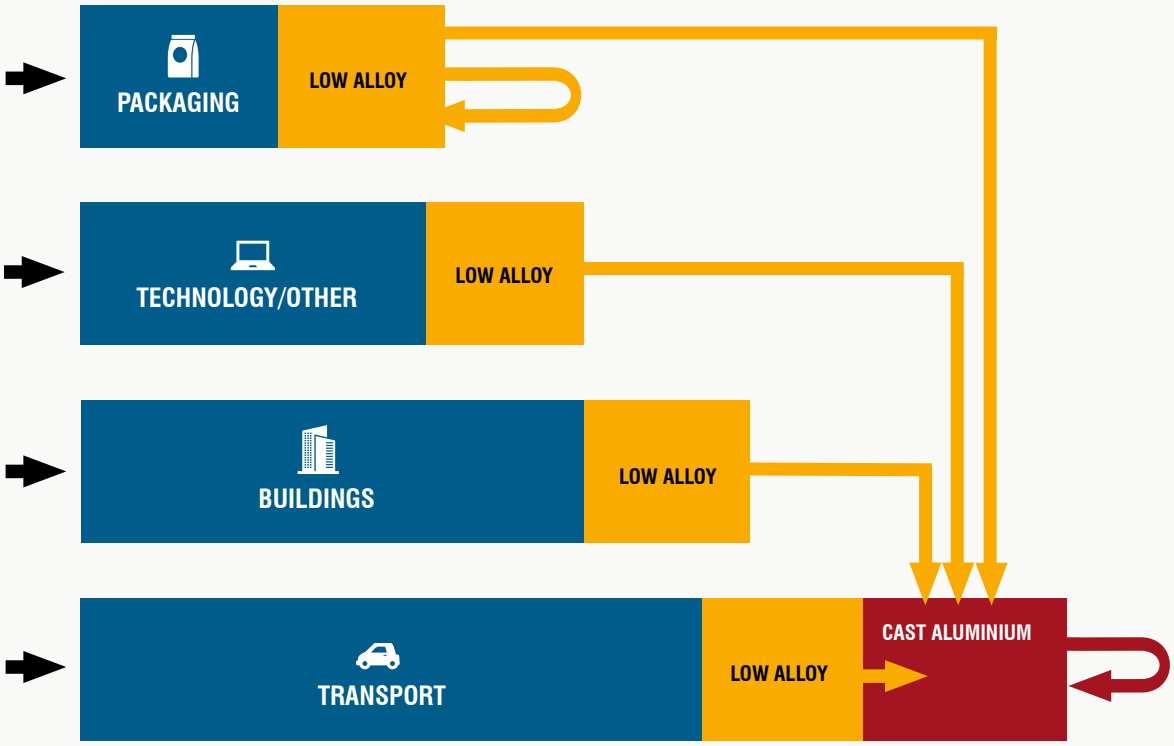
ALUMINIUM FOIL	WINDOW FRAME	BICYCLE FRAME	CAR WHEEL
> 99 % ALUMINUM	0,4 % SI 0,05 % CU 0,8 % MG	0,6 % SI 0,25 % CU 1,2 % MG 0,2 % CR	7 % SI 0,4 % MG

SOURCE: ADAPTED FROM MÜLLER (2017).[24]

Today, remelters and refiners handle these challenges by downcycling from wrought aluminium to less-pure casting alloys. Only around 20% of end-of-life scrap is turned into wrought aluminium, even though wrought products account for two-thirds of all aluminium in use. The main uses for casting alloys, in turn, are in the automotive sector. Overall, a large share of aluminium recycling today involves turning end-of-life aluminium from a range of sectors into cast aluminium auto parts. The main exception is used beverage cans, which are recycled in a 'closed loop', where the same metal is used repeatedly for the same purpose. (Exhibit 4.7).[25] In addition to downcycling, both refining and remelting involve diluting ('sweetening') more highly alloyed aluminium with up to 25% of either primary aluminium, or low-alloyed scrap.[26]

Exhibit 4.7

THE CURRENT ALUMINIUM CYCLE DEPENDS ON DOWNCYCLING TO CAST ALUMINIUM USED IN THE AUTOMOTIVE SECTOR



SOURCE: ADAPTED FROM MODARESI AND MÜLLER (2012).[27]

***Downcycling to cast aluminium** will no longer be a viable strategy as the automotive industry shifts production to electric vehicles.*

Up until now, downcycling makes economic sense. Continuous growth in the demand for casting alloys of aluminium has been able to absorb available post-consumer scrap. Europe and North America have already reached the point where there is 'excess scrap' – i.e., scrap that exceeds domestic requirements for cast aluminium, but which is too mixed or highly alloyed to be used for other categories. However, this has been handled by exporting the scrap to other regions.[28] Downcycling has thus helped fulfil demand for cast aluminium while minimising the cost of separation of products and sorting of scrap by alloy category. The main loss is one of value, as less-pure secondary aluminium trades at a discount to purer forms.[29] It is not likely that it has resulted in any additional production of primary aluminium.

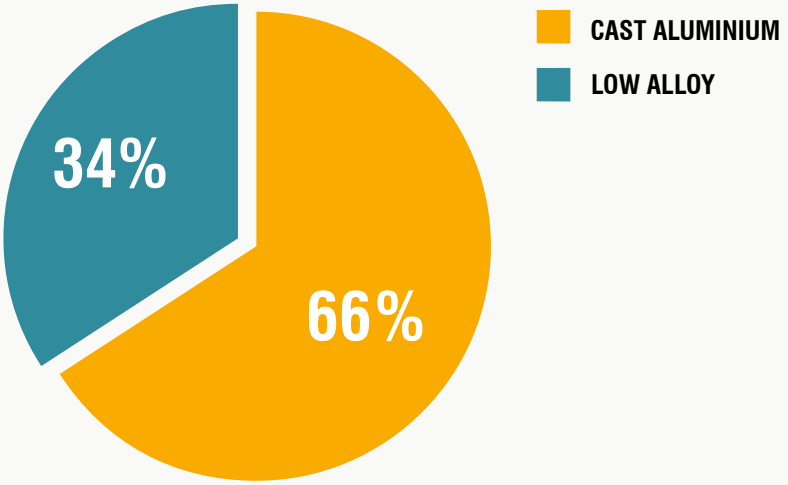
However, this is not sustainable in the long term. As noted above, the amount of post-consumer scrap is growing globally. At some point, it will exceed the demand for casting alloys, even with extensive trade across regions. Unless post-consumer scrap can be used for wrought products, more primary aluminium will be required. Much of the potential for circularity would then be wasted.

One other factor makes this issue even more pressing. Today, around two-thirds of the aluminium content of vehicles is cast aluminium.[30] However, a large share of that material is used in drive trains, motor blocks, heat exchangers, and other components linked to the use of internal combustion engines. Yet it is increasingly clear that electric vehicles will make up a fast-growing share of the market in the coming decades.[31] As the automotive industry shifts production to electric vehicles, the cast aluminium content per car could fall by half.[32] Demand for cast aluminium therefore looks set to slow, even as post-consumer scrap of aluminium grows. In that context, downcycling will no longer be a viable strategy. New approaches are needed.

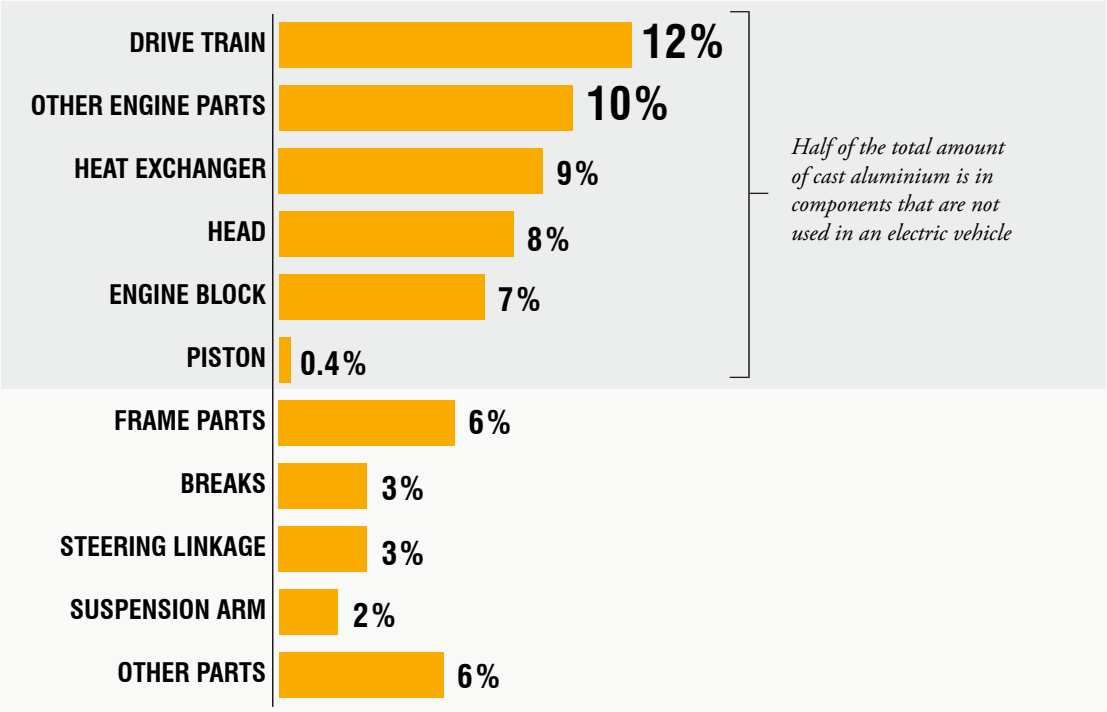
Exhibit 4.8

A HIGHER SHARE OF ELECTRIC VEHICLES COULD SIGNIFICANTLY REDUCE THE DEMAND FOR CAST ALUMINIUM ALLOYS

CAST ALUMINIUM COMPRISES THE LARGEST VOLUME OF ALUMINIUM CONTAINED IN TODAY'S PASSENGER CARS
BREAKDOWN BASED ON CONTAINED ALUMINIUM



ELECTRIC VEHICLES CHALLENGE THE USEFULNESS OF CAST ALUMINIUM
SHARE (%) CAST ALUMINIUM OF TOTAL CONTAINED ALUMINIUM



SOURCE: MATERIAL ECONOMCIS ANALYSIS OF MULTIPLE SOURCES.[33]

4.4 A CIRCULAR SCENARIO FOR ALUMINIUM

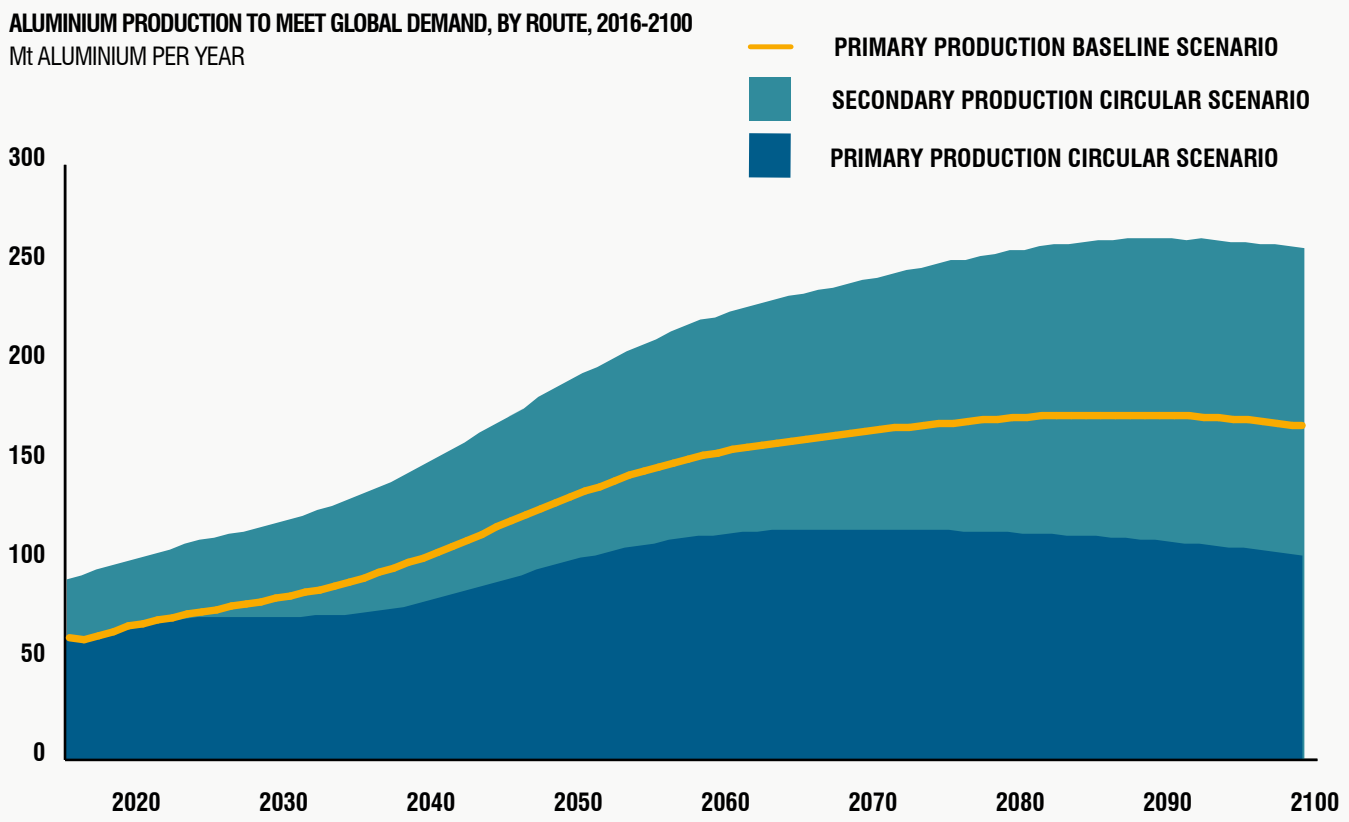
Reducing losses and avoiding the need for downcycling could make a major difference to the sustainability of aluminium. Exhibit 4.9 contrasts the effect of a baseline scenario, with only marginal improvement on current practice, with a circular scenario with much higher degree of separation and sorting of scrap.[34]

The results are striking: the circular scenario requires far less primary aluminium to serve the same demand. By 2050, the difference is 30 Mt per year, half of current primary production volume. Later in the century, the gains are still greater: instead of rising to 174 Mt per year, primary production can peak at 116 Mt per year, and then decline even as total aluminium demand continues to grow. This shows the great potential of aluminium as a circular material, and the gains of ensuring that the aluminium stock is kept as pure as possible. By reducing losses and enabling high-quality recycling, secondary production could then replace more than half of primary production. However, we must keep stressing that significant changes on current practice are needed to achieve this.[35]

The CO_2 implications are similarly stark (Exhibit 4.10). In a baseline scenario, emissions increase to 1,300 Mt CO_2 per year, but in a circular scenario are kept to 1000 Mt CO_2, or 24% lower. The baseline scenario includes the switch to low-carbon energy described above. However, this transition takes time. Increased circularity reduces the need for primary metals production while it is still highly emissions-intensive. To give a sense of the scale of resource savings: if the circular opportunity were not captured, but same CO_2 savings had to be achieved by decarbonising the energy supply, the aluminium sector would require as much low-carbon electricity as was produced by all wind and solar power in the EU in 2016. It is clear that recycling can be a major contributor to aligning aluminium use with climate objectives.

Exhibit 4.9

A CIRCULAR SCENARIO CAN REDUCE THE NEED FOR PRIMARY ALUMINIUM PRODUCTION BY 30 Mt BY 2100

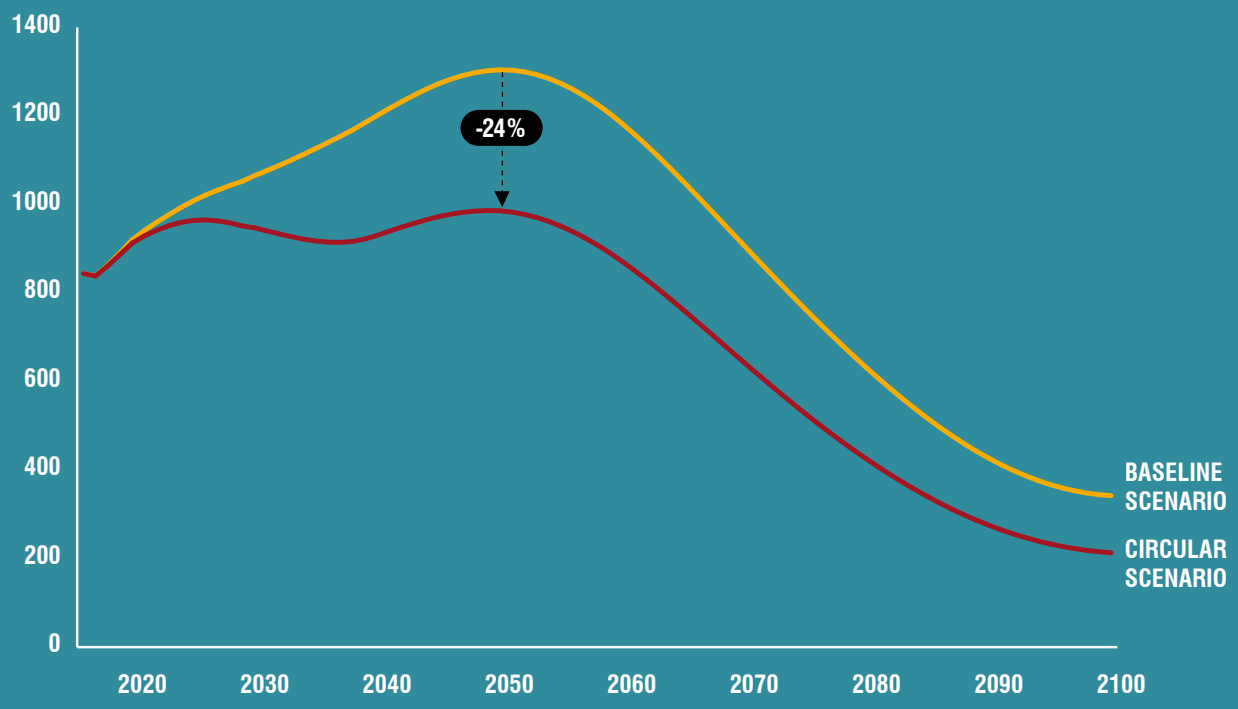


SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT.

Exhibit 4.10

CO_2 EMISSIONS ARE 300 Mt LOWER GLOBALLY IN A CIRCULAR SCENARIO

GLOBAL CO_2 EMISSIONS FROM ALUMINIUM PRODUCTION BY ROUTE
Mt CO_2 PER YEAR, 2016–2100



SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT, SEE ALSO ENDNOTE.[36]

EU CO_2 EMISSIONS AND PRODUCTION

Turning to the EU, the gains from greater circularity are even more pronounced (Exhibit 4.11). As discussed in Section 4.1, the availability of post-consumer scrap is set to increase significantly in the EU, creating the potential for a much more circular system. With current practice, however, this potential would not be captured. More scrap would become available, but the EU would need to use primary aluminium instead – the same amount in 2050 as today. Exporting excess cast aluminium scrap would not solve the problem, as other regions also would have an excess. In contrast, by improving circularity, and making sure that more wrought aluminium demand can be met from available post-consumer scrap, the need for primary aluminium could be cut by 38%.

Given the much higher energy-intensity of primary production, it is clear that reducing the need for primary aluminium also makes a big contribution to reducing the CO_2 emissions arising from European aluminium use. After the closure of several smelters, Europe now imports half of its primary aluminium. Any reduction in demand for primary aluminium in the EU thus avoids whatever CO_2 emissions are associated with production of those imports. In our scenario, this corresponds to almost 10 tonnes CO_2 per tonne of primary aluminium, even in 2050.[37] A circular scenario for aluminium in the EU alone would thus reduce global emissions by 29 million tonnes of CO_2.

This raises an important difference between aluminium and other materials investigated in this study: most emissions savings from circularity are likely to occur not within the EU, but in the countries from which aluminium is imported. Nonetheless, they are real, net savings to global emissions: a more circular system in Europe reduces the global need for primary aluminium, after accounting for all the possibilities of trade and adaptation of use of aluminium in other markets. It therefore constitutes an unusual opportunity for Europe to adjust not just its own territorial emissions, but also the emissions associated with its consumption.

There is an additional opportunity for European industry to produce and market CO_2-free aluminium. As noted earlier, overall, European production uses mainly low-carbon energy. Life-cycle emissions from EU aluminium are about 7 tonnes CO_2 per tonne of aluminium, versus a global average of 18 tonnes CO_2, and 20 tonnes in China.[38] Some companies are already seizing this business opportunity; for example, Norsk Hydro now markets certified primary aluminium with life-cycle emissions of no more than 4 tonnes CO_2 per tonne of metal.[39]

The gradual decarbonisation of the aluminium supply in the EU can go hand in hand with efforts to improve the circularity of European aluminium use. By both decarbonising supply, and reducing the need for (imported) primary metal to serve demand, the EU can act on two complementary fronts to bring aluminium in line with low-carbon objectives.

SENSITIVITY ANALYSIS – THE FINDINGS ARE ROBUST TO A RANGE OF ASSUMPTIONS

Casting alloys of aluminium, and automotive aluminium in particular, are the main potential future bottleneck to a more circular aluminium system, and therefore the focus of this analysis. Wrought aluminium is treated as one category, which is a simplification, as there are limitations on which wrought alloys can be turned into other wrought alloys.

On the other hand, the circular scenario is not a theoretical '100% circular' benchmark, but is intended as an ambitious, yet realistic, representation. Instead of assuming full circularity for aluminium, it involves some continued dilution and downcycling.[40] Of course, if these limitations could be overcome, the CO_2 reductions from a more circular aluminium system would be even bigger than indicated above.

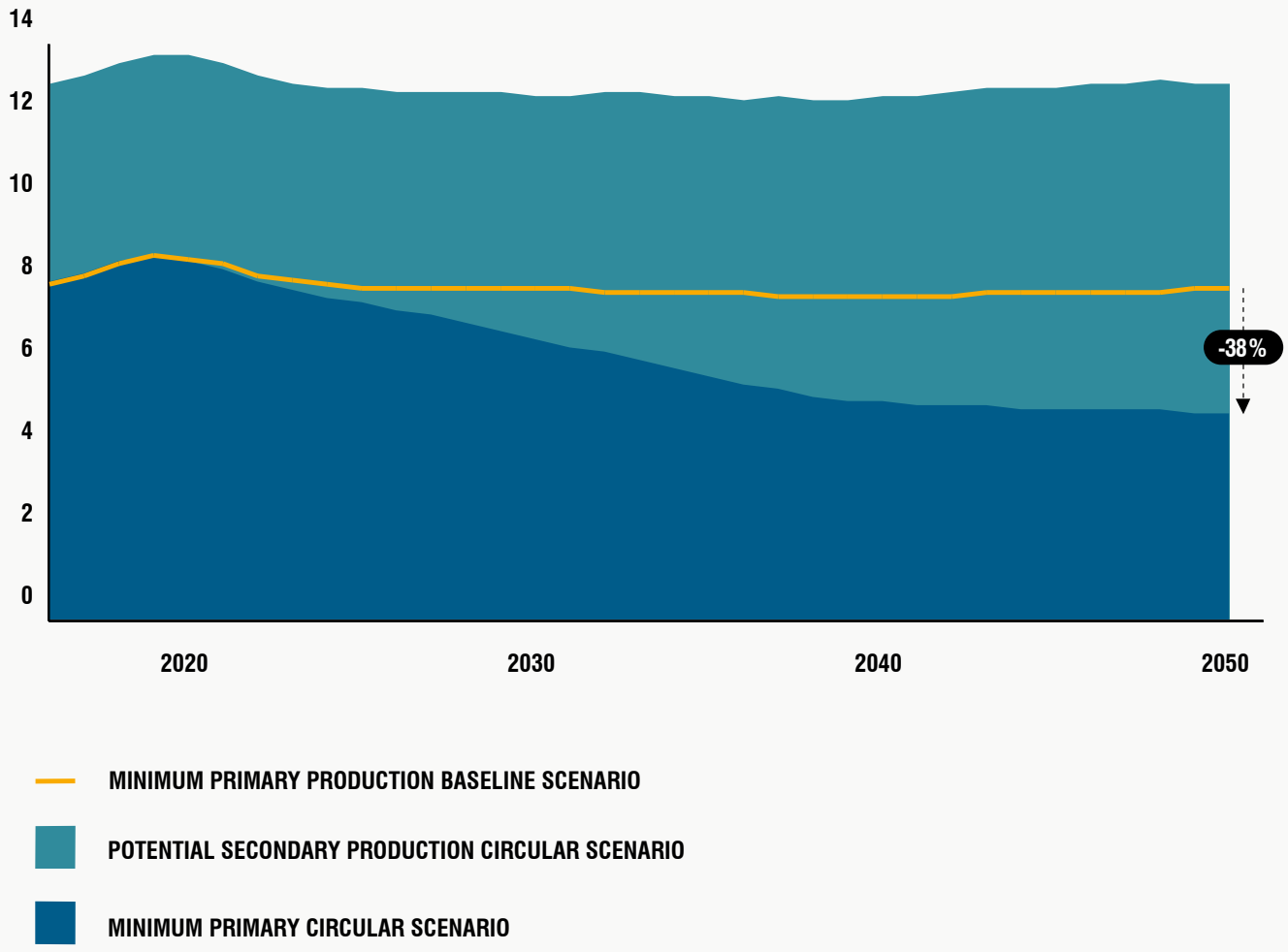
The analysis underlying the results depends on many factors that are uncertain in a 2050 perspective (let alone in scenarios to 2100). However, the overall findings are robust to variation in many key assumptions. In particular, they do not rely on a relatively flat demand profile. If the EU stock were to grow much more to 2050 (as suggested in some industry forecasts), production might need to reach 20 Mt of aluminium per year, and primary metal would have a much greater share. However, despite the fast-growing stock, the gains from circularity would in fact be still greater, with abatement potential increasing from 29 Mt CO_2 per year in 2050, to 44 Mt CO_2 per year. Likewise, assuming a less aggressive adoption of electric vehicles, or a larger pool of future cast aluminium demand more generally, reduces the abatement potential by only around 15%. Overall, the findings therefore seem robust to a range of assumptions.

The main question instead is what actions need to be taken to achieve greater circularity, and whether policy support is needed to get there – the topic of the next section.

Exhibit 4.11

MINIMUM PRIMARY ALUMINIUM PRODUCTION TO SERVE EU DEMAND IS 38% LOWER IN A CIRCULAR SCENARIO BY 2050

ALUMINIUM PRODUCTION TO MEET EU DEMAND, BY ROUTE, 2016-2050
Mt ALUMINIUM PER YEAR



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

4.5 HOW TO GET THERE – MEASURES TO PROMOTE THE CIRCULARITY OF ALUMINIUM

What would it take to transition from today's practices to a more circular scenario? The key topics are the reduction of losses, and addressing downcycling.

MEASURES TO REDUCE LOSSES

Most of the losses of aluminium occur as products reach their end of life, so this is where to focus attention. Collection systems is one aspect: while collection from buildings and cars is already very high, the rates are much lower for consumer products that are often handled through public waste management systems. One option could be to introduce additional deposit systems, similar to those used for beverage cans today. Where waste is publicly handled, it would help to separate metals ahead of other treatment. More generally, attention throughout the chain would help reduce losses. For example, a greater share could be recovered if initial product design ensured easy separation of aluminium components upon dismantling.

Reducing process scrap would also reduce losses of aluminium. Collection rates are already high, so the main promise is likely in reducing formation of new scrap in the first place. There are large differences today: some car manufacturers, for example, generate more than 40% scrap, even as best practice is closer to 25%. New production techniques, such as additive manufacturing, could also lead to lower scrap volumes.

MEASURES TO PHASE OUT DOWNCYCLING

The key issue for downcycling is to improve the handling of post-consumer scrap. If, as in the circular scenario described above, two-thirds of end-of-life aluminium is to be reusable as wrought aluminium, significant changes will be required on current practice.

The good news is that there will be strong market incentives for this, especially as the amount of excess scrap grows. Note that 'excess' secondary metal does not mean that aluminium would be discarded, but that its price would fall. Today's price difference between secondary and primary aluminium is relatively small (on the order of 10-15%, depending on circumstances), but this could grow significantly if the supply-demand balance shifted. There would then be a strong underlying financial gain from taking action to avoid it, and today's remelters would have strong incentives to develop and invest in additional separation and sorting.

Although much could be achieved by greater sorting of existing scrap flows, this does not mean that the aluminium industry should be the only one to act. The cost of achieving purer scrap flows could be much smaller if not achieved just post-hoc, but instead simultaneously addressed by actors throughout the value chain: manufacturers using aluminium, public deposit systems, collection systems of end-of-life metal, practices for dismantling products, scrap markets, and users of recycled metal. The more integrated the aluminium industry, the easier it will be to get there, but in any scenario it will also be necessary to engage manufacturing companies and others.

This is an area that needs much more investigation, but the broad areas of action are as follows:

- **Improved product design:** As noted throughout this report, there are currently few incentives for product design to account for the impact on recycling. With aluminium this already has some negative effects (chiefly in the form of losses), but with the need for much more detailed separation and sorting of scrap, it becomes more urgent. Among options to discuss, the EU framework for producer responsibility could address the feasibility of achieving pure scrap flows.
- **Materials specification:** Aluminium continues to develop, with new alloys invented to serve new uses, and to improve on previous versions. This has many benefits, and doubtless will continue, making it possible to use aluminium in new applications. At the same time, the proliferation of different alloys also makes it much more difficult to use recycled content. Thus, there needs to be a countervailing movement to avoid needless over-specification. One step would be for the industry to shift away from the current practice of specifying the precise composition of alloys, to specifying and buying aluminium based on function instead – leaving it up to the supplier to meet this in the best way possible. Recycled aluminium could then meet more of the demand. It also is worth considering whether regulations and particular practices prevent such developments. Examples include the intellectual property invested in some alloys, or industry standards.
- **Reuse:** Downcycling can be avoided entirely by reusing components rather than remelting metal, a topic returned to later in this report.
- **Closed-loop recycling systems:** Reusing metal for a very similar purpose is the shortest route to handling the issue of secondary aluminium alloys. Today the only major flow of this kind is used beverage cans, but it would be possible to do it for additional product categories as well. For consumer products, publicly run systems are the most likely to succeed. Deposit schemes would be one way to support this. However, much more analysis is required to identify the pros and cons of such initiatives.
- **New processes for dismantling of products:** Today's dismantling is often rudimentary, whether it involves demolition of buildings or shredding of vehicles. The result is that different categories of aluminium are mixed, and other metals enter aluminium flows. Given the importance of the automotive sector for aluminium use, a long-term priority should be to create effective automated disassembly systems to separate auto parts before shredding. Even with today's technology, however, it is possible to carry out more component separation of cars and thereby reduce the mixing of different aluminium categories.[41]
- **Increased separation and sorting:** A large share of the effort towards purer scrap flows must be with the process of sorting scrap flows. The aluminium industry is already investing significantly in this, and new possibilities arise with cheaper sensor and automation technologies. Further reducing the cost of sorting must be a priority, and could be a significant competitive advantage in a future industry with a much greater share of post-consumer scrap.
- **A more sophisticated market for scrap:** In parallel, there will be a need for a more developed market for scrap, with additional specification of categories. One possibility is to move towards much more real-time information about different scrap flows available in a geography, perhaps tracked through distributed ledgers or similar information technology.
- **Production process development:** Finally, it is possible that methods could be developed to improve the commercial viability of removing impurities from aluminium. Many methods for refining aluminium are already in use and could be developed further, including electrolysis, electroslag refining, fractional solidification, fluxing refining, etc.

Taken together, the above is an ambitious list for industrial development. Vertical integration, coordination across the supply chain, and new technology are among the key themes. Policy may well have a role to play as well, not least to coordinate the important action required in the areas of product design, public collection systems, and end-of-life dismantling. All are areas that needs further investigation.

5. MOBILITY

THE PROMISE OF A SHARED CAR SYSTEM

Personal mobility offers a major opportunity for a more circular economy. Transportation is of undoubted economic and social importance, accounting for 15% of household disposable income. It is a major feature of everyday life and shapes the cities and communities we live in. In this chapter, we show how circular economy principles could enable the same travel to occur with much lower materials requirements – and at a lower cost.

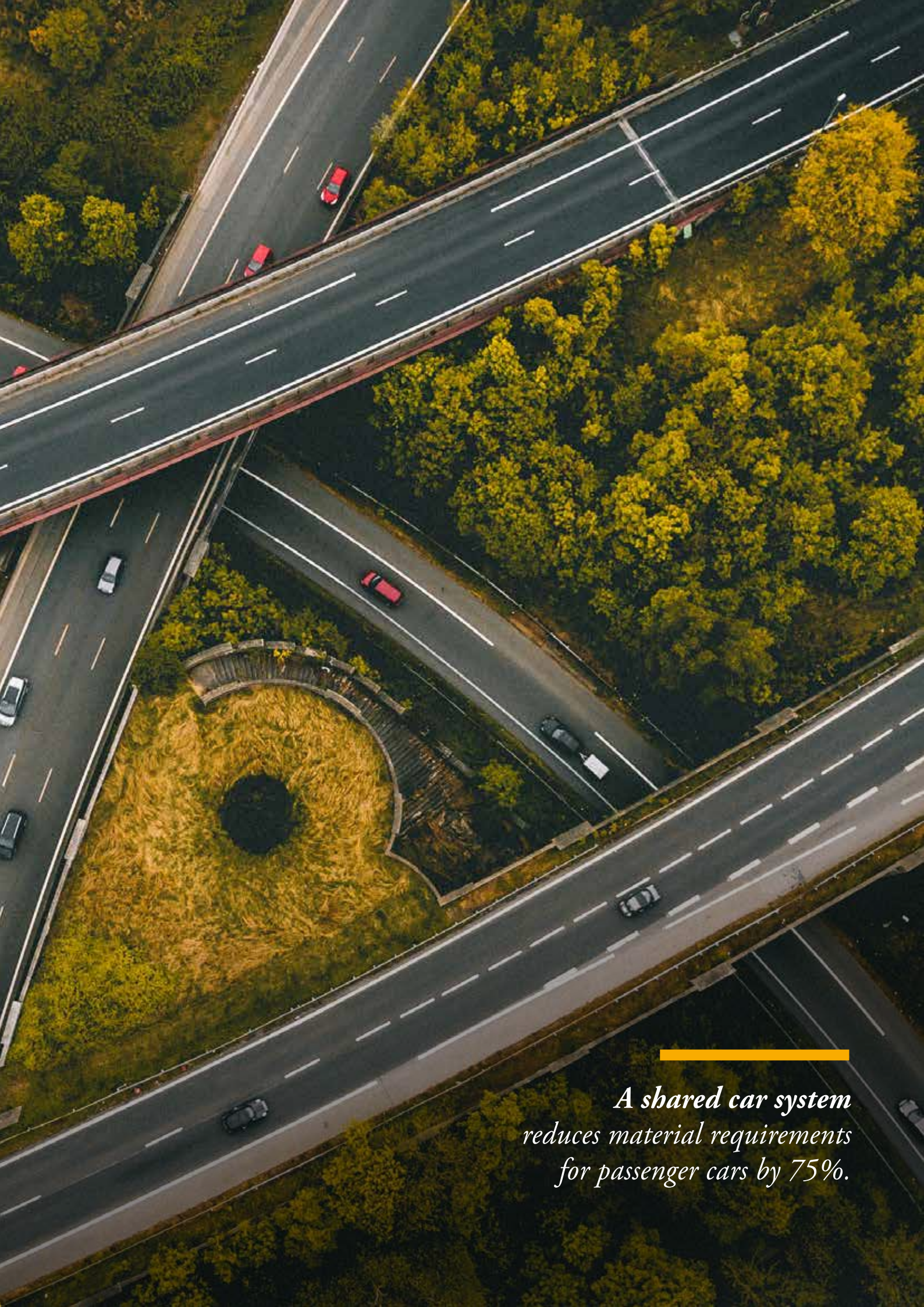
We focus on passenger cars, which provide 83% of travel today. In a scenario where professionally managed, shared vehicle fleets account for two thirds of travel, materials requirements could fall by as much as 75%, reducing annual CO_2 emissions from materials production by 43 Mt by 2050.

The reason why the potential savings are so large is that our use of cars today is extremely inefficient. The vast majority of cars are owned and operated by a single household, and this results is overcapacity: five-seat cars used mostly for one-passenger trips, and vehicles that are stationary 92% of the time. Vehicle design is also optimised for this structure of use and ownership.

A system built around professionally managed fleets of shared cars, on the other hand, would enable much more intensive use of each vehicle. Once the use of these fleets achieves sufficient scale, there will be enormous incentives for changes to the design of vehicles and for innovation. Higher utilisation justifies much more investment in upfront costs, from the higher cost of electric-vehicle drivetrains, to more advanced automation technology, or higher-performance materials.

Professionally managed fleets also enable much greater control over vehicle maintenance, parts inventory, reuse of components, and remanufacture. In addition, the cars used can be matched much more closely to the needs of individual trips, thus reducing the average size of vehicles substantially.

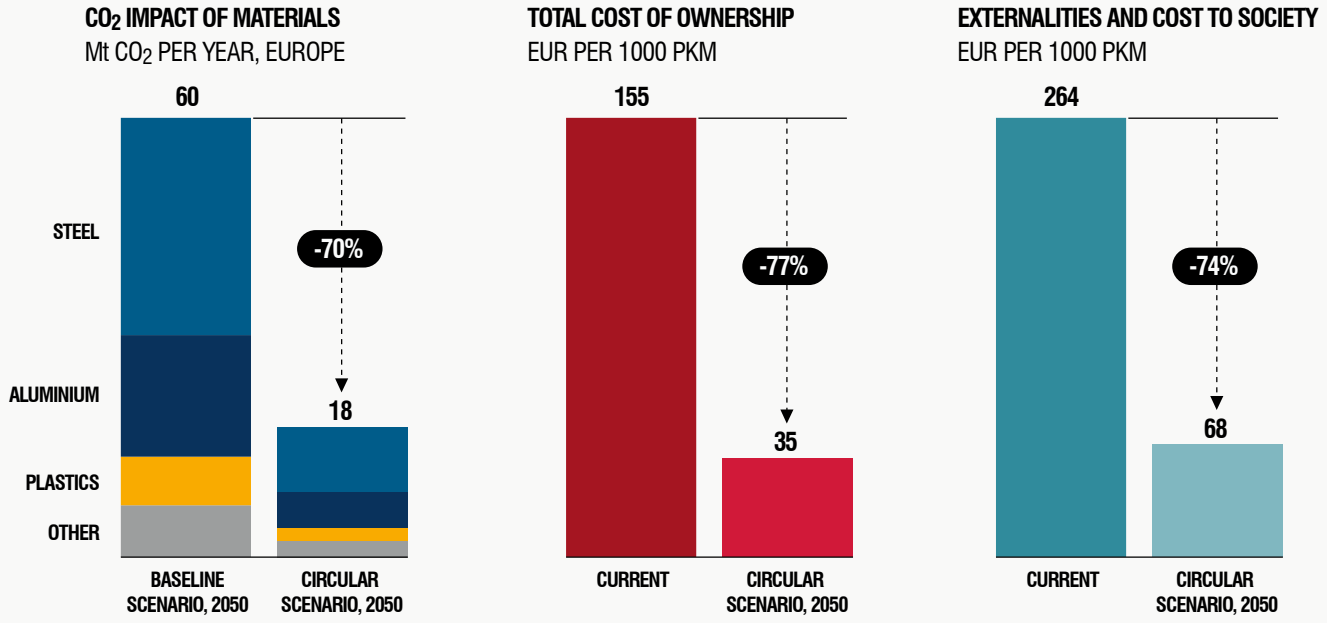
The average car would be smaller, requiring far less material, and be far more durable and better maintained. The initial design and materials choices would be optimised for much more intensive use, and the effective lifetime could more than double. Lightweighting techniques that use advanced materials would be far more economic than when applied to a personal car. The same is true of using automation to reduce accidents, and applying more advanced manufacturing methods to reduce materials losses at the production stage.



A shared car system
reduces material requirements for passenger cars by 75%.

Exhibit 5.1

A SHARED MOBILITY SCENARIO IS A HIGHLY ATTRACTIVE VISION FOR PASSENGER CARS



NOTE: PKM DENOTES PASSENGER-KILOMETRES.

Although the focus of this report is on materials use and associated CO_2 emissions, the main motivation for such a system is the much wider productivity opportunity that it represents. We calculate that the cost per passenger-kilometre could be as much as 77% lower than that of individually owned cars. Major externalities could be reduced by three-quarters, including major costs from factors such as traffic congestion, air pollution and collisions. Although the pace of change will depend on many factors, not least travellers' expectations and norms about car ownership, it is clear that the benefits of achieving a mobility system based on shared cars would be very large – contributing to economic productivity as well as climate goals.

5.1 UNDERSTANDING FUTURE MOBILITY NEEDS

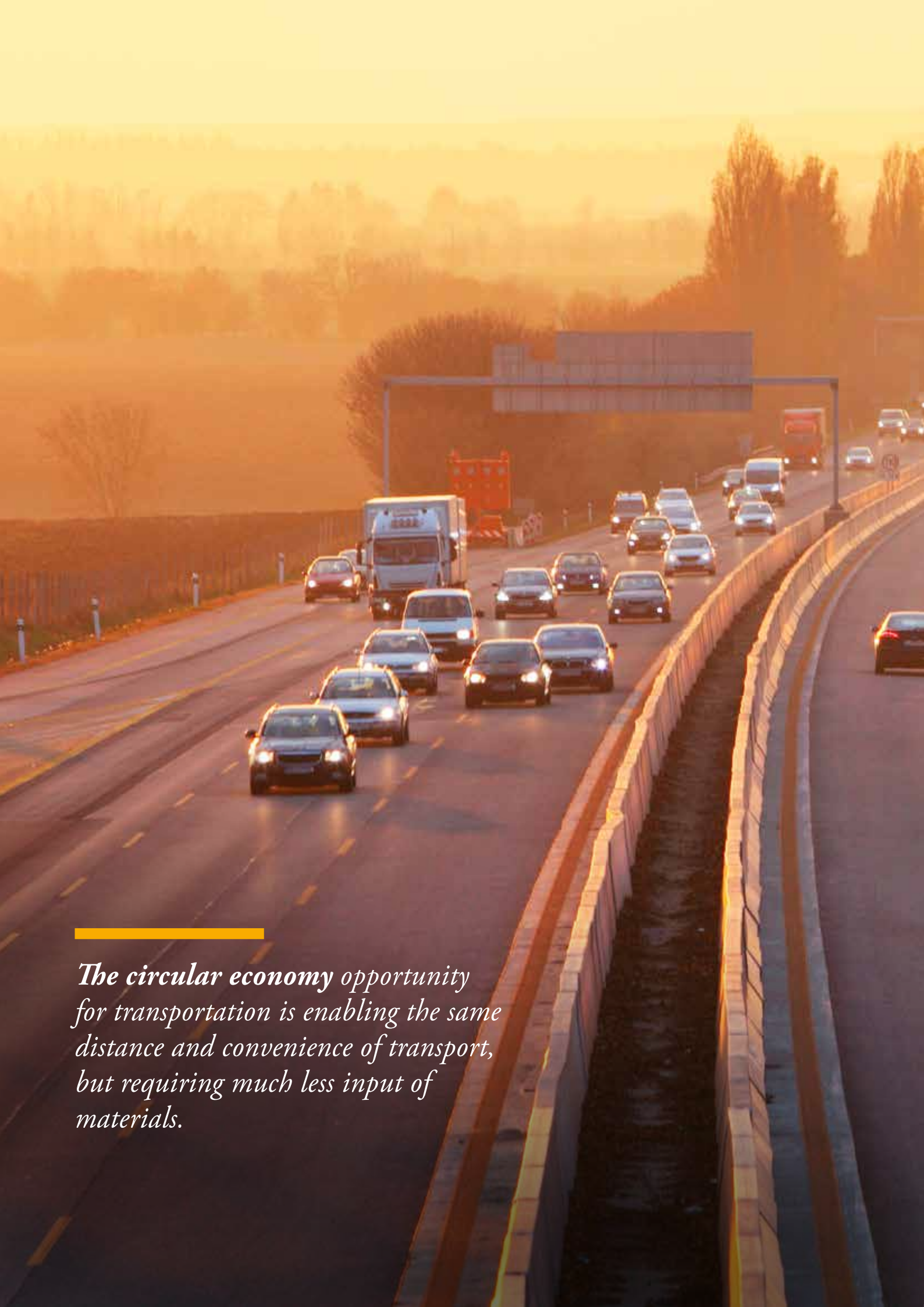
In its 2011 White Paper on transportation, the European Commission wrote: "Transport is fundamental to our economy and society. Mobility is vital for the internal market and for the quality of life of citizens as they enjoy their freedom to travel."[1]

For personal travel, mobility is overwhelmingly a story of passenger cars. Despite the undoubted importance of public transport, cars account for 83% of land transportation in the EU.[2] Passenger transport grew by 5% between 2004 and 2014,[3] and the number of cars is growing faster than the population.[4]

Cars are also major capital assets, both for households and in the wider economy. The price of a new car is on the same level as average annual household disposable income.[5] There are more than 250 million passenger cars in the EU with a replacement value of more than 5,700 billion EUR[6] – twice as much as total investment in the entire EU28 economy in a year.[7] Adding the running costs of fuel, maintenance, insurance and more, total expenditure on driving takes up some 13% of household disposable income in the EU.[8]

In addition, today's transport system has large impacts on public health, well-being, and the environment. Road traffic leads to local air pollution, traffic congestion, noise and accidents, and transport fuels are a major source of CO_2 emissions. Car travel also depend on large public expenditure on infrastructure, and it claims valuable land area. As we discuss below, these costs can in fact exceed even the substantial direct costs of transport by passenger car.

These issues set the frame for the main focus of this study, which is the materials use associated with car transport.[9] The average car contains 1.4 tonnes of materials, dominated by steel, aluminium and plastics.[10] Still more materials are used in manufacturing, as it is not uncommon that 40% of metals used are lost as scrap on the factory floor.[11] As a result, the automotive sector uses 25% of aluminium, 12% of steel, and 9% of plastics consumed in the EU.[12] Car manufacturing has also been a major force behind materials development, from new applications of aluminium, to high-strength steel, to reinforced plastics and carbon fibre. At end of life, vehicles are also a major factor in materials recycling.

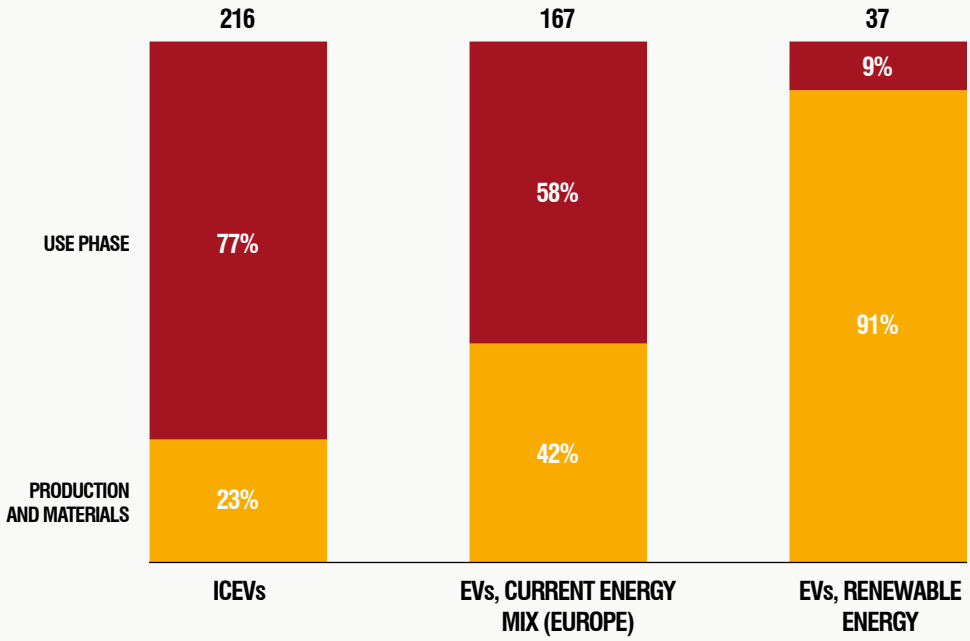


The circular economy *opportunity for transportation is enabling the same distance and convenience of transport, but requiring much less input of materials.*

Exhibit 5.2

EMISSIONS FROM MATERIALS AND PRODUCTION WILL BE THE MAIN SOURCE OF CO_2 FROM FUTURE CARS

LIFECYCLE CO_2 EMISSIONS FROM INTERNAL COMBUSTION ENGINE VEHICLES (ICEVs) VERSUS ELECTRIC VEHICLES (EVs)
g CO_2 PER CAR-KM



NOTE: THE DATA SHOW LIFECYCLE GREENHOUSE GAS EMISSIONS FROM PRODUCTION AND THE USE -PHASE FOR A LARGE PASSENGER CAR WITH A LIFETIME DRIVING RANGE OF 180,000 KM.
SOURCE: ELLINGSEN ET AL. (2016)[13]

As detailed in the preceding chapters of this report, the production of these materials leads to large CO_2 emissions. To date, analyses of CO_2 emissions from vehicles have focused on the use phase rather than on emissions from materials production and manufacturing. This is understandable, as emissions from fuels account for 70% of total lifecycle emissions of a typical car today (Exhibit 5.2). However, as fuel emissions are reduced and eventually reach zero, the emissions from materials become the remaining obstacle to CO_2-free transportation. In an electric vehicle using zero-carbon energy, almost all the remaining emissions come from vehicle production and materials use.

Given the economic importance of cars, and their large share of materials use, it matters greatly how cars are used. As discussed below, our current model of car ownership and use is highly materials intensive: large volumes of steel, aluminium, plastics and other materials are required to achieve relatively little transportation benefit. The circular economy opportunity for transportation is to improve this, enabling the same distance and convenience of transport, but requiring much less input of materials.

5.2 THE CIRCULAR ECONOMY OPPORTUNITY IN MOBILITY

In previous chapters, the focus was on the potential of materials recycling to replace new production of materials such as steel, plastics and aluminium. However, the opportunities for a circular economy also encompass many strategies that focus on the products themselves. By reducing the amount of material required for each product, materials efficiency can increase. Then, by ensuring that each product provides more useful services, the resource claims can be reduced even further.

In the case of passenger cars, the relevant 'service' is *mobility*, best measured in 'passenger-kilometres' (Exhibit 5.3). Materials efficiency for cars centres primarily on two opportunities: reducing the average weight of each car, and reducing the input of materials by reducing scrap in manufacturing and increasing reuse and remanufacturing. Two additional opportunities are central to providing more useful travel with each vehicle: increased sharing to increase the utilisation and occupancy of each vehicle, and longer lifespans to make it possible for each car to serve a greater number of passenger-kilometres once produced.

Exhibit 5.3

FOUR CIRCULAR ECONOMY STRATEGIES CAN SHARPLY REDUCE THE MATERIALS REQUIREMENTS OF MOBILITY

PRODUCT MATERIALS EFFICIENCY
TONNES MATERIALS PER CAR

1. REDUCE WEIGHT PER VEHICLE

- *Lower average vehicle size in a shared car system, better matching vehicles to actual trip needs*
- *Advanced design and materials choices*

2. REUSE AND REMANUFACTURING

- *Reduced waste in vehicles production*
- *Modular design and replacement of components with limited lifetime*
- *Increased re-use of durable components at end-of-life*
- *Controls over inventory and flows in a fleet-managed system of shared cars*

X

CIRCULAR BUSINESS MODELS
NUMBER OF CARS REQUIRED

3. SHARING

- *Large increase in utilisation in a shared-car system*
- *Higher occupancy per vehicle with mobility as a service*

4. LONGER LIFESPANS

- *More intensive use increases incentives for durable design*
- *Electric drivetrains with intrinsically better durability*
- *Proactive maintenance of fleet-managed vehicles*
- *Modular design to enable replacement of components with shorter lifespans*

=

MATERIALS INTENSITY OF TRANSPORT
TONNES MATERIALS TO ENABLE TRAVEL

MATERIALS INPUTS REQUIRED TO SUPPORT MOBILITY

- *Large reduction in total amount of materials that must be produced for useful travel (materials per passenger kilometres)*

Today's cars have an effective ***utilisation of just 2%.*** *Increasing this is at the core of the circular opportunity.*

THE CURRENT STATE OF CIRCULARITY IN MOBILITY: POTENTIAL WAITING TO BE UNLEASHED

Our current use of cars is highly wasteful. For all the economic importance of passenger cars, they are used very little. Cars are parked for 92% of daylight hours[14], and when in use, only 1.5 of the typical five seats are occupied.[15] The overall utilisation rate thus is 2%[16] – an extremely low number compared to other assets of similar economic importance. Utilisation matters: the current situation amounts to locking in a large store of value and embodied CO_2 but getting only a low level of benefit in return.

Summarising the current trends, there is at best slow movement towards reducing cars' claims on resources (Exhibit 5.4). As noted above, total travel demand is increasing in the EU, and the number of cars is growing faster than the population, leading to lower rather than higher utilisation for each vehicle. Although there have been major efforts to reduce vehicle weight to lower fuel consumption and to comply with emissions regulations, the total weight of vehicles is rising rather than falling.[17] As noted, manufacturing remains wasteful, with 40% or more of metals lost as manufacturing scrap. There is also no discernible increase in the average occupancy of individual vehicles. Car lifetime is the main area where there is some improvement, as cars last for around 20% more kilometres of travel today than they did 10 years ago.[18]

Why is the picture so bleak? Unsurprisingly, there are powerful reasons for the current situation, rooted in the model of individual car ownership. Individually owned cars must be able to serve each household's peak travel needs. They serve relatively low annual travel needs, are maintained in households' leisure time, and are used only when individuals in each household need to travel.

The case of vehicle lifetimes provides perhaps the clearest example of why this model of ownership and operation limits circularity. Cars are driven some 200,000 km before being scrapped[20], but as each car is driven a relatively short distance, it takes many years to get to that point.[21] The average lifetime of all cars in use is more than 10 years, and vehicles are on average 14 years old when scrapped.[22] Any improvement to lifetime is therefore felt only long after purchase, too far off to justify a higher price, and also of limited benefit to users (as cars 15–20 years old would be out of date, lagging behind in technology, safety and design). Even incremental change is difficult, mainly a by-product of improving reliability. A step-change in lifetime, on the other hand, is all but precluded by the current ownership model: cars designed and maintained to last for, say, 500,000 km would be 35 years old when finally scrapped. There would be little or no consumer demand for such vehicles. The main lesson is that today's more limited car lifetime is no absolute, technical limitation, but follows from the low rate of utilisation.

Exhibit 5.4

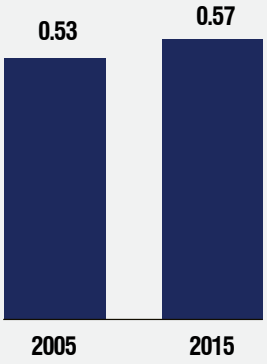
CURRENT TRENDS SEE LITTLE IMPROVEMENT IN THE MATERIALS INTENSITY OF EU MOBILITY

1

TRAVEL DEMAND
TRILLION PASSENGER-KM BY CAR PER YEAR

3

CAR OWNERSHIP
CARS PER CAPITA, EU28

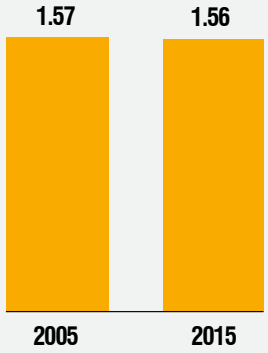


5

CAR WEIGHT
TONNES PER CAR

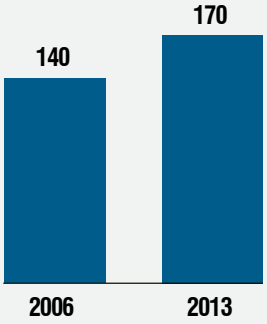
2

OCCUPANCY PER CAR
CAR OCCUPANCY (PASSENGER PER CAR), UK



4

CAR LIFETIME
CAR KM PER CAR DURING LIFETIME



6

SCRAP IN CAR MANUFACTURING
% SCRAPPED MATERIALS

~40%

SOURCE: MATERIAL ECONOMICS ANALYSIS OF A RANGE OF SOURCES.[19]

The current ownership model also creates a disconnect between car manufacturing and the subsequent treatment of cars at end of life. Recycling of end-of-life vehicles focuses primarily on avoiding the release of hazardous substances and recovering spare parts. Materials recovery is far less of a concern. Although regulation now requires that most materials be recycled, the process results in significant degradation of quality and loss of materials value (Exhibit 5.5). The steel in vehicles is often highly specialised, including highly alloyed varieties, but shredding results in scrap that is often so contaminated and mixed that it is usable only for basic construction steels. By one estimate, only 8% of the steel recycled from vehicles is of a quality that it could be used again for its original purpose.[23] In the case of aluminium, low-alloyed wrought aluminium products are mixed with highly alloyed cast aluminium components when cars are dismantled, and other, undesired metals are introduced to the aluminium scrap.[24] In the case of plastics, recycling tends to be limited to a few, large pieces, but overall recovery rates are low.[25]

For these reasons, the scrapping value of a car is close to zero, even though just the major raw materials that go into a car have a value of some 2,000–3,000 EUR. In many countries, cars are returned for recycling only after a delay,[27] and many vehicles are not fully accounted for.[28] Just as with extending lifetime, however, there is little incentive for the manufacturer to enable higher-quality recycling of materials as long as that value accrues only 15 years in the future, and then to another party.

Exhibit 5.5

CARS ARE AT THE CENTRE OF KEY CHALLENGES TO A MORE CIRCULAR MATERIALS SYSTEM

DOWNGRADING AND COPPER MIXING OF STEEL

ONLY 8% OF STEEL RECYCLED FROM VEHICLES CAN BE USED AS MATERIALS FOR NEW CARS

- *Shredding of vehicles mixes copper with steel which is a serious long term contaminant of the steel stock*
- *Alloys are not separated, leading to lost values of alloy metals, waste of critical materials, and downcycling of steel*

PREVENTION OF PLASTICS RECYCLING

HIGH-VALUE RECYCLING IS NOT FEASIBLE FOR A LARGE SHARE OF VEHICLE PLASTIC VOLUMES

- *Current practices leaves plastics in a mixed fraction that often is landfilled / incinerated*
- *Material substitution for lightweighting leads to fibre reinforced plastics that contaminates other plastics flows and that is difficult to recycle*

DOWNGRADING OF ALUMINIUM

MIXING OF ALUMINIUM ALLOYS RESULTS IN DOWNGRADING OF WROUGHT ALUMINIUM AUTO PARTS

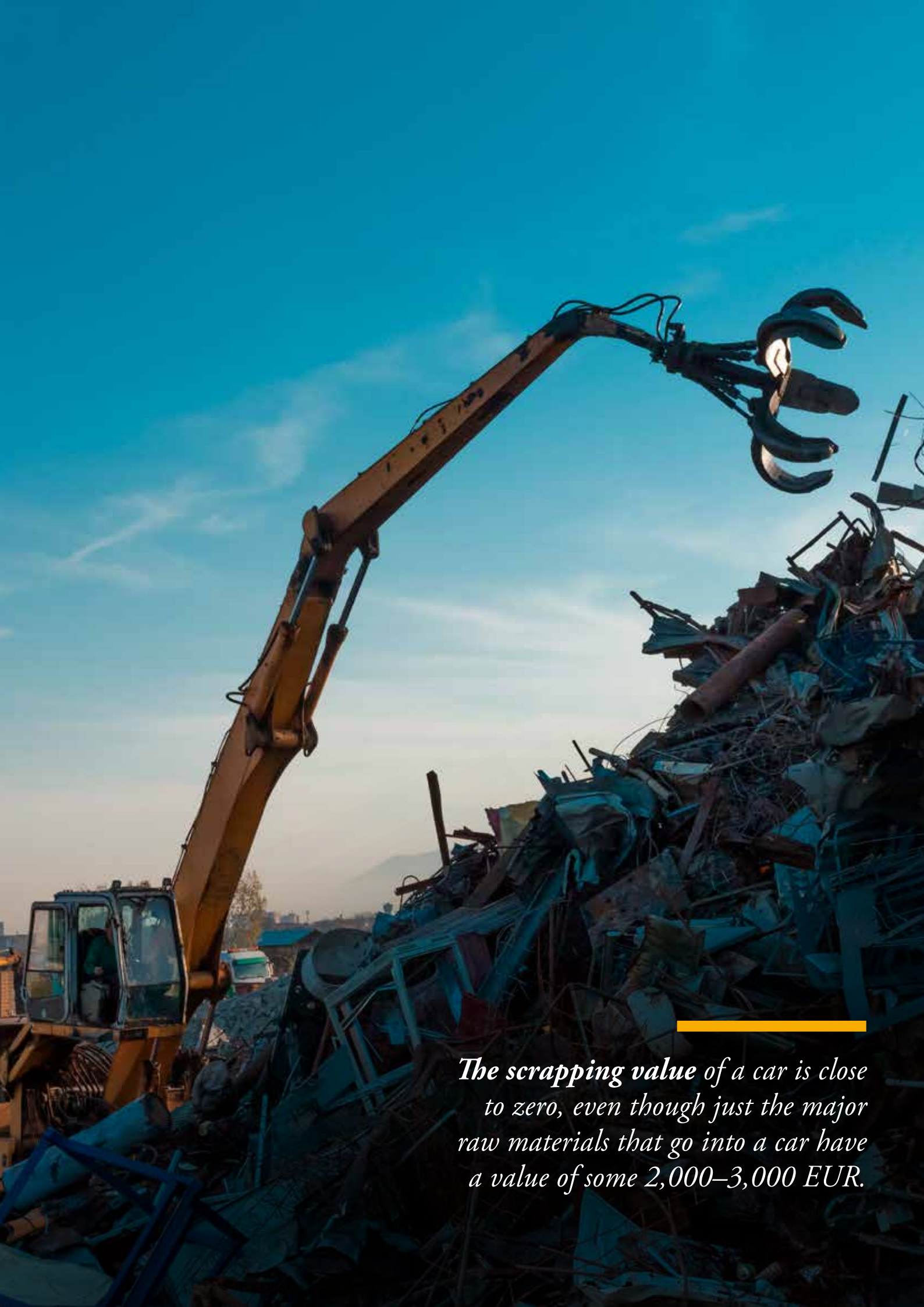
- *Cars make up >40% of cast aluminium demand, a key 'sink' for aluminium recycling*
- *Aluminium used in cars is downgraded when mixed with cast aluminium, precluding other uses*

LIMITED RECYCLING OF RARE CRITICAL METALS

END-OF-LIFE VEHICLES LEADS TO LARGE LOSSES OF CRITICAL METALS

- *Rare critical metals can make up 1% of total vehicle materials*
- *Only eight out of 25 scarce metals are recycled, with the remainder lost to carrier metals, construction and backfilling materials and landfills*

SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES.[26]



The scrapping value *of a car is close to zero, even though just the major raw materials that go into a car have a value of some 2,000–3,000 EUR.*

Exhibit 5.6

A CIRCULAR SCENARIO SEE MAJOR CHANGES IN CAR OWNERSHIP, DESIGN, AND MATERIALS USE

FROM: AN OWNED CAR ECONOMY

TO: A SHARED CAR ECONOMY

A FUNDAMENTAL SHIFT IN OWNERSHIP AND OPERATING MODEL

- ***Effective utilisation*** *of a typical European car is 2%, reflecting the needs of individual car owners*
- ***Slow adoption*** *of capital intensive technologies (such as autonomous drive and electric drivetrains) due to high investment cost and low utilisation*

→

- ***Cars shared and operated*** *in fleets increase both utilisation and occupancy per car*
- ***High utilisation dramatically*** *changes incentives for durability, maintenance, re-use, as well as a range of more capital-intensive solutions*

CARS DESIGNED AND MANAGED FOR RUN-TIME

LIFETIME OF ~12 YEARS OR 230,000 KM, MATCHING THE NEEDS OF INDIVIDUAL OWNERS

- ***Low utilisation*** *places limits on up-front investment and on benefits of longer lifetime*
- ***Limited maintenance,*** *and disconnect between end-of-life vehicles and first owners*

→

LIFETIME INCREASED TO 700,000 KM, MATCHING THE NEEDS OF INTENSIVELY USED VEHICLES

- ***Electric drivetrains*** *with intrinsically longer lifetime*
- ***Investments in more*** *durable materials (more attractive for highly utilised cars)*
- ***Proactive maintenance*** *and modular design enable re-manufacturing*

MATERIALS IMPACT MINIMISED

LOW UTILISATION, HIGH WEIGHT, AND LIMITED LIFETIME RESULTS IN HIGH MATERIALS INTENSITY

- ***Cars weigh 1.4 tonnes,*** *as each vehicle needs carry for five seats and have high safety standard*

→

RANGE OF SIZES, ADVANCED MATERIALS, AND AUTONOMOUS DRIVING REDUCE FOOTPRINT

- ***Smaller average size*** *adapted to needs of each trip*
- ***Fleet management*** *and more expensive materials incentivise re-use of parts and EOL recovery*

5.3 A CIRCULAR SCENARIO FOR MOBILITY CAN CUT CO_2 EMISSIONS BY 70%

The above diagnostic may sound like a litany, but in fact it points the way to a major productivity opportunity. In a 2050 perspective, not just an incremental shift is possible, but there is an opportunity to reorganise mobility from an owned car economy to one dominated by shared cars (Exhibit 5.6). This comes with major advantages not just in terms of CO_2 emissions and materials use, but in drastic cost reductions, and it helps address major negative effects on public health and the environment.

The core of this scenario is a major shift in how vehicles are owned and operated. Instead of individually owned vehicles that are mostly stationary, 64% of cars would be operated as shared vehicles, with much higher utilisation (the total time the vehicle is in use), and higher average occupancy (the number of passengers per trip). Shared vehicles would operate as a service to end-users, who would be able to call on a car when needed without having to own individual vehicles. Ownership and management instead would lie with service providers, who would own and operate fleets of cars. Self-driving vehicles would be integral to this business model, making it possible to call on vehicles when needed without large costs. This in turn can unlock a number of step-change improvements in the productivity of transportation:

- **Faster adoption of electric and automated vehicles:** Higher utilisation would fundamentally shift the incentives for how vehicles are designed and operated. The same upfront investment would be paid back earlier, over a much larger number of kilometres driven. This makes electric vehicles more economic, as the higher upfront cost can be rapidly recovered. It also enables more rapid adoption of connected and self-driving vehicles, both because the upfront cost is easier to bear with higher utilisation, and because its value is much higher in a shared-car business model.

- **Increased lifespan:** A shared model also creates incentives for cars with much longer lifetimes. Cars might not be older, counted in years, but would cover the same distance in a much shorter period of time. The additional cost of achieving a longer lifetime would thus be more than offset by benefits over just a few years of intensive use (instead of paying off over more than 14 years, as is the case today). The switch to electric vehicles is an integral part of longer technical lifespans, as the 20-or-so moving components of an electric motor are intrinsically much longer-lasting than the 2,000 moving parts of an internal combustion engine.[29] Improved maintenance also helps; in a fleet-managed system this could resemble that of aircraft today, with detailed and predictive maintenance schedules for each component.

- **Increased reuse and remanufacturing:** The transaction costs and inventory problems that limit reuse and remanufacturing would also be much easier to overcome in a fleet-managed system. Longer lifetime need not depend on all parts of a car living longer, but can be enabled by a modular design that allows for components with shorter lifespans (whether for technical, aesthetic or other reasons) to be easily replaced, and intrinsically long-lived components to be reused even when vehicles are scrapped.

- **Smaller and lighter vehicles:** It would also be possible to vary car size so it matches the needs of each trip. Instead of each vehicle dimensioned for its maximum capacity (typically, five passengers), cars could range in size from single- to multi-person vehicles, matched to the needs of each trip. The cost of more advanced materials required for lighter weight, such as high-strength steel, advanced plastics, carbon fibre or aluminium, would also be much easier to motivate with higher rates of utilisation.

- **Better end-of-life management:** Finally, with more expensive materials, more scope for remanufacturing, and more predictable end-of-life flows, it would be much more profitable to design vehicles for full recovery of materials at end of life. Manufacturers and operators of shared-car fleets could directly link up (or vertically integrate) to monetise the benefits. Vehicles could be designed for much more automated disassembly, which also is integrated with the increased reuse and remanufacturing described above.

ANATOMY OF A SHARED, FLEET-MANAGED CAR IN 2050

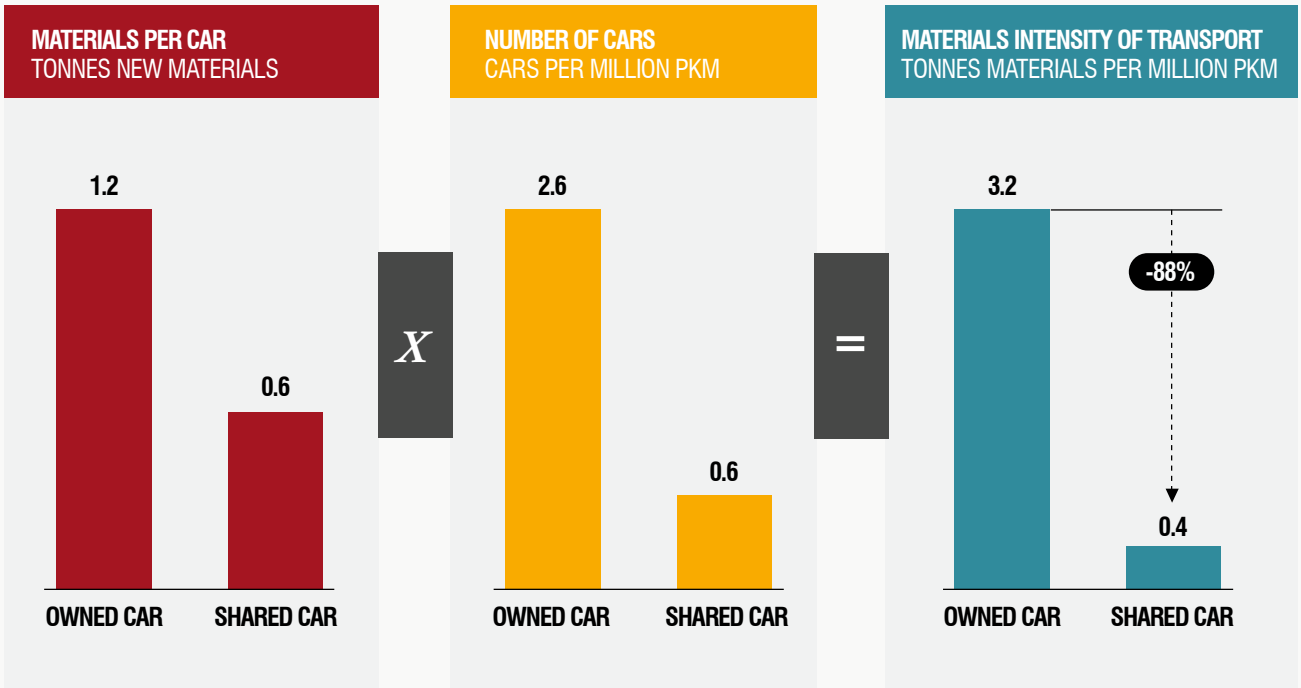
To see the extent of improvement possible, it is useful to consider the 'materials intensity' of current car travel. Today, to achieve one million passenger-kilometres of travel, some 3,200 kg of materials must be supplied. This may not sound like much, but given the 4.7 trillion passenger-kilometres served by cars in the EU each year, it adds up to more than 20 million tonnes per year of steel, aluminium, plastics and other materials annually, just to keep the car fleet going.

These changed incentives of a shared-car system could transform the key parameters in this equation. The average materials requirements per car could be cut in half, from 1,200 kg to 600 kg per vehicle. Still more important, each vehicle could service much more travel. Today, serving one million passenger-kilometres requires the equivalent of 2.6 cars. With lifetime increased to 450,000 kilometres, occupancy increased to 1.93, and 11% of components remanufactured, this falls to just 0.6. Putting these effects together, materials requirements fall to just one-eighth: from 3,200 kg to just 400 kg of materials per million passenger-kilometres provided.

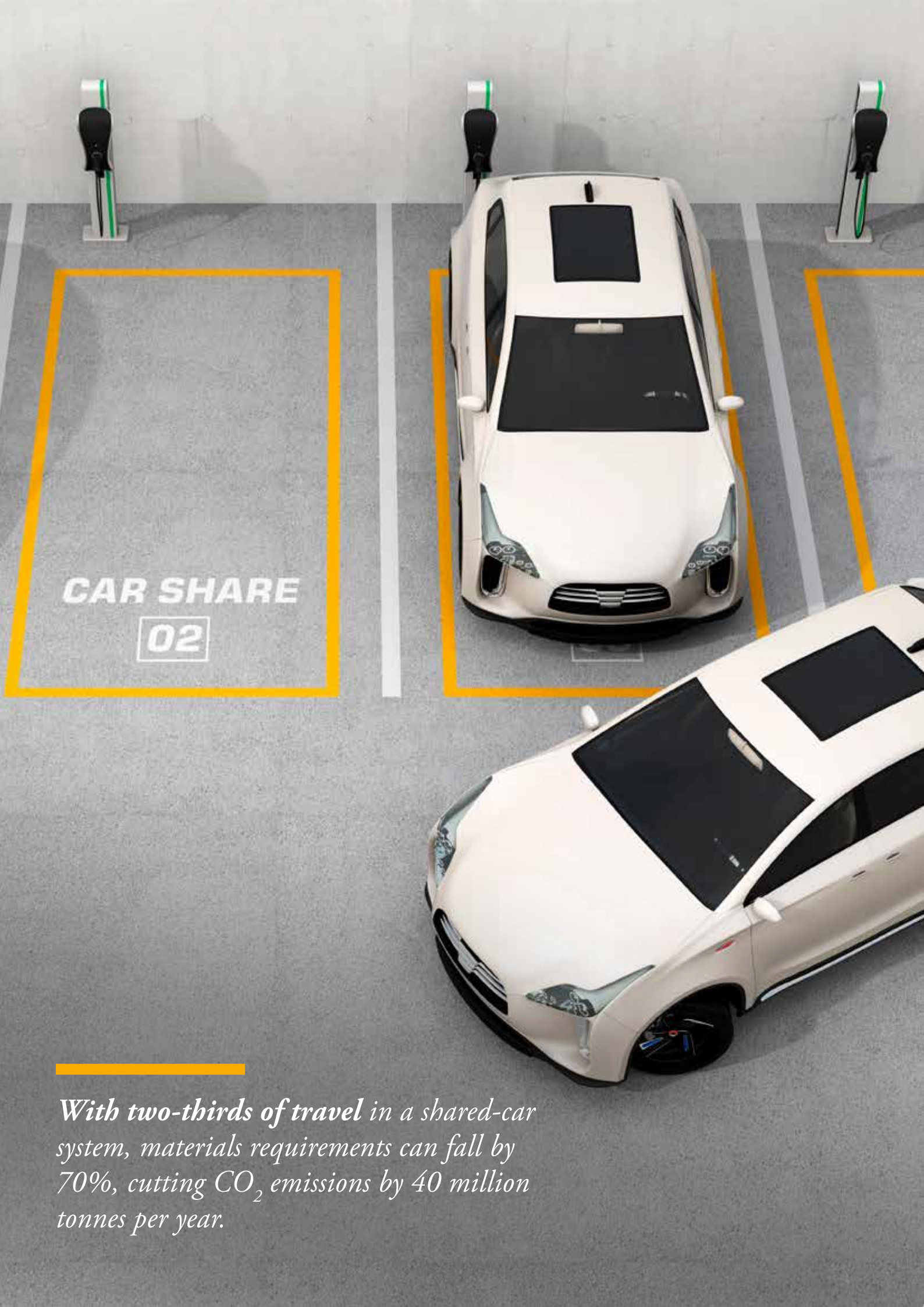
This is an astounding productivity improvement – but is it realistic? We would argue that it is. Already today, the early indications are that shared cars can replace 4–10 private cars in Europe and 9–13 private cars in North America.[30] In terms of lifetime, London 'black cabs' already have a lifetime of up to 1,600,000 kilometres,[31] about 9 times greater than that of ordinary passenger cars. The key is a custom-made vehicle, designed for durability and easy maintenance during intensive use. With improved technology and greater use of electric drivetrains by 2050, the 700,000 kilometres assumed here does not seem far-fetched. In terms of weight reduction, the 600 kg average size need not mean that all vehicles need to be small, let alone unsafe. Rather, it reflects a smaller average size required when vehicles are matched to the typical two-person trip rather than to the maximum five-person trip. The average would include vehicles that are both smaller and larger. The lower accident rates with autonomous driving also enable lighter vehicles, as does the greater viability of more expensive and advanced materials for a vehicle with higher utilisation. Likewise, the higher average occupancy would include solitary trips, but some share of travel would take place in vehicles with more passengers than today.

Exhibit 5.7

CIRCULAR STRATEGIES JOINTLY REDUCE THE MATERIALS INTENSITY OF TRANSPORT BY 88%



NOTE: PKM DENOTES PASSENGER-KILOMETRES



With two-thirds of travel *in a shared-car system, materials requirements can fall by 70%, cutting* CO_2 *emissions by 40 million tonnes per year.*

A CIRCULAR SCENARIO CUTS CO_2 EMISSIONS BY 70%

The above describes the characteristics of an individual vehicle. To understand the impact on total materials demand and CO_2 emissions from materials, it is necessary to construct a scenario for the mobility system as a whole.

We construct a circular scenario to 2050 to explore this, with two-thirds of travel served by shared and fleet-managed vehicles as described above, and the remainder by individually owned cars much like those in use today. In aggregate terms, the outcome is an average of a shared and an individually owned system (Exhibit 5.8). The share of new materials per vehicle falls to 89% with remanufacturing, while the average weight falls from 1,300 kg to 900 kg. Average lifetime increases, from 280,000 to 450,000 kilometres, while average occupancy goes up by 18%, to 1.91 passengers per car.

Combining these, the effect on CO_2 from vehicle materials falls by as much as 70%, or almost 40 million tonnes of CO_2 per year (Exhibit 5.9). Reuse/remanufacturing, lightweighting, and sharing all contribute some part of this, but more than half occurs because of longer lifetimes. This is thus a prime example of how demand-side strategies can address CO_2 emissions, and in an important sector. It is also an important element of the saturation of metal stocks discussed in Chapters 2 and 4. In fact, with a shared mobility system, stocks could fall rather than increase or saturate.

Exhibit 5.8

A CIRCULAR SCENARIO REDUCES MATERIALS REQUIREMENTS IN MULTIPLE WAYS

2050 FLEET AVERAGE IN A BASELINE VERSUS CIRCULAR SCENARIO

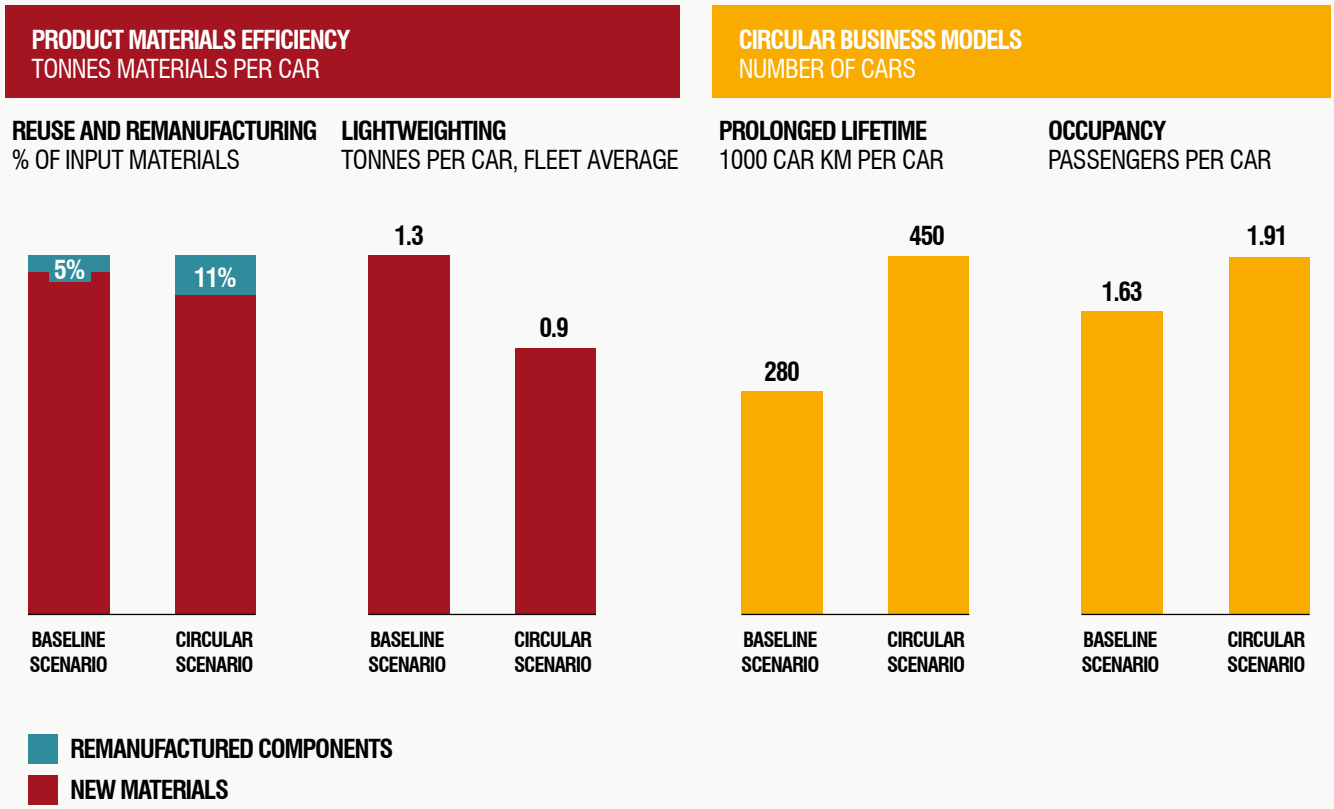
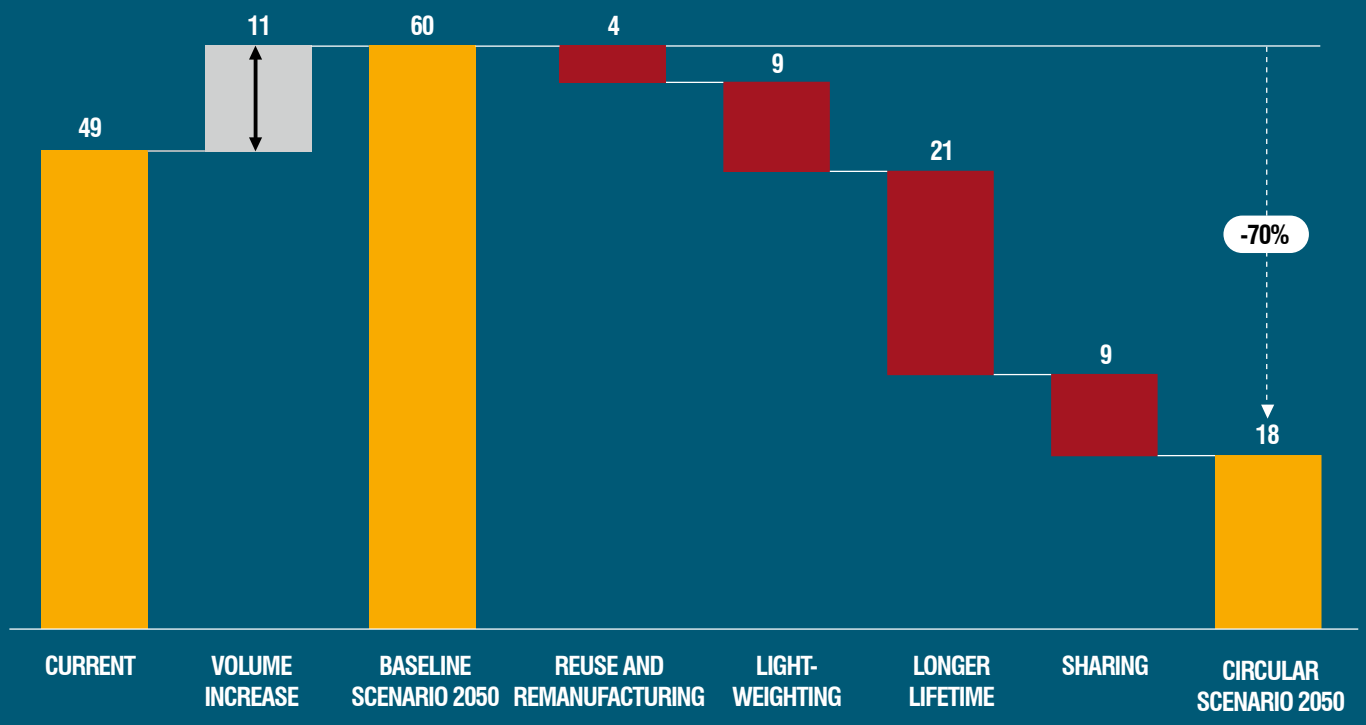


Exhibit 5.9

2050 CO_2 EMISSIONS FROM MATERIALS FALL BY 70% IN A CIRCULAR SCENARIO

CARBON DIOXIDE EMISSIONS FROM MATERIALS USED IN EU PASSENGER CARS, 2050
Mt CO_2, PER YEAR



5.4 A SHARED-MOBILITY SYSTEM IS HIGHLY COST-EFFECTIVE

Although the shared-mobility system described above would be much more resource-efficient, the main motivating factor would be its much greater economic productivity. By using both inputs and products much more intensively, the costs would be lower, and technologies that cut running costs (such as electric drivetrains) would be more profitable.

This can be explored by looking at the costs of individual ownership vs. the shared car model (Exhibit 5.10). Even when allowing for increased costs associated with factors such as more durable design, valuable materials, higher capital expenditure for electric vehicles, and more advanced automation for self-driving vehicles, costs fall substantially. The extra costs are simply overpowered by the greatly increased utilisation, smaller size of the average vehicle, and productivity gains from reuse and remanufacturing. Comparing the circular scenario with one dominated by individually owned vehicles, the net result is a reduction in the average cost per passenger-kilometre of as much as 77%. This may seem like an astounding claim, but other analyses have reached similar findings.[32] This gives a clear example of how new circular business models can combine improvements in economic productivity with greater resource efficiency.

The reduced cost of travel would also come with greater convenience, as passengers would not need to own their own vehicles, including the risk of value depreciation and hassle of repairs and maintenance. Self-driving cars can also free up driving time for other purposes, reducing the trade-off between travel and either work or leisure.

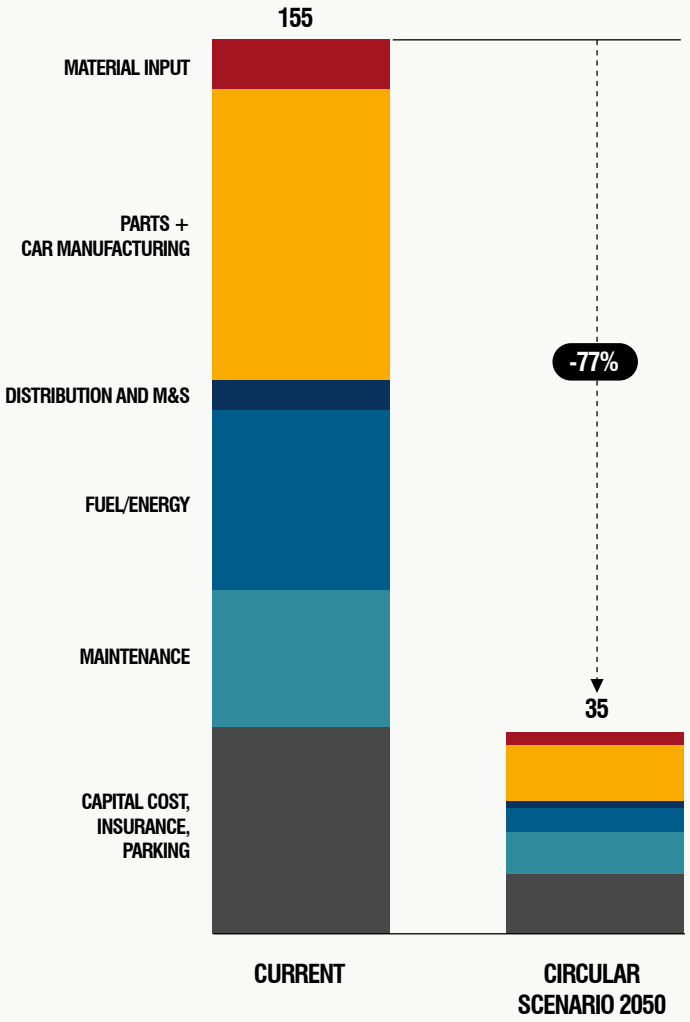
If travel becomes both cheaper and more convenient, one likely response is to boost total distance travelled – a so-called 'rebound' effect. The above analysis allows for this, assuming a 20% rebound effect. The rebound could very well grow larger still if left unmanaged, but policy-makers have a number of options to contain it, whether through charges or regulation. As important as the total volume of travel is the integration of shared and self-driving cars with other transport modes, and especially public transport. A major task for future city planners will be to ensure integrated transport solutions that serve overall social objectives.

A shift towards a shared mobility system could also help mitigate many of the negative effects of today's transport system (Exhibit 5.11). These are very significant today. Congestion costs up to 2% of GDP in major EU cities.[34] Every year, 26,000 people die in traffic accidents in the EU, and another 1.5 million are injured.[35] Road transport also accounts for 39% of nitrous oxide and 11% of particulate matter (PM2.5) air pollution in the EU, which are at the root of 475,000 premature deaths each year.[36] Noise pollution is another major factor, with costs only very partially accounted for today. Added to these 'externalities', a number of costs of transport are socialised, such as when public funds pay for infrastructure, valuable land is given up for roads, and parking is subsidised. Valuing these effects is notoriously tricky, and the exact amounts can be controversial. Nonetheless, standard estimates from the literature suggest externalities and other public costs add up to more even than the total cost paid by car owners.

Exhibit 5.10

EXTERNALITIES AND COSTS TO SOCIETY CAN BE CUT SIGNIFICANTLY IN A CIRCULAR SCENARIO

COST REDUCTION POTENTIAL
EUR PER 1000 PASSENGER KILOMETRES



KEY DRIVERS OF LOWER COST OF OWNERSHIP

SHARING

- *Higher utilisation per car together with reduced cost through autonomous car fleets lower costs per kilometre*

PROLONGED LIFETIME

- *Reduced total cost per kilometre despite increased cost for input materials*

LIGHTWEIGHTING

- *Smaller average cars in shared fleets reduce materials input and total cost, despite increased cost for lightweight materials*

REUSE AND REMANUFACTURING

- *Larger share reduces input materials and average cost of materials, modular design makes maintenance cheaper*

SOURCE: MATERIAL ECONOMICS ANALYSIS.[33]

***Autonomous vehicles** offer the prospect of reducing accidents sharply, as more than 90% of accidents are attributable to human error.*

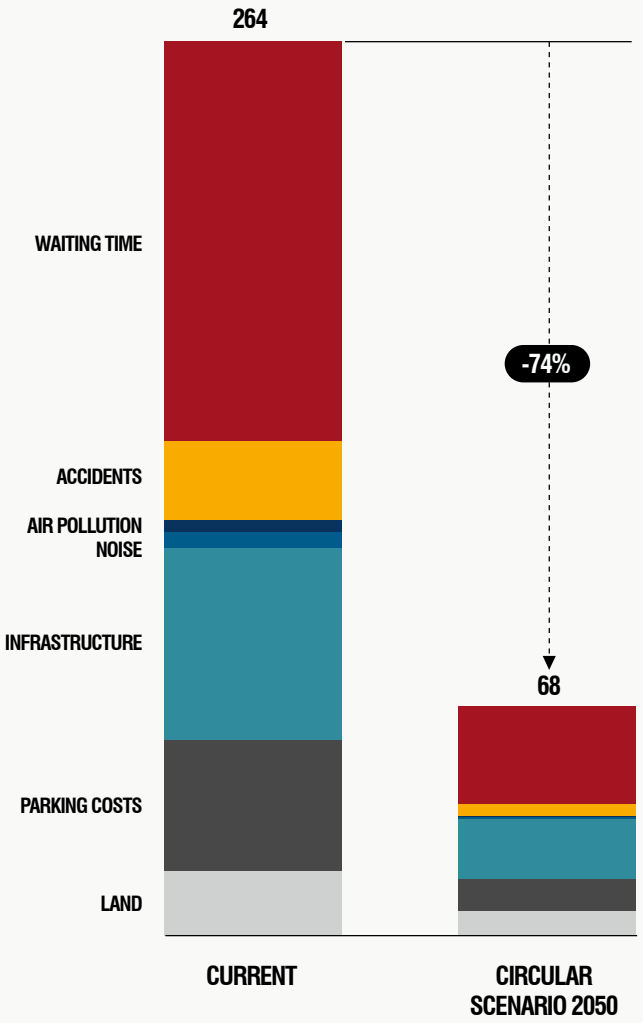
A shared mobility system would help reduce many of these costs. The total number of cars required to serve a given travel need would be lower, because of higher occupancy and sequential sharing over the course of a day. Autonomous vehicles offer the prospect of reducing accidents sharply, as more than 90% of accidents are attributable to human error.[37] Self-driving and connected cars can also optimise traffic flows, drive more densely than is possible with human drivers, and do not need parking space in city centres – thus reducing congestion as well as land use requirements for roads and parking.[38] By speeding up the adoption of electric vehicles, a shared car system would also contribute to reduced air and noise pollution. A systematic analysis of different factors suggests as much as 70% of externalities and public costs could be eliminated (Exhibit 5.11).

Like with rebound, this outcome depends on carefully managing the transition to a shared system. For example, early experiments with car sharing have resulted in more congestion rather than less in some cities, by taking passengers out of public transport systems and into shared cars.[40] Individual car-sharing services have also been controversial at times, mostly for reasons unrelated to the potential benefits we describe above (e.g. tax status, employment rights, impact on existing taxi services, etc.). However, these are particular to individual situations and represent at most incremental change; there is little reason to think that these are intrinsic to shared mobility. Nonetheless, they serve as a reminder that large transitions in fundamental systems such as personal mobility often unfold in bumpy ways. Policy-makers and business leaders alike need to be alert to problems that may arise. For all that, the intrinsic higher productivity and other benefits of such a system are so large that it is well worth aiming for.

Exhibit 5.11

EXTERNALITIES AND COST OF SOCIETY CAN BE SIGNIFICANTLY REDUCED IN A CIRCULAR SCENARIO BY 2050

EXTERNALITIES AND PUBLIC COSTS OF CAR TRANSPORTATION
EUR PER 1000 PASSENGER KILOMETRES



REDUCED EXTERNALITIES AND PUBLIC COST

- **REDUCED NUMBER OF CARS**
  Due to higher occupancy and increased utilisation result in improved air quality, reduced noise level, less congestion and less need for inner-city parking
- **AUTONOMOUS AND CONNECTED CARS**
  Are safer, reduce need for signs, lanes and other infrastructure and can optimise traffic flows, which reduces congestion and land use for roads
- **ELECTRIC VEHICLES**
  Reduce noise level and have positive impact on air quality, especially when shifting towards renewable energy sources

SOURCE: MATERIAL ECONOMICS ANALYSIS.[39]

HOW TO GET THERE – A POSITIVE INNOVATION SPIRAL

Although car-sharing is growing strongly, it has only taken the first tentative steps in the EU.[41] Even if it is an end-state worth aiming for, is there a credible path from today's system to the one described above?

The key to unlocking this is a set of self-reinforcing dynamics – a positive innovation spiral (Exhibit 5.12). The shared-car system requires vehicles that are designed and operated to different specifications, with joint innovation in materials, design, manufacturing, and business models. Once started, these changes become self-reinforcing in multiple dimensions. Higher utilisation enables earlier adoption of costlier automation technologies. These in turn enable business models based on sharing, in turn boosting utilisation further. Once a business model for mobility-as-a-service takes root, it creates the precondition for fleet-managed vehicles, enabling better maintenance, component reuse, remanufacturing, and more control over end-of-life flows. Longer lifetime in turn becomes an enabler of the intensive use underpinning a sharing business model, which reinforces the higher utilisation that helps motivate the higher upfront costs of more durable vehicle design.

In multiple ways, then, the overall shift is away from maximising upfront sales volumes and prices, and towards making the passenger car a well-functioning and effective part of urban mobility. Technology development and innovations within the shared car segment are likely to have positive spillovers for other vehicles, leading to even larger productivity gains. The agenda for industry is relatively clear.

The other major shift required is in expectations and attitudes. Today, car ownership is bound up with many things besides travel: cars have symbolic value, signalling a range of attributes from status to freedom. Partly for that reason, even the circular scenario sees one-third of travel continue in individually owned cars. At the same time, norms shift over time, and the greater convenience and lower cost of shared and autonomous mobility are powerful forces in a perspective to 2050.

The final area of change is policy and regulations. Though much is at stake for public policy objectives, policy may in fact have a relatively limited role to play. Private and public incentives are, on the whole, powerfully aligned.

Nonetheless, there are some areas for policy-makers to pay attention to. First, the more that air pollution, congestion and other negative effects of today's mobility system are discouraged, the more force there will be behind a move to a shared system with lower such impacts. Second, policy-makers can ensure that various other areas of regulation are adapted so they account for shared mobility. One example could be data policy, to safeguard end-user privacy in what will be a highly data-intensive business model. Another is to promote the emergence of effective insurance solutions for shared cars, and yet another to clarify and strike the right balance for safety and liability regulation for self-driving vehicles. Third, it is important not to let the early disappointments and controversies surrounding some of today's car-sharing muddy the waters; the potential benefits of shared mobility are extensive and real, whatever the precise performance of early experiments.

Finally, city authorities will have an important task to incorporate shared mobility with other important city initiatives. Given the last shift ahead, they can make clear their support for the transition – such as the city of Helsinki's stated ambition to enable a fully functional system of 'mobility on demand' to provide a service equivalent to that of private cars, by 2025. As noted, it will be important to integrate shared mobility solutions with public transport. City planning will also need to adapt as patterns of mobility change in response to the different circumstances of shared car system.

* * *

In its 2011 transport White Paper, the European Commission wrote: "Since the first big oil crisis 40 years ago – despite technical progress, potential for cost-effective energy efficiency improvements and policy efforts – the transport system has not fundamentally changed" – noting the challenges this creates for greenhouse gas emissions, cost, oil import dependence, congestion, pollution and more. The possibility of a shared mobility system now offers the prospect of such fundamental change – with significant gains for resource efficiency, lower costs, public health, and the environment. A more circular economy can be a major force for a better transport system.

Exhibit 5.12

SHARING CAN CATALYSE A POSITIVE SPIRAL OF NEW INNOVATION OPPORTUNITIES FOR PASSENGER CARS

MAJOR SHIFT OF INNOVATION FOCUS

FROM: Maximizing upfront sales volume and price
TO: Making the car a wellfunctioning effective part of urban mobility

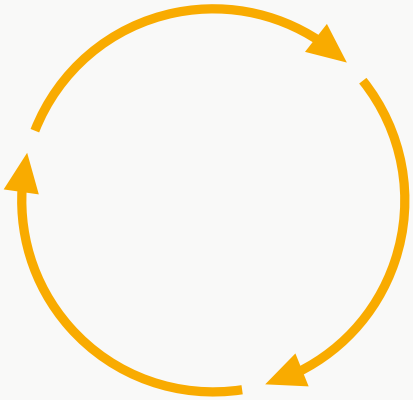
HIGHER UTILISATION PER CAR

SHARING BUSINESS MODELS

- *New business models to suit new customer groups*
- *Integration with public transport system*

DIGITISATION AND AUTOMATION

- *Self-driving cars enables new service models*
- *Data-intensive optimisation of traffic*



VEHICLES RE-DESIGNED AND MANAGED TO MAXIMISE RUN TIME

LONGER VEHICLE LIFETIMES

- *High returns to durability*
- *Longer-lived electric vehicles profitable*
- *Professionally maintained fleet*

MODULARITY AND REUSE

- *Design for quick repair and upgrade-ability*
- *Reuse built into vehicle design*

LOWER VEHICLE WEIGHT

- *More varied car sizes with shared fleet*
- *Advanced materials more profitable*

HIGHER PROFITABILITY OF CIRCULAR BUSINESS MODELS

END-OF-LIFE VALUE

- *Higher EOL value (modularity, valuable materials etc.)*
- *EOL flows more predictable in fleet owned system*

LOWER COST OF TRANSPORT

- *New design and high utilisation reduce total cost*
- *Competitiveness with other modes of transport increases*

6. BUILDINGS AND CEMENT

MORE VALUE FROM LESS MATERIALS

The EU uses as much as 1.6 billion tonnes (Gt) of materials for buildings per year, and that amount is likely to grow as building stock continues to slowly expand, and as large numbers of post-war buildings require substantial renovation or replacement in the decades ahead. The CO_2 footprint of these materials is significant, and in the EU countries that have gone furthest in improving energy efficiency and decarbonising heat, construction now accounts for as much as half of the lifetime CO_2 footprint of a building (and the use phase for the rest).[1]

How we use construction materials therefore matters greatly for future climate targets. By 2050, just the cement, steel, aluminium and plastic used for construction will result in emissions of 230 Mt CO_2 in a baseline scenario where they are made with today's production processes. Demand-side measures could reduce this by more than half, or 123 Mt CO_2, by the second half of this century. Of this, 80 Mt CO_2 per year would be available by 2050, making a major contribution to EU mid-century climate targets.

Key measures that could reduce demand for building materials include design changes to increase buildings' longevity and adaptability; disassembly at the end of life; and reuse of intact structural components, on site or within local markets. Improved design of building components, new construction techniques, and use of high-strength steel and concrete could reduce the materials needed for new buildings. Increased standardization, improved planning, and appropriate storage and transportation could reduce waste. New business models for buildings in which spaces are shared, e.g. co-working spaces, could reduce the total built area needed. Finally, there is potential to recycle cement from demolition, by reprocessing concrete to recover some unreacted clinker.

Cost-effective strategies may be underused because of diverging interests: the party making decisions is not the one who would benefit (similar to how landlords have little incentive to invest in energy efficiency if their tenants pay the energy bills). In other cases, the business case is not strong enough yet, but could improve with new technology. Increased digitalisation of the construction process will be a key factor for the adoption of circular opportunities, through the use of building information modelling, and the gradual automation of more of the construction process. Both of these can significantly reduce the cost of techniques to reduce materials use.

Increased digitalisation *of the construction process will be a key factor for the adoption of circular opportunities, through the use of building information modelling system and increased automation.*

6.1 UNDERSTANDING FUTURE BUILDING NEEDS

We spend most of our time in buildings. EU residents use an average of 48 m^2 of floor area – for housing, offices, education, lodgings and other purposes; housing costs alone consume 22% of disposable income.[2] The effort that goes into creating and maintaining this building stock also is a major economic sector, accounting for 8.6% of the EU's GDP and employing 18 million people.[3]

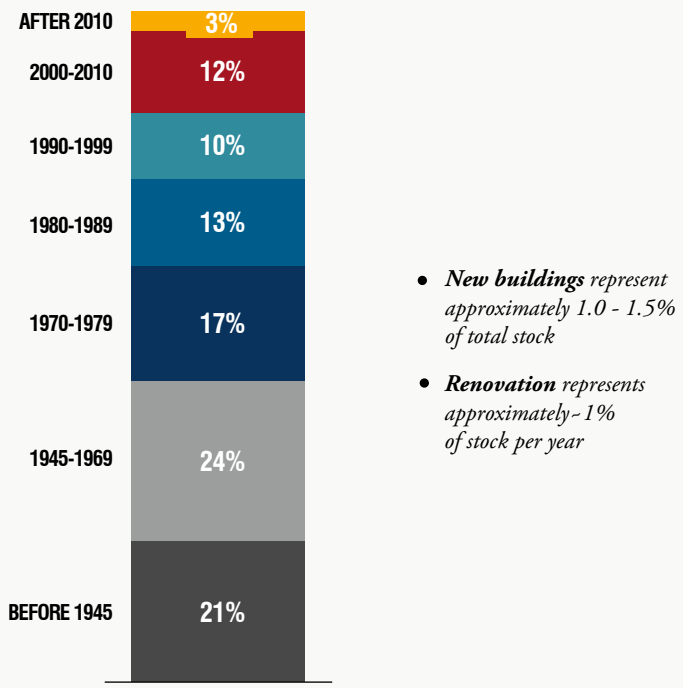
The building stock changes only slowly, so the decisions made today have very long-term consequences. Each year, 1% of EU buildings are renovated, and new buildings are added that make up 1–1.5% of the total stock.[4] The EU's building stock is aging – 45% of buildings are over half a century old, and a large share of housing was built just after World War II – so in the coming years, significant renovations and upgrades will be needed (Exhibit 6.1). To meet climate targets, the EU will also have to retrofit buildings to improve their energy efficiency at two or three times today's pace.[5]

Even though the turnover rate for buildings is slow, construction is a major user of materials. Buildings account for two-thirds of cement use, more than a third of steel, a quarter of aluminium, and almost 20% of plastics.[7] Adding aggregates and other materials such as bricks, gypsum, lime and copper, buildings alone use some 1.6 billion tonnes of materials per year, as noted below. Producing these materials, in turn, results in about 250 million tonnes (Mt) of CO_2 emissions annually (Exhibit 6.2). Cement, steel, aluminium and plastics account for almost 80% of those emissions. Construction and demolition (including infrastructure) also generate 25–30% of total waste volumes,[8] far more than any other sector.

Exhibit 6.1

THE BUILDING STOCK EVOLVES SLOWLY, WITH 1% RENOVATION AND 1–1.5% NEW CONSTRUCTION PER YEAR

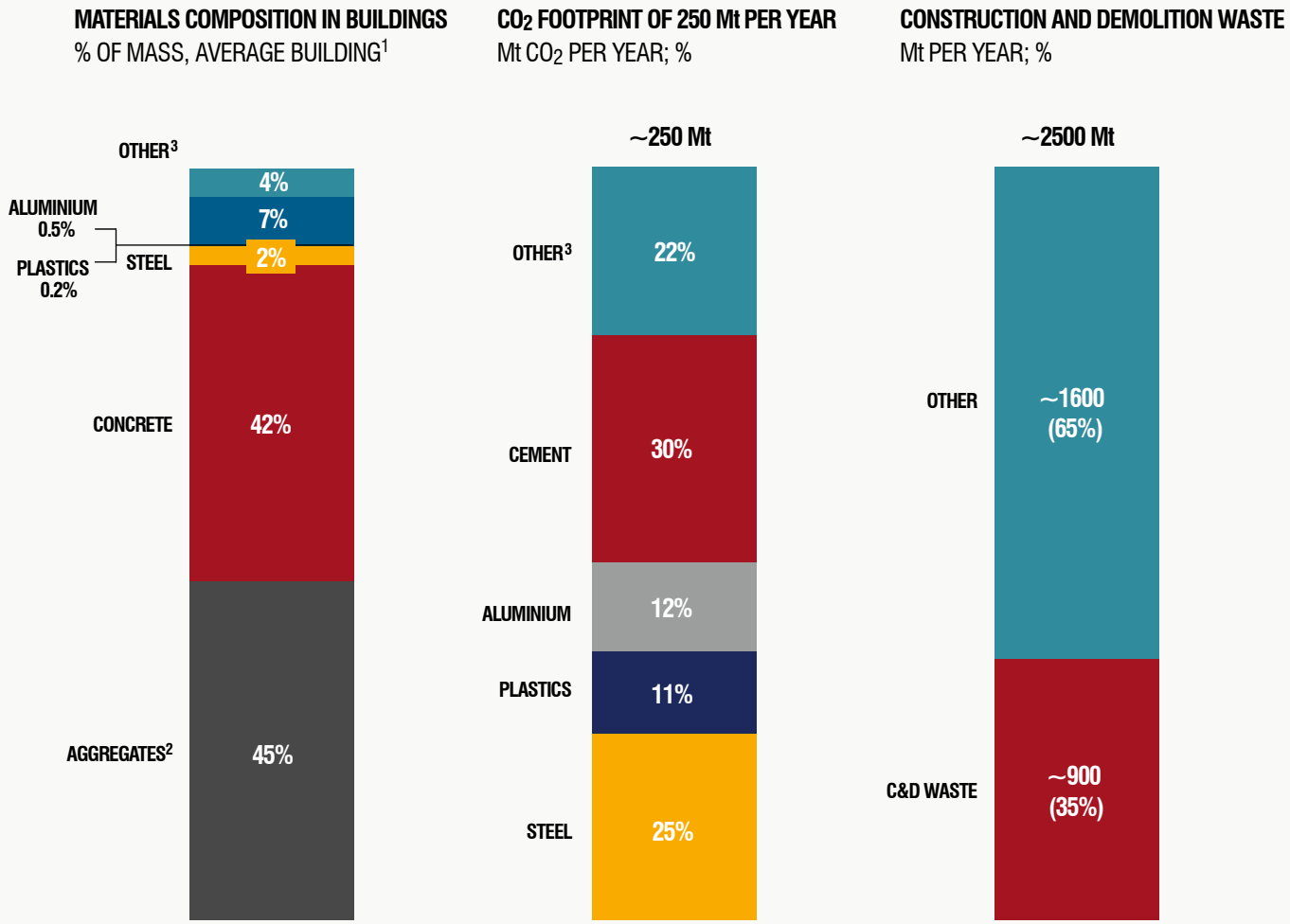
AGE DISTRIBUTION OF BUILDING STOCK, 2013
% OF TOTAL BUILDING STOCK, EUROPE



SOURCE: ANALYSIS BASED ON MULTIPLE SOURCES[6]

Exhibit 6.2

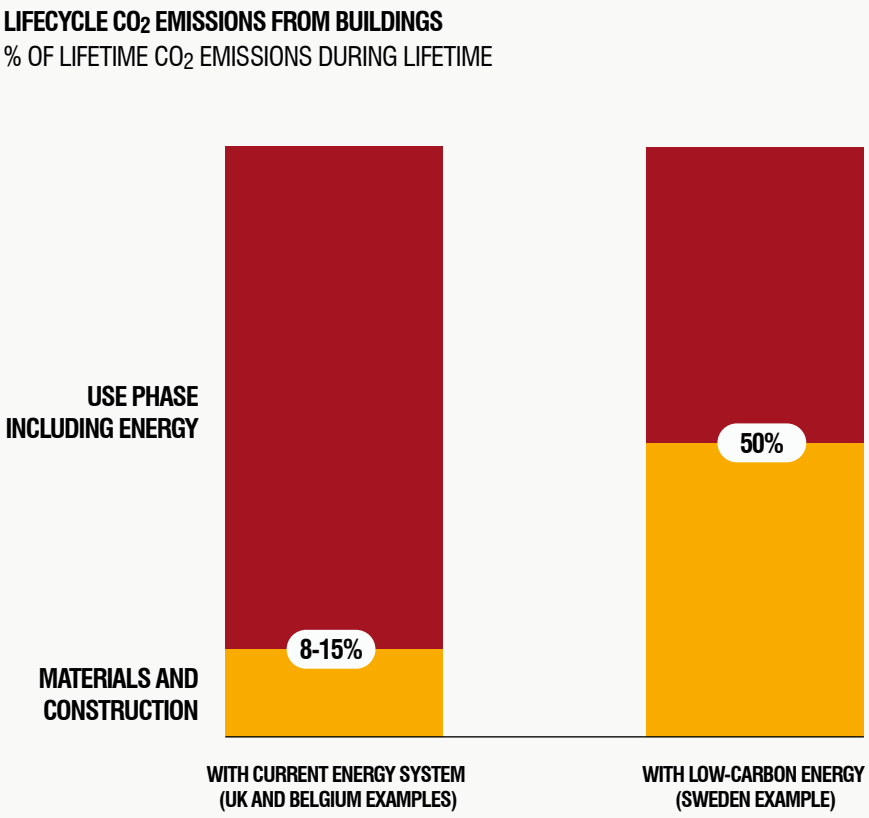
EU BUILDING MATERIALS HAVE A CO_2 FOOTPRINT OF 250 MILLION TONNES PER YEAR



NOTE: 1 DATA FOR MATERIALS COMPOSITION OF BUILDINGS INCLUDE RESIDENTIAL, PUBLIC AND COMMERCIAL BUILDINGS, BUT NOT INDUSTRIAL, 2 EXCLUDING AGGREGATES USED IN CONCRETE, 3 INCLUDING WOOD, STONE, GLASS, AND CLAY
SOURCES: ECORYS AND COPENHAGEN RESOURCE INSTITUTE (2014), EUROSTAT (2017).

Exhibit 6.3

MATERIALS WILL BE A MAJOR FUTURE SOURCE OF CO_2 EMISSIONS FROM BUILDINGS



SOURCE: IVA (2014), ROSSI, MARIQUE AND REITER (2012), CUÉLLAR-FRANCA AND AZAPAGIC (2012)[13]

To date, most discussions of the CO_2 impact of buildings have focused on the use phase, especially on energy consumption. This is understandable: buildings account for 40% of final energy demand in the EU, and 36% of CO_2 emissions.[10] Still, around 15% of total lifecycle CO_2 emissions from EU buildings today are attributable to materials and construction (Exhibit 6.3). As energy efficiency and low-carbon energy reduce energy emissions, the CO_2 'embodied' in materials will become ever more important. In countries where electricity and heating systems are already low-carbon, building materials already account for half of the total CO_2 footprint of new buildings.[11] Other EU countries will follow a similar route as their energy systems decarbonise. Thus, it is high time that discussions about sustainable buildings pay attention to building materials.[12]

It is high time *that discussions about sustainable buildings pay attention to building materials.*

EMISSIONS FROM CEMENT PRODUCTION

Cement accounts for a large share of the embodied emissions in buildings, and is a major source of global CO_2 emissions. The chemical reaction involved in the production of clinker (the main ingredient of cement) results in some 1.4 billion tonnes of CO_2 per year globally.[14] Another 1 Gt CO_2 results from the large amounts of energy required to produce cement. The total of 2.4 Gt CO_2 corresponds to 7% total global CO_2 emissions from energy and industry.[15]

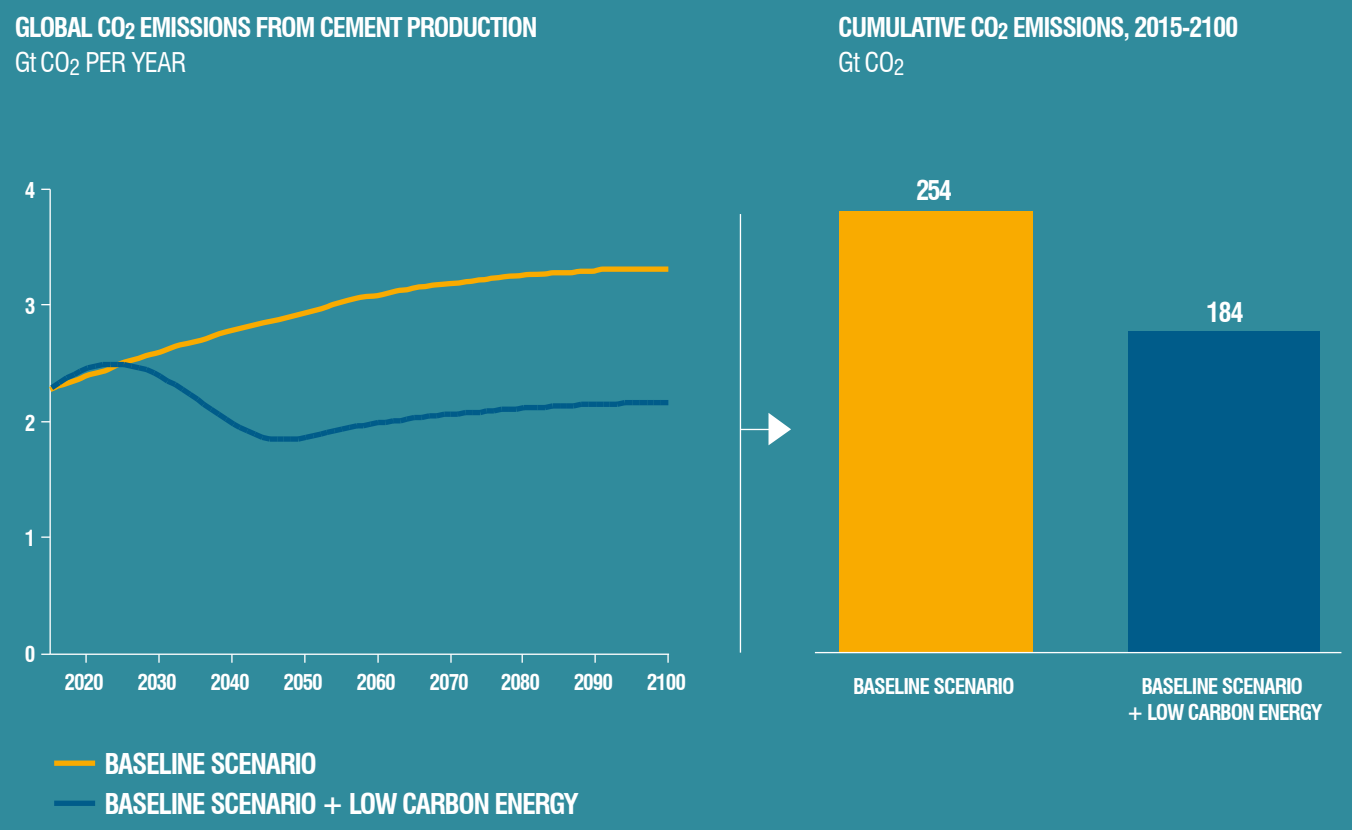
Looking ahead, global cement production is set to grow further. Many developing countries still have stocks of 5 tonnes per person or less, less than a quarter of many developed countries.[16] To explore the emissions implications of global cement use for CO_2 emissions, we modelled a scenario in which demand rises to 7 billion tonnes per year by 2100.[17] Even using the best available techniques for production, total emissions would rise to almost 4 Gt CO_2 per year, with the cumulative emissions of more than 250 Gt by 2100 (Exhibit 6.4). A rapid switch to low-carbon energy in cement production would help, but large chemical process emissions would remain. Even fully decarbonised energy leaves in place 2 Gt per year of CO_2 emissions from cement production, claiming 184 Gt of the global CO_2 budget to 2100.

In the face of such daunting numbers, many low-carbon scenarios assume carbon capture and storage as the main way to address future cement emissions.[18] Others see great potential in materials substitution, by using existing alternatives to clinker,[19] or switching to polymer cements or other innovative options.[20]

Cement production is a significant source of emissions in the EU as well: 114 Mt CO_2 per year today. As noted above, construction activity and demand are likely to increase somewhat. Even with incremental process improvements, emissions in 2050 therefore would be similar to today's, at 113 Mt CO_2 per year. Given this challenge, any opportunity to reduce the demand for cement – without compromising on well-being – could make an important contribution to EU climate targets.

Exhibit 6.4

EMISSIONS FROM GLOBAL CEMENT PRODUCTION RISK CLAIMING MOST OF THE CARBON BUDGET AVAILABLE FOR ALL MATERIALS PRODUCTION



6.2 THE CIRCULAR ECONOMY OPPORTUNITY IN BUILDINGS

The circular economy opportunities in buildings are in three main categories (Exhibit 6.5):

- **Materials recirculation:** Recycling materials from end-of-life buildings, and designing and dismantling buildings so that high-value recycling is possible (the recirculation of steel, plastics, aluminium was discussed in Chapters 2–4, so we focus on cement below).
- **Building materials efficiency:** Reducing the amount of materials that are required for a given floor area. The main opportunities are to reduce waste during the construction process; reduce the amount of material in each building by avoiding over-specification and using user higher-strength materials; and reusing buildings and building components.
- **Circular business models:** Increasing the useful service from materials, by extending the lifetime of buildings, and/or by increasing the utilisation of floor space through sharing and other mechanisms.

Together, these opportunities could significantly reduce the amount of construction materials needed in the EU. Before discussing them in detail, however, it is useful to consider some of the reasons why materials use is so inefficient today. After all, building materials constitute a major part of the total cost of construction, so there should already be strong economic incentives to optimise their use.

Exhibit 6.5

A BROAD PALETTE OF CIRCULAR ECONOMY OPPORTUNITIES CAN IMPROVE MATERIALS USE IN BUILDINGS

MATERIALS RECIRCULATION
TONNES CO_2 PER TONNE MATERIALS

CEMENT RECYCLING AND VALUE CAPTURE AT END OF LIFE

- *Improved waste management, better separation of materials and increased recycling*
- *Less downcycling of concrete through adoption of new technologies to recover unused cement and aggregates*
- *"Design for disassembly" as a key principle*

BUILDING MATERIALS EFFICIENCY
TONNES MATERIALS PER m^2

REDUCED WASTE IN CONSTRUCTION

- *Reduced loss of materials during construction through improved materials management*

MATERIALS EFFICIENCY OF BUILDINGS

- *Less material per building through less over-specification, improved design, and high-strength materials*

REUSE OF BUILDING COMPONENTS

- *Reuse of structural components at end of life and during renovations through new local markets*

CIRCULAR BUSINESS MODELS
USEFUL SERVICE FROM EACH m^2

PROLONG LIFETIME

- *Adapt and renovate of buildings to avoid demolition and new build*
- *Improved maintenance to extend lifespan of key components*
- *Design for flexible use and to enable deep renovation*

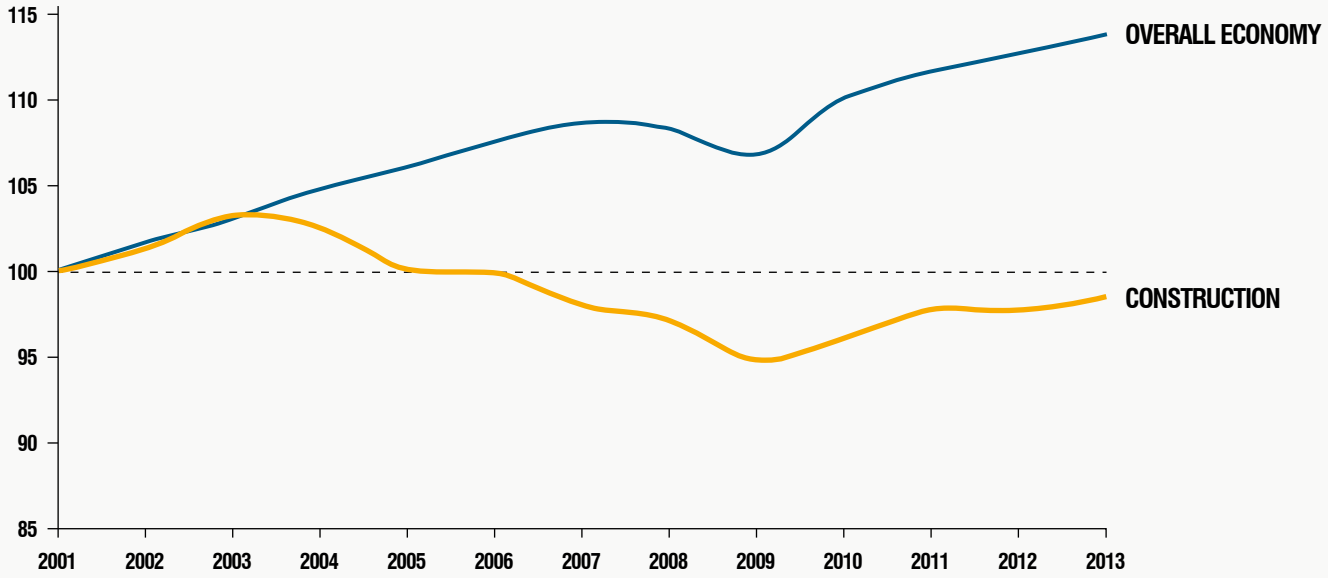
SHARING TO REDUCE FLOOR SPACE REQUIREMENTS

- *Reduce total area required through mechanisms such as peer-to-peer sharing, office sharing, and more communal space*

Exhibit 6.6

THE CONSTRUCTION SECTOR FACES A MAJOR PRODUCTIVITY CHALLENGE

LABOUR PRODUCTIVITY IN CONSTRUCTION VERSUS OVERALL ECONOMY
INDEXED: 100 = 2001, EU28



SOURCE: EUROPEAN COMMISSION (2015)[22]

However, the construction industry faces significant challenges.[21] First of all, it is fragmented, comprising numerous, often small companies. It is cyclical and volatile, and EU construction companies are still recovering from the sharp downturn that came with the financial crisis. The workforce is relatively unstable, and profit margins and capitalisation are lower than in many other sectors. The stakeholders and value chain are fragmented, with complex contracting across multiple parties that often results in inefficiencies and poorly aligned incentives. Construction has also been slow to adopt new technologies or methods; there has been no analogue of manufacturing's 'lean' improvements. For all these reasons, unlike in any other sector of comparable economic importance, productivity improvements in construction have stalled (Exhibit 6.6).

For these reasons, and because of the social and economic importance of buildings, regulators often intervene heavily in the sector. The long chain of actors and time lag between initial construction and eventual occupation (let alone demolition) mean that commercial contracts can rarely cover all aspects of public importance. Regulations and building standards cover many issues – fire safety, energy performance, aesthetics, permitting, construction products, structural safety, etc. However, materials efficiency is not yet included in such regulations.

Another important theme is that many barriers could mitigated by increased digitalisation. High transaction costs, risk, and labour costs are three of the main factors in the current industry structure that lead to the inefficient use of materials, and digitalisation-related strategies could help address them, as discussed below.

MATERIALS EFFICIENCY IN THE CONSTRUCTION PROCESS

The main reasons for overuse of materials are waste during construction, over-specification in the building, and discarding instead of reusing structural elements before their end of life.

Waste of materials during construction: Industry insiders indicate that as much as 15% of buildings materials are wasted in the construction process, ranging from 10% in the best cases to 20% or more in the worst.

There are many reasons for this waste. Contracts are often structured in such a way that those making decisions about materials use do not bear the cost of any waste – but they do bear the cost of delays, so they order extra materials as a buffer. Due to lack of standardisation and local markets, however, surpluses often cannot be sold on or returned. Many construction companies do not even have firm data on the amount of materials they waste, showing how little attention the issue has received.

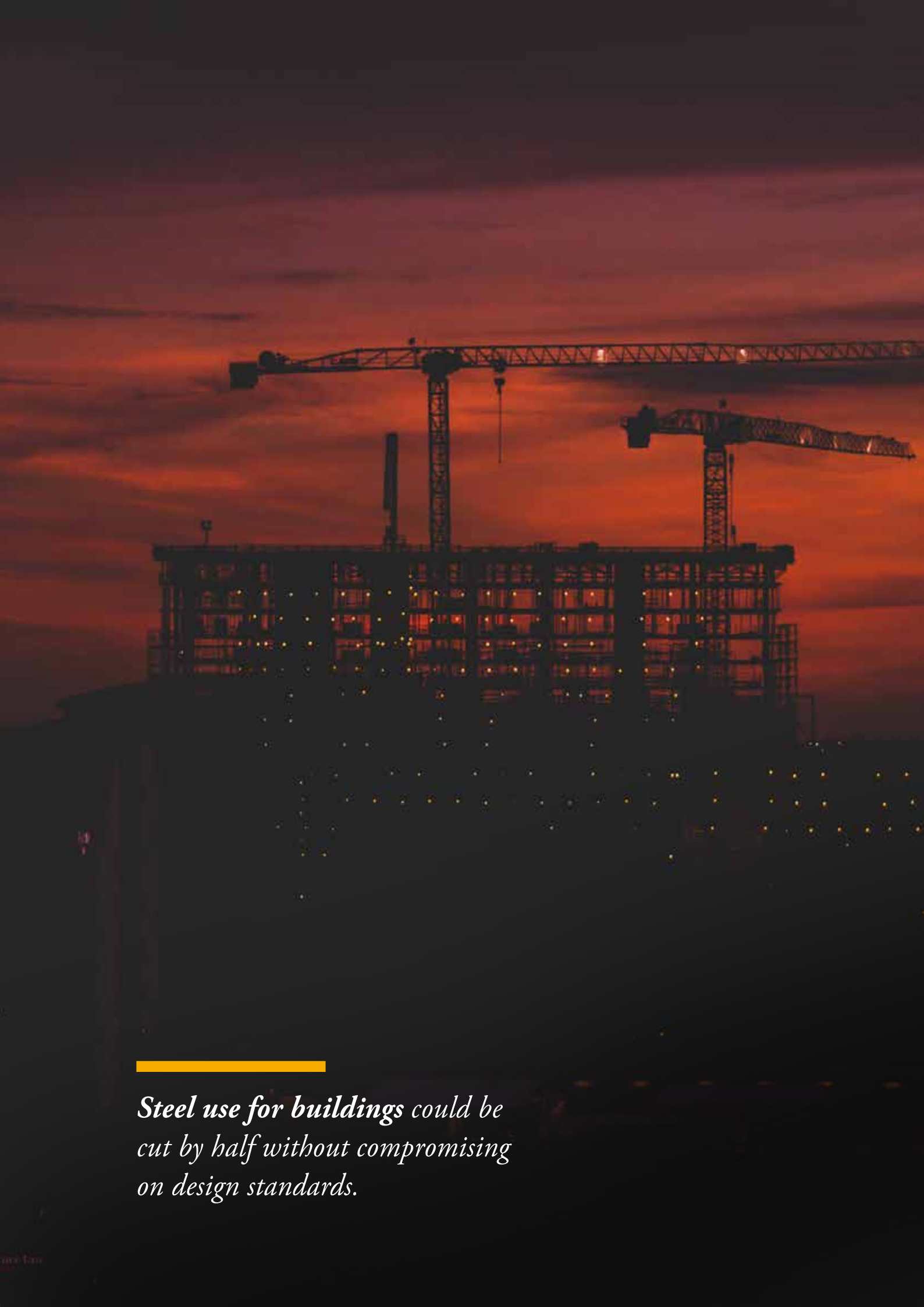
Over-specification of materials inputs: Up to 85% of the materials in a building are in the structural elements, with steel and concrete making up the large majority.[23] There is a widespread tendency for these elements to be over-specified, using more materials than are needed for a sound and safe structure. This is particularly true with steel: detailed case studies show its use could be cut by half without compromising on design standards.[24] This is an astounding number, with immediate significance for total steel use; as noted above, construction accounts for more than half of total steel demand. It also shows clearly how little attention there is in today's construction process to efficient materials use.[25] This also suggests that greater use of digital tools and automated assembly could do much to address this issue.

High-strength materials offer another route to reduce the total use of materials. For example, high-strength steel can reduce materials needs and CO_2 footprint by 15–20% in some building types.[26] There also are benefits from ultra-high strength concrete in some applications.[27]

Reuse of components: Many of the components of buildings are still fully functional even when the building reaches its end of life, creating an opportunity for reuse, especially of concrete and steel components. There are already some examples of successful reuse. A new residential area of Copenhagen is being built out of structural elements from abandoned houses[28], while a German residential area near Berlin similarly reused precast concrete elements, reducing the cost of construction by 30%.[29] Although these examples demonstrate the viability of reuse, they are rare exceptions, and the amount of concrete being reused is still tiny relative to new concrete demand. There also are many examples of successful reuse of steel[30], but overall, only 5% of end-of-life steel from buildings is in fact reused, a small share of the total potential.

A range of barriers stand in the way.[32] The most immediate obstacles are availability and coordination: even when reusable parts are in fact available, there often are no local markets capable of matching connecting those dismantling buildings with those who could use the parts, or of storing the parts until someone can use them. Inconsistent or unpredictable supplies of materials could result in costs or delays for other parts of a building project, and the quality may be difficult to trace or certify. As important, the practice is simply unfamiliar, at odds with established routines. Industry experts also say there is little demand from clients to test them.

To overcome these barriers, it would be necessary both to 'design for deconstruction', and to enable much closer tracking of materials in- and outflows to the building stock.



Steel use for buildings *could be cut by half without compromising on design standards.*

MAKING MORE OF EACH BUILDING: INCREASED LIFETIME AND UTILISATION

Increasing the building lifetime is one of the single most effective actions that can be taken to reduce the need for construction materials. As noted above, around 85% of the CO_2 footprint of materials is associated with structural elements. Yet when buildings are demolished, it is typically not because their structures are no longer usable in any technical sense – most are perfectly sound.[33] Instead, old buildings are razed for social or economic reasons: because architectural tastes have changed, new types of housing or commercial space are needed; the neighbourhood has evolved; or the cost of renovating the building is higher than demolition and new construction. There is also significant variation in how long buildings stand: some low-quality developments are torn down only some decades after construction, whereas at the other extreme many European cities take pride in high-quality, beautiful buildings that may have stood for centuries. Despite what is actually possible, the technical lifetime of new buildings is often assumed to be just 50 years.[34]

This suggests a major agenda to extend the life of buildings. The key is for buildings to be *adaptable* to the changing requirements of their users: whether they change in function (e.g. from commercial to residential), or in appearance and design. This requires high quality and an emphasis on design that is modular and enables deep renovation. In addition, improved maintenance can extend lifetimes by preventing the deterioration of facades and other parts, which in turn become the trigger for wholesale demolition.

Above all, a longer life for buildings will require a different mindset, where buildings are intended and expected to last, and to be reconfigured multiple times over long time periods. This may require public intervention, as the societal benefits of 'build to last' principles are felt only a long time in the future.

The need for materials in buildings also can be reduced by making more of the building stock that is already in place. Sharing offers one option. For example, much European office space is occupied only for 40% of the time[35], and there is a trend both towards more compact and shared offices. Services such as Airbnb also offer the possibility of using spare or idle residential space more effectively.

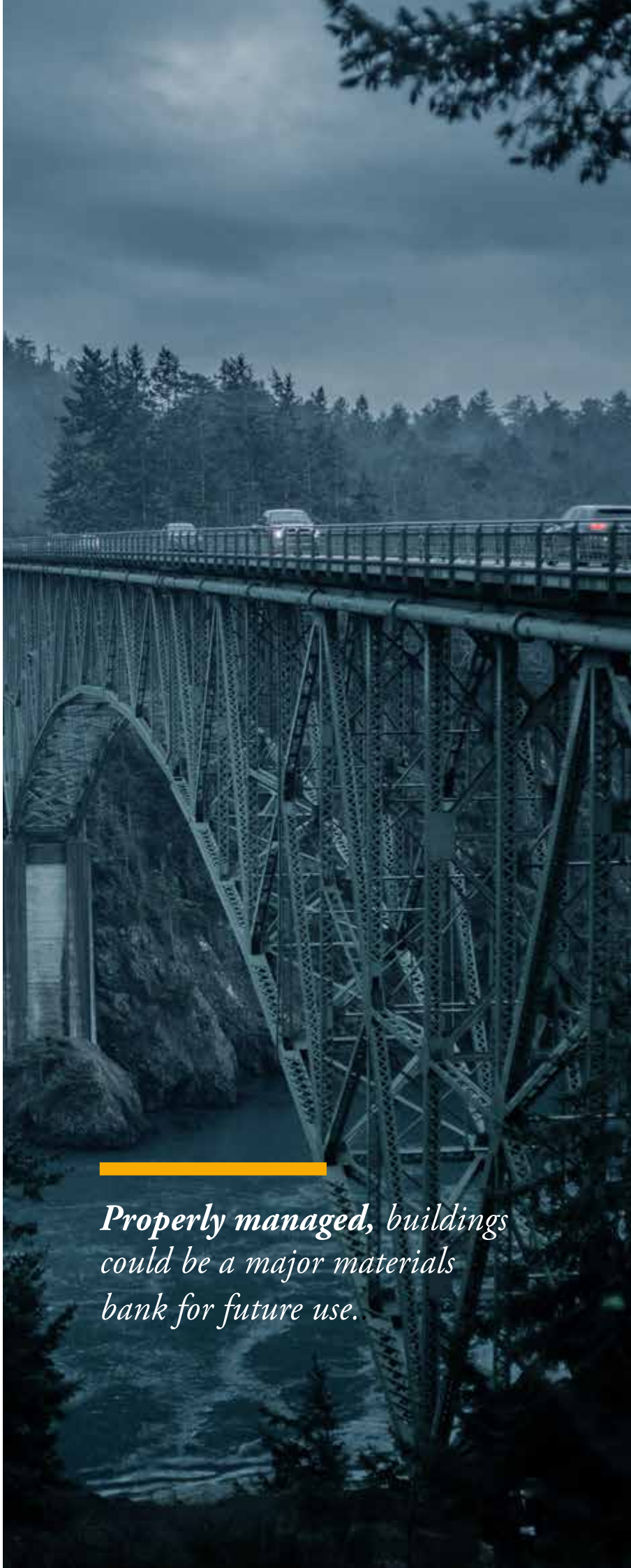
In the residential sector, the opportunity is different. One aspect is a mismatch of space and occupancy. Many European countries have long had a discussion about tax systems discouraging downsizing from large to small houses. Architects also have highlighted the opportunity to make better use of communal space in new residential developments – perhaps chiefly to create a more socially attractive place to live, but also making it possible for each individual dwelling to be smaller without compromising on residents' requirements.

IMPROVED END-OF-LIFE DISASSEMBLY FOR HIGH-VALUE REUSE AND RECYCLING

The building stock in Europe constitutes an enormous repository of highly specialised materials: a range of different metals, specific alloys or composites, plastics with a wide range of different properties, insulation materials, and much more. The prospect of 'buildings as a materials bank' expresses the notion that, properly managed, end-of-life buildings could become a major source of materials for future needs.

The starting point is very different, however. Standard practice when buildings reach their end of life is demolition. Although official statistics state that 47% of EU construction and demolition waste is reused or recycled, this stretches any meaningful definition of recycling: mostly, materials with high embodied energy and CO_2 are turned into bulk aggregates or backfill, sometimes at no net CO_2 benefit.[36] Concrete may be crushed to recover reinforcing steel, and then either landfilled or used as aggregates. Steel elements are typically remelted as scrap, or lost. As noted in Chapter 3, some plastics from buildings are recycled, but far from the full potential. Except for metals and some plastics recycling, current practice is at best very heavy downcycling, combined with no small share of landfilling.

To change this, several things must happen. One is to properly track the content of buildings through 'materials passports' and logbooks, so that the potential for materials recovery is known at end of life, and to track changes during a building's lifetime. Another is to design buildings for deconstruction, as noted above, and otherwise for separation into clean streams of high-value materials. The demolition process would need to change, as today's speed-focused methods often damage or mix the materials to the point where they can only be recovered as aggregates.



Properly managed, *buildings could be a major materials bank for future use.*

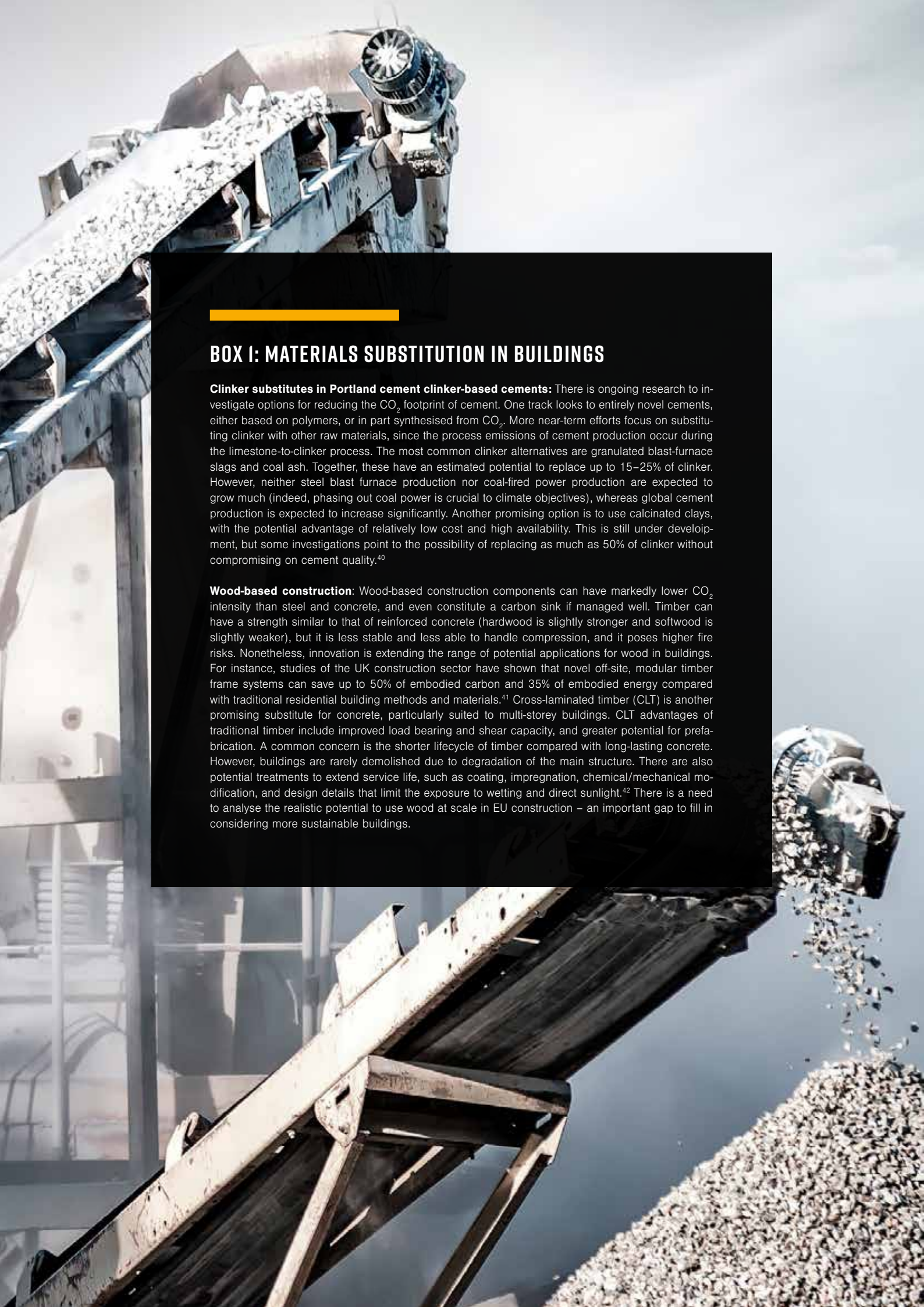
LOWER CO_2 INTENSITY OF BUILDING MATERIALS AND CEMENT RECYCLING

The remaining key strategy to reduce CO_2 emissions from buildings is to use materials with lower CO_2 emissions per tonne. One demand-side option is to substitute from high-carbon to low-carbon materials (see Box 1 for two prominent examples). The other is to recycle materials (here we focus on cement, but see Chapters 2–4 for discussions of recycling steel, plastics and aluminium).

Cement cannot be recycled in the same sense as metals or plastics, as the process of making cement clinker is irreversible. Nevertheless, there are opportunities to recover unused cement from concrete at end of life. As much as 30–40% of the clinker often remains unused (or unhydrated)[37] and can therefore in principle be used again to replace new cement.

Technologies to capture these opportunities are under development. For example, SmartCrusher in the Netherlands has found in pilots that it is possible not only to recover unreacted cement, but also to retrieve aggregates from end-of-life concrete with improved quality relative to new aggregates.[38] In turn, the recovered aggregates with improved strength require up to 15% less cement than new aggregates. Overall, the recovered cement can replace up to 80% of new cement in construction, saving almost half of the CO_2.[39]

These technologies have yet to enter into commercial use at scale. In addition to technology development, it is necessary to set up the regulatory framework and adapt standards to accommodate recycled materials. Given transport costs, markets for recovered cement would mostly be local, or even integrate the demolition of existing structures directly into the production of raw materials for replacement buildings.



BOX I: MATERIALS SUBSTITUTION IN BUILDINGS

Clinker substitutes in Portland cement clinker-based cements: There is ongoing research to investigate options for reducing the CO_2 footprint of cement. One track looks to entirely novel cements, either based on polymers, or in part synthesised from CO_2. More near-term efforts focus on substituting clinker with other raw materials, since the process emissions of cement production occur during the limestone-to-clinker process. The most common clinker alternatives are granulated blast-furnace slags and coal ash. Together, these have an estimated potential to replace up to 15–25% of clinker. However, neither steel blast furnace production nor coal-fired power production are expected to grow much (indeed, phasing out coal power is crucial to climate objectives), whereas global cement production is expected to increase significantly. Another promising option is to use calcinated clays, with the potential advantage of relatively low cost and high availability. This is still under develoipment, but some investigations point to the possibility of replacing as much as 50% of clinker without compromising on cement quality.[40]

Wood-based construction: Wood-based construction components can have markedly lower CO_2 intensity than steel and concrete, and even constitute a carbon sink if managed well. Timber can have a strength similar to that of reinforced concrete (hardwood is slightly stronger and softwood is slightly weaker), but it is less stable and less able to handle compression, and it poses higher fire risks. Nonetheless, innovation is extending the range of potential applications for wood in buildings. For instance, studies of the UK construction sector have shown that novel off-site, modular timber frame systems can save up to 50% of embodied carbon and 35% of embodied energy compared with traditional residential building methods and materials.[41] Cross-laminated timber (CLT) is another promising substitute for concrete, particularly suited to multi-storey buildings. CLT advantages of traditional timber include improved load bearing and shear capacity, and greater potential for prefabrication. A common concern is the shorter lifecycle of timber compared with long-lasting concrete. However, buildings are rarely demolished due to degradation of the main structure. There are also potential treatments to extend service life, such as coating, impregnation, chemical/mechanical modification, and design details that limit the exposure to wetting and direct sunlight.[42] There is a need to analyse the realistic potential to use wood at scale in EU construction – an important gap to fill in considering more sustainable buildings.

6.3 A CIRCULAR SCENARIO FOR BUILDINGS CAN CUT CO_2 EMISSIONS BY MORE THAN HALF

The above discussion lays out a rich set of options to reduce the demand for materials in construction without compromising on the benefits derived from buildings. To explore the impact of those options on CO_2 emissions, we built a circular scenario with the gradual adoption of a wide-ranging palette of circular opportunities in buildings by 2050. The analysis shows that CO_2 emissions from materials in buildings could be reduced by as much as half (Exhibit 6.7). Without further action, the total emissions from materials for buildings are likely to grow from 208 Mt CO_2 today to just over 230 Mt CO_2 per year by 2050. The circular opportunities jointly could cut emissions by 80 Mt CO_2 by 2050, and a further 43 Mt CO_2 later in the century, as the effect of longer building lifetimes takes hold.[43] The largest reductions are from materials efficiency strategies (less waste, less over-specification, use of high-strength materials) and reuse. The total reduction of 123 Mt CO_2 thus cuts emissions by more than half.

Exhibit 6.7

A CIRCULAR SCENARIO REDUCES CO_2 EMISSIONS FROM BUILDING MATERIALS BY 53%

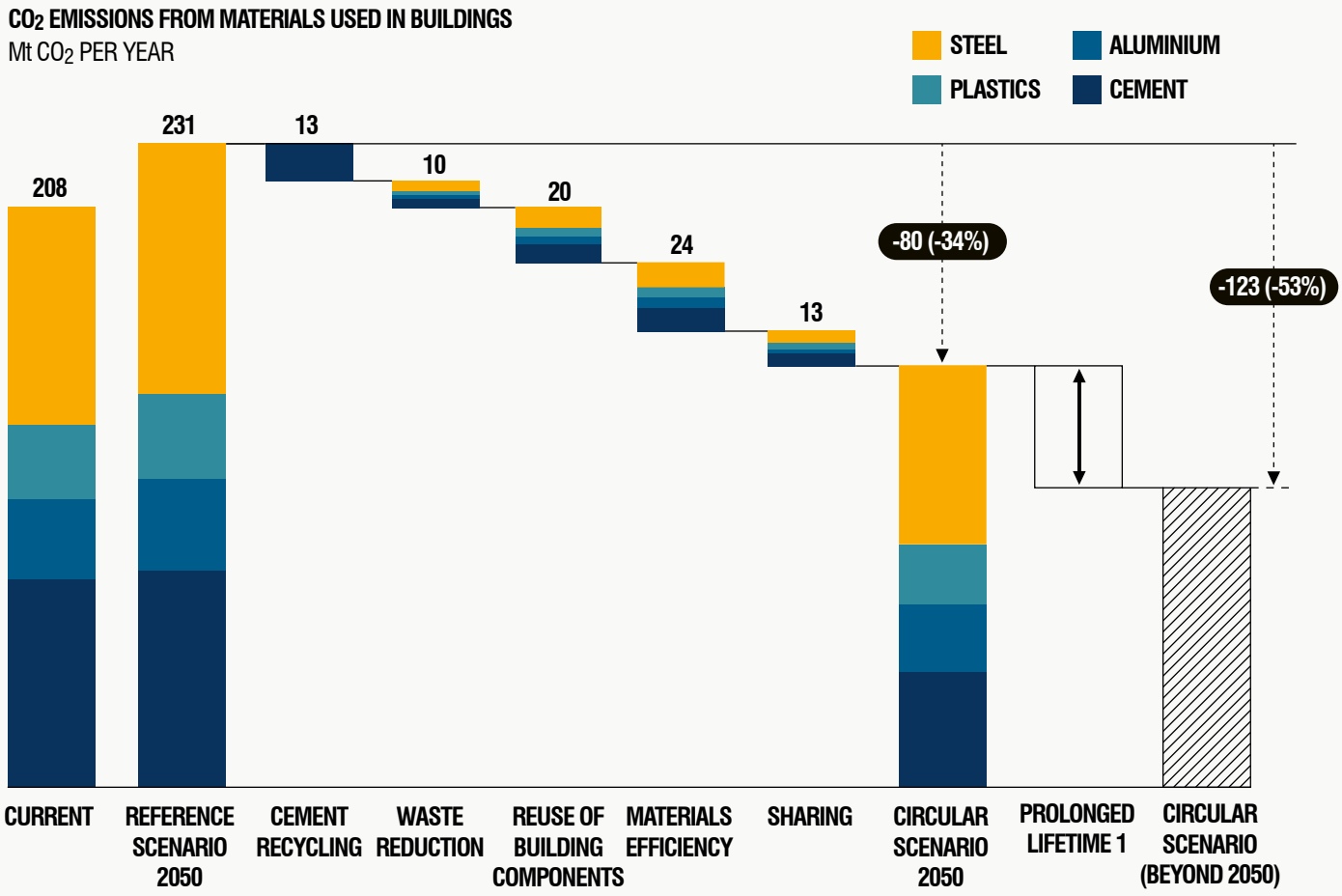
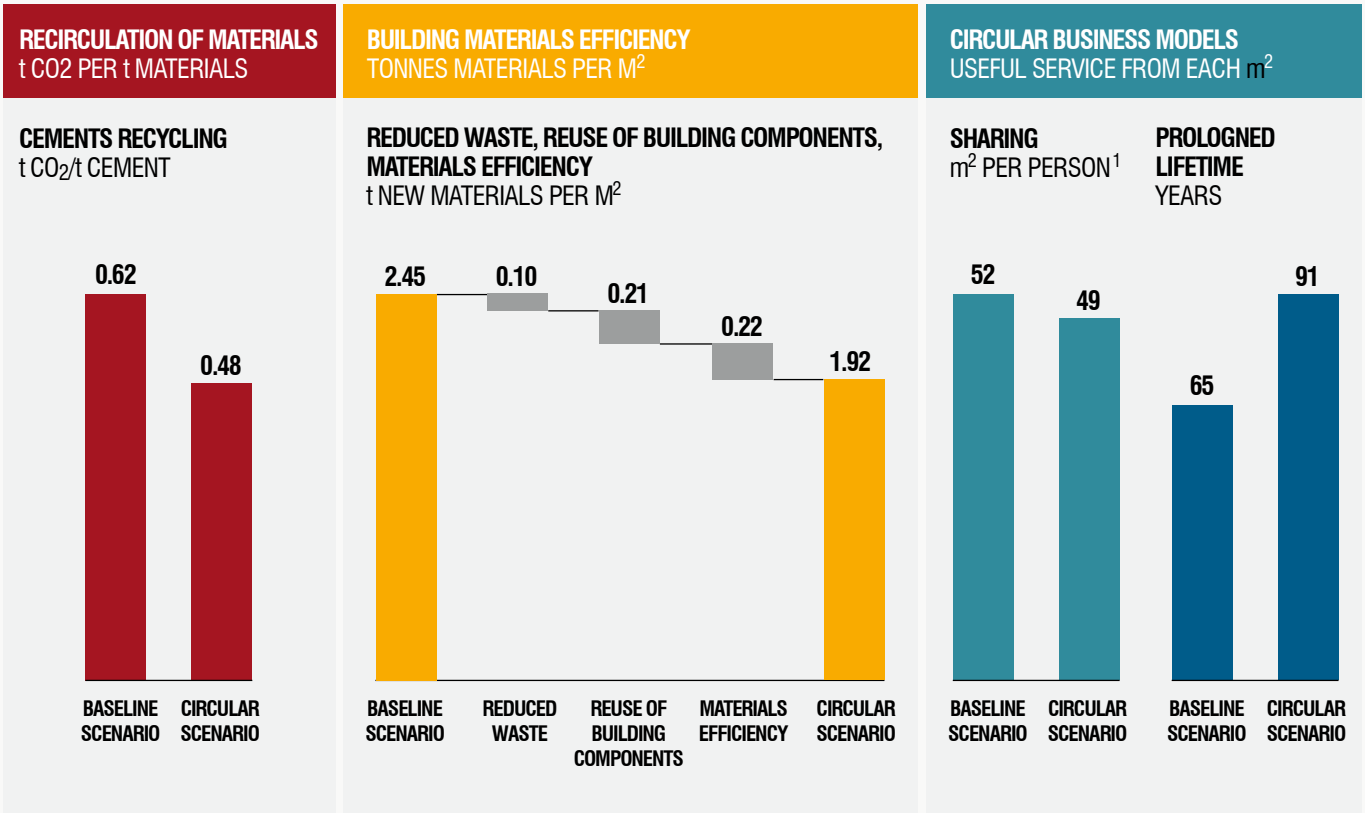


Exhibit 6.8

A CIRCULAR SCENARIO SEES IMPROVEMENT ACROSS ALL ASPECTS OF BUILDING MATERIALS USE



NOTE: 1 ACROSS ALL BULIDING TYPES EXCEPT INDUSTRIAL BUILDINGS

To achieve this, a range of changes are necessary (Exhibit 6.8.):

- **Cement recycling becomes** widespread, cutting the average CO_2-intensity of cement production by 23%, from 0.62 to 0.48 tonnes CO_2 per tonne cement.
- **The materials efficiency** strategies reduce the amount of new building materials that are required, from an average of 2.45 tonnes of materials for each square metre of building, to 1.92 tonnes. To achieve this, waste during construction is reduced to 5%, while steel and cement use falls by 20–30%, as a result of reduced over-specification and use of higher-quality materials. 15% of structural building components are reused.
- **Circular business models** enable both higher utilisation and longer lifetime. Sharing reduces floor area requirements by 5%, summed across all building categories. The average lifetime of buildings increases by 40%, through a combination of adaptive buildings and the 'build to last' principles and improved maintenance described above. Combining this, the benefit of each tonne of building material increases: for each year of service from a building, the materials input is one-third lower in the circular scenario – although as noted, the benefit of longer lifetimes takes a long time to show up in actual materials demand.

Exhibit 6.9

NEW BUSINESS MODELS AND DIGITALISATION ENABLE IMPROVEMENT ACROSS THE ENTIRE BUILDING VALUE CHAIN

FROM: CONFLICTING OBJECTIVES, LACK OF TRANSPARENCY AND ACCOUNTABILITY		TO: COLLABORATION BETWEEN ACTORS, TRANSPARENCY AND LONG TERM OBJECTIVES
• *Involvement only at early stage, limited accountability for outcomes (e.g. EOL)* • *Long term assets and frequent change of owners creates risk for higher up-front investment*	**DESIGN**	• *BIM enables information transfer and enables return on investments in circular principles (design for disassembly, durable and flexible designs)* • *Buildings designed with view to future 'material banks'*
• *Incentive to reduce construction costs through low-cost materials and fast construction* • *Constructor optimises labour cost, few incentives to reduce waste or materials use*	**CONSTRUCTION**	• *New construction techniques and digitalisation improve productivity and reduce over-specification* • *Lower trade-off with labour cost results in improved materials usage and quality*
• *Frequent shift in ownership with limited transfer of knowledge or value capture of investment* • *Ownership model with risk of lock-in effects and ineffective use of space*	**USE PHASE**	• *'Real estate as a service' enabled by digitalisation* • *Size adapted to needs* • *Digitalisation enables ongoing optimisation, e.g. of office space*
• *No documentation of materials content* • *Rapid demolition and resulting degrading of components and materials*	**EOL TREATMENT**	• *Design for disassembly enables value capture at EOL* • *BIM facilitates EOL treatment and ensure quality and usability of recovered materials and components*

The circular scenario illustrated here is intended to be ambitious, but still mostly incremental. There are significant changes in parts of the construction supply chain, but nothing that amounts to a revolution in practices (Exhibit 6.9). A common theme is to better align incentives across different phases of design, construction, occupancy and end-of-life treatment of buildings. New business models will be required in some cases, with better alignment of incentives, risk-sharing, and an emphasis on 'real estate as a service'. Some of these may require much more extensive vertical integration, with construction companies more involved in the use phase of buildings. New practices also must be able to bridge the time gap between initial decision and specification, and the ultimate effect on materials use and recovery.

DIGITALISATION OF CONSTRUCTION IS A KEY ENABLER OF CIRCULAR OPPORTUNITIES

Many of these changes are made possible by digitalisation, which could help overcome many of the barriers to improved materials use in today's system. Above all, a range of data-driven strategies enable coordination that makes economically viable arrangements that otherwise are possible only in coordinated, whole supply chain approaches. Some of the key aspects of this change are set out in Exhibit 6.10.

Data-driven strategies during construction and operation of buildings: Ubiquitous use of much more advanced Building Information Modelling (BIM) is a centrepiece of the circular scenario. BIM has the potential not just to store detailed 3D object data, but also to enable advanced control over scheduling, cost, and operations and maintenance during the use phase. This can address the transaction costs and lack of information that hold back a number of circular opportunities in buildings: cutting buildings materials waste by tightly managing the flow of construction materials; creating shared platforms or exchanges for the flow of end-of-life components for reuse and materials for recycling; enabling more advanced inventories and advanced construction techniques that are required to reduce over-specification; and serving as the repository for information required for buildings as materials banks, notably materials passports. BIM can be complemented by drones and 3D scanners to provide real-time data on the construction process.

New digital construction technologies: The other major leg of digitalisation is the automation of the construction process. Some of this consists of moving construction off-site, through pre-fabrication – in turn enabled by more advanced and customised inventory and manufacturing processes. As important, the building process itself can be automated. One major construction company summarised its vision for 2050 by saying: "The construction site of 2050 will be human-free. Robots will work in teams to build complex structures using dynamic new materials. Elements of the build will self-assemble."[45] Whether or not this vision materialises, the first forays into construction robotics are already proving capable of performing some tasks faster than unaided human labour,[46] and it is clear that the trade-off with labour cost that now underlies much materials overuse, over-specification, and risk aversion can be mitigated to a very large extent through automation. Add to this construction techniques such as 3D printing and self-assembling. 3D printing already is in advanced development, with the Chinese company WinSun 3D using the technology at large scale.[47] Finally, automation also has significant promise for disassembly of buildings in ways that avoid the destructive practices of today's demolition.

Exhibit 6.10

DIGITALISATION IS A KEY ENABLER OF CIRCULAR OPPORTUNITIES IN BUILDINGS

BUILDING INFORMATION MANAGEMENT

BUILDING INFORMATION MODELLING (BIM)
- *Platform for integrated design, modelling, planning and collaboration*
- *Reduces cost and saves construction time*
- *Facilitates re-use and recycling of EOL materials*

DRONES AND 3D SCANNERS
- *Can be used for construction site inspections*
- *Reduces labour costs and time*
- *Improves safety for workers*

NEW DIGITAL TECHNOLOGIES IN CONSTRUCTION

AUTOMATION AND PREFABRICATION
- *Improves quality and precision*
- *Reduces labour cost, delivery time and waste in construction*

ROBOTICS IN CONSTRUCTION
- *Enables complex tasks with human monitoring*
- *Improves quality and precision*
- *Reduces labour cost and delivery time and improves safety*

3D PRINTING
- *Enables construction of complex shapes*
- *Reduces construction time and cost of customised components*
- *Reduces waste in construction due to better precision*

6.4 HOW TO GET THERE – ACTIONS TO PROMOTE A MORE CIRCULAR BUILDINGS SECTOR

Regulators intervene heavily in the buildings sector, but to date have paid little attention to the efficient use of materials. Strategies used to promote energy efficiency may be helpful here. For example, it might be possible to introduce labelling schemes similar to those used for energy performance for aspects related to materials uses – such as the amount of reused content, measures of the degree of over-specification, or adherence to design principles conducive to high-value disassembly.

Regulations also have a major role in the end-of-life treatment of buildings. To date the focus has been primarily on the safe disposal of construction and demolition waste. To realise the circular opportunities described here, it would be necessary to enable a range of other practices. One example is the introduction of materials passports, which exist in detail in some EU countries but not in others.

A third area where regulation can play a role is in promoting the emergence of coordination and integration mechanisms that currently are lacking to enable circular business models. This could include exchange platforms for building materials, or standards for reused components.

Finally, the public sector has major roles both as a customer of building and infrastructure projects, and as a principal actor through its influence on city planning. These are key areas to start for the transformation required to give buildings longer lifetimes, through greater durability and adaptability. A bold first step would be to articulate a vision and roadmap at the city level towards much more long-lived structures within a continuously developing urban landscape.

For industry, many of the practices described in this study would require changes to business practices – but often more in the nature of integration and extension of current practice than any radical new departure. As European construction seeks a path towards greater productivity, a step change in digitalisation, and more sustainable construction, circular economy opportunities are a central component. The pioneers of these business models and practices could well find the innovations a source of competitive advantage.

As European construction *seeks a path towards greater productivity, a step change in digitalisation, and more sustainable construction, circular economy opportunities are a central component.*

ENDNOTES

CHAPTER 1.

[1] This includes both direct emissions and the emissions from the production of electricity used by industry (International Energy Agency, 2017). Direct emissions are closer to 30% (IPCC, 2014).

International Energy Agency (2017). Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations. International Energy Agency, Paris.

Intergovernmental Panel on Climate Change (2014). Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the IPCC 5th Assessment Report: Technical Summary.

[2] Pauliuk, S., Wang, T. and Müller, D. B. (2013). Steel all over the world: Estimating in-use stocks of iron for 200 countries. Resources, Conservation and Recycling, 71. 22–30. DOI:10.1016/j.resconrec.2012.11.008.

[3]The remaining 25% includes some additional materials (such as lime, other non-ferrous metals, ceramics, and glass), but also manufacturing and chemicals production.

[4] See subsequent chapters for discussion and comparison with other scenarios. In overview, the steel scenario assumes somewhat higher growth than other long-range scenarios, which tend to assume that steel stocks will only saturate much later, into the 22nd century. For cement, the scenario is in the middle of ranges for other scenarios, but somewhat higher than what is used in many 'integrated assessment models' to study low-carbon economic pathways. For aluminium, views diverge widely, but the saturation assumption is again close to the middle of other assumptions in the literature. Finally, much less long-range work has been done on plastics, but the assumption results in similar growth of plastics production as in industry and consultant forecasts for the next decades.

[5] European Commission (2015). The Paris Protocol – A blueprint for tackling global climate change beyond 2020. Climate Action - European Commission. https://ec.europa.eu/clima/policies/international/negotiations/paris_en.

[6] This is complicated by the fact that most scenarios assume substantial amounts of 'negative emissions' that can offset some of the remaining emissions. However, the 250–300 Gt budget share refers to actual emissions from industry, even accounting for the fact that large amounts of negative emissions are assumed to be available. Specifically, around 400 Gt CO_2 is available for all of industry, but at least 100 Gt must be devoted to other industrial activity – from manufacturing to chemicals, pulp & paper, and other uses.

[7] Intergovernmental Panel on Climate Change, IPCC (2014). IAMC AR5 Scenario Database. https://secure.iiasa.ac.at/web-apps/ene/AR5DB/.

[8] Specifically, this assumes zero emissions from all thermal energy in cement production is zero-carbon as well as the electricity inputs to aluminium smelting steel electric arc furnaces. For plastics, the addition of external zero-carbon heat can reduce production emissions by around half. Finally, for primary steel production, zero-carbon energy does little, but the scenario posits that production is converted to the lowest-emitting current process proven at scale, which is the direct reduction of iron ore using natural gas.

[9] The carbon budget for materials production is based on the average of available scenarios in the IPCC AR5 database (Intergovernmental Panel on Climate Change, 2014), adjusted for the needs of other industrial activity. The overall carbon budget is based on Mercator Research Institute on Global Commons and Climate Change, 'Remaining Carbon Budget' (2018), which gives a remaining budget of 705 billion tonnes of CO_2 (range of 335-885) for a 2 °C scenario. Adjusting for CO_2 emissions data for recent years from Global Carbon Project (2017), 'Global Carbon Budget 2017', this corresponds to a budget around 800 billion tonnes for the period 2015-2100. CO_2 emissions from materials production are based on the gradual adoption of current 'best available technique' as described in subsequent chapters of the report, but no other decarbonisation. The low-carbon production scenario sees the gradual elimination of energy emissions from cement, half of emissions from steel (e.g. through natural-gas direct reduction or the use of biomass feedstock), decarbonisation of electricity as an input to aluminium production, and use of renewable energy to produce plastics, but not a switch to bio-feedstock.

Intergovernmental Panel on Climate Change, IPCC (2014). IAMC AR5 Scenario Database.

Mercator Research Institute on Global Commons and Climate Change (2018). Remaining carbon budget. https://www.mcc-berlin.net/en/research/co2-budget.html.

Global Carbon Project (2017). Global Carbon Budget 2017. 60.

[10] Plastics emissions include emissions from production (representing 50% of emissions in the best available technique (BAT) scenario and 36% in the zero carbon scenario), incineration and landfill.

[11] International Energy Agency (2016). 20 Years of Carbon Capture and Storage - Accelerating Future Deployment.

[12] In China, the cement and steel industry jointly account for more than half of the particulate matter pollution (Lei et al., 2011; Wang et al. 2016).
Lei, Y., Zhang, Q., Nielsen, C. and He, K. (2011). An inventory of primary air pollutants and CO_2 emissions from cement production in China, 1990–2020. Atmospheric Environment, 45(1). 147–54. DOI:10.1016/j.atmosenv.2010.09.034.
Wang, K., Tian, H., Hua, S., Zhu, C., Gao, J., Xue, Y., Hao, J., Wang, Y. and Zhou, J. (2016). A comprehensive emission inventory of multiple air pollutants from iron and steel industry in China: Temporal trends and spatial variation characteristics. Science of The Total Environment, 559. 7–14. DOI:10.1016/j.scitotenv.2016.03.125.

[13] European Commission (2011). Energy Roadmap 2050 Impact Assessment and Scenario Analysis. SEC(2011) 1565 final. https://ec.europa.eu/energy/sites/ener/files/documents/roadmap2050_ia_20120430_en_0.pdf.

[14] The European Steel Association (2013). A Steel Roadmap for a Low Carbon Europe 2050.

The European Cement Association (2013). The Role of Cement in the 2050 Low Carbon Economy. http://lowcarboneconomy.cembureau.eu/.
CEFIC (2013). European Chemistry for Growth: Unlocking a Competitive, Low Carbon and Energy Efficient Future. http://www.cefic.org/Industry-support/.

[15] This includes the emissions from the generation of electricity used by these sectors.

[16] The calculation accounts for a number of ways in which different circular economy opportunities interact. For example, a higher share of steel recycling reduces the CO_2 intensity of steel production, which in turn reduces the savings that are availble from reduced steel use in products. We account for this in the cost curve by showing the potential available for each measure (each 'bar' in the cost curve) available when all other measures are also implemented. If calculated in isolation, most measures would have larger potential.

[17] The CO_2 intensity of aluminium varies strongly with the source of electricity used. Coal-based production in China and some other parts of Asia results in a CO_2 intensity of 18 t CO_2 per tonne aluminium, whereas gas-based electricity in the Middle East is closer to 7-8 tCO_2 / tonne aluminium. Aluminium produced from clean electricity (such as Icelandic geothermal or Norwegian hydropower) can reach CO_2 emissions as low as 2 t CO_2 per tonne aluminium. Unlike the other materials discussed here, aluminium therefore has potential to address the large majority of the CO_2 emissions through the use of renewable energy (Hydro, 2017).

Hydro (2017). Capital Markets Day 2017. https://www.hydro.com/en/investor-relations/presentations/capital-markets-days/.

[18] IVA, S. B. (2014). Klimatpåverkan från byggprocessen. http://www.iva.se/publicerat/.

[19] Moynihan, M. C. and Allwood, J. M. (2014). Utilization of structural steel in buildings. Proceedings. Mathematical, Physical, and Engineering Sciences / The Royal Society, 470(2168). DOI:10.1098/rspa.2014.0170.

[20] Another major opportunity is to substitute construction materials, a topic not covered in this report. The use of cross-laminated timber has been proposed as an option to reduce the use of cement and steel in the construction of buildings, potentially with a large negative impact of CO_2 both from avoided emissions in materials production, and from an effective CO_2 sink within the wood (Kuilen et al., 2011)
Kuilen, J. W. G. V. D., Ceccotti, A., Xia, Z. and He, M. (2011). Very Tall Wooden Buildings with Cross Laminated Timber. Procedia Engineering, 14. 1621–28. DOI:10.1016/j.proeng.2011.07.204.

CHAPTER 2.

[1] World Steel Association (2014). Steel Solutions in the Green Economy. https://www.worldsteel.org/en/dam/jcr:a3776cb0-7b75-4de7-810a-dcab78122464/PDF%253A+Affordable+social+housing.pdf.

[2] Pauliuk, S., Wang, T. and Müller, D. B. (2013). Steel all over the world: Estimating in-use stocks of iron for 200 countries. Resources, Conservation and Recycling, 71. 22–30. DOI:10.1016/j.resconrec.2012.11.008.

[3] Pauliuk et al. (2013). Steel all over the world.
Graedel, T. E. (2010). Metal Stocks in Society: Scientific Synthesis. UNEP, Nairobi.
Pauliuk, S., Wang, T. and Müller, D. B. (2012). Moving Toward the Circular Economy: The Role of Stocks in the Chinese Steel Cycle. Environmental Science & Technology, 46(1). 148–54. DOI:10.1021/es201904c.

[4] The methodology used here builds on the excellent and foundational work described in Pauliuk, Milford, et al. (2013), Milford et al. (2013), and Daehn et al. (2017), which has been crucial to developing the estimates and insights presented here. The scenarios and assumptions we use differ in some respects, especially in relating future steel demand more closely to recent projected GDP developments. However, the implementation of a stock-driven model of future demand as well as the foundational data are the same.

Pauliuk, S., Milford, R. L., Müller, D. B. and Allwood, J. M. (2013). The Steel Scrap Age. Environmental Science & Technology, 47(7). 3448–54. DOI:10.1021/es303149z.

Milford, R. L., Pauliuk, S., Allwood, J. M. and Müller, D. B. (2013). The Roles of Energy and Material Efficiency in Meeting Steel Industry CO2 Targets. Environmental Science & Technology, 47(7). 3455–62. DOI:10.1021/es3031424.

Daehn, K. E., Cabrera Serrenho, A. and Allwood, J. M. (2017). How Will Copper Contamination Constrain Future Global Steel Recycling? Environmental Science & Technology, 51(11). 6599–6606. DOI:10.1021/acs.est.7b00997.

[5] Pauliuk et al. (2013). The Steel Scrap Age.

[6] United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision. ST/ESA/SER.A/399. https://esa.un.org/unpd/wpp/.

[7] Specifically, saturation takes place once regions reach a GDP (purchasing power parity) of 40,000 USD per capita, as per the forecasts used in the Shared Socioeconomic Pathway 2 'Middle of the Road' (Fricko et al. 2017). This is significantly more accelerated than in the original article by Pauliuk, Milford, et al. (2013), and accounts for some of the differences in the results.

Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., et al. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change, 42. 251–67. DOI:10.1016/j.gloenvcha.2016.06.004.
Pauliuk et al. (2013). The Steel Scrap Age.

[8] Pauliuk et al. (2013). Steel all over the world.

[9] World Steel Association (2017). Steel Statistical Yearbook 2017. Brussels/Beijing. https://www.worldsteel.org/en/dam/jcr:3e275c73-6f11-4e7f-a5d8-23d9bc5c508f/Steel+Statistical+Yearbook+2017.pdf.

Bureau of International Recycling (2017). World steel recycling in figures 2012-2013, Steel Scrap - a Raw Material for Steelmaking.
[10] Total steel demand; Material Economics projection, builds on Pauliuk (2013) but with other assumptions for saturation.

Pauliuk et al. (2013). The Steel Scrap Age.

McKinsey (2018). Decarbonizing Steel. Workshop Document.

Global Calculator (2015). Global Calculator Technical Documentation: Manufacturing Sector. http://uncached-site.globalcalculator.org/sites/default/files/Manufacturing%20technical%20documentation%20part%202.pdf.

Pauliuk et al. (2013). The Steel Scrap Age.

van Ruijven, B. J., van Vuuren, D. P., Boskaljon, W., Neelis, M. L., Saygin, D. and Patel, M. K. (2016). Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries. Resources, Conservation and Recycling, 112. 15–36. DOI:10.1016/j.resconrec.2016.04.016.
International Energy Agency (2017). Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations. International Energy Agency, Paris.

Xylia, M., Silveira, S., Duerinck, J. and Meinke-Hubeny, F. (2017). Weighing regional scrap availability in global pathways for steel production processes. Energy Efficiency, . 1–25. DOI:10.1007/s12053-017-9583-7.

Allwood, J. M., Cullen, J. M., Carruth, M. A., Cooper, D. R., McBrien, M., Milford, R. L., Moynihan, M. C. and Patel, A. C. (2012). Sustainable Materials: With Both Eyes Open. UIT Cambridge Ltd.

[11] World Steel Association (2017). Steel Statistical Yearbook 2017.

[12] In estimates presented here we include direct emissions at steel plants, as well as indirect emissions from the production of the electricity used. We do not attempt to account for full life-cycle emissions (which would include items such as the mining of ore and transportation of raw materials). The emissions factors used build on the detailed discussion in Milford et al. (2013).

Milford et al. (2013). The Roles of Energy.

[13] Increased process efficiency: The BOF route is already highly optimised and efficient. Current estimates suggest that the amount of additional efficiency potential through use of the best available technologies is on the order of 15% (Milford et al. 2013). Direct reduced iron: DRI cuts emissions by almost 50%, with estimates of emissions intensity ranging between 1.1-1.3 tCO_2 per tonne steel. (International Energy Agency 2017; Milford et al. 2013; Birat and Maizières-lès-Metz 2010). Bio-based inputs: Bio-derived raw materials are used in some countries, such as Brazil, where local conditions are favourable. Emissions reductions can be around 50% (Mathieson et al. 2011). Carbon capture and storage: capturing the CO_2 from the blast furnace of an integrated steel plant can reduce overall emissions by 60% (Rootzén 2015; Birat and Maizières-lès-Metz 2010). To date, only one such facility is operational, but the technology features heavily in long-range roadmaps for the reduction of CO_2 emissions from steelmaking. Fundamental process innovation: One proposed route is to use pure hydrogen instead of coal or natural gas to produce DRI. This is now under active research, but has not been achieved at scale. Electrolysis offers a much more speculative, long-term option (Milford et al. 2013) If these can be achieved, they offer the advantage that, like EAF production, they could use low-carbon electricity as the key energy input.

Milford et al. (2013). The Roles of Energy.

International Energy Agency (2017). Energy Technology Perspectives 2017.

Birat, J. P. and Maizières-lès-Metz, D. (2010). Global Technology Roadmap for CCS in Industry - Steel Sectoral Report. UNIDO and ArcelorMittal. https://hub.globalccsinstitute.com/sites/default/files/publications/15671/global-technology-roadmap-ccs-industry-steel-sectoral-report.pdf.

Mathieson, J., Rogers, H., Somerville, M., Ridgeway, P. and Jahanshahi, S. (2011). Use of biomass in the iron and steel industry - An Australian perspective. 1st International Conference on Energy Efficiency and CO2 Reduction in the Steel Industry (EECR Steel 2011) - incorporated in METEC InSteelCon 2011 10p. , Dusseldorf, Germany. The Steel Institute VDEh.

Rootzén, J. (2015). Pathways to Deep Decarbonisation of Carbon-Intensive Industry in the European Union: Techno-Economic Assessments of Key Technologies and Measures. Doktorsavhandlingar vid Chalmers Tekniska Högskola. Chalmers University of Technology, Göteborg.

[14] This would require a combination of replacement of BOF-based capacity with DRI, or the retrofitting of CCS, or the large-scale use of bioenergy. In addition, in this scenario, we also assume that CO_2 emissions from electricity production are eliminated by 2050, reducing the emissions intensity of EAF production.

[15] Willeke, R. (2017). EU-28 Steel scrap statistics. https://www.euric-aisbl.eu/facts-figures/statistics/download/231/63/32.

[16] Pauliuk et al. (2013). Steel all over the world.

World Steel Association (2009). The Three Rs of Sustainable Steel. Brussels/Beijing.

[17] Jernkontoret Research (2013). The Steel Eco-Cycle - Environmental Research Programme. Closing the Loop in the Manufacture and Use of Steel in Society. Scientific Report 2004-2012. http://www.jernkontoret.se/en/publications/steel-research/open-reports-serie-d/d-853/.

[18] World Steel Association (2009). The Three Rs.

[19] Allwood et al. (2012). Sustainable Materials.

[20] Cullen, J. M., Allwood, J. M. and Bambach, M. D. (2012). Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. Environmental Science & Technology, 46(24). 13048–55. DOI:10.1021/es302433p.

[21] Price, D. (2009). Yield improvement in the steel industry. Ironmaking & Steelmaking; London, 36(7). 482–86.
Pauliuk et al. (2013). The Steel Scrap Age.

[22] Reck, B. K. and Graedel, T. E. (2012). Challenges in Metal Recycling. Science, 337(6095). 690–95. DOI:10.1126/science.1217501.

[23] Ohno, H., Matsubae, K., Nakajima, K., Nakamura, S. and Nagasaka, T. (2014). Unintentional Flow of Alloying Elements in Steel during Recycling of End-of-Life Vehicles. Journal of Industrial Ecology, 18(2). 242–53. DOI:10.1111/jiec.12095.

[24] Daehn et al. (2017). How Will Copper Contamination Constrain.

[25] Björkman, B. and Samuelsson, C. (2014). Chapter 6 - Recycling of Steel. In Handbook of Recycling. Elsevier, Boston. 65–83. DOI:10.1016/B978-0-12-396459-5.00006-4.

[26] We focus on copper here, as the most significant constraint on steel recycling. However, there also are other tramp elements, such as tin and nickel, that can cause analogous problems. The solutions in many cases must be similar to those discussed in relation to copper. See e.g. Ohno et al. (2014).

Ohno, H., Matsubae, K., Nakajima, K., Nakamura, S. and Nagasaka, T. (2014). Unintentional Flow of Alloying Elements in Steel during Recycling of End-of-Life Vehicles. Journal of Industrial Ecology, 18(2). 242–53. DOI:10.1111/jiec.12095.

[27] Haupt, M., Vadenbo, C., Zeltner, C. and Hellweg, S. (2017). Influence of Input-Scrap Quality on the Environmental Impact of Secondary Steel Production. Journal of Industrial Ecology, 21(2). 391–401. DOI:10.1111/jiec.12439.

[28] Global product mix: Material Economics modelling. Copper limits: Daehn et al. (2017).

Daehn et al. (2017). How Will Copper Contamination Constrain – Supplementary Information.

[29] In addition, some steel alloys contain copper for corrosion resistance.

[30] Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., Tasaki, T. and Nagasaka, T. (2012). Quality- and Dilution Losses in the Recycling of Ferrous Materials from End-of-Life Passenger Cars: Input-Output Analysis under Explicit Consideration of Scrap Quality. Environmental Science & Technology, 46(17). 9266–73. DOI:10.1021/es3013529.

[31] OECD (2015). Excess Capacity in the Global Steel Industry and the Implications of New Investment Projects. OECD Science, Technology and Industry Policy Papers, (18). DOI:10.1787/5js65x46nxhj-en.

[32] World Steel Association (2017). Steel Statistical Yearbook 2017.

[33] Global emissions are a different matter. If the EU were instead to export large volumes of scrap, emissions within the EU would increase, but emissions elsewhere could fall, as less primary production would be required there.

[34] Azevedo, J. M. C., CabreraSerrenho, A. and Allwood, J. M. (2018). Energy and material efficiency of steel powder metallurgy. Powder Technology, 328. 329–36. DOI:10.1016/j.powtec.2018.01.009.

[35] Haupt et al. (2017). Influence of Input-Scrap Quality.

[36] Direct strip casting is one method: the steel is cast in a protected atmosphere, which combines short oxidation time with rapid cooling and direct rolling. This poses a suitable alternative for products that do not contain high levels of copper during their useful life.

[37] Nakajima, K., Takeda, O., Miki, T., Matsubae, K. and Nagasaka, T. (2011). Thermodynamic Analysis for the Controllability of Elements in the Recycling Process of Metals. Environmental Science & Technology, 45(11). 4929–36. DOI:10.1021/es104231n.

[38] Daehn et al. (2017). How Will Copper Contamination Constrain.

CHAPTER 3.

[1] Each tonne of plastics uses c. 1.1 tonnes of oil (Levi and Cullen, 2018), which means 903 million tonnes of oil would be needed for plastics production in 2050. 2050 oil consumption in the International Energy Agency's (2017) 2 °C scenario is just over 3900 million tonnes. In addition, producing this volume of plastics would require large volumes of natural gas.

Levi, P. G. and Cullen, J. M. (2018). Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products. Environmental Science & Technology, 52(4). 1725–34. DOI:10.1021/acs.est.7b04573.

International Energy Agency (2017). Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations. International Energy Agency, Paris.

[2] Geyer, R., Jambeck, J. R. and Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7). e1700782. DOI:10.1126/sci-adv.1700782.

3 Haward, M. (2018). Plastic pollution of the world's seas and oceans as a contemporary challenge in ocean governance. Nature Communications, 9(1). 667. DOI:10.1038/s41467-018-03104-3.

[4] However, microplastics and plastics in the ocean are a broader problem that also depend on plastic products in fishing industries, microplastics added to cosmetics and consumer products, plastic fibres in textiles and wear on tires (Boucher and Friot, 2017).
Boucher, J. and Friot, D. (2017). Primary Microplastics in the Oceans: A Global Evaluation of Sources. IUCN International Union for Conservation of Nature. DOI:10.2305/IUCN.CH.2017.01.en.

[5] Emissions differ by plastics type, from 1.6 tonnes CO_2 per tonne plastic for polypropylene, 1.8 for polyethylene, 1.99 for PVC, 2.15 for PET, 3.3 for polystyrene, and 4.8 for a weighted average of the remaining mix of plastics in use (Deloitte and Plastics Recyclers Europe, 2015; Plastics Europe, 2018a). These numbers include the indirect emissions from electricity, as well as the production of precursors such as chlorine.
Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment. http://www.plas-ticsrecyclers.eu/sites/default/files/BIO_Deloitte_PRE_Plastics%20Recycling%20Impact_Assesment_Final%20Report.pdf.
Plastics Europe (2018a). Eco-profiles. http://www.plasticseurope.org/plastics-sustainability-14017/eco-profiles.aspx.

[6] This on the assumption that a net-zero 2050 position would involve some residual emissions, offset by 'negative emissions' from a variety of sources, such as CO_2 sinks.

[7] Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets.

[8] Plastics Europe (2018a). Eco-profiles.

Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets.

Zhu, J.-B., Watson, E. M., Tang, J. and Chen, E. Y.-X. (2018). A synthetic polymer system with repeatable chemical recyclability. Science, 360(6387). 398–403. DOI:10.1126/science.aar5498.

[9] PE (29%); PP (19%); PVC (10%); PS (7%); PET (7%).

[10] Plastics Europe (2018b). Plastics - the Facts 2016. Plastics Europe. http://www.plasticseurope.org/Document/plastics---the-facts-2016-15787.aspx?FolID=2.

[11] European Commission (2018). A European Strategy for Plastics in a Circular Economy. http://ec.europa.eu/environment/circular-economy/pdf/plastics-strategy.pdf.

[12] Material Economics (2018). Ett Värdebeständigt Svenskt Materialsystem. http://resource-sip.se/content/uploads/2018/01/vardebestmtrlsystemrapport180118.pdf.

[13] Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets.

[14] Plastics Europe (2018b). Plastics - the Facts 2016.

Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets.

[15] Ellen MacArthur Foundation (2016). The New Plastics Economy: Rethinking the future of plastics & Catalysing action. https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics-catalysing-action.

[16] Ellen MacArthur Foundation (2016). The New Plastics Economy.

[17] Also, Europe has long sent almost half of it to China as a lower-cost alternative, which has discouraged investment in European recycling capacity. This is now changing dramatically, as China has recently restricted plastic waste imports, setting higher quality and purity requirements.

[18] Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets.

Plastics Europe (2018b). Plastics - the Facts 2016.

[19] Other assessments have come to a similar conclusion, notably Ellen MacArthur Foundation (2017).
Ellen MacArthur Foundation (2017). The New Plastics Economy - Catalysing Action. Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/assets/downloads/New-Plastics-Economy_Catalysing-Action_13-1-17.pdf.

[20] Bazzanella, A. M. and Ausfelder, F. (2017). Low Carbon Energy and Feedstock for the European Chemical Industry. DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V. https://dechema.de/dechema_media/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf.

CHAPTER 4.

[1] Aluminium use patterns are more complex and show more variation than for example steel. For example, the United States has an aluminium stock of about 600 kg per person, while that in European countries varies between 200–500 kg per person (Liu and Müller, 2013). The stock data used for the analysis here is aggregated for regions as given in (World Aluminium, 2018a) and described in (Bertram et al., 2017). These data show that stocks have grown steadily in countries at all levels of development, although recently, its growth has slowed in Japan and North America. Expert interviews also indicate that stocks are saturating in some sectors also in Europe, notably in buildings.

Liu, G. and Müller, D. B. (2013). Centennial Evolution of Aluminum In-Use Stocks on Our Aluminized Planet. Environmental Science & Technology, 47(9). 4882–88. DOI:10.1021/es305108p.

World Aluminium (2018a). Mass Flow Statistics. http://www.world-aluminium.org/statistics/massflow/.

Bertram, M., Ramkumar, S., Rechberger, H., Rombach, G., Bayliss, C., Martchek, K. J., Müller, D. B. and Liu, G. (2017). A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products. Resources, Conservation and Recycling, (125). 48–69. DOI:10.1016/j.resconrec.2017.05.014.

[2] Liu, G., Bangs, C. E. and Müller, D. B. (2013). Stock dynamics and emission pathways of the global aluminium cycle. Nature Climate Change, 3(4). 338–42. DOI:10.1038/nclimate1698.

[3] United Nations, Department of Economic and Social Affairs, Population Division (2017). World Population Prospects: The 2017 Revision. ST/ESA/SER.A/399. https://esa.un.org/unpd/wpp/.

[4] Bertram et al. (2017). A regionally-linked.

[5] Liu and Müller (2013). Centennial Evolution.

[6] World Aluminium (2018a). Mass Flow Statistics.

[7] Note that this refers to European demand, not European production. Published data by World Aluminium (2018a) gives total input to fabrication as more than 16 million tonnes in 2016. However, this appears to be an anomalous number, with a much lower number of 13.8 million tonnes stated for 2015, and 13.4 for 2017.

World Aluminium (2018a). Mass Flow Statistics.

[8] The shape of future demand is very uncertain, of course. There is a strong logic behind the notion that stocks in the EU will saturate, but it is much less clear at what level, and when. For illustration, if stock build-up were to accelerate instead, and reach 600 kg per person by 2050, some 20 million tonnes per year of production would be needed to meet EU demand. However, as discuss in Section 4.4, the saturation level is not critical to the main findings of our analysis. The higher the overall demand, the more important it is to pursue the circularity measures presented in this chapter.

[9] Europe exported 5.6 million cars in in 2017 (ACEA - European Automobile Manufacturers' Association, 2017), with an average aluminium content of around 140 kg per car.

ACEA - European Automobile Manufacturers' Association (2017). Economic and Market Report Q4 2017. http://www.acea.be/statistics/article/economic-and-market-report-key-takeaways-about-the-eu-auto-industry-for-17.

[10] Based on data from International Energy Agency (2017).

International Energy Agency (2017). Energy Technology Perspectives 2017: Catalysing Energy Technology Transformations. International Energy Agency, Paris.

[11] World Aluminium (2018d). Primary Aluminium Smelting Power Consumption. http://www.world-aluminium.org/statistics/primary-aluminium-smelting-power-consumption/.

[12] According to World Aluminium (2018d), 88% of European production uses non-fossil sources of electricity.
World Aluminium (2018d). Primary Aluminium.

[13] Emissions are calculated from data in World Aluminium Association (2018a, 2018b, 2018c, 2018d) and the International Energy Agency (2017). Emissions from anodes are estimated based on expert interviews.

World Aluminium (2018a). Mass Flow Statistics.

World Aluminium (2018b). Metallurgical Alumina Refining Fuel Consumption. http://www.world-aluminium.org/statistics/metallurgical-alumina-refining-fuel-consumption/.

World Aluminium (2018c). Perfluorocarbon (PFC) Emissions. http://www.world-aluminium.org/statistics/perfluorocarbon-pfc-emissions/.
World Aluminium (2018d). Primary Aluminium.

International Energy Agency (2017). Energy Technology Perspectives 2017.

[14] The International Energy Agency (2017) estimates that direct emissions from aluminium production were 261 Mt CO_2 in 2014 and electricity consumption of 926 TWh, with associated emissions of 542 Mt CO_2, which gives total emissions of 803 Mt CO_2. For comparison, World Aluminium (2018d), which gives electricity consumption as 844 TWh for 2016 for smelting. The two sources give a range of emissions (including perflourocarbons as well as CO_2) of 12.5-15 t CO_2 per tonne aluminium.

International Energy Agency (2017). Energy Technology Perspectives 2017.

World Aluminium (2018d). Primary Aluminium.

[15] Strictly speaking this is greenhouse gases measured in 'carbon dioxide equivalents' rather than just carbon dioxide. This distinction arises because a small but not insignificant share of emissions come from perflourocarbons, a very potent greenhouse gases that is produced in small quantities during aluminium smelting. In the following, the shorthand 'CO_2' is used for the sake of brevity and familiarity.

[16] The baseline scenario sees a gradual decarbonisation of all energy use in alumina refining and aluminium smelting, complete by 2100. The 'reference' scenario instead follows the decarbonisation in the International Energy Agency's (2017) 'Reference Technology Scenario'. Note that the 'reference' scenario is only shown to illustrate the impact of a slow energy transition on emissions; it is not used for any evaluation of the benefits of greater circularity described in this report. Specifically, the reference scenario sees the electricity input to the 70% share of aluminium production now powered by fossil fuels following the trajectory of Asian electricity generation in the International Energy Agency's (2017) 'Reference Technology Scenario'. This translates into a 60% reduction in emissions intensity of the current fossil share. After 2060, the emissions intensity is kept constant.
International Energy Agency (2017). Energy Technology Perspectives 2017.

[17] There are also ongoing efforts to reduce other emissions. Improving the smelting production process could reduce energy demand somewhat, but there are technical limits; even a 10–15% reduction would be a major achievement. Perflourocarbon (PFC) emissions have already fallen dramatically already but could be reduced further (World Aluminium, 2018b). Emissions from alumina refining could in principle be addressed by using zero-carbon energy inputs, although this is not done today. Fully eliminating direct emissions from smelting, on the other hand, would require a process breakthrough. One potential route for this was announced by Elysis Technologies in 2018 (Alcoa, 2018).

World Aluminium (2018c). Perfluorocarbon (PFC) Emissions.

Alcoa (2018). Alcoa and Rio Tinto Announce World's First Carbon-Free Aluminum Smelting Process. http://news.alcoa.com/press-release/alcoa-and-rio-tinto-announce-worlds-first-carbon-free-aluminum-smelting-process

[18] The figure of 77% is based on the rates reported in Bertram et al. (2017). Ciacci et al. (2013) gives a similar number for Italy, while European Aluminium (2017) states that more than 90% of end-of-life scrap from buildings and automotive sectors is collected in Europe. However, all estimates are highly uncertain, and some estimates differ. For example, Ciacci et al. (2013) find lower rates in the United States.

Bertram et al. (2017). A regionally-linked, dynamic material flow modelling tool.

Ciacci, L., Chen, W., Passarini, F., Eckelman, M., Vassura, I. and Morselli, L. (2013). Historical evolution of anthropogenic aluminum stocks and flows in Italy.

Resources, Conservation and Recycling, 72. 1–8. DOI:10.1016/j.resconrec.2012.12.004.

European Aluminium (2017). 2015 Sustainability Highlights. https://www.european-aluminium.eu/media/1836/20170323-sustainability-performance-report.pdf.

[19] Cullen, J. M. and Allwood, J. M. (2013). Mapping the Global Flow of Aluminum: From Liquid Aluminum to End-Use Goods. Environmental Science & Technology, 47(7). 3057–64. DOI:10.1021/es304256s.

[20] Liu et al. (2013) gives a collection rate of 98%.

Liu et al. (2013). Stock dynamics.

[21] Bertram et al. (2017) gives rates used in this study.

Bertram et al. (2017). A regionally-linked.

[22] Cullen and Allwood. (2013). Mapping the Global Flow of Aluminum.

[23] Nakajima, K., Takeda, O., Miki, T., Matsubae, K. and Nagasaka, T. (2011). Thermodynamic Analysis for the Controllability of Elements in the Recycling Process of Metals. Environmental Science & Technology, 45(11). 4929–36. DOI:10.1021/es104231n.(Nakajima et al. 2011)

[24] Müller, D. B. (2017). The global aluminum cycle: challenges and solution options.

[25] Modaresi, R. and Müller, D. B. (2012). The Role of Automobiles for the Future of Aluminum Recycling. Environmental Science & Technology, 46(16). 8587–94. DOI:10.1021/es300648w.

Løvik, A. N., Modaresi, R. and Müller, D. B. (2014). Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements. Environmental Science & Technology, 48(8). 4257–65. DOI:10.1021/es405604g.

[26] Cullen and Allwood (2013). Mapping the Global Flow of Aluminum.
Modaresi and Müller (2012). The Role of Automobiles

[27] Modaresi and Müller (2012). The Role of Automobiles

[28] Bertram et al. (2017). A regionally-linked.

[29] Koffler, C. and Florin, J. (2013). Tackling the Downcycling Issue—A Revised Approach to Value-Corrected Substitution in Life Cycle Assessment of Aluminum (VCS 2.0). Sustainability, 5(11). 4546–60. DOI:10.3390/su5114546.

Material Economics (2018). Ett Värdebeständigt Svenskt Materialsystem. http://resource-sip.se/content/uploads/2018/01/vardebestmtrlsystemrapport180118.pdf.

[30] Ducker Worldwide (2016). Aluminium Content in Cars. https://european-aluminium.eu/media/1721/european-aluminium-ducker-study-summary-report_sept.pdf.

[31] International Energy Agency (2017) projections for electric vehicles.

International Energy Agency (2017). Energy Technology Perspectives 2017.

[32] This is based on expert interviews, and similar to the assumption in (Modaresi and Müller 2012). CRU Group (2018), an industry consultant, points out that some of the components of electric vehicles, such as battery casings, could use either wrought or cast components, but nonetheless assume an even larger decline in the share of secondary castings per vehicle than is assumed here.

Modaresi and Müller (2012). The Role of Automobiles.

CRU Group (2018). Electric vehicles to transform aluminium demand. https://www.crugroup.com/knowledge-and-insights/insights/2018/electric-vehicles-to-transform-aluminium-demand/.

[33] Material Economics analysis building on Ducker Worldwide (2016), European Aluminium (2011), Magma (2018), and Keshavaram (1999), and Ducker Worldwide (2011).

Ducker Worldwide (2016). Aluminium Content in Cars.

European Aluminium (2011). The aluminium automotive manual. https://www.european-aluminium.eu/resource-hub/aluminium-automotive-manual/.
Magma (2018). Manufacturing State of the Art Aluminum Cylinder Head Castings. https://www.magmasoft.com/en/company/references/reference/manufacturing-state-of-the-art-aluminum-cylinder-head-castings/.

Keshavaram, B. N. (1999). Aluminum Alloys for Automotive Disc Brake Calipers. 1999-01–0346. SAE International, Warrendale, PA. DOI:10.4271/1999-01-0346.

Ducker Worldwide (2011). Ducker Worldwide Presents at CRU's 16th World Aluminum Conference. Ducker. http://www.ducker.com/news-insights/ducker-worldwide-presents-crus-16th-world-aluminum-conference-full-presentation.

[34] The scenarios differ in the degree of sorting and separation and losses. Sorting and separation: Both scenarios see a gradual change from current practice to 2050. In the baseline scenario, only one-third of wrought end-of-life scrap is sorted separately so that it can be recycled into wrought scrap again. In the circular scenario, this increases to two-thirds by 2050. In both scenarios, all new scrap is sorted separately into wrought and cast alloys. Losses: Losses are lower in the circular scenario, with a gradual halving of the losses that take place today, chiefly by increasing the collection rate for end-of-life scrap, and to a lesser extent by reducing the formation of new scrap and associated remelting losses. Trade: In both scenarios, 70% of any 'excess scrap' can be exported, as long as there are other world regions that still have a shortage of post-consumer scrap to serve demand for cast alloys. Trade is not 100% perfect; as recent developments in both China and the United States have shown, countries are keen to have some self-sufficiency in aluminium production. Electric vehicles: demand for cast aluminium is modelled bottom up for vehicles, and a fixed share of other demand is assumed to be cast aluminium in other applications. The penetration of electric vehicles follows that in Bloomberg New Energy Finance (2017) 'New Economic Outlook' scenario. The aluminium content vehicles is based on (Ducker Worldwide 2016) and the cast aluminium content of electric vs. ICE vehicles on expert interviews, with numbers similar to those in Modaresi and Müller (2012). Dilution: the dilution rate is 20% in all scenarios. This is less than the rate reported in Cullen and Allwood (2013) but on the same level as the baseline assumption in Modaresi and Müller (2012)

Bloomberg New Energy Finance (2017). New Energy Outlook 2017. p.201. https://about.bnef.com/new-energy-outlook/.

Ducker Worldwide (2016). Aluminium Content in Cars.

Modaresi and Müller. (2012). The Role of Automobiles.

Cullen and Allwood. (2013). Mapping the Global Flow of Aluminum.

[35] These findings may seem surprising, but they are in fact in line with other estimates. For example, Modaresi and Müller (2012) find that there could be 6 Mt excess scrap in 2030, rising to up to 18 Mt in 2050. Our scenario estimates 7 Mt by 2030, and 23 Mt by 2050.
Modaresi and Müller. (2012). The Role of Automobiles.

[36] Scenarios assume different degrees of losses of aluminium and sorting of post-consumer scrap to avoid downcycling. The baseline scenario keeps current practice, whereas the circular scenario sees a significant increase in the feasibility of using post-consumer scrap for wrought aluminium by 2050. In both scenarios, the CO2-intensity of aluminium production falls over time, as described above.

[37] There is a more nuanced point here about how to evaluate the emissions savings from reducing primary aluminium use in the EU. First, in an international commodity market, increases or reductions of global demand over the course of decades serves to reduce supply at the margin: less demand in the EU leads to less primary capacity overall. A more circular system in the EU therefore avoids the emissions associated with global marginal supply. This is the case regardless of what exact sources the might EU import from in 2050, which is anyway impossible to predict. If anything, global marginal supply is likely to be more CO_2-intensive than the average emissions factor used here. Second, it is less relevant over time what share of current EU aluminium smelting is powered by legacy low-carbon sources of electricity production. By 2050, if low-carbon electricity production were not used for primary aluminium, the same low-carbon resource could serve some other electricity demand. In a 2050 perspective, reduced demand for primary aluminium production therefore has the same effect as any energy efficiency measure, helping accelerate the transition to a low-carbon energy system, and to contain the amount of low-carbon power required to achieve full decarbonisation. For both these reasons, the CO_2 reductions resulting from reduced primary aluminium demand in Europe are calculated using the world average CO_2 intensity of production. As noted above, in the baseline scenario this average follows a pattern of gradual decarbonisation where current fossil production reduces its CO_2 intensity of electricity used by half to 2050, and all electricity is fully CO_2-free by 2100. (An alternative interpretation would be to take a weighted average of EU domestic emissions intensity and global, marginal supply; although this has less of a basis in economic logic, it happens this gives a very similar result).

[38] European Aluminium (2017). 2015 Sustainability Highlights.

[39] Norsk Hydro (2017). Low-carbon aluminium: Hydro 4.0 and Hydro 75R. https://www.hydro.com/en/products/low-carbon-aluminium-hydro-4.0-and-hydro-75r/.

[40] Specifically, the circular scenario assumes that 20% primary metal is still required to dilute and 'sweeten' recycled aluminium, and one-third of wrought aluminium scrap remains mixed to the point where it can only be used for casting alloys.

[41] Løvik et al. (2014). Long-Term Strategies.

CHAPTER 5.

[1] European Commission (2011). Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System. 0144 final. European Commission. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0144.

[2] This share is nearly constant over time, varying between 83.0- 83.7% in the period 2004-2014 (Eurostat Statistics Explained, 2017).
Eurostat Statistics Explained (2017). Passenger transport statistics. http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_transport_statistics#Relative_growth_of_passenger_transport_and_the_economy.

[3] Eurostat Statistics Explained (2017). Passenger transport statistics.

[4] Vehicle ownership increased from 530 vehicles per 1000 people in 2005 to 570 in 2015 (ACEA - European Automobile Manufacturers' Association,2017b).
ACEA - European Automobile Manufacturers' Association (2017b). Report: Vehicles in Use. http://www.acea.be/statistics/article/Report-Vehicles-in-Use.

[5] Average value per car is approximately 22 thousand EUR (ACEA - European Automobile Manufacturers' Association, 2017a) which can be compared with adjusted gross disposable income of households per capita that was 21,903 EUR in 2016 (Eurostat, 2018a).

ACEA - European Automobile Manufacturers' Association (2017a). Economic and Market Report Q4 2017. http://www.acea.be/statistics/article/economic-and-market-report-key-takeaways-about-the-eu-auto-industry-for-17.

Eurostat (2018a). Adjusted gross disposable income of households per capita in PPS. http://ec.europa.eu/eurostat/tgm/table.do?tab=table&language=en&pcode=tec00113.

[6] 252 million cars in the EU, with an approximate replacement value of 22 thousand EUR each, based on number of passenger cars exported from the EU and total value of passenger car exports (ACEA - European Automobile Manufacturers' Association, 2017a).

ACEA - European Automobile Manufacturers' Association (2017a). Economic and Market Report Q4 2017.

[7] Eurostat (2018b). Gross fixed capital formation (investments). http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tec00011&plugin=1.

[8] Eurostat (2016). Mean consumption expenditure by detailed COICOP level (in PPS). http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do.

[9] This study focuses on the materials implications of a shared mobility system. For a perspective on the wider economic implications within a more circular economy, see Ellen MacArthur Foundation (2015), which also has provided inspiration and insight for the analysis presented here.
Ellen MacArthur Foundation (2015). Growth Within: A Circular Economy Vision for a Competitive Europe. Ellen MacArthur Foundation together with Stiftungsfonds für Umweltökonomie und Nachhaltigkeit (SUN) and McKinsey Center for Business and Environment. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/EllenMacArthurFoundation_Growth-Within_July15.pdf.

[10] ACEA - European Automobile Manufacturers' Association (2017c). Vehicles in Use - Europe 2017. http://www.acea.be/statistics/article/vehicles-in-use-europe-2017.

[11] See Horton and Allwood (2017). However, performance varies widely, and expert interviews indicate that the best carmakers achieve on the order of 25% scrap, showing the significant potential for reduction.

Horton, P. M. and Allwood, J. M. (2017). Yield improvement opportunities for manufacturing automotive sheet metal components. Journal of Materials Processing Technology, 249. 78–88. DOI:10.1016/j.jmatprotec.2017.05.037.

[12] Plastics Europe (2018). Plastics - the Facts 2016. Plastics Europe. http://www.plasticseurope.org/Document/plastics---the-facts-2016-15787.aspx?FolID=2.
World Steel Association (2014). Steel Solutions in the Green Economy. https://www.worldsteel.org/en/dam/jcr:a3776cb0-7b75-4de7-810a-dcab78122464/PDF%253A+Affordable+social+housing.pdf.

Bertram, M., Ramkumar, S., Rechberger, H., Rombach, G., Bayliss, C., Martchek, K. J., Müller, D. B. and Liu, G. (2017). A regionally-linked, dynamic material flow modelling tool for rolled, extruded and cast aluminium products. Resources, Conservation and Recycling, (125). 48–69. DOI:10.1016/j.resconrec.2017.05.014.

[13] The bars show the lifecycle greenhouse gas emissions from materials and use phase per car, as calculated in the article by Ellingsen et al. (2016). The article defines the use phase as a total driving range of 180,000 km. The emissions are displayed per type of vehicle comprising internal combustion engine vehicles, electric vehicles powered by the current European electricity mix and electric vehicles in a prospective green energy scenario. The article looks at four car segments: mini, medium, large and luxury car, out of which we have used at the large car segment with an average weight of 1528 kg per car. All numbers have been recalculated from ton CO_2-eq per car over the lifetime of 180,000 km to g CO2-eq. per car km.
Ellingsen Ager-Wick, L., Singh, B. and Hammer Strømman, A. (2016). The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. http://iopscience.iop.org/article/10.1088/1748-9326/11/5/054010.

[14] Pasaoglu, G., Fiorello, D., Martino, A., Scarcella, G., Alemanno, A., et al. (2012). Driving and Parking Patterns of European Car Drivers: A Mobility Survey. Publications Office, Luxembourg.

[15] European Environment Agency (2010). Occupancy rates of passenger vehicles. https://www.eea.europa.eu/data-and-maps/indicators/occupancy-rates-of-passenger-vehicles/occupancy-rates-of-passenger-vehicles. Indicator Assessment.
UK Department for Transport (2017). National Travel Survey: England 2016.

[16] For clarity: 1.5/5 multiplied by 8% gives a utilisation rate of 2.4 percent.

[17] ICCT - The International Council on Clean Transportation (2018). European Vehicle Market Statistics 2017/2018. 63.

[18] Dun, C., Horton, G. and Kollamthodi, S. (2015). Improvements to the definition of lifetime mileage of light duty vehicles.(1). 68.

[19] Dun et al. (2015) Improvements to the definition of lifetime mileage.

European Environment Agency (2017b). Passenger transport demand. https://www.eea.europa.eu/data-and-maps/indicators/passenger-transport-demand-version-2/assessment-9. Indicator Assessment.

UK Department for Transport (2017). National Travel Survey

ICCT - The International Council on Clean Transportation (2016). European Vehicle Market Statistics: Pocketbook 2016/2017. Berlin.

ACEA - European Automobile Manufacturers' Association (2018). Vehicles Per Capita, by Country. http://www.acea.be/statistics/tag/category/vehicles-per-capita-by-country.

Horton and Allwood (2017) Yield improvement opportunities.

[20] Dun et al. (2015) Improvements to the definition of lifetime mileage.

[21] Annual driving range per car is on average 12,000 km, based on average lifetime of 14 years per car an170,000 km driven per car (Dun et al., 2015).
Dun et al. (2015) Improvements to the definition of lifetime mileage.

[22] Dun et al. (2015) Improvements to the definition of lifetime mileage.

[23] Ohno, H., Matsubae, K., Nakajima, K., Nakamura, S. and Nagasaka, T. (2014). Unintentional Flow of Alloying Elements in Steel during Recycling of End-of-Life Vehicles. Journal of Industrial Ecology, 18(2). 242–53. DOI:10.1111/jiec.12095.

[24] Modaresi, R. and Müller, D. B. (2012). The Role of Automobiles for the Future of Aluminum Recycling. Environmental Science & Technology, 46(16). 8587–94. DOI:10.1021/es300648w.

Løvik, A. N., Modaresi, R. and Müller, D. B. (2014). Long-Term Strategies for Increased Recycling of Automotive Aluminum and Its Alloying Elements. Environmental Science & Technology, 48(8). 4257–65. DOI:10.1021/es405604g.

[25] See discussion in Chapter 3.

[26] Sources include Daehn et al. (2017); Luben et al. (2003); Andersson et al. (2017); and expert interviews.

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CHAPTER 6.

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Hradil, P., Talja, A., Wahlström, M., Huuhka, S., Lahdensivu, J. and Jussa Pikkuvirta (2014). Re-Use of Structural Elements; Environmentally Efficient Recovery of Building Components. VTT Technical Research Centre of Finland. DOI:10.13140/2.1.1771.9363.

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Nusselder et al. (2015) Closed Loop Economy

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Ecofys, Fraunhofer Institute for Systems and Innovation Research and Öko-Institut (2009). Methodology for the Free Allocation of Emission Allowances in the EU ETS Post 2012. https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/bm_study-lime_en.pdf.

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THE CIRCULAR ECONOMY
A POWERFUL FORCE FOR CLIMATE MITIGATION

Transformative innovation for prosperous and low-carbon industry

This report investigates how a more circular economy can contribute to cutting CO_2 emissions. It explores a broad range of opportunities for the four largest materials in terms of emissions (steel, plastics, aluminium, and cement) and two large use segments for these materials (passenger cars and buildings).

The key conclusion is that a more circular economy can make deep cuts to emissions from heavy industry: in an ambitious scenario, as much as 296 million tons CO_2 per year in the EU by 2050, out of 530 Mt in total – and some 3.6 billion tonnes per year globally. Making better use of the materials that already exist in the economy thus can take EU industry halfway towards net-zero emissions. Moreover, doing so often is economically attractive. Initiatives for a more circular economy therefore deserve a central place in EU climate and industrial policy.

MATERIAL ECONOMICS

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