



MATERIAL ECONOMICS

INDUSTRIAL TRANSFORMATION 2050

Pathways to Net-Zero Emissions from EU Heavy Industry



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Pathways to Net-Zero Emissions from EU Heavy Industry

About Industrial Transformation 2050. This report is part of the *Industrial Transformation 2050* project, an initiative convened by the European Climate Foundation in collaboration with the Cambridge Institute for Sustainability Leadership, the Children's Investment Fund Foundation, Climate-KIC, the Energy Transitions Commission, RE:Source, and SITRA. It is published as part of the *Net-Zero 2050* series, an initiative of the European Climate Foundation.

Industrial Transformation 2050 seeks to work with industry and other stakeholders to set out pathways and policy options for net-zero heavy industry in Europe by 2050, achieving the objectives of the Paris Agreement while strengthening industrial competitiveness and the EU's overall economic development and performance.

The objective of *Net-Zero 2050* is to build a vision and evidence base for the transition to net zero emission societies in Europe and beyond, by mid-century at the latest. Reports in the series seek to enhance understanding of the implications and opportunities of moving to climate neutrality across the power, industry, buildings, transport, agriculture and forestry sectors; to shed light on near-term choices and actions needed to reach this goal; and to provide a basis for discussion and engagement with stakeholders and policymakers.

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PREFACE

There is intense debate about how to close the gap between current climate policy and the aim of the Paris Agreement to achieve close to net-zero emissions by mid-century. Heavy industry holds a central place in these discussions. The materials and chemicals it produces are essential inputs to major value chains: transportation, infrastructure, construction, consumer goods, agriculture, and more. Yet their production also releases large amounts of CO₂-emissions: more than 500 Mt per year, or 14% of the EU total. Their emissions have long been considered 'hard to abate' compared to those from sectors such as buildings or electricity.

Policymakers and companies thus have a major task ahead. There is an urgent need to clarify what it would take to reconcile a prosperous industrial base with net zero emissions, and how to get there in the 30 remaining years to 2050. The journey starts from a point of often challenging market conditions for EU companies, and the EU and its companies rightly is asking how climate and wider industrial strategy can be joined together. There is no doubt that significant innovation and entrepreneurship will be required, by companies, policymakers, cities, and a range of other actors.

This study seeks to support these discussions. It characterises how net zero emissions can be achieved by 2050 from the largest sources of 'hard to abate' emissions: steel, plastics, ammonia, and cement. The approach starts from a broad mapping of options to eliminate fossil CO₂-emissions from production, including many emerging innovations in production processes. Equally important, it integrates these with the potential for a more circular economy: making better use of the materials already produced, and so reducing the need for new production. Given the uncertainties, the study explores several different 2050 end points as well as the pathways there, in each case quantifying the cost to consumers and companies, and the requirements in terms of innovation, investment, inputs, and infrastructure. The ambition is to explore how

the myriad of new technologies and business models being discussed can fit together into consistent European industrial strategies to combine a prosperous industrial base with Paris compatibility, and what big choices and 'no regrets' Europe faces when developing such industrial strategies.

This report thus explores the technical and economic aspects of the transition but stops short of concrete policy recommendations. In a separate report, An Industrial Strategy for a Climate Neutral Europe, a group of policy experts explore what European policy is best suited to achieve a balanced transition.

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EXECUTIVE SUMMARY

This study explores multiple ways to achieve net-zero emissions from EU steel, plastics, ammonia and cement production while keeping that production in the EU. It quantifies the potential impact of different solutions and finds that emissions from those industries can be reduced to net zero by 2050, confirming the findings of the pathways presented in the Commission's *A Clean Planet for All*. Many new solutions are emerging, thanks to a more circular economy with greater materials efficiency and extensive recycling of plastics and steel, as well as innovative industrial processes and carbon capture and storage.

Many different industrial strategies and pathways can be combined to achieve net-zero emissions. The analysis finds that the impact on end-user/consumer costs will be less than 1% regardless of the path pursued – but all pathways require new production processes that are considerably costlier to industry, as well as significant near-term capital investment equivalent to a 25–60% increase on today's rates. Keeping EU companies competitive as they pursue deep cuts to emissions will thus require a new net-zero CO₂ industrial strategy and policy agenda. There is a need to accelerate innovation, enable early investment, support costlier low-CO₂ production, overcome barriers to circular economy solutions, and ensure that companies can access the large amounts of clean electricity and other new inputs and infrastructure they need. Time is short, with 2050 only one investment cycle away, and any further delays will hugely complicate the transition. As the EU ponders its industrial future, this transformation should be a clear priority.

NET-ZERO EMISSIONS FROM EU HEAVY INDUSTRY IS POSSIBLE BY 2050

The EU has set out a vision to achieve net-zero greenhouse gas emissions by mid-century as a contribution to achieving the Paris Agreement objectives of limiting global warming.

Resource and energy intensive industry holds a central place in this vision. The production of key materials and chemicals – steel, plastics, ammonia and cement – emits some 500 million tonnes of CO₂ per year, 14% of the EU total. Materials needs are still growing, and on the current course, EU emissions from these sectors might increase as well. Globally, these emissions are growing faster still, already accounting for 20% of the total. The EU needs to lead the way in combining the essential industrial base of a modern economy with the deep cuts to emissions required to meet climate targets.

To date, emissions from these sectors have been considered especially ‘hard to abate’. Existing industrial low-carbon roadmaps left up to 40% of emissions in place in 2050. This would make industrial emissions one of the main roadblocks to overall net-zero emissions. The European Commission’s *A Clean Planet for All* broke new ground by also considering pathways that eliminate nearly all emissions from industry.

This study confirms that it is possible to reduce emissions from industry to net zero by 2050. It reaches this conclusion by considering a much wider solution set than what is often discussed. Whereas most existing analyses have emphasised carbon capture and storage as the main option for deep cuts, a range of additional solutions are now emerging. A more circular economy is a large part of the answer. Innovations in industrial processes, digitisation, and renewable energy technologies can also enable deeper reductions over time.

Crucially, these deep cuts to emissions need not compromise prosperity. Steel, chemicals and cement fulfil essential functions, underpinning transportation, infrastructure, packaging, and a myriad of other crucial functions. The analysis of this study is based on the premise that all these benefits continue, and also that the EU continues to produce the materials it needs within its borders to the same extent as today.

A WIDE RANGE OF SOLUTIONS FOR NET-ZERO INDUSTRY IS AVAILABLE AND EMERGING

There are many paths to net-zero emissions, and a wide portfolio of options provides some choice and redundancy. At the same time, industry will need a clear sense of direction, so there is a need to debate and investigate the pros and cons of different options.

This study seeks to enable such discussion. It aims to be as comprehensive as possible in describing the available solutions and finds an encouraging breadth of available options. It explores multiple different pathways, each with its own benefits and requirements, and facing different roadblocks. All pathways reach net zero, reducing emissions by more than 500 Mt per year in 2050, but reflect different degrees of success in mobilising four different strategies for emissions reductions:

A. Increased materials efficiency throughout major value chains (58–171 Mt CO₂ per year by 2050). The EU uses 800 kg per person and year of the main materials and chemicals considered here. However, there is in fact nothing fixed about these amounts. This study carries out a comprehensive review of opportunities to improve the productivity of materials use in major chains such as construction, transportation, and packaged goods. All offer major

opportunities for materials efficiency: achieving the same benefits and functionality with less material. The opportunity is surprisingly wide-ranging, including new manufacturing and construction techniques to reduce waste, coordination along value chains for circular product design and end-of-life practices, new circular business models based on sharing and service provision; substitution with high-strength and low-CO₂ materials; and less over-use of materials in many large product categories. For example, many construction projects use 30–50% more cement and steel than would be necessary with an end-to-end optimisation. Similarly, new business models could cut the materials intensity of passenger transportation by more than half, while reducing the cost of travel. Much like energy efficiency is indispensable to the overall energy transition, improving materials efficiency can make a large contribution in a transition to net-zero emissions from industry. In a stretch case achieving extensive coordination and a deep shift in how Europe uses materials, these solutions can reduce material needs from today’s 800 kg per person per year to 550–600 kg, reducing emissions as much as 171 Mt CO₂ per year by 2050. In a more traditional pathway, emphasising supply-side measures instead, the reductions could be at a lower 58 Mt CO₂.

B. High-quality materials recirculation (82–183 Mt CO₂ per year by 2050). Large emissions reductions can also be achieved by reusing materials that have already been produced. Steel recycling is already integral to steel production, substantially reducing CO₂ emissions. The opportunity will grow over the next decades as the amount of available scrap increases, and as emissions from electricity fall. The share of scrap in EU steel production can be increased by reducing contamination of end-of-life steel with other metals, especially copper. With plastics, mechanical recycling can grow significantly but also needs to be complemented by chemical recycling, with end-of-life plastics that cannot be mechanically recycled used as feedstock for new production. Unlike most other forms of recycling, chemical recycling of plastics requires lots of energy, but is almost indispensable to closing the ‘societal carbon loop’, thus escaping the need for constant additions of fossil oil and gas feedstock that in turn becomes a major source of CO₂ emissions as plastic products reach their end of life. By 2050, a stretch case could see 70% steel and plastics produced through recycling, directly bypassing many CO₂ emissions, as steel and plastics recycling can use green electricity and hydrogen inputs. The total emissions reductions could be 183 Mt CO₂ per year in a highly circular pathway, but just 82 Mt if these are less successfully mobilised.

C. New production processes (143–241 Mt CO₂ per year by 2050). While the opportunity to improve materials use and reuse is large, the EU will also need some 180–320 Mt of new materials production per year. As many current industrial processes are so tightly linked to carbon for either energy or feedstock, deep cuts often require novel processes and inputs. Ten years ago, the options were limited, but emerging solutions can now offer deep cuts to CO₂ emissions. For steel, several EU companies are exploring production routes that switch from carbon to hydrogen. In cement, new cementitious materials like mechanically activated pozzolans or calcined clays offer low-CO₂ alternatives to conventional clinker. For chemicals, several proven routes can be repurposed to use non-fossil feedstocks such as biomass or end-of-life plastics. Across the board, innovations are emerging to use electricity to produce high-temperature heat. Many solutions are proven or in advanced development, but economics have kept them from reaching commercial scale. They now need to be rapidly developed and deployed if they are to reach large shares by

2050. In addition, large amounts of zero-emissions electricity will be needed, either directly or indirectly to produce hydrogen. In a pathway heavily reliant on new production routes, as much as 241 Mt CO₂ could be cut in 2050 by deploying these new industrial processes, falling to 143 Mt in a route that emphasises other solutions instead.

D. Carbon capture and storage / use (45–235 Mt CO₂ per year by 2050). The main alternative to mobilising new processes is to fit carbon capture and storage or use (CCS/U) to current processes. This can make for less disruptive change: less reliance on processes and feedstocks not yet deployed at scale and continued use of more of current industrial capacity. It also reduces the need for electricity otherwise required for new processes. However, CCU is viable in a wider net-zero economy only in very particular circumstances, where emissions to the atmosphere are permanently avoided. CCS/U also faces challenges. In steel, the main one is to achieve high rates of carbon capture from current integrated steel plants. Doing so may require cross-sectoral coupling to use end-of-life plastic waste, or else the introduction of new processes such as direct smelting in place of today’s blast furnaces. For chemicals, it would be necessary not just to fit the core steam cracking process with carbon capture, but also to capture CO₂ upstream from refining, and downstream from many hundreds of waste incineration plants. Cement production similarly takes place at around 200 geographically dispersed plants, so universal CCS is challenging. Across all sectors, CCS would require public acceptance and access to suitable transport and storage infrastructure. These considerations mean that CCS/U is far from a ‘plug and play’ solution applicable to all emissions. Still, it is required to some degree in every pathway explored in this study. High-priority areas could include cement process emissions; the production of hydrogen from natural gas; the incineration of end-of-life plastics; high-temperature heat in cement kilns and crackers in the chemical industry; and potentially the use of off-gases from steel production as feedstock for chemicals. In a high case, the total amount of CO₂ permanently stored could reach 235 Mt per year in 2050, requiring around 3,200 Mt of CO₂ storage capacity. However, it also is possible to reach net-zero emissions with CCS/U used mainly for process emissions from cement production. In this case, the amount captured would be around 45 Mt per year.

*Net-zero emissions from
EU heavy industry is
possible by 2050.*



ADDITIONAL COSTS TO CONSUMERS ARE LESS THAN 1%, BUT COMPANIES FACE 20–115% HIGHER PRODUCTION COSTS

An analysis of the costs of achieving net-zero emissions reveals a telling contradiction. On the one hand, the total costs are manageable in all pathways: consumer prices of cars, houses, packaged goods, etc. would increase by less than 1% to pay for more expensive materials. Overall, the additional cost of reducing emissions to zero are 40-50 billion EUR per year by 2050, around 0.2% of projected EU GDP. The average abatement cost is 75-91 EUR per tonne of CO₂.

On the other hand, the business-to-business impact is large and must be managed. All pathways to net-zero require the use of new low-CO₂ production routes that cost 20-30% more for steel, 20-80% for cement and chemicals, and up to 115% for some of the very ‘last tonnes’ that must be cut. These differences cannot be borne by companies facing both internal EU and international competition, so supporting policy will be essential.

Cost alone is not a basis for choosing one pathway over another. Total costs are similar whether the emphasis is on CCS or on new production technologies. The attractiveness of solutions will vary across the EU, not least depending on electricity prices. A more circular economy and affordable electricity are among the most important factors to keep overall costs low.

Most EU companies know the current status quo offers little intrinsic advantage in a situation of trade uncertainties, global over-capacity, and often lower fossil feedstock and energy costs in other geographies. Low-carbon routes emphasising deep value chain integration, continued process and product innovation, and reliance on local end-of-life resources may well prove a more sustainable route for EU competitiveness. It will also offer a head start in developing solutions that will eventually be needed globally. In the longer run, low-CO₂ production systems may in fact be the more promising route to keep EU industry competitive.

A low-CO₂ industrial transition can offer similar employment levels as today, provided that economic activity does not migrate from the EU. Overall, circular economy solutions are more rather than less labour-intensive, so implementing them would create additional jobs in the overall value chains. Changes to industrial production, meanwhile, would likely still occur on current sites and in existing clusters, with little systemic impact on industrial employment.

THE TRANSITION WILL REQUIRE A 25-60% INCREASE IN INDUSTRIAL INVESTMENT, WITH IMPORTANT NEAR-TERM DECISIONS

All pathways also require an increase in capital expenditure. Whereas the baseline rate of investment in the core industrial production processes is around 4.8–5.4 billion EUR per year, it rises by up to 5.5 billion EUR per year in net-zero pathways, and reaches 12–14 billion EUR per year in the 2030s. Investment in other parts of the economy also will be key, including some 5–8 billion EUR per year in new electricity generation to meet growing industrial demand.

How much is invested and where depends on the pathway, with generally much lower investment requirements for materials efficiency and circular economy solutions than for traditional production. Some additional investment occurs because low-CO₂ routes are inherently more capital-intensive, but many others are one-off transition costs for demonstration, site conversion, and to provide redundancy in uncertain situations. Investment also will be required in infrastructure for electricity grids, CO₂ transportation and storage, and handling of end-of-life flows.

For society as a whole these are not, in fact, large amounts. They correspond to just 0.2% of gross fixed capital formation and would be fully covered, including a return on capital, by

paying on average 30 EUR per tonne more for plastics and steel that often cost 600-1,500 EUR per tonne in today's markets.

For companies, however, the investment will be a major challenge. The case for investment in the EU's industrial base has been challenged for more than a decade. All investment relies on a reasonable prospect of future profitability. In capital-intensive sectors, choosing a low-CO₂ solution instead of reinvesting in current facilities can amount to a 'bet the company' decision – especially when future technical and commercial viability is uncertain. Investment in demonstration and other innovation often has highly uncertain returns. For all these reasons, strong policy support will therefore be needed in the near term.

In all pathways, EU companies will make important investment decisions in the next few years. Each will create a risk of lock-in unless low-CO₂ options are viable at these forks in the road. Changes to value chains and business models, meanwhile, may take decades to get established. There is time for deep change until 2050, but it will have to happen at a rapid pace, and any delay will hugely complicate the transition.

NET-ZERO INDUSTRY WILL REQUIRE LARGE AMOUNTS OF ELECTRICITY AND BIOMASS AS WELL AS A MORE CIRCULAR ECONOMY

Steel, cement, plastics and ammonia production together use 8.4 EJ of mostly imported oil, coal and natural gas. A major benefit of a more circular economy would be to reduce these needs by up to 3.1 EJ per year in 2050 through improved materials efficiency, new business models in major value chains, and large shares of materials recirculation.

Remaining needs would be replaced by sustainably sourced biomass (1.1–1.3 EJ), used primarily as feedstock, and large amounts of electricity (2.5–3.6 EJ), used directly or for the production of hydrogen. The remaining fossil fuels and feedstock would be as low as 0.2 EJ, though with high levels of CCS, 3.1 EJ could remain. All in all, Europe could become much less dependent on imports of inputs to its industrial production, even if some basic constituents (such as ammonia or hydrogen) were eventually to be imported.

Industry electricity demand will increase significantly. In a maximum case, an additional 710 TWh per year is required (for comparison, all of industry and manufacturing uses 1,000 TWh today). However, up to four times larger amounts are proposed in other analyses that envision a greater use of CO₂ and 'Power-to-X' as feedstock to decar-

bonise industry. Electricity must be all but zero-emissions, or emissions would simply migrate to the energy sector. It also needs to be affordable (the cost estimates presented here assume a price of 40–60 EUR per MWh, depending on the application). The main ways to reduce electricity needs is to achieve a more circular economy, which can reduce requirements by 310 TWh, or large-scale deployment of CCS, which can cut some 275 TWh.

Sustainable biomass is a scarce resource, and industry must prioritise how it is used. Nearly all biomass used in the pathways is as feedstock for chemicals, to enable a 'societal carbon loop' for plastics and other chemicals without new additions of fossil carbon from oil and gas. The 85–105 Mt required are within available resources, especially if non-conventional streams such as mixed waste can be mobilised. Still, it is key to minimise the amount of biomass required. The main ways to do so are high recycling rates (mechanical and chemical) for plastics, increased materials efficiency, innovation to enable new polymers suited to bio-feedstock, and CCS to enable some continued use of fossil feedstock.

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THE TRANSFORMATION REQUIRES STRONG SUPPORT ACROSS CLIMATE AND INDUSTRIAL POLICY

A successful transition will require concerted efforts by government, industrial companies, companies in major value chains, cities, civil society, and individuals. The transition is technically feasible but requires a step-change in support to be economically plausible. The next 5–10 years will be crucial in enabling EU heavy industry and major value chains to chart a low-CO₂ course.

Many EU industrial companies know that ‘doing nothing’ is a far from viable approach. Indeed, EU industry has long gravitated towards increased specialisation, performance and efficiency to counter pressures ranging from energy costs, trade practices or global overcapacity. A low-CO₂ track would be a continuation and acceleration of these trends. Low-CO₂ solutions pioneered and commercialised in Europe will eventually be needed globally in a world with large unmet materials needs. Meanwhile, the EU would transition to a much more secure position: a more materials-productive economy that is less reliant on imported fossil fuels and feedstock, and more attuned to domestic sources of comparative advantage: local integration, digitisation, end-of-life resources, etc.

Nonetheless, the first steps of this transition will not occur without a step-change both in policy and in company strategic choices. To launch a new economic and low-CO₂ agenda for EU heavy industry, major policy innovation and entrepreneurship will be required. The EU ETS provides a fundamental framework, but many stakeholders see limits to the credible commitments to future CO₂ prices that it can provide, not least given international competition. On its own, carbon pricing also does not provide sufficient incentives for innovation, nor does it address market failures that hold back many circular economy solutions.

While all pathways require broad policy support, requirements differ for different options. Effective policy therefore must start from a deep understanding of the change required, and the business case for different options. Just like the solution set for net-zero industry is wide-ranging, this policy agenda must have many parts, each addressing different aspects of the transition. Options currently not in use but which can be considered include:

- **Launch major new mechanisms for innovation.** This includes some industrial R&D ‘moonshots’ and mission-driven innovation. Equally important will be to support the later stages towards fully commercial solutions: define and embed an innovation agenda in all EU and national programs, provide direct public finance for demonstration, emphasise early learning by doing (deployment), and develop new joint public-private models for large demonstration plants.
- **Create lead markets for low-carbon production.** This starts with creating an initial business case to

enable companies to make a near-term strategic choice for low-CO₂ production. It also requires a commitment to continued support. The EU ETS offers an option, but wider climate policy offers a broad menu of fiscal/financial support and regulatory instruments that could be deployed, such as contracts for differences for low-CO₂ production, standards for materials’ or products’ CO₂ performances, public procurement, and possible trade and investment mechanisms to ensure fair international competition.

- **Enable early investment and reduce the risk of lock-in.** Especially early in the transition, before technical and commercial risk can be fully resolved, financing instruments for direct investment supports will likely be required. Options include using public financial institutions, risk-sharing models, concessional finance, and early direct public investment. It also will be necessary to handle the risk of stranded assets.
- **Create systems for high-quality materials recirculation.** Both steel and plastics recycling are indispensable parts of any net-zero materials system, but incentives for clean end-of-life flows are skewed and insufficient. Regulatory change is required to open up waste flows as a major, large-scale feedstock resource, regulate against contamination of end-of-life flows, and optimise product design and end-of-life dismantling for high-quality recovery.
- **Integrate materials efficiency and new business models in key value chains.** As with energy efficiency, policy can help overcome barriers and market failures such as incomplete contracts and split incentives, large transaction costs and missing markets, and incomplete information. Standards, quotas, labelling and other approaches in energy efficiency policy need rapid translation to major materials-using value chains – while avoiding undesired outcomes of such regulations, including potential hidden costs.
- **Safeguard access to key inputs and infrastructure.** Key policy objectives in this area include public or regulated models for carbon transport and storage, hydrogen supply for major industrial clusters, an accelerating electricity system transition, and modified incentives for biomass use that maximise the benefits of its use. Policies that encourage industrial clusters and symbiosis for heat, hydrogen and other flows also can contribute.

Perhaps the most important near-term prerequisite for success will be to create a shared expectation: that, much like the energy sector now focuses nearly all its efforts on low-carbon resources, the EU heavy industry and major materials-using value chains will now direct innovation and investment towards solutions that enable deep cuts to CO₂ emissions. The sooner this is achieved, the greater the likelihood of success – and the greater the opportunity to build an EU industrial advantage in low-CO₂ production and in circular economy business models.

1. ACHIEVING PROSPEROUS, NET-ZERO EU INDUSTRY BY 2050

1.1 NET-ZERO MATERIALS – THE NEED FOR A NEW ANSWER TO INDUSTRIAL CO₂

There is intense debate about how to close the gap between current climate policy and the aim of the Paris Agreement to achieve close to net-zero emissions by mid-century.

Heavy industry holds a central place in this vision. The production of key materials and chemicals – steel, plastics, ammonia and cement – emits more than 530 million tonnes of CO₂ per year (including electricity and end-of-life emissions). Materials needs are still growing, and on the current course, EU emissions from these sectors would be little lower in 2050 than they are today.

Globally, these emissions are growing faster still, already accounting for 20% of the total. In fact, without deep change, the production of basic materials alone would exhaust the available ‘carbon budget’ for a 2°C objective, and make it completely impossible to keep warming ‘well below’ 2°C. Thus, in finding a way to maintain

the robust industrial base of modern economies while making deep cuts to emissions, the EU can not only help achieve its climate targets, but also develop and demonstrate solutions that are urgently needed across the globe.

Yet emissions from these sectors have long been considered ‘hard to abate’. Carbon is inextricably linked into current production processes, either as a building block of the material (plastic), or in the process chemistry of their production (ammonia, cement, steel). Existing industrial low-carbon roadmaps have eschewed significant change, emphasising carbon capture as the key route to deep cuts – but still leaving some 30–40% of emissions in place in 2050. Industrial emissions are thus one of the main roadblocks to a net-zero economy. Recognising the need to address this problem, the European Commission’s *A Clean Planet for All* broke new ground by considering pathways that eliminate nearly all emissions from industry as well.



This study confirms that it is possible to achieve net-zero emissions from industry – if one considers a much wider solution set than is typically envisioned. Carbon capture still plays a role, but many other solutions also hold significant potential. A large part of the answer lies in a more circular economy and new business models, both to improve materials efficiency and to enable the recirculation of end-of-life plastic and steel as feedstock for new production. Innovations in industrial processes, digitisation, and renewable energy technology likewise help enable deeper reductions over time.

Crucially, these deep cuts to emissions need not compromise prosperity. Steel, chemicals, and cement fulfil essential functions, underpinning transportation, infrastructure, packaging, and many other crucial functions. The pathways in this study start from the premise that all these benefits continue, and also that the EU keeps producing the materials it needs within its borders to the same extent as today.

However, technical feasibility is only a start. The transition to net-zero emissions will require profound change throughout the materials system: in core production processes, in how materials are used in major value chains, and in how they are treated at end of life.

This raises understandable concerns. The current business and policy environment is not conducive to these industries undertaking such an investment- and innovation-heavy transition.

On the contrary, many companies in the relevant sectors have struggled in the aftermath of the financial crisis. They also face unfavourable international market conditions, including overcapacity, trade uncertainty, and adverse structural shifts in energy and feedstock prices. A major transformation from this starting point will be daunting for many. In a capital-intensive industry with long-lived assets, investing in a low-CO₂ option instead of reinvesting in current high-CO₂ processes could amount to a 'bet the company' decision.

This study attempts to address those concerns directly, by describing not just a set of solutions to reduce emissions, but different potential pathways to net-zero by 2050, recognising today's realities. It quantifies the cost, investment, input requirements, and innovation needs of each approach. The aim is to show what it would take to reach net-zero in each sector, both for business leaders making decisions about their companies' path ahead, and for policy-makers who need to create an enabling policy environment. The analysis recognises that achievement of climate objectives must go hand in hand with continued competitiveness of EU industry. While clarifying what needs to change for low-CO₂ solutions to be viable, it also shows how a successful transition will involve profound innovation, new sources of value throughout the major value chains, and opportunities for EU companies to lead in the creation of solutions that will eventually be required globally.

THE EU MATERIALS SYSTEM – THE PRODUCTION, USE AND END OF LIFE OF KEY MATERIALS

The scope in this study is four major materials and chemicals: steel, cement and concrete, plastics, and ammonia.

The EU is a major producer of all these. In 2015, EU companies produced 413 million tonnes (Mt), equivalent to 812 kilograms (kg) for every person in the EU. This activity employs half a million people and adds €40 billion to the EU's gross domestic product (GDP) each year. European companies were pioneers in the development of heavy industry, and Europe is still home to large production assets, with more than 50 steam crackers, about 200 steel plants, 200 cement plants, and 42 ammonia production facilities at the core. These operations are complex and highly integrated, having been carefully optimised over their lifetimes.

Overall, production has held steady or grown modestly over the long term. However, in the aftermath of the 2008 financial crisis, there was a major shift, as both steel and cement production dropped by a third, with only partial recovery since.

Most of these products are commodities, with significant international trade and price competition. For example, the EU exports 14% of its steel production and 29% of its plastic production, and imports comparable amounts. Although EU producers have largely maintained their market position, international competition is a challenge. In steel, massive increases in production in China have led to global overcapacity and depressed prices and profitability. In chemicals, the cost of both ethylene and ammonia production can be as much as three times more expensive in the EU than in regions with access to cheap natural gas fossil feedstock. Cement remains a local market, but seaborne imports are a real possibility if large cost differences were to develop between the EU and its neighbours.

The core materials and chemicals produced by these industries are used in major value chains of the economy. Transportation, construction, packaging, and food account for as much as 70% of use. Infrastructure and machinery add another 20%. The business models, manufacturing and construction methods, materials choices, and design principles in these value chains thus directly determine how much of each material is needed to underpin essential economic functions. This is why, as discussed below, these value chains are crucial in a transition towards a more circular economy that can significantly reduce CO₂ emissions.

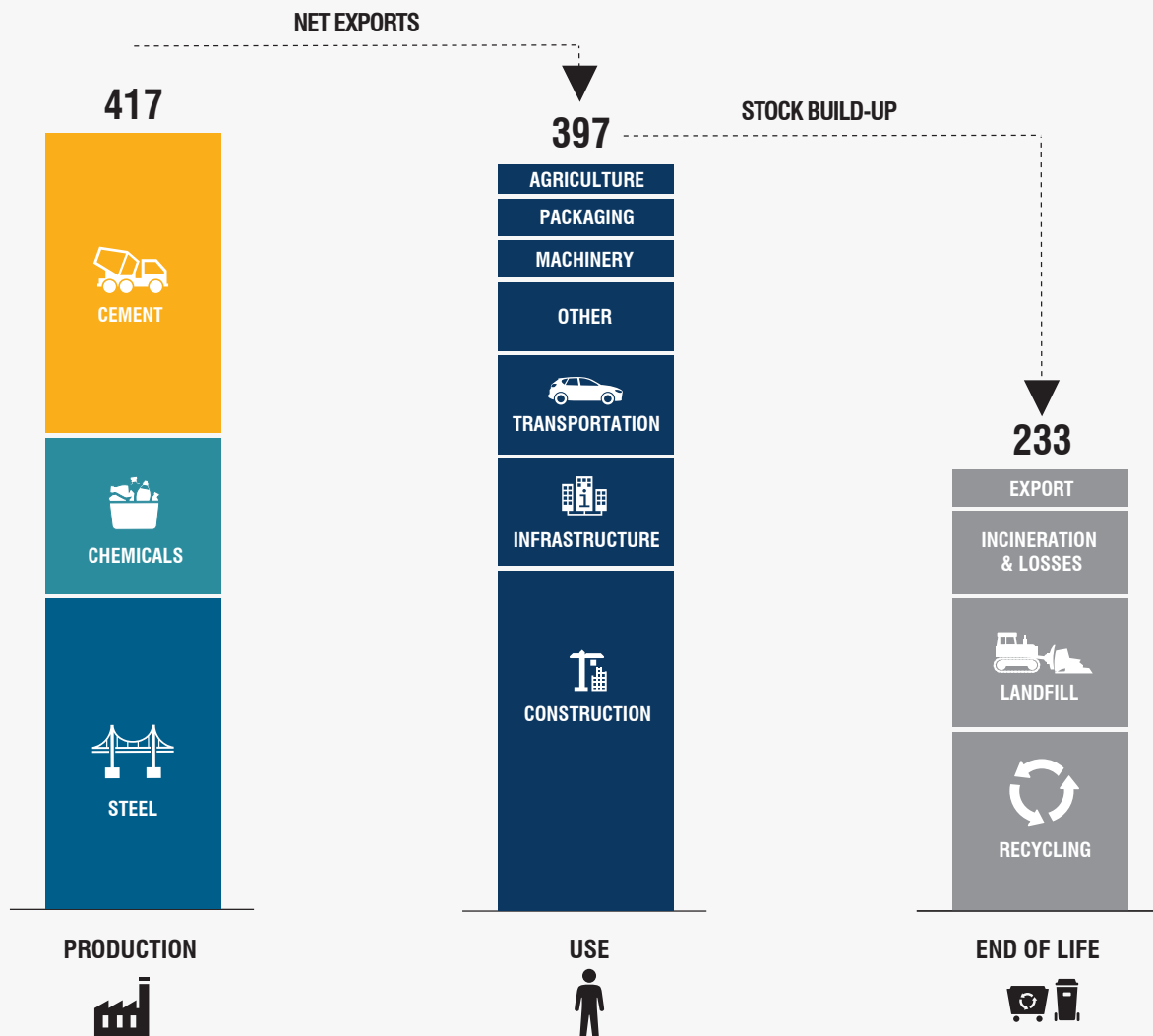
Large amounts of these materials also exit economic use each year, as products or structures reach the end of their lives. For example, EU citizens discard about twice their weight in packaging. There are similarly large volumes of end-of-life vehicles and demolished buildings. In some cases, these flows have a large economic value. For example, the 90 Mt of steel scrap generated in Europe each year is worth some €20–25 billion when it is either exported or reprocessed in the EU to make new steel. The other materials are far less circular and preserve less of the original materials value. Plastic recycling is still limited, producing volumes corresponding to around 10% of total plastics use.

Together, the production, use and end-of-life flow of materials make up the EU *materials system*: a set of interlocking production processes, products, business models, infrastructures, and end-of-life handling involving large economic values – and as described below, also large CO₂ emissions. To reduce these emissions, change across the entire system is possible.

Exhibit 1.1

THE EU MATERIALS SYSTEM: MORE THAN 400 MILLION TONNES OF STEEL, CEMENT, PLASTICS, AND AMMONIA FLOW THROUGH THE EU ECONOMY EACH YEAR

PRODUCTION, USE, AND END OF LIFE FOR EU STEEL, CEMENT, PLASTICS, AND AMMONIA
Mt, 2017



SOURCE: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.¹⁰

MATERIALS AND CO₂ EMISSIONS – WHY INDUSTRY IS SEEN AS ‘HARD TO ABATE’

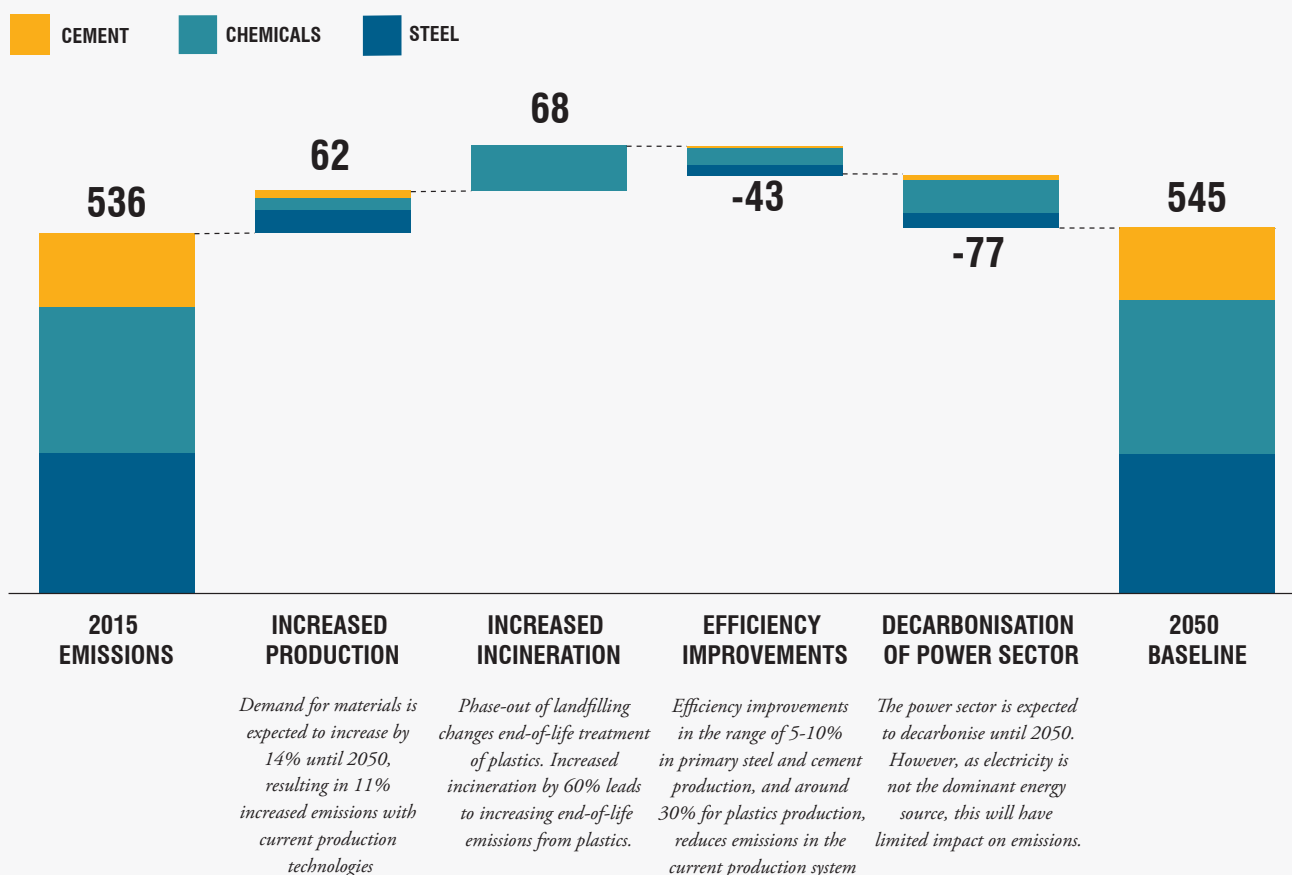
These four heavy industries are major energy users and large sources of carbon dioxide (CO₂) emissions. For every kilogram of cement that is produced, 0.7 kg of CO₂ is released into the air. The equivalent figure for the primary production of steel in the EU is just under 2 kg of CO₂, while 1 kg of plastic leads to 4.6 kg of CO₂, more than half of which results from embedded emissions that are released if plastics are incinerated at end of life. Including electricity and end-of-life emissions, total annual emissions from these materials were 536 Mt of CO₂ in the EU in 2015. That is 14% of the EU's total CO₂ emissions from energy and industry.¹¹

Continuing today's pattern of materials use in an expanding EU economy would require an estimated 14% increase in materials production and use by 2050. Thus, in a baseline scenario, overall emissions from the four industries would also grow (Exhibit 1.2). Incremental improvement in energy efficiency and some fuel switching would slightly reduce production emissions, but EU plans to phase out landfilling would lead to much greater levels of incineration of plastics, causing additional fossil CO₂ emissions.

Exhibit 1.2

WITHOUT DEEP CHANGE, CO₂ EMISSIONS FROM STEEL, CHEMICALS, AND CEMENT WOULD REMAIN AT MORE THAN 500 MT CO₂ PER YEAR

EMISSIONS IN A BASELINE SCENARIO
Mt, CO₂ PER YEAR



SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS.

*Total annual emissions
from these materials represent
14% of the EU's total CO₂
emissions from energy
and industry.*



Any strategy to reduce emissions needs to address the main sources of CO₂. For the sectors in scope here, three issues are particularly important: high-temperature heat, process emissions, and end-of-life emissions. These together make up as much as 84% of emissions from the four sectors (Exhibit 1.3):

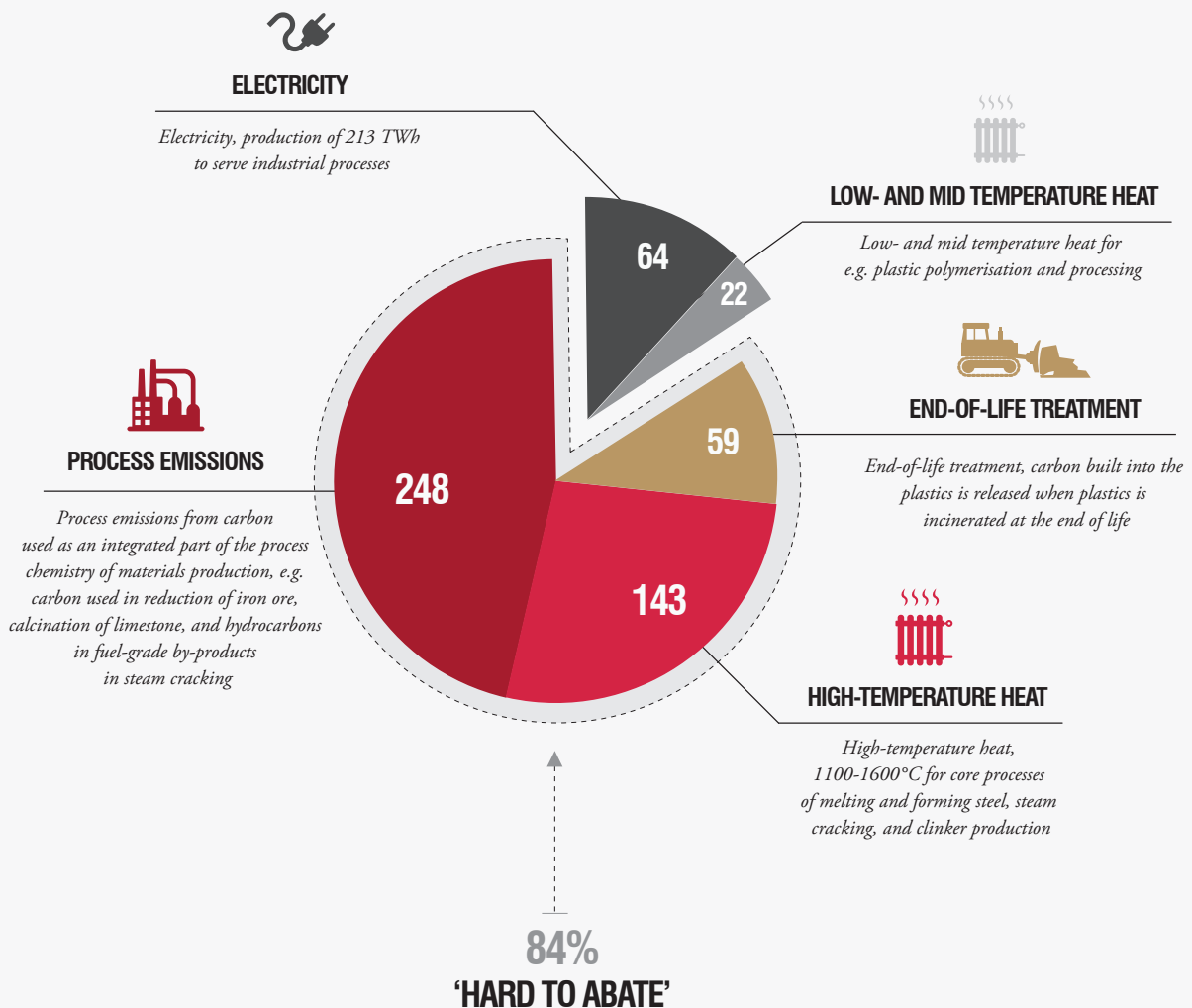
- **High temperature heat:** The core processes to melt and form steel, crack hydrocarbons into bulk chemicals, and transform limestone to cement clinker require very high temperatures, 850–1,600°C. This sets strict requirements for the energy sources and technologies used. In particular, while electricity already is used for some for these (notably, in electric arc furnaces to melt steel), in most cases neither the technologies nor the economics are yet in place to do so.
- **Process emissions:** All major processes in the four sectors use carbon not just for energy, but also as an integrated part of their process chemistry, with significant CO₂ emissions as a result. In the case of steel, carbon is used to remove oxygen from iron ore to produce iron. In the case of cement, the calcination of limestone to produce calcium oxide releases large amounts of carbon contained in the rock. In steam cracking, some 35–45% of the carbon in the feedstock ends up not as high-value chemicals, but as hydrocarbon by-products that release fossil CO₂ when burnt as fuel. And in the case of ammonia, CO₂ is released in the production of hydrogen from natural gas. Eliminating these emissions requires changing the fundamentals of the underlying industrial processes – not just the energy sources, but the feedstocks and equipment.
- **End-of-life emissions:** In the case of plastics, carbon is built into the materials which is released as CO₂ when incinerated at end of life. On average, as much as 2.7 kg of CO₂ is emitted for every kg of plastic. To address these, the carbon can be recirculated instead, while new feedstock must be changed to a non-fossil source of carbon (notably, biomass).¹²

Exhibit 1.3

WHY CO₂ EMISSIONS FROM INDUSTRY ARE 'HARD TO ABATE'

SOURCES OF CO₂ EMISSIONS FROM STEEL, CEMENT, PLASTICS, AND AMMONIA (100% = 536 Mt CO₂)

Mt CO₂, 2015



SOURCE: MATERIAL ECONOMICS ANALYSIS, SEE ENDNOTE.¹³



METHODOLOGY AND MODELLING APPROACH

The study covers cement and concrete, plastics (production of olefins and aromatics and polymerisation), primary and secondary steel (including downstream processing), and ammonia. The modelling approach starts from a characterisation of future activity levels. A baseline scenario for demand in 2050 is estimated using a range of models. For steel, the principal tool is a dynamic materials flow analysis along with assumptions about future saturation levels for the steel stock in different end use segments. For plastics, cement and ammonia, activity levels are based on scenarios for future construction, mobility, food production, and other activity. In the baseline scenario, no major shift in materials intensity or industry structure is assumed. As the aim is to characterise an EU net-zero CO₂ industrial system, no change in net imports is assumed.

The next step defines a wide range of low-CO₂ production routes. The analysis characterises the technological maturity, investment requirements, energy and feedstock inputs, other operating costs, mass balance, and CO₂ emissions of each process. Costs of energy inputs are based on widely used energy-economic scenarios from the International Energy Agency and other organisations. The scope of CO₂ emissions includes emissions from electricity generation, but also the carbon contained in products that may be released as CO₂ at end of life.¹⁴ Electricity generation is assumed to be fully carbon free by 2050, but the analysis explores scenarios where this is not the case. On the other hand, CO₂ created in the production of other raw materials (such as the extraction of oil and gas or mining of iron ore) are not included, nor are impacts on transportation estimated (e.g., the reduced transportation activity from lower materials requirements). In addition to new production routes, current production routes are characterised, including the reinvestment requirements and scope for process and energy efficiency improvement.

Alongside the production side, the analysis uses a range of models to explore opportunities for circular economy opportunities: improved materials efficiency and increased materials circulation. A model of packaging characterises 35 classes of packaging and estimates opportunities for reduced materials use, as well as options for substitution with other materials. Models of the mobility and buildings value chains estimate the potential for a range of materials efficiency strategies, as well as for changed use patterns (eg. based on sharing models) with new business models. Other quantities estimated include potential to reduce scrap generation in manufacturing, cement levels in concrete, food waste, fertiliser application through increased precision, etc. Costs and input requirements of these measures are estimated and included alongside the production routes.¹⁵ In all cases, the estimates are based on the premise that the underlying service or benefit provided (e.g., passenger-kilometres for mobility, shelter from buildings, protection from packaging) should be maintained as in the baseline.

The third component is a characterisation of end-of-life flows of materials and production routes that use these as inputs for new materials production. For steel, a dynamic materials flow model is used to estimate future availability of steel scrap and scenarios for scrap generation, collection rates, and levels of tramp elements. For plastics, a range of end-of-life flows are estimated based on levels of stock buildup and product lifetimes, and are mapped for their suitability for mechanical recycling, including impacts on yields, quality, and resulting effective replacement of new plastics production. Chemical recycling is characterised as a new plastics production route, with focus on routes with high carbon mass balance. The incineration of plastics at end-of-life is modelled and the CO₂ accounted for. For cement, the potential for recycling of concrete fines and recovery of unhydrated cement are estimated.

These three components are put together in a scenario analysis. All scenarios are constructed to achieve close to zero emissions of CO₂ from industrial production by 2050. Backcasting is used to create pathways in five-yearly intervals, accounting for capital stock turnover, gradual improvement in technological maturity, lead times for construction, and other constraints. The aim of the pathways is to describe 'what it would take' to achieve net-zero emissions in each of the four industrial sectors. The aim is not to find one optimal pathway, but to illustrate both 'no regret' moves and important choices ahead. Further details on the assumptions and approach are contained in the sector-specific chapters of this report, as well as in Appendices.

THE BUILDING BLOCKS OF NET-ZERO EU INDUSTRY

The aim of this study is to lay out pathways for the steel, plastics, ammonia, and cement industries to achieve net-zero emissions by 2050. This is far more ambitious than many existing analyses or ‘roadmaps’, which have typically focused on near-term opportunities or laid out scenarios that still leave up to 40% of industry emissions in place in 2050.¹⁶

A focus on a net-zero economy requires a different approach (see Box to the left for more details about the methodology used). First, it is necessary to consider system-wide emissions, including emissions from electricity generation and from end-of-life treatment. This is to avoid solutions that reduce emissions from industrial production only to shift them to other parts of the economy. Second, the focus must be on fully zero-CO₂ production routes. There are many measures that achieve partial reductions of CO₂, and that can make important contributions to early emissions reductions. However, in this study they are always accompanied by a full transition to fully fossil CO₂-free production in 2050.¹⁷

Finally, for deep cuts, all solutions must be included. A major focus of this study is to include opportunities for more efficient use and reuse of materials, which in turn reduces the need for new production.

On the other hand, the study does not consider ‘offsets’, whereby ‘negative emissions’ in other parts of the economy would compensate for continued emissions in industry. It also does not consider the reduction of emissions through increased imports. Both are very real possibilities. The analysis of costs and potentials in this study can be an important contribution to debates about how they should be handled.

The study includes four main categories of emissions reduction strategies (Exhibit 1.4):

- **Materials efficiency and new business models in major value chains:** These consist of opportunities to reduce the amount of materials needed to deliver a given benefit or service, thus achieving CO₂ reductions without having to compromise on economic or societal benefits. This is analogous to the role of energy efficiency in the wider energy transition, and this study builds on other work that finds that ‘materials efficiency’ should be considered a major climate solution.¹⁸
- **Materials recirculation and substitution:** Recirculating steel, plastics, and cement can bypass the process emissions of primary production processes, avoid end-of-life emissions, and significantly reduce energy use compared with new production. This study also considers the option of switching from high-CO₂ to lower-CO₂ materials.
- **New low-emissions processes:** These opportunities consist of fundamental changes to the underlying production processes and feedstocks, often eliminating fossil carbon from the outset. Only processes that are proven or at advanced stages of development are included in this study. Even so, many options are available. Several use electricity as input, either directly or in the production of hydrogen, or else they use biomass as an alternative to fossil sources of carbon feedstock.
- **Carbon capture and storage/use (CCS/U):** These consist of processes to capture and permanently store nearly all the CO₂ emissions from production, feedstock production, or end-of-life incineration. Opportunities for carbon capture and use (CCU) also are considered, but always with end-of-life emissions in mind. Only CCS/U solutions that achieve very high capture rates can significantly contribute to net-zero objectives, and often they require a major reconfiguration of production processes.

Exhibit 1.4

A SOLUTION SET FOR ACHIEVING...

CIRCULAR ECONOMY IN MAJOR VALUE CHAINS



MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS

Reducing the amount of materials used for a given product or structure, or increasing the lifetime and utilisation through new business models



MATERIALS RECIRCULATION AND SUBSTITUTION

Using end-of-life materials as input to new production, or using low-CO₂ alternative materials that provide the same function

MATERIALS EFFICIENCY

- New design principles to reduce materials use
- Reduce over-specification and overuse
- Use of high-performance materials to reduce the amounts required
- Optimise component design and manufacturing processes to reduce process waste

MATERIALS RECIRCULATION

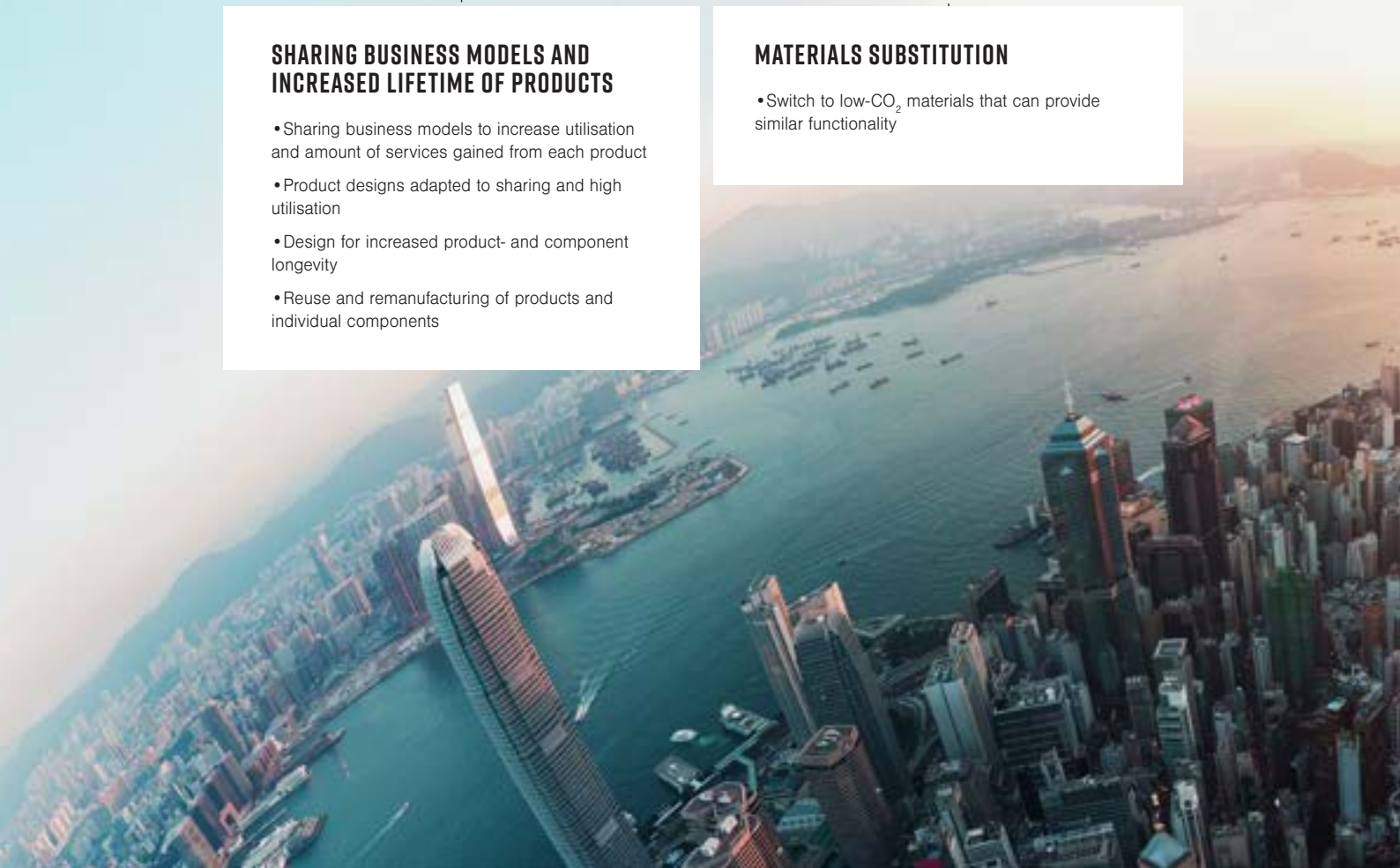
- Increase collection rates
- Improve sorting and decrease contamination for higher quality of recycled materials
- Increase process waste recovery and recycling
- Design for disassembly to facilitate materials separation

SHARING BUSINESS MODELS AND INCREASED LIFETIME OF PRODUCTS

- Sharing business models to increase utilisation and amount of services gained from each product
- Product designs adapted to sharing and high utilisation
- Design for increased product- and component longevity
- Reuse and remanufacturing of products and individual components

MATERIALS SUBSTITUTION

- Switch to low-CO₂ materials that can provide similar functionality



...A LOW-CO₂ MATERIALS SYSTEM

CLEAN PRODUCTION OF NEW MATERIALS



NEW AND IMPROVED PROCESSES

Shifting production processes and feedstocks to eliminate fossil CO₂ emissions



CARBON CAPTURE

Capture and permanent storage of CO₂ from production and end-of-life treatment of materials, or use of captured CO₂ in industrial processes

CLEAN UP CURRENT PROCESSES

- Increase process- and energy efficiency
- Switch to lower-CO₂ fuels and electricity

CARBON CAPTURE AND STORAGE

- CCS on existing production and end-of-life processes
- Reconfigure production processes to enable high concentration of CO₂ and consequently higher capture rates

NEW PROCESSES AND FEEDSTOCKS

- Steel: hydrogen-based steelmaking, smelting reduction, CCU
- Chemicals: bio-based polymers, chemical recycling processes, new processes for by-products
- Ammonia: CO₂-free hydrogen
- Cement: electrification, new binders

CARBON CAPTURE AND UTILISATION

- Use of captured carbon as feedstock in ways that permanently prevent release to the atmosphere as CO₂ emissions

ELECTRIFICATION

- Electrification of production processes and production of key inputs, including hydrogen

A. Circular economy - materials efficiency and new business models in major value chains (58–171 Mt CO₂ potential).

As noted, the EU uses more than 800 kg of steel, cement, plastics, and ammonia per person per year. On the current course, this could increase to 870 kg by 2050. However, there is nothing fixed or absolute about these amounts. Materials are not consumed for their own benefit, but for the services they provide: structure in buildings or vehicles, protection and barrier properties in packaging, etc. The idea of materials efficiency is to provide the same benefits and functionality with less materials use – or, equivalently, getting more useful service out of every tonne used.

This concept is hardly new to climate policy. Indeed, for energy, the EU has adopted a principle of ‘efficiency first’.¹⁹ The large policy attention devoted to energy efficiency is based on the

proven potential to achieve the same lighting, mobility, thermal comfort, etc., with less energy input. Materials efficiency plays an analogous role in the transition to a low-CO₂ industrial economy.

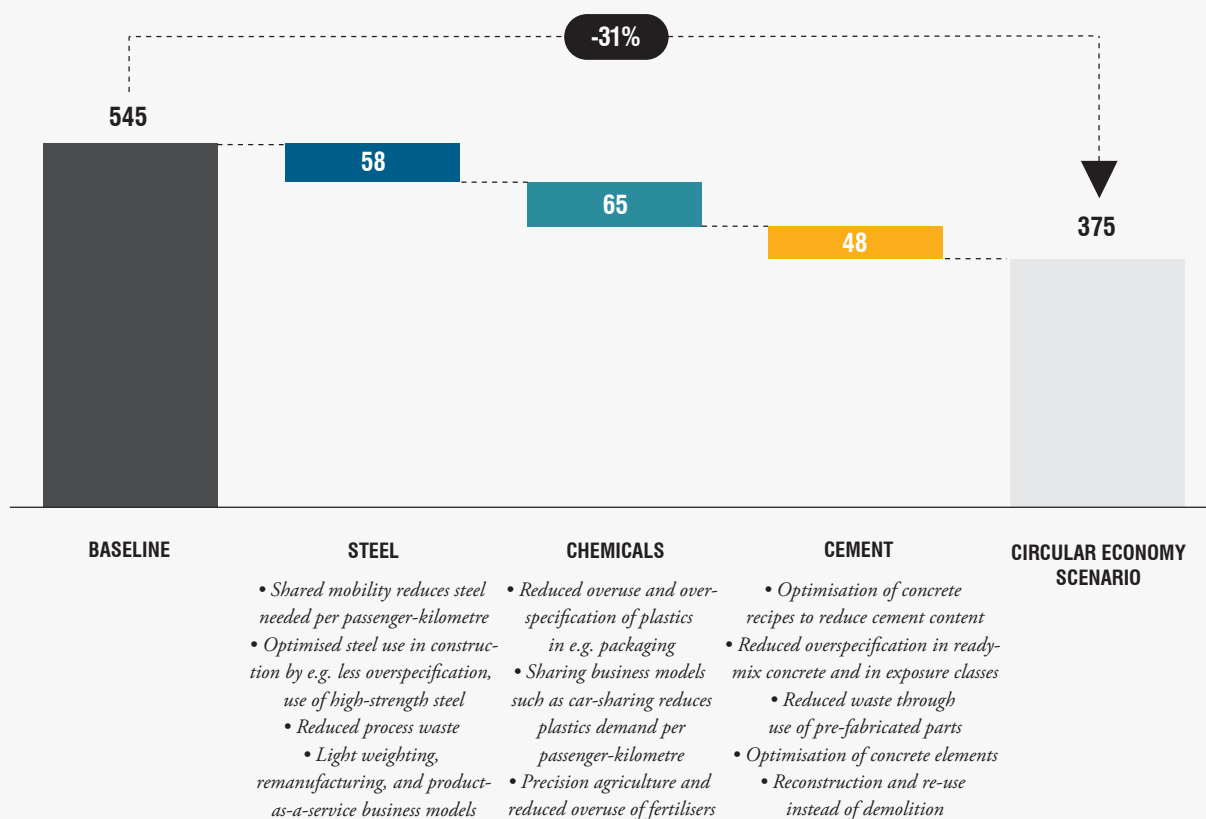
This study builds on an extensive review of opportunities to improve the productivity of materials use in large value chains including construction, transportation, and packaged goods. It finds that the opportunity is surprisingly large: whereas *A Clean Planet for All* explored reductions of 6–11% of materials use, this study finds potential to reduce steel, plastics, ammonia and cement use from 870 to 570 kg per person per year, without compromise on the underlying benefits – a reduction of 35%. This translates to a reduction of CO₂ emissions of 171 Mt CO₂ per year, or 31%, in an ambitious case (Exhibit 1.5).

Therefore, a key finding is that materials efficiency can make a major contribution to climate objectives.

Exhibit 1.5

MATERIALS EFFICIENCY AND NEW BUSINESS MODELS IN MAJOR VALUE CHAINS CAN CUT EMISSIONS BY 31%

EMISSION REDUCTIONS FROM MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS
Mt CO₂ PER YEAR, EU, 2050



SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS.

*Materials efficiency place
an analogous role in the
transition to a low-CO₂
circular economy.*



The opportunities range widely, including:²¹

- **Improved design:** Redesign of products with materials efficiency in mind can result in significant savings. Innovation in design is also critical for recycling (see next section).
- **High-performance materials:** For example, high-strength steel and techniques such as post-tensioning can reduce the amount of steel needed for some construction projects by 30%, with similar opportunities for high-performance concrete.
- **Reduced waste during production:** Scrap in some manufacturing chains can be cut by up to 50%, both by adopting current best practice, through more pre-fabrication, and through advanced production techniques like 3D printing. In construction, some 15% of some classes of building materials are wasted.
- **Less over-specification:** Construction projects often use 35–45% more steel than is strictly necessary. Similarly, it is often possible to achieve the same structural strength with only 50–60% as much cement as used today, both by reducing the cement content of concrete and by using less concrete in structures.
- **Higher intensity of use:** New business models based on digitisation, such as car-sharing and product-as-a-service arrangements, enable more concurrent benefits from products, but are also major enablers of other materials efficiency measures. For example, a shared mobility system would enable longer-lived vehicles, improved maintenance, variation in car sizes, and in-

creased use-intensity that jointly can reduce materials use in transport by 50–70% per passenger-kilometre (Exhibit 1.6).

- **Longer lifetimes for products and structures:** A combination of reuse and remanufacturing can ensure materials and products stay in use much longer, reducing the need for new material.

These measures require changes by multiple actors in the main value chains: construction companies, concrete producers, car manufacturers, shared-mobility providers, technology providers, packaging producers, etc. Digitisation is often a key enabler. As with energy efficiency, a long value chain with multiple actors means there are many barriers and market failures, including split incentives, coordination, incomplete contracts, and missing markets. The policy agenda thus needs to not just send the right price signals, but also overcome many other barriers.

An analysis of costs also finds that mobilising these measures can improve the cost-effectiveness of reducing emissions. Many, such as car-sharing, are significant productivity opportunities of new business models, where reduced materials use is one consequence of an overall much more efficient use of resources. In other cases, using less materials requires new inputs: use of data, increased labour inputs, increased inventory and logistics costs, etc. For example, optimising concrete elements or steel beams to reduce total materials use often comes at the cost of increased complexity and coordination, and a need for increased pre-fabrication. Overall, however, the cost of this potential is lower than that of many low-carbon production opportunities.²²

Exhibit 1.6

SHARED MOBILITY CAN DRAMATICALLY CUT EMISSIONS FROM MOBILITY AND REDUCE MATERIALS INTENSITY OF TRANSPORTATION

MAJOR SHIFT OF INNOVATION FOCUS

FROM: Maximizing upfront sales volume and price

TO: Making the car a well-functioning effective part of urban mobility



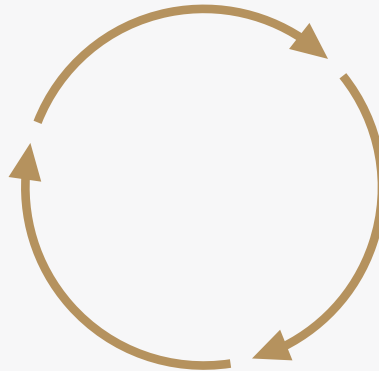
HIGHER UTILISATION PER CAR

SHARING BUSINESS MODELS

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

DIGITISATION AND AUTOMATION

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



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*



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*

SOURCE: MATERIAL ECONOMICS (2018).²³

B. Materials circularity and substitution (82–183 Mt CO₂ potential).

These solutions focus on recirculating steel, plastics, and cement as inputs to new production, instead of making new materials from scratch. Increasing the share of recirculation materials can lead to significant emissions reductions, for three reasons:

1. Recirculation bypasses the process emissions of new production, so it eliminates some of the hardest-to-abate emissions.
2. The energy requirements are much smaller in most cases, and recycling typically can use electricity, which is much easier to render CO₂-free than are fuels used in primary production.
3. In the case of plastics, recirculation helps avoid the emissions from end-of-life incineration.

Steel recycling is already well established, with a largely electrified process. Its use could increase to 2050, as more scrap will become available in the future as the EU steel stock saturates. The EU could therefore choose a path where it meets up to 70% of its needs for iron for steelmaking through recycling. However, this would require significant changes to current practice. Today's product design, end-of-life dismantling, and scrap handling processes result in end-of-life steel being polluted with 'tramp elements' (especially copper) that degrade quality and cannot be removed. A concerted agenda to reduce copper contamination should thus be high on an industrial climate agenda. Alternatively, the EU could export its steel scrap, reducing the need for new iron production in other countries. In either case, preventing the downgrading of the steel stock would make an important contribution to global climate objectives.

In contrast to steel, plastics recycling is only a minor part of the industry. Today's effort focuses on 'mechanical' recycling, where plastic is cleaned and re-melted. However, despite significant efforts, the effective replacement of new plastics production through mechanical recycling in the EU is likely only around 5-10% of the total.²⁴ Much higher rates are possible, but will require major changes. The most important is in how products are designed and used in the first place; even small adaptations can drastically improve the chances of high-quality recycling. Other measures include significant improvements in collection and sorting of plastic waste, and reduced contamination of recycling streams. In

a stretch case, mechanical recycling could supply up to a third of total plastic needs.

For deep emissions cuts, higher rates of recirculation are needed than can be achieved by mechanical recycling alone. 'Chemical' recycling of plastics will be needed. These methods break down plastic molecules and reconstitute them into new products. The idea would be to make end-of-life plastics a major source of feedstock for the EU chemical industry. The processes required are largely known, but need to be further developed to become commercially viable, and there is large scope for innovation. Doing so is a crucial step towards enabling a 'societal carbon loop' that keeps the carbon from plastics circulating in society, instead of escaping into the atmosphere as CO₂. Together, the two approaches to recycling could recirculate up to 60-70% of the carbon in plastics, approaching the recycling levels for aluminium today. Where possible, mechanical recycling is preferable, as it is much more energy- and CO₂-efficient. Chemical recycling requires large amounts of energy input in pyrolysis and electrified crackers, and for hydrogen production.

Recycling opportunities also exist for cement, where the reuse of concrete 'fines' (particles with a small diameter) can reduce process emissions by substituting for new cement. It also is possible to recover some unreacted cement from existing concrete, and to use this in place of new cement.

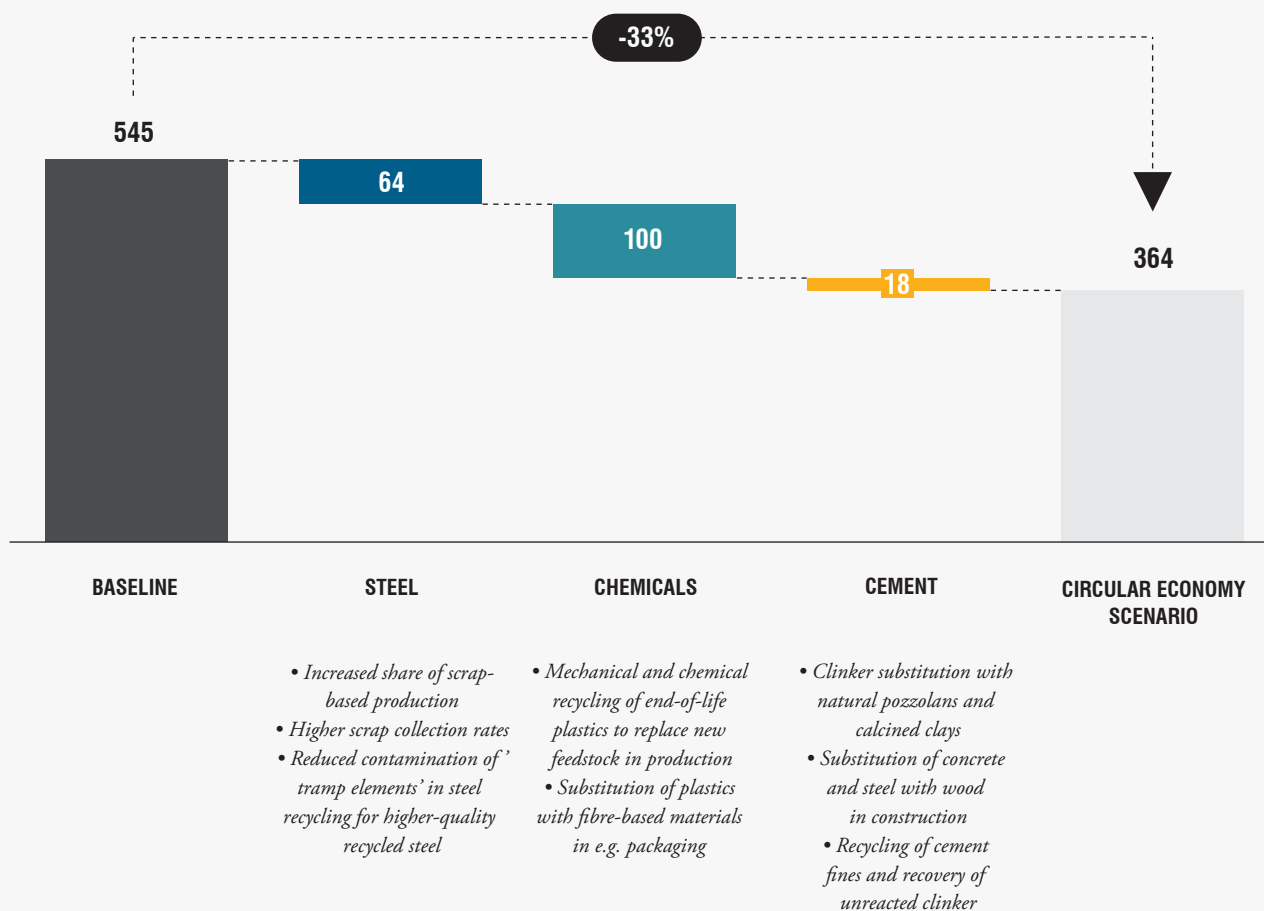
Another option is to replace materials that are hard to make emissions-free with ones that provide similar function but whose emissions (process, energy and end-of-life) are easier to cut. Key examples include the use of materials based on wood fibre instead of plastics in packaging, and the use of wood instead of concrete and steel in construction. Another is to use alternatives to clinker in cement-making, such as calcined clays or natural pozzolans. CO₂ savings could be substantial, but the benefits of such substitution depend heavily on achieving zero emissions from the substituting material. For wood, a key requirement is that the underlying forestry practices capture at least as much carbon as do standing forests (this often is the case with managed silviculture in the EU today).

The total potential for recirculation is large. By 2050, increased recycling of steel, plastics and cement could replace some 150 Mt of new materials production. By also rendering the recycling processes CO₂-free, it is possible to cut emissions by 187 Mt.

Exhibit 1.7

INCREASED MATERIALS RECIRCULATION AND SUBSTITUTION CAN REDUCE EMISSIONS BY 33%

EMISSION REDUCTIONS FROM MATERIALS RECIRCULATION AND SUBSTITUTION

Mt CO₂ PER YEAR, EU, 2050

NOTE: INDIVIDUAL NUMBERS DO NOT SUM UP TO TOTAL DUE TO ROUNDING.

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SECTOR CHAPTERS.

C. New low-emissions processes (143-241 Mt CO₂ potential).

In a baseline case, annual primary production (i.e., new production from new raw materials, as opposed to recycling) of steel, plastics, ammonia, and cement in the EU would amount to some 380 Mt in 2050. Increased materials efficiency and recirculation can cut the need for new production substantially, but 180–320 Mt will still be required. Globally, the need is still larger, as the opportunities for recirculation are lower in economies that have not yet built up their stock of materials to the same level as the EU. For net-zero emissions to be possible, new materials and chemicals production therefore must be rendered CO₂-free.

Such solutions exist or are emerging across all four materials and chemicals (Exhibit 1.8). They have in common that they replace or substantially modify the current core industrial processes. Many are already proven or in advanced development, but need to be further developed and brought to deployment and full commercial scale. In many cases, the new processes require large amounts of electricity – either directly, or indirectly for the production of hydrogen.²⁵ Changing to new processes therefore depends on simultaneously achieving a CO₂-free wider energy system.

Added to that, switching to new processes requires a complex transition from the current production plant, which has a cumulative sunk asset value measured in billions of euros. Finally, Europe must ensure that the new methods are commercially viable, even when they cost more than current methods.

Prominent examples include:

- **For steel**, the two main options are hydrogen-based direct reduction (H-DRI) and smelting reduction. H-DRI builds on existing DRI iron-making technologies, which use natural gas to remove oxygen from iron ore. H-DRI replaces natural gas with hydrogen, eliminating carbon from this step. Direct smelting reduces the number emissions sources from integrated steelmaking, cutting

energy use. However, its main benefit from a CO₂ perspective is that it concentrates emissions to the point where CCS/U is much more feasible (see below).

- **For chemicals**, new processes are needed to enable the use of non-fossil feedstocks: biomass and recirculated plastics. New process steps are also required to process large flows of carbon in fuel-grade products into useful chemicals, thus avoiding process emissions. The new processes would be variations of ones already used extensively in chemicals production. Proven gasification, pyrolysis, digestion, reforming and other steps combine with new platform chemicals and routes (notably, methanol-to-olefins). Together, these can achieve the carbon mass balance of 95–100% required for net-zero production.
- **In current cement production**, 26% of the Portland cement clinker is already replaced with low-CO₂ cementitious materials, such as blast-furnace slag or fly ash. These will need to be gradually replaced by alternatives, including natural pozzolans and calcined clays, while also eliminating CO₂ from their production and processing.
- **High-temperature processes** need to be electrified. This includes electrification of steam crackers, cement kilns, iron ore sintering, steel reheating furnaces, and high-temperature steam production. Several technologies are being investigated and/or developed, including plasma, induction, and microwave energy. In the steel sector, electric arc furnaces are already being used to re-melt steel scrap to new steel. Plasma heating has been successfully used to provide the heat for calcination in cement production. In some cases, substantial energy savings and process improvements could be achieved through electrification.

Producing materials and chemicals through these processes would cut emissions by as much as 241 Mt CO₂ per year by 2050, compared to using current processes.

Exhibit 1.8

KEY NEW INDUSTRIAL PRODUCTION PROCESSES FOR A LOW-CO₂ INDUSTRY TRANSFORMATION



- **Hydrogen direct reduction of iron.** Replacing natural gas with pure hydrogen in direct reduction ironmaking
- **Smelt reduction.** New metallurgy to reduce iron in a molten stage, reducing energy needs while increasing the feasibility of high rates of CO₂ capture for CCS
- **Blast furnace + CCU.** A combination of a) switching to largely circular or bio-based inputs, b) recycling and reprocessing off-gases for chemicals production, and c) CCS on residual emissions
- **Electrowinning.** Producing steel through direct electrolysis (not included in pathways)
- **Electrification of other process steps,** including ore sintering and reheating furnaces (c 1200°C)



Plastics

- **Bio-based plastics** produced from biomass. Key routes include anaerobic digestion or gasification into methanol, and production of olefins via methanol-to-olefins (MTO), or production of bio-ethylene via fermentation of biomass into ethanol
- **Chemical recycling** of end-of-life plastics through e.g. depolymerisation, solvolysis, gasification or pyrolysis + steam cracking
- **Electrification of steam crackers** and reprocessing of by-products into chemicals (e.g. via methanol and MTO) to avoid fuel emissions
- **Reprocessing of by-products** from cracking processes into olefins via e.g. methane-to-methanol and methanol-to-olefins (MTO) to avoid fuel emissions from burning of by-products
- **Innovation and further development** including a) polymers from biomass with closer affinity to the molecular composition of biomass, to increase mass balance and reduce energy demand and b) a range of new catalysts to improve efficiency of all process step

Ammonia

- **Hydrogen production via electrolysis** for ammonia production using renewable electricity and water.



- **Electrification of sintering and calcination** processes (1450 °C) e.g. via plasma or microwave options
- **Alternative binders** such as efficient low-CO₂ processing of natural pozzolans or calcined clays for use as cementitious materials

CROSS-CUTTING THEMES

- **Further development of electrolysis** for energy-efficient production of hydrogen through e.g. solid oxide electrolysis cell (SOEC)
- **Electrification of other core processes** such as steam boiling, and low/medium temperature heat

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SECTOR CHAPTERS.

D. Carbon capture and storage or use (CCS/U) (45–235 Mt CO₂ potential).

CCS relies on trapping carbon dioxide at its source, then permanently storing it so it cannot escape to the atmosphere (normally underground). CCU is a variation on this, embedding it in products instead. In a net-zero economy, CCU would need to provide equivalent certainty that the carbon will not be released as CO₂ emissions.

The potential attraction of CCS is that it would allow the continued use of current processes and production assets, and reduce the need to mobilise large amounts of electricity and biomass. In the four industries studied, CCS could be deployed in a range of settings, both on existing industrial processes, to produce feedstock (especially hydrogen from natural gas), and to handle end-of-life emissions, by combining waste incineration with CCS.

Technology to capture CO₂ is already in an advanced stage, and there are few technical obstacles to prevent the capture of large amounts of CO₂ from the existing industrial base to provide immediate, near-term reductions in emissions. However, neither large-scale demonstration plants nor CO₂ transport and storage infrastructure are yet in place for any of the sectors under consideration here. A significant acceleration of effort would be needed if CCS is to be a large-scale solution by 2050.

Moreover, CCS is far from a ‘plug-and-play’ solution for deep emissions cuts from the industrial sectors considered here. Significant further development would be needed to achieve the capture rates of 90% or more required for a net-zero outcome:

- **In integrated iron- and steel-making**, there are multiple, interlinked emissions sources, which makes it highly challenging to capture more than 60% of emissions. Therefore, to achieve deep cuts through CCS, new ‘smelting reduction’ processes need to be developed that concentrate CO₂ emissions to a single

source, and some process steps, such as ore sintering, will need to be electrified. The alternative is a combination of CCU and CCS, involving significant modification to the current use of blast-furnace production, with recycling and reprocessing of off-gases in combination with using bio-based or recirculated carbon for much of the feedstock, and CCS for the remaining CO₂. Both cases would require major changes to current production, amounting to the introduction of altogether new production processes.

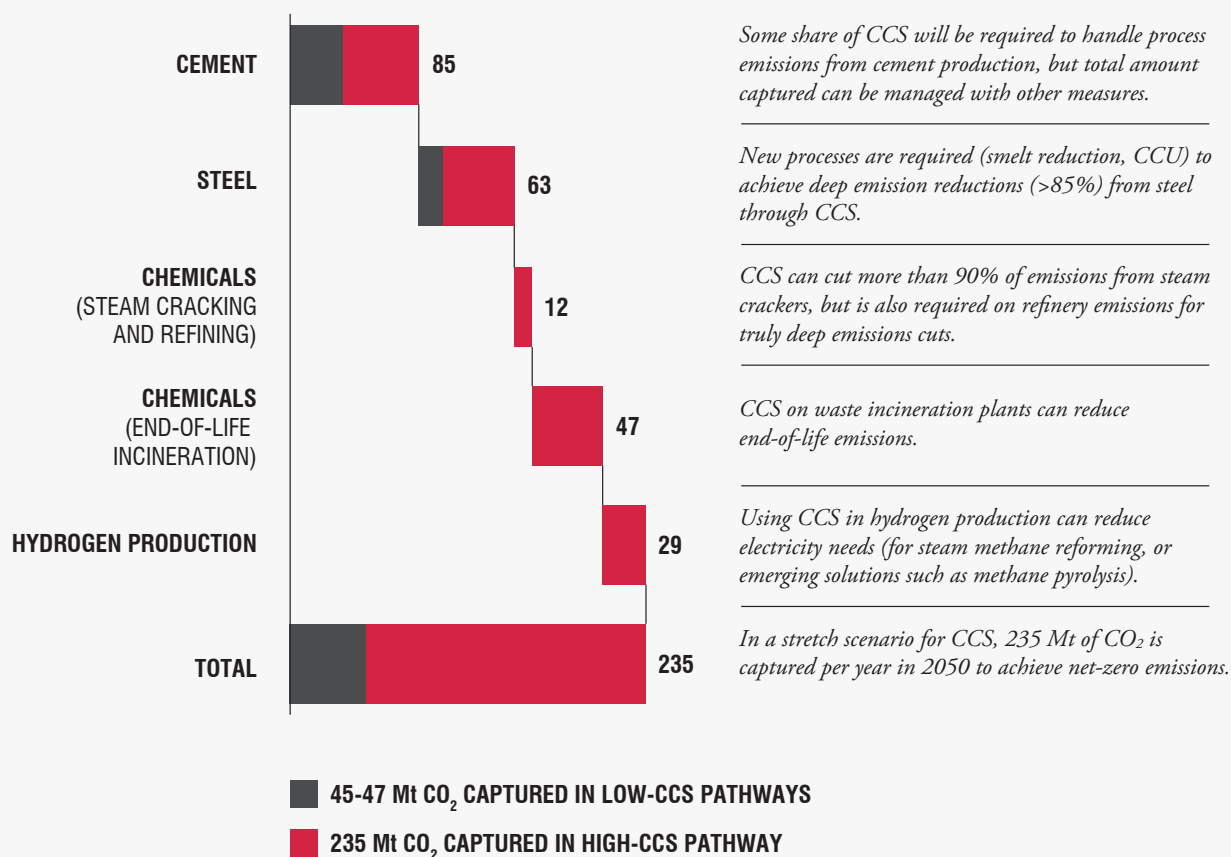
- **For chemicals**, even if high capture rates were achieved from steam crackers, the ‘embedded’ carbon in the product would still remain, as would the upstream emissions to produce feedstock in refineries. CCS works best on large point sources with highly concentrated CO₂ emissions in proximity to suitable storage. In contrast, CCS as a solution to plastics emissions would require capture not just at the roughly 50 steam crackers in the EU, but also on many hundred widely distributed waste incineration plants and on upstream refineries.
- **For cement and end-of-life** emissions from plastics, the challenge is similar to waste incineration, in that these industries are highly dispersed. There are nearly 200 cement kilns scattered across the EU. Deep cuts through CCS alone would require near-universal transport and storage infrastructure throughout the EU.

Finally, large-scale use of carbon capture technologies requires an extensive transport and storage infrastructure. Public provision and/or regulation may be a requirement. Public acceptance of CO₂ storage has also been a major stumbling block to early attempts to scale up CCS.

Despite these challenges, there is no question that CCS could provide valuable early emissions reductions and play a role in a fully net-zero production. High capture rates of 90% or more could be combined with bio-based inputs for a truly net zero-CO₂ solution. In a stretch case, some 235 Mt of CO₂ could be captured from a wide range of sources in the overall materials system (Exhibit 1.9).

*Exhibit 1.9***CCS COULD BE USED ACROSS A WIDE RANGE OF INDUSTRIAL SOURCES, WITH 235 Mt CO₂ CAPTURED BY 2050 IN A STRETCH CASE**

CARBON CAPTURE AND STORAGE (CCS)
Mt CO₂ CAPTURED PER YEAR, 2050



NOTE: INDIVIDUAL NUMBERS DO NOT SUM UP DUE TO ROUNDING.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SECTOR CHAPTERS.

1.2 THE CHOICE AHEAD: PATHWAYS TO NET-ZERO EMISSIONS FOR INDUSTRY

The sheer breadth of solutions across the four strategies for emissions reductions is encouraging. However, views will inevitably differ on which solution is most promising. Conversations with a large number of industry and other stakeholders for this study reveal large differences of opinion about which solutions will be easiest to mobilise rapidly and at scale, with the greatest advantages for European competitiveness.

The approach taken here is therefore not to try and predict a most likely (let alone an ‘optimal’) path ahead. Instead, the study recognises that EU companies and society can choose different ways, and explores three illustrative pathways (Exhibit 1.10). All three have in common that they leave no or very few emissions in place in 2050, and all three use the full set of solutions for net-zero industry, but each with different emphasis (see figure below).



NEW PROCESSES

Pathway

New Processes relies heavily on new core industrial processes, often driven by electricity.



CIRCULAR ECONOMY

Pathway

Circular Economy hinges on the potential of a more circular economy for materials recirculation and increased materials efficiency.



CARBON CAPTURE

Pathway

Carbon Capture emphasises a greater role for carbon capture and storage (CCS).

The intention of the analysis is to aid both policy-makers seeking to enable a low-CO₂ transition industry, and companies setting their strategy in highly uncertain times. The pathways show some no-regret options, such as solutions required in all three pathways, and innovation and infrastructure priorities.

They also illustrate some of the major dependencies, sensitivities and choices ahead. (For example, if the electrici-

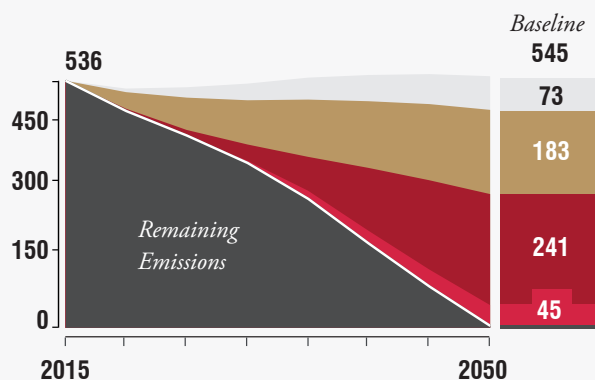
ty requirements in one pathway seem unmanageable, how much could they be reduced by mobilising circular economy solutions or CCS? Alternatively, if large-scale CCS were to prove difficult, how quickly would new, non-fossil production processes need to scale?) The analysis also estimates the costs (to society, to consumers, and to companies) of achieving net-zero emissions, as well as the requirements in terms of investment and inputs.

Exhibit 1.10

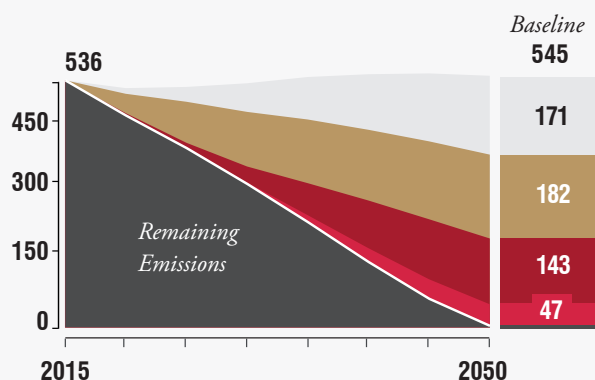
PATHWAYS TO NET-ZERO EMISSIONS FOR STEEL

EMISSION REDUCTIONS FROM STEEL, CHEMICALS, AND CEMENT

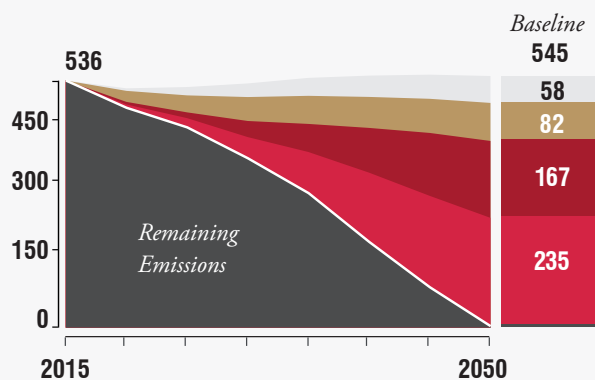
Mt CO₂/YEAR



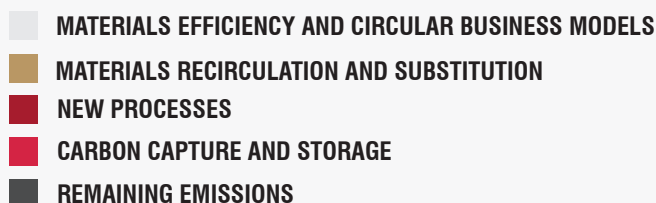
- Relies heavily on new core industrial processes driven by electricity, either directly or through the use of hydrogen
- Key enablers are abundant and cost-competitive electricity supply and rapid commercialisation of new processes



- Hinges on the potential of a more circular economy for materials recirculation and increased materials efficiency
- Key enablers are new business models, digitisation and extensive coordination across the value chain



- Emphasis on a greater role for carbon capture and storage (CCS)
- Key enablers are a critical mass of infrastructure and risk distribution for CCS, and reconfiguration of production processes to allow for high CO₂ capture rates



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SECTOR CHAPTERS.



NEW PROCESSES

Pathway

New Processes pathway

In this scenario, most emissions reductions are achieved through the introduction of new core production processes and new feedstocks. This is near a maximal electricity demand scenario, and also emphasises new feedstocks including end-of-life plastics and bio-based inputs for chemicals. Key themes are innovation, electrification and investment.

To get on this pathway, innovation must accelerate significantly. Emerging low-CO₂ production routes need to be rapidly developed and start large-scale commercialisation by the 2030s, followed by rapid investment and deployment. Current industrial companies are key actors, making early decisions to adjust production to new production routes. Policy must enable the associated investment and provide the basis for an underlying business case. The more abundant and cost-competitive that zero-carbon electricity becomes, the easier this pathway becomes.



CIRCULAR ECONOMY

Pathway

Circular Economy pathway

Here the EU succeeds in a transition to a much more circular economy, capturing a large share of the potential for materials recirculation, materials efficiency, and new business models. Jointly, these account for nearly 50% of the emissions abatement. As a result, the need for materials production from raw materials falls to just 180 Mt, as compared with 380 Mt in the baseline.

Much of the abatement is undertaken by actors in the main materials-using value chains: concrete producers, building companies, manufacturers, new mobility providers, retailers and packaging companies, etc. Innovation in product design and digitisation to measure and track materials use are major enablers, as are new business models based on sharing and product-as-a-service, and the deployment of new construction and manufacturing techniques. In addition, the pathway requires tight control and large mobilisation of end-of-life materials flows (steel scrap, demolition waste, end-of-life plastics, and other waste).

In this pathway, new clean production processes are also required, with emphasis on those that have close affinity to recycling: H-DRI used jointly with a high share of scrap in steel production, and new processes for chemical recycling in plastics production.



CARBON CAPTURE

Pathway

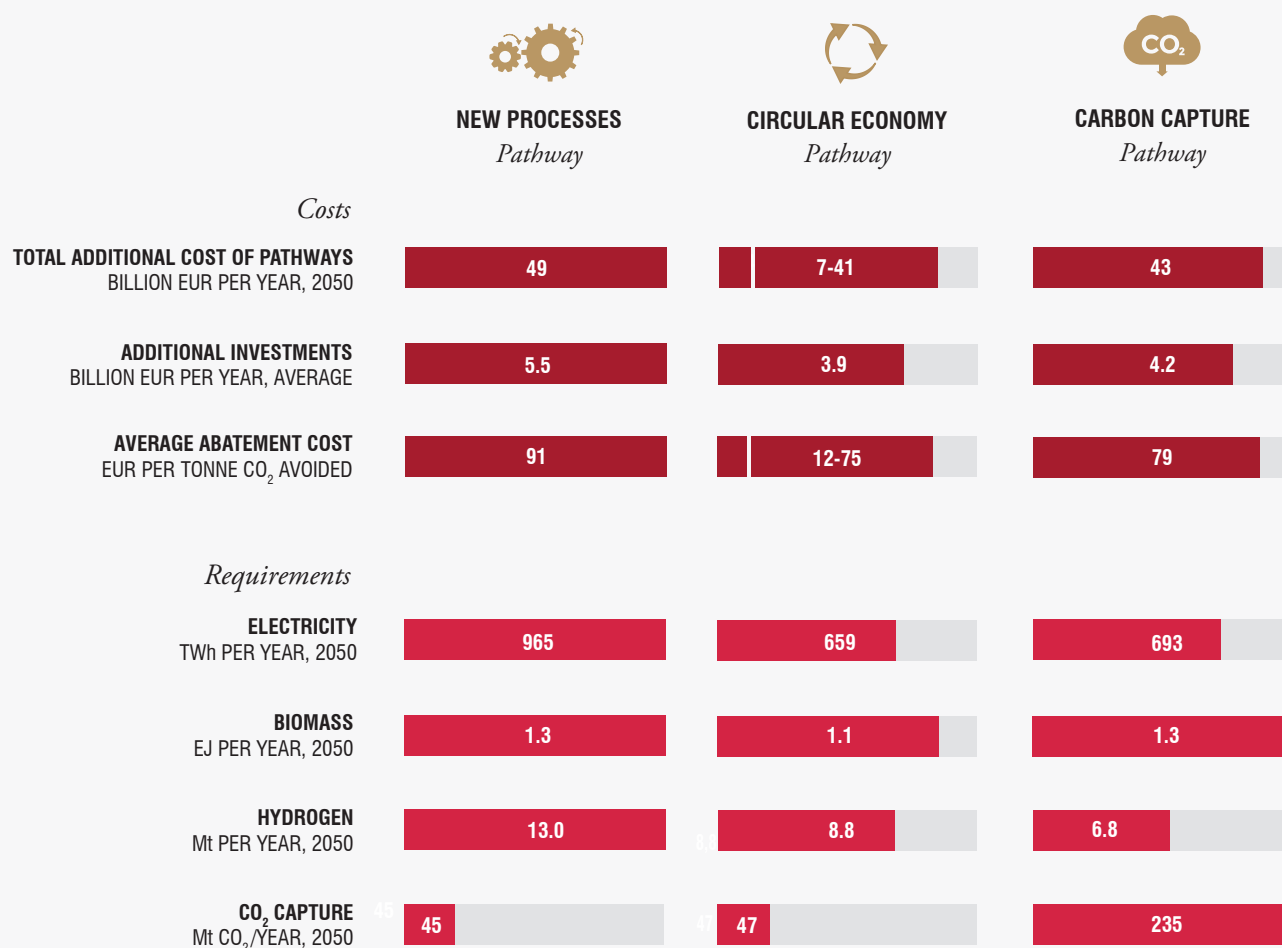
Carbon Capture pathway

In this pathway, a critical mass of infrastructure for carbon capture is a key enabler of major emissions cuts. Most of the 235 Mt of captured CO₂ is stored underground. CCU can play a role, notably in sector coupling of steel and chemicals production. Extensive carbon capture provides early emissions reductions, buying time for a more gradual introduction of new processes. It also reduces electricity demand relative to the New Processes pathway.

In this pathway, there is concerted effort to demonstrate the viability of CCS across multiple uses, with demonstration plans in place by the early 2020s across multiple sectors and uses. Companies across all sectors need to start the development agenda to adapt production processes as required for high CO₂ capture rates. Policy plays a key role not only in giving confidence that the increase costs to companies can be recovered, but also in coordinating carbon capture with the building and operation of infrastructure for transport and storage. Social acceptance of carbon storage is a requirement. By 2050, CCS is a standard feature across industrial production and waste-to-energy plants.

Exhibit 1.11

COSTS, INVESTMENTS AND INPUT REQUIREMENTS FOR NET-ZERO EMISSIONS IN 2050



NOTES: RANGES FOR CIRCULAR ECONOMY PATHWAY COSTS REPRESENT LOW AND HIGH COST ESTIMATES.

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SECTOR CHAPTERS.

TOTAL COSTS TO THE ECONOMY ARE MODEST, BUT INDUSTRIAL COMPANIES WOULD FACE COSTS UP TO 115% HIGHER THAN CURRENT PRODUCTION

An analysis of the costs of achieving net-zero emissions in the four industries reveals a telling contradiction.

On one hand, the total costs for consumers and the overall economy are manageable. The prices of end products such as cars, houses, and packaged goods would increase by less than 1% to pay for more expensive materials. Therefore, the added cost of low-CO₂ materials will barely be noticeable in the 2050 cost of transportation, infrastructure, buildings, packaging and consumer goods.

On the other hand, the business-to-business impact is large. New low-carbon production routes cost 20–30% more for steel, 70–115% more for cement, and potentially 15–60% for chemicals (plastics and ammonia), consider-

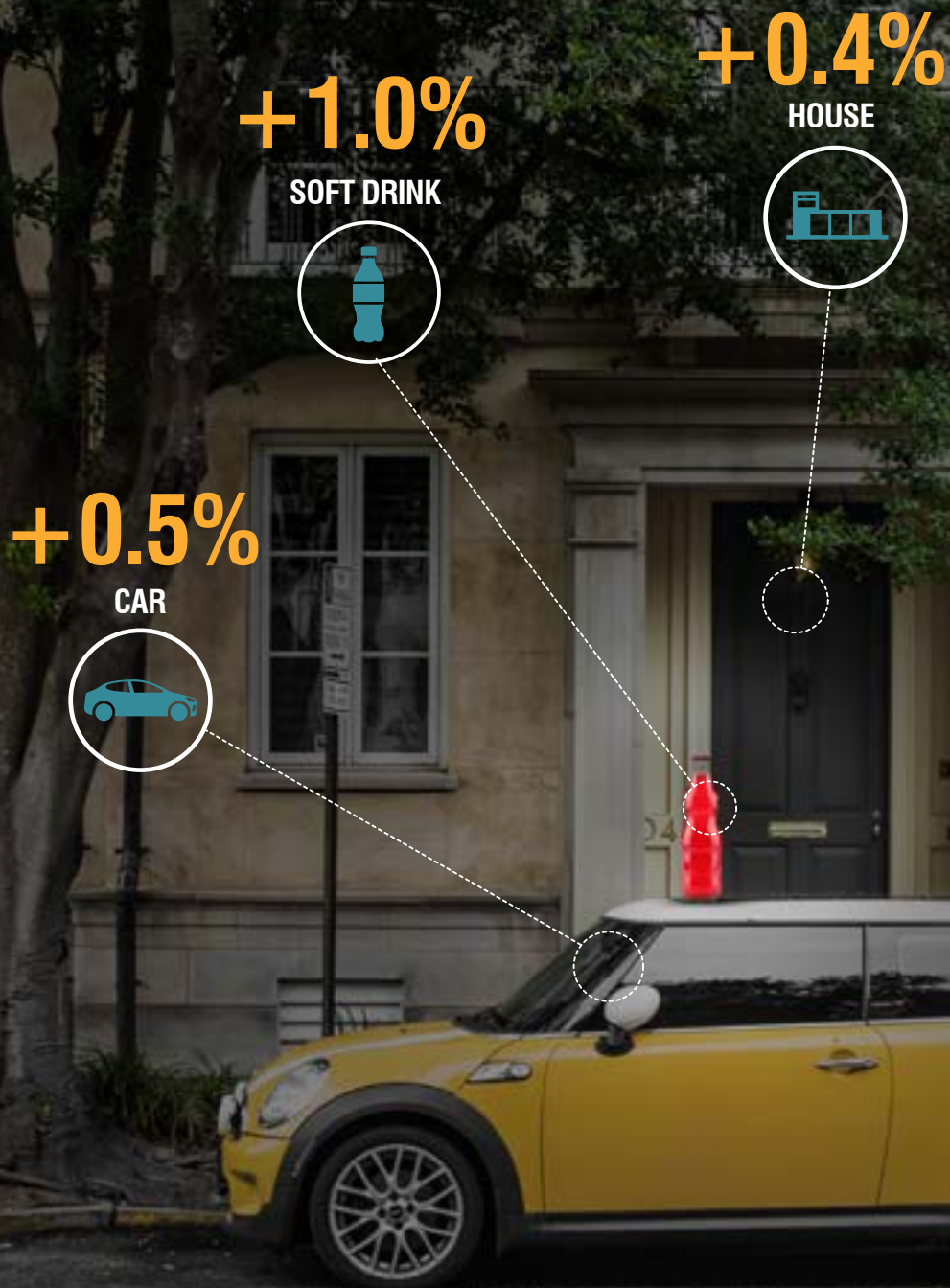
ing both capital and operating expenditures (Exhibit 1.13). Significant policy support will therefore be required for low-CO₂ processes to become viable. Many of the relevant products are sold on commodity markets, where systematic cost differences cannot be borne. Finding a way to handle this is essential for a successful EU industrial transition: both to avoid EU companies losing out to international competitors ('leakage'), and to enable pioneers within the EU.

Policy-makers need to keep both issues in mind. The transition need not be costly to consumers, or have a large impact on GDP, but a successful transition to net-zero industry nonetheless depends on ensuring that companies remain profitable and competitive.

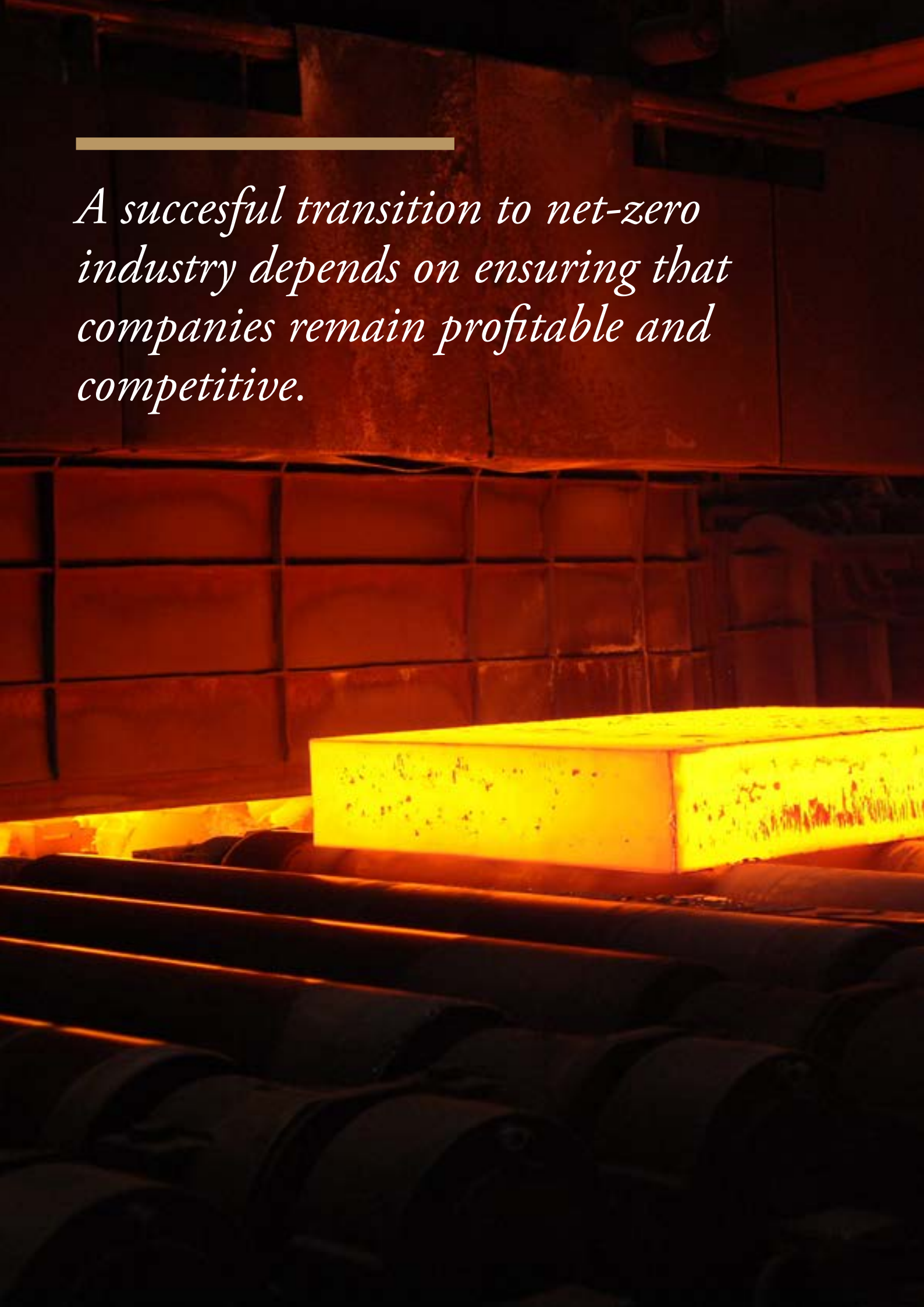
Exhibit 1.12

COSTS FOR END-USERS INCREASE BY LESS THAN 1% IN NET-ZERO PATHWAYS

TOTAL PRODUCT COST INCREASE WITH INCREASED MATERIAL COSTS
% INCREASE



SOURCE: MATERIAL ANALYSIS, SEE ENDNOTE.²⁶

A glowing yellow rectangular object, possibly a piece of metal or a light source, is positioned on a dark, textured surface. The background is dark and indistinct, with some faint, blurry shapes that could be other objects or parts of a machine. The overall lighting is dim, with the primary light source being the glowing object.

*A succesful transition to net-zero
industry depends on ensuring that
companies remain profitable and
competitive.*

Exhibit 1.13

COSTS OF MATERIALS PRODUCTION INCREASE IN A LOW-CO₂ TRANSITION



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SECTOR CHAPTERS.

There are differences between pathways, but not to the point where cost alone is a basis for choosing one production route over another.

Specifically, the estimated cost of providing the required materials and chemicals in a baseline scenario is €201 billion per year (this refers to core processes only, not to finished products). In the pathways this increases by 3–25%, to €208–251 billion per year. The average abatement cost is €12–91 per tonne of CO₂ (Exhibit 1.14).

There are differences between pathways, but not to the point where cost alone is a basis for choosing one production route over another. More emphasis on CCS does not appear systematically cheaper than new production processes, if electricity prices remain below €50 per MWh.

Instead, the main difference between pathways is that a more circular economy could capture some significant productivity improvements that reduce costs. In the Circular Economy pathway, costs could be as low as €208 billion, just 3% higher than in the baseline. The average abatement cost would then be just €12

per tonne of CO₂. This is because some of the measures offer productivity opportunities and thus cost savings compared with the production of new materials. Examples include car-sharing models for mobility, reduced contamination of end-of-life flows, reduced waste in manufacturing, construction enabled by new manufacturing techniques, and co-benefits from the reduction of other externalities.

On the other hand, estimates of the cost of demand-side measure are much less developed than are ones of production. As with energy efficiency, there is a possibility that there are 'hidden' transaction costs that are missing from bottom-up estimates. A highly conservative approach would be to entirely exclude the possibility of cost savings (so that no measure is ever cheaper than the production of an equivalent amount of new materials). In such a scenario, costs would rise to €242 billion per year, virtually identical to the CCS pathway.

Exhibit 1.14

THE TOTAL COST OF ACHIEVING THE NET-ZERO PATHWAYS IS 3-25% HIGHER THAN IN THE BASELINE

TOTAL COST OF PATHWAYS, 2050
BILLION EUR PER YEAR

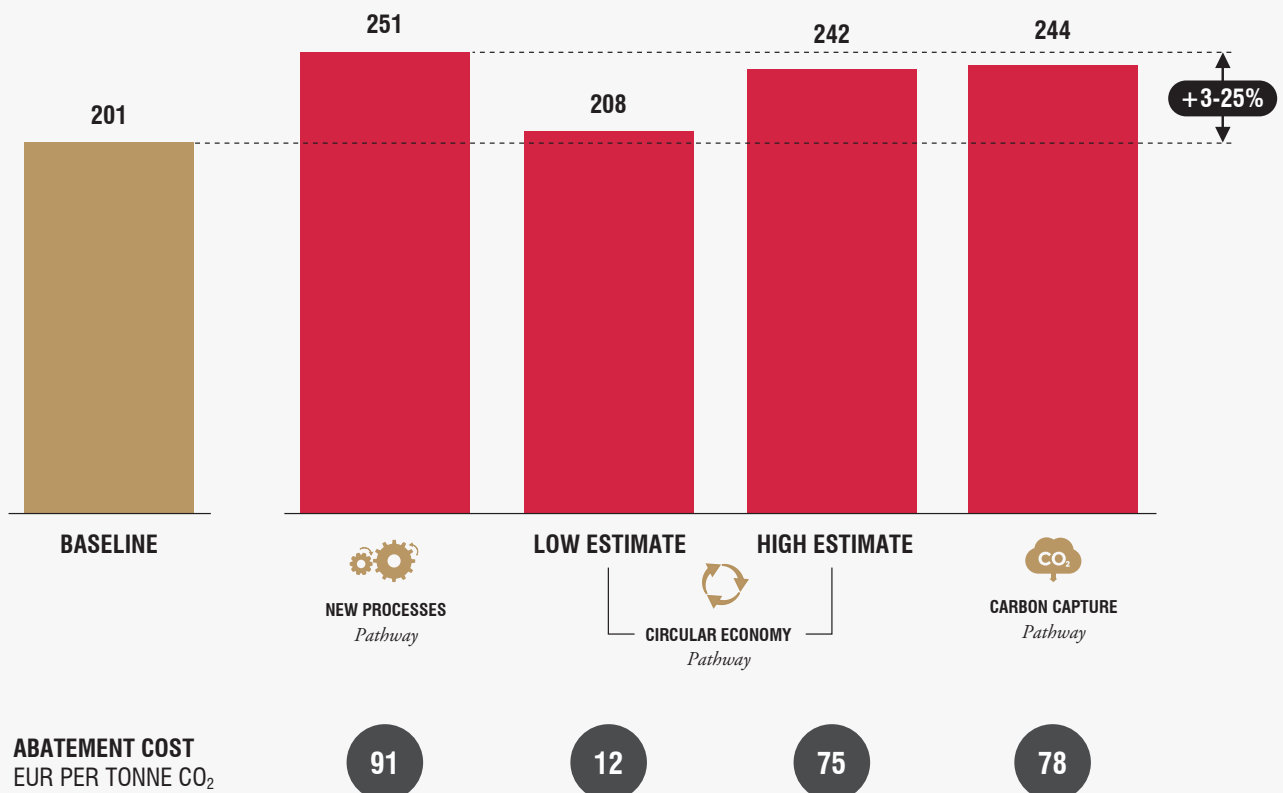
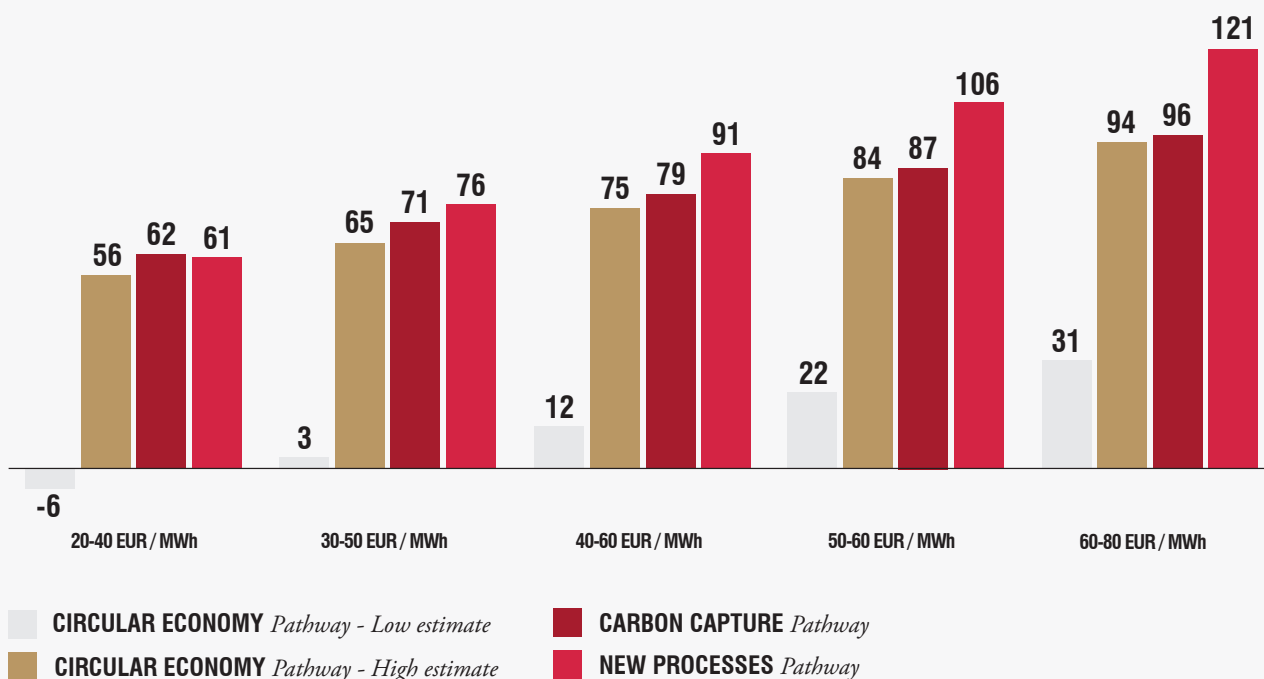


Exhibit 1.15

THE AVERAGE COST OF ABATEMENT VARIES FROM €56–121 / t CO₂ DEPENDING ON ELECTRICITY COST AND PATHWAY

AVERAGE ABATEMENT COST IN PATHWAYS FOR DIFFERENT ELECTRICITY PRICES, 2050
EUR per tonne CO₂



NOTE: THE LOWER END OF THE RANGE REFLECTS THE COST OF ELECTRICITY FOR FLEXIBLE HYDROGEN ELECTROLYSIS. THE HIGHER END OF THE RANGE REFLECTS PRICES FOR NEAR-CONSTANT LOADS, SUCH AS ELECTRICAL PROCESS HEATING. THE BAR CHART IN THE MIDDLE (40-60 EUR/MWH) IS USED IN THE PATHWAYS.

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

For the zero-CO₂ production opportunities, the main determinant is the cost of inputs. The estimates presented here are based on fossil fuel and biomass prices in widely accepted climate scenarios, and similar to today's levels.²⁸ For electricity, the price range is €40–60 per megawatt-hour (MWh), depending on application. The higher end of the range is for 'always on' loads, such as electrified heating, and is similar to 'whole system' cost estimates for a system largely based on renewable energy.²⁹ The lower end of the range is based instead on prices available to flexible loads, and specifically to hydrogen production.³⁰ These prices rely on continued reductions in the price of renewable electricity generation.

Costs of electricity as well as other resources will vary both across the EU and over time. This is another reason why cost alone is not a basis for choosing between different production routes at this point in time.

Arguably, these estimates of future costs are conservative, as they rely solely on currently known processes. Innovation may well lead to substantial cost cuts, particularly if R&D in these areas is enhanced. Nonetheless, the safe bet for EU policy is that low-emissions cement and chemicals production, in particular, will still face a cost disadvantage relative to production based on fossil fuels.

Input costs will also affect processes and thus pathways in different ways. In general, average abatement costs are similar across pathways for electricity prices up to €50 per MWh (Exhibit 1.15). After that point, the New Processes pathway starts to become more expensive, reflecting its higher dependence on electricity. This illustrates how the circular economy and carbon capture pathways provide ways to insulate against scenarios with very high electricity costs.

THE TRANSITION WILL REQUIRE ADDITIONAL INVESTMENTS OF €3.9–5.5 BILLION PER YEAR

All pathways require an increase in capital expenditure. Whereas the baseline rate of investment in the core industrial production processes is around €5.1 billion per year, it rises by up to €5.5 billion per year in net-zero pathways, reaching €11–14 billion per year in the 2030s. Investments are highest in the New Processes pathway. In the Circular Economy pathway, less investment capital is needed be-

cause many solutions are less capital-intensive than is new production. In the Carbon Capture pathway, somewhat less investment is required because more of existing production assets can be maintained, but from a 2050 perspective, the effect is relatively modest. Overall, investments thus increase by 76–107% on a baseline scenario where current production routes are maintained.

Exhibit 1.16

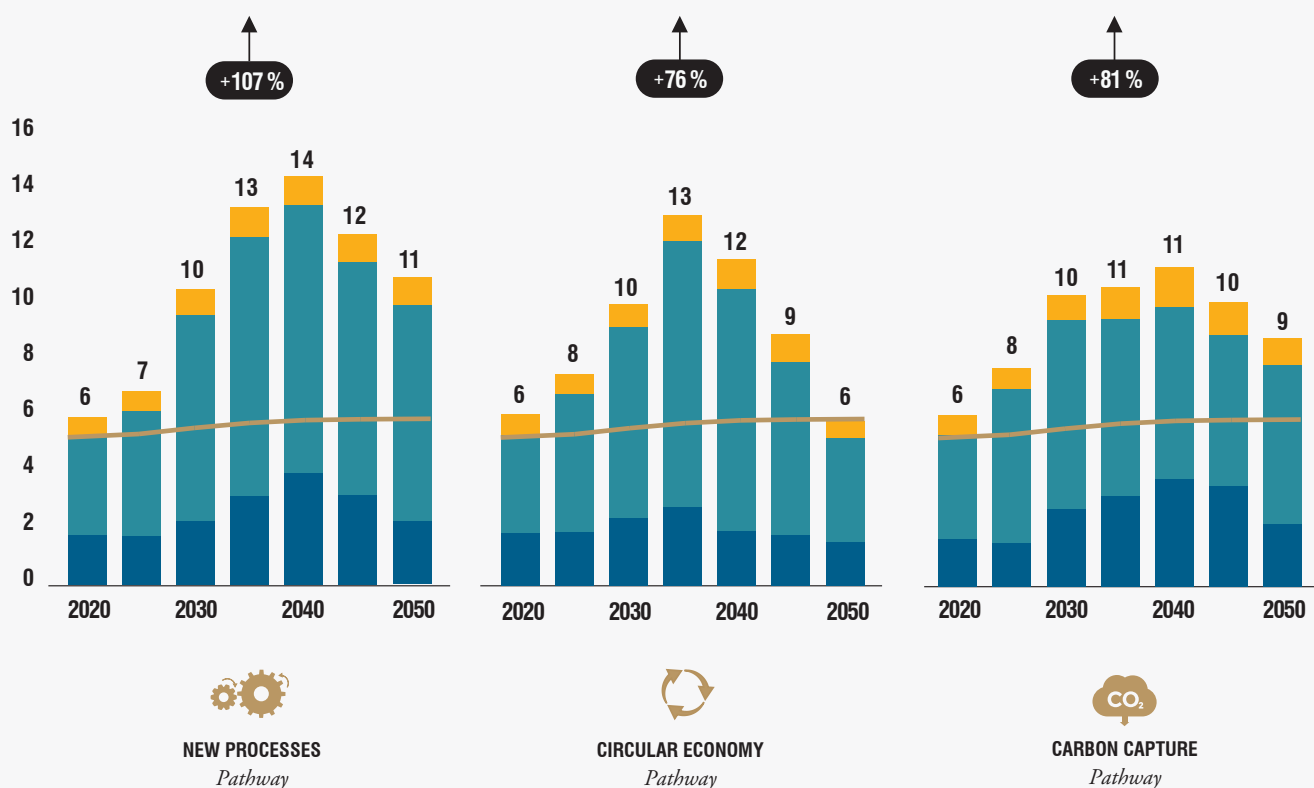
INVESTMENT NEEDS INCREASE BY 76–107% ACROSS THE PATHWAYS

INVESTMENTS IN PRODUCTION OF CRUDE STEEL, CEMENT, AND CHEMICALS
BILLION EUR PER YEAR

INCREASE RELATIVE TO BASELINE

+ X %

CEMENT
CHEMICALS
STEEL
BASELINE



NOTE: INVESTMENT IN CORE INDUSTRIAL PROCESSES ONLY, DOES NOT INCLUDE DOWNSTREAM PRODUCTION.

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN SECTOR CHAPTERS.

The most important policy instrument for investment in low-CO₂ production is to ensure a future business case for higher-cost production routes.

For society as a whole these are not, in fact, large amounts. They correspond to just 0.2% of gross fixed capital formation. For steel and plastics, they could be recovered, including a return on capital, by paying on average €30 per tonne more for products that often cost €600–1,500 per tonne in today's markets.

For industrial companies, however, the investment will be a major challenge. In capital-intensive sectors, choosing a low-CO₂ solution instead of reinvesting in current facilities can amount to a 'bet the company' decision – especially when future technical and commercial viability are uncertain. Added to this, the underlying case for investment in the EU's industrial base has been challenged for more than a decade. Strong policy support will be required for investment to be viable.

In addition to investment in the materials system itself, there is a need for investment in new infrastructure. For example, whereas oil and gas require investment in new exploration and extraction (largely outside the EU), mobilising the additional electricity required for a low-CO₂ industry would require on the order of €5–8 billion per year. A similar logic applies to the transport and storage infrastructure required for CCS at scale, and (to a lesser extent) to new waste handling, logistics, and other infrastructure required for increased materials recirculation.

The most important policy instrument for investment in low-CO₂ production is to ensure a future business case for

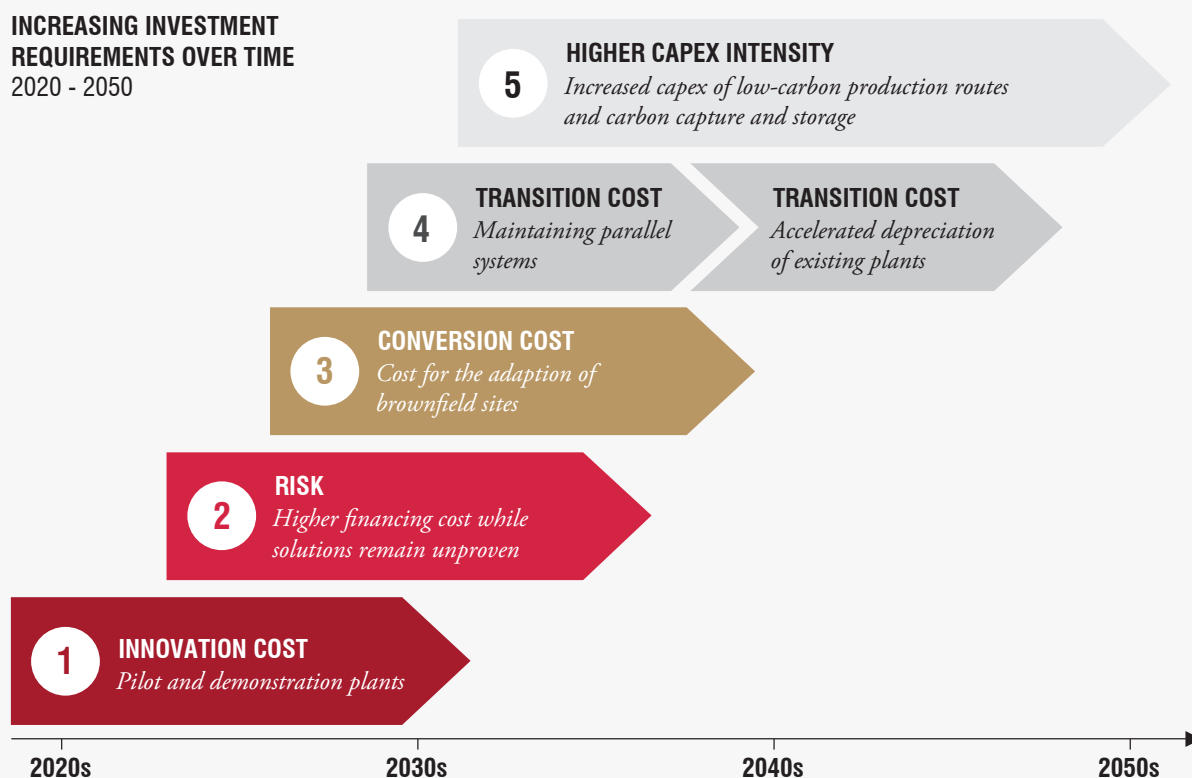
higher-cost production routes. However, doing this right requires understanding why increased investment is needed at different points in the transition. There are five distinct reasons, each with their own dynamic (Exhibit 1.17).

Many of these investment decisions are imminent. While 2050 is more than 30 years away, many core production assets have a lifetime of 20–50 years or more. Many EU industrial facilities such as coke ovens, blast furnaces and steam crackers will need replacement or large re-investment in the next 15 years. There is a risk of lock-in unless low-CO₂ options are viable at these forks in the road. Changes to value chains and business models, meanwhile, may take decades to get established. There is time for deep change until 2050, but it will have to happen at a rapid pace, and any delay will hugely complicate the transition.

In the Circular Economy pathway, investments are lower than those in traditional production. This is especially so as the additional investments in electricity generation and in carbon transport and storage (not included above) are not required. Still, some investment is required in assets ranging from new waste handling infrastructure to new systems for tracking and sorting materials. In addition to mobilising more capital, it will therefore be necessary to enable a new set of actors to invest, and to enable existing producers to vertically integrate into these new sources of value creation. As with any shift in the type of actor and investor, new sources of finance will need to be mobilised.

Exhibit 1.17

INVESTMENT NEEDS INCREASE BY 76–107% ACROSS THE PATHWAYS



Innovation costs:

Early on in the transition, it will be necessary to invest in pilot and demonstration plants. The investment amounts required are not, in fact, large compared with overall investment volumes in the sectors. For individual companies they can be among the most challenging, as demonstration rarely offers a return in its own right. As much of the benefit from these innovations go to society as a whole, there is a high risk of underinvestment without policy support.

Increased risk:

The early investments will be undertaken in a situation of significant uncertainty about technical viability, future availability and cost of new inputs, and degree of policy support. Increased risk in turn increases the bar for raising capital, and the cost of both debt and equity.

Conversion costs:

Additional investment will be required to adapt current production sites. Much of the new, low-CO₂ production capacity will be on the same locations as current industrial facilities. Switching the process then requires investment not just in the core production machinery, but also in a range of supporting and integrating functions: raw materials loading and storage, site transportation, pipeline networks, electricity and utility supply, buildings to house new production, etc. These one-off costs come when the new technologies are first put in place, and in steel and chemicals, they can be substantial.

Transition costs:

Many companies will want to keep their options open and maintain some degree of redundancy, to avoid fully committing themselves to a risky solution. The gradual transition from one system to another will thus require some degree of parallel production systems, with dual investment requirements as a result. In addition, unless all investments are perfectly timed, there is a risk that existing assets must be written off ahead of the end of their technical lifetime.

Higher capex intensity:

From the mid-2030s, the main reason for increased investment will be the intrinsic higher capex associated with some low-CO₂ processes and with carbon capture and storage. This is particularly marked in chemicals, where there is a need to replace a single core process (steam crackers) with alternatives containing multiple loops to achieve a high carbon balance and very low CO₂ emissions.

INPUTS – FROM IMPORTED FOSSIL FUELS TO INDIGENOUS RESOURCES AND LARGE ELECTRICITY USE

In all sectors, the transition to net-zero emissions takes place through a marked shift in the inputs used for materials production. Steel, cement, plastics, and ammonia production together use 8.4 EJ of mostly imported oil, coal and natural gas, rising to 9.1 EJ in a baseline scenario. In the pathways, this is largely replaced by domestic resources: increased materials efficiency, recirculated steel and plastics, electricity, hydrogen and biomass (Exhibit 1.18). Only with widespread use of CCS does substantial use of fossil fuel and feedstock persist, amounting to 3.1 EJ in 2050.

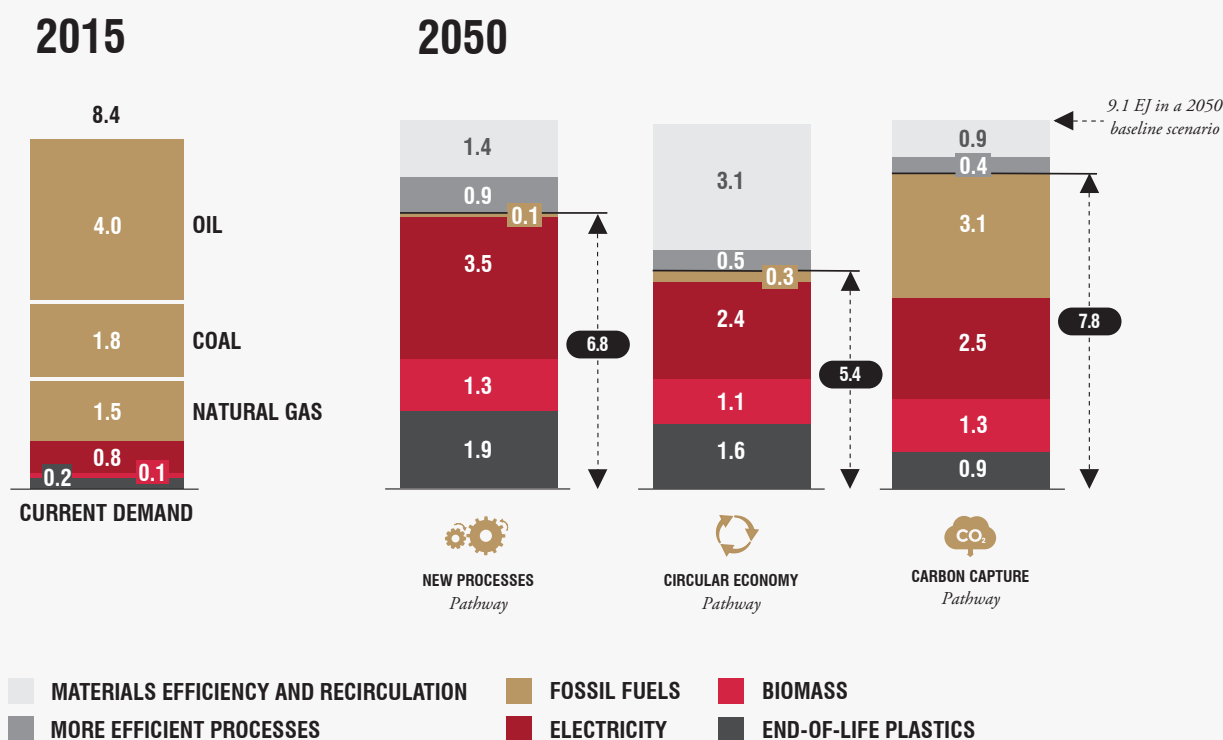
Circular economy solutions play a major part in enabling this transition away from fossil resources. As much as

3.1 EJ of fossil fuels and fossil feedstock can be avoided through the recirculation of materials and more efficient use in major value chains. The main reason is the materials efficiency solutions substitute energy and feedstock resources for other inputs: labour, digitisation, logistics, and comparatively simple industrial and manufacturing processes. The other reason is that recirculating materials is much less energy-intensive, and it eliminates the need for new feedstock materials. The main exception here is chemical recycling: while this eliminates the need for new feedstock, it can require as much energy as today's production routes in order to achieve the very low emissions required for net-zero solutions.

Exhibit 1.18

THE TRANSITION TO NET-ZERO EMISSIONS INDUSTRY ENTAILS A REDUCTION IN ENERGY AND FEEDSTOCK USE AND A MAJOR CHANGE IN INPUTS

ENERGY NEED AND MIX, TODAY AND IN 2050
EJ PER YEAR



SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS.



ELECTRICITY REQUIREMENTS WOULD GROW BY 450–750 TWh

Electricity needs are particularly large. Depending on the pathway, 450–750 terawatt-hours (TWh) of additional low-carbon electricity will be needed in the production of steel, plastics, ammonia and cement (Exhibit 1.19). For comparison, all EU industries today use 1000 TWh per year, which is 32% of total electricity production in the EU today and corresponds to 200,000 wind turbines.³¹ In the pathways, the chemicals sector uses the largest amount, followed by steel. In both cases, a major source of demand for electricity is water electrolysis for the production of hydrogen, which varies between 7 and 13 Mt per year in 2050.

Despite the large numbers, these levels of electricity demand are significantly lower than in some other analyses of a net-zero emissions future for industry. For instance, one report for the chemicals sector estimated that for the chemicals industry to achieve major emissions cuts would require 4,900 TWh of low-emissions power.³²

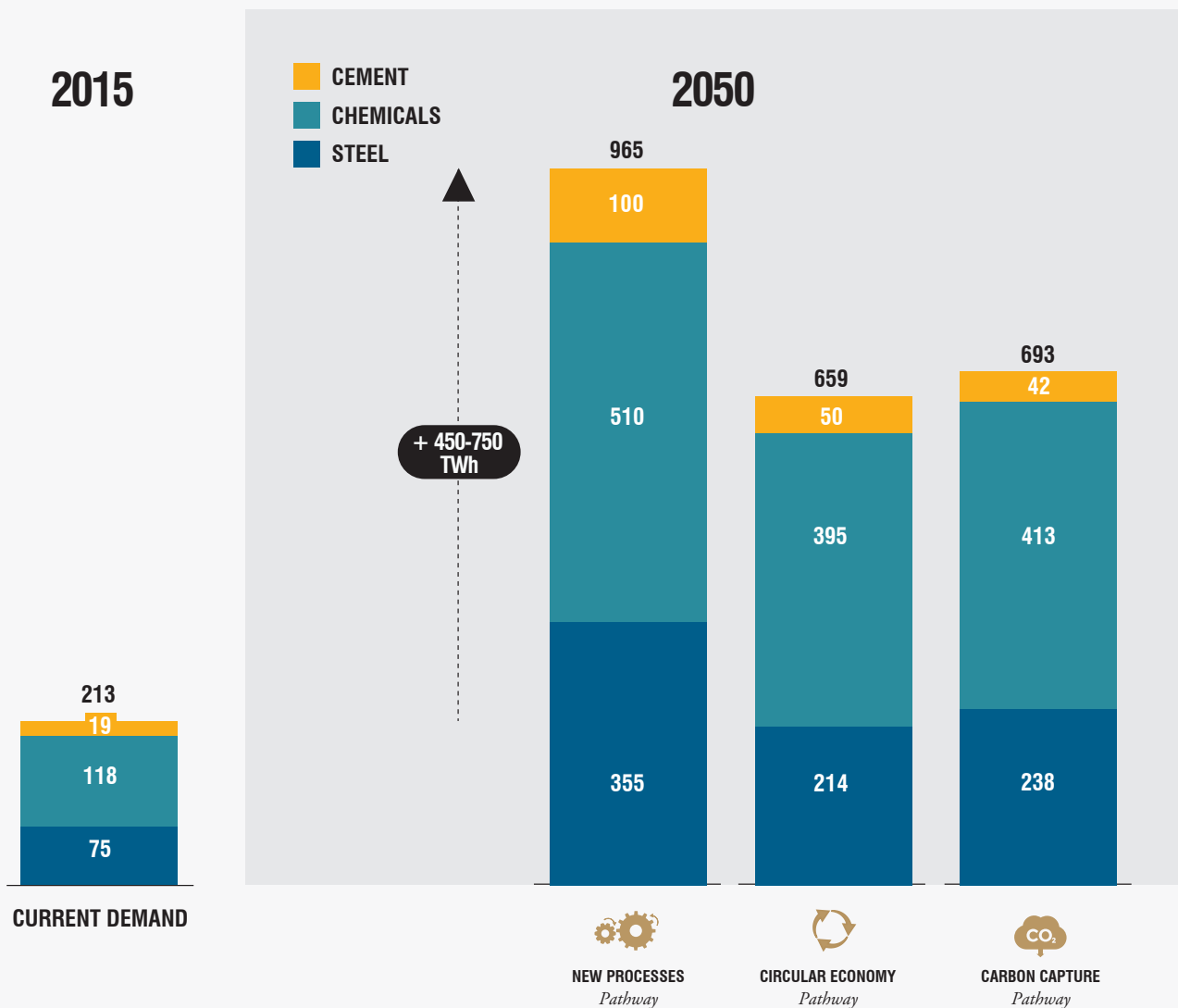
There are two major reasons why the estimates in this study are lower. First, some previous analyses have gone ‘all in’ to illustrate what would happen if all production were electrified. In contrast, all three pathways in this study use a range of solutions. Instead of resorting solely to very electricity-intensive options, some degree of materials efficiency, materials recirculation, and carbon capture play a role even in the electrification-reliant New Processes pathway.

Second, this study largely eschews solutions based on synthetic chemistry that uses CO₂ as feedstock to make materials like plastic or fuels (synthetic fuels, or ‘synfuels’). Such solutions are particularly electricity-intensive. For illustration, capturing CO₂ from the atmosphere (‘direct air capture’) and then using hydrogen from electrolysis to synthesise high-value chemicals requires three times as much electricity as producing the same chemicals from recirculated plastics.

Exhibit 1.19

LOW-EMISSIONS PATHWAYS REQUIRE AN ADDITIONAL 450-750 TWh OF ELECTRICITY

ELECTRICITY DEMAND PER PATHWAY IN A NET-ZERO CO₂ EMISSIONS INDUSTRY
TWh



SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.³³

The electricity requirements depend strongly on the pathway chosen. As much as 310 TWh can be avoided by successfully mobilising circular economy solutions. This is because making less new material requires less energy, and recycling is less energy-intensive than new production. CCS also offers a way to reduce electricity needs, for two reasons: it offers an alternative route to hydrogen production (which otherwise consumes large amounts of electricity for electrolysis); and it enables some continued use of fossil fuels instead of hydrogen-based processes or electrification of heat. Together, such CCS opportunities could reduce electricity requirements by some 270 TWh.

Mobilising the electricity required will be a matter not just of large aggregate numbers, but of highly concentrated needs. For example, a steam cracker in the chemicals industry has a heat load similar in size to the output of a coal-fired power plant (1 MW). A large steel plant producing iron through hydrogen would require some 16 TWh of elec-

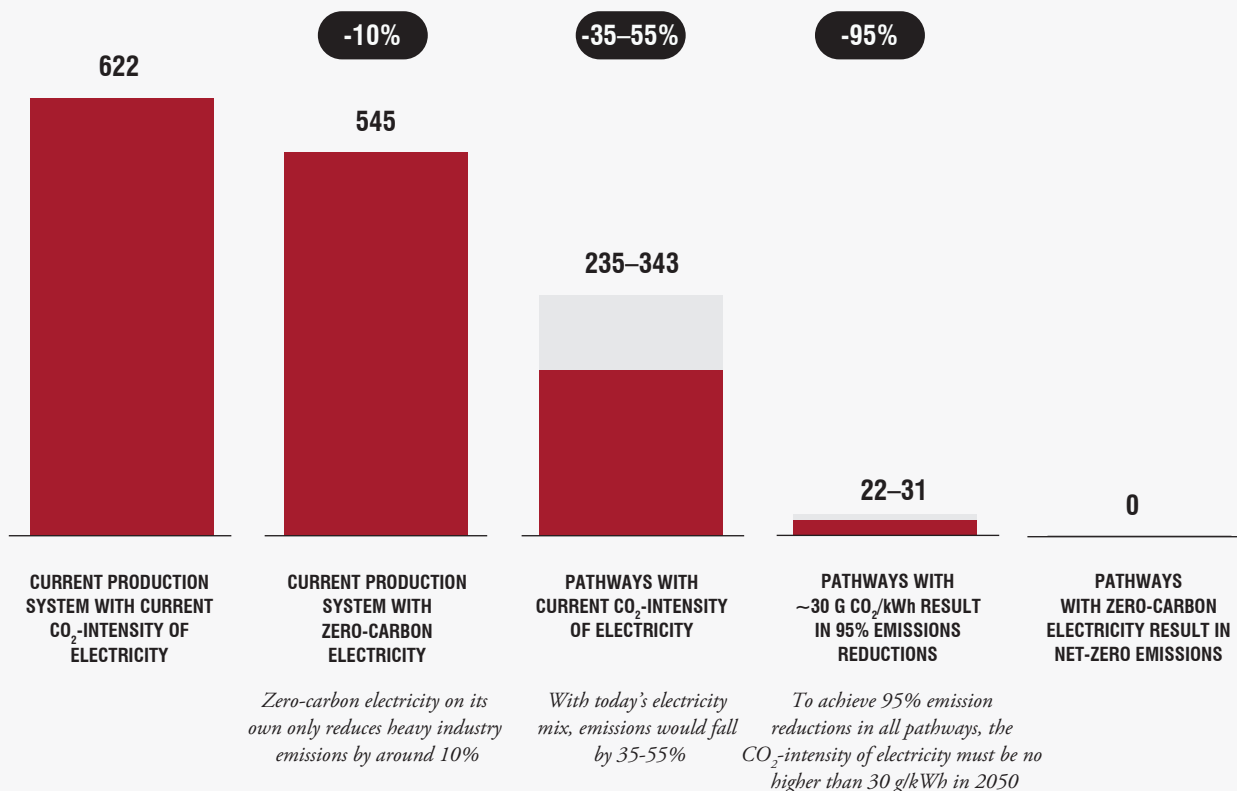
tricity – more than the total electricity consumption of Croatia.³⁴ The electrification of heavy industry therefore adds to the pressure to integrate EU electricity production through reinforced grids, so that low-cost resources across the continent can be used to their full potential.

Achieving close to net-zero emissions electricity is clearly an essential enabler of emissions reductions in industry. Just as CCS has the challenge of eliminating the last tonnes (as 100% CO₂ capture is unlikely to be feasible), heavy electricity use will be a net-zero strategy only if production is essentially zero-emissions (Exhibit 1.20). For illustration, if EU electricity remained as reliant on coal and gas as it is today (releasing an average of 350g of CO₂ per kWh), some 235–343 Mt CO₂ would remain in 2050. To cut emissions by 95%, electricity generation would need to release less than a tenth of today's level, or 30 g CO₂ per kWh. With completely CO₂-free electricity, emissions would be close to zero. The more reliant on electricity a pathway is, the more sensitive it is to this dynamic.

Exhibit 1.20

ELIMINATING CO₂ FROM ELECTRICITY GENERATION WILL BE CRUCIAL FOR CUTTING INDUSTRIAL EMISSIONS

EMISSIONS FROM STEEL, CHEMICALS, AND CEMENT FOR DIFFERENT CO₂-INTENSITIES OF ELECTRICITY
Mt CO₂, 2050



NOTE: EMISSION REDUCTION POTENTIALS COMPARED TO EMISSIONS IN A 2050 BASELINE SCENARIO..

SOURCE: MATERIAL ECONOMICS MODELLING AS DESCRIBED IN TEXT.

*A decarbonised electricity
system is an essential enabler of
net-zero emissions from industry.*



BIOMASS WILL BE REQUIRED PRIMARILY FOR FEEDSTOCK

Achieving net zero emissions for the economy as a whole will lead to multiple competing claims on scarce biomass resources. The use of biomass for fuel or feedstock can compete with alternative uses for land like food or feed production, conservation for maintained biodiversity, or as a 'sink' for CO₂ emissions. Furthermore, once the biomass has been extracted, there are multiple competing uses, from simple combustion for heat or electricity generation (the largest use today) to the production of transportation fuels, or use with CCS for 'negative emissions' to offset remaining emissions in other sectors.

All the pathways nonetheless make significant use of biomass. The total amount varies between 1.1 and 1.3 EJ, compared with current EU biomass use of 5.9 EJ. Estimates of the amount of sustainable biomass available in the EU in 2050 range between 12 and 16 EJ, so the amount used in the pathways is around 15% of the total.³⁶

Bioenergy can provide a drop-in solution via wood pellets or biogas. This can provide valuable early emissions cuts, but switching a large amount of industrial energy to biomass rapidly starts to make large claims and electricity can often be an alternative. This is one reason that the further development of electricity for high-temperature applications is important.

Instead, the main use of biomass in the pathways is as a feedstock and source of non-fossil carbon in industrial processes. Whereas today's discussion and scenarios focus on 'bioenergy', in fact we will also need 'bio-feedstock'.

The main, near-indispensable use of biomass is in the chemicals sector. It is not possible to achieve 100% recirculation of plastics (even steel, the most circular material today, has a recycling rate of 85%), nor to entirely eliminate emissions from chemical processes so that 100% of carbon ends up in the products. Even if the 'societal carbon loop' could become more than 80% circular, some carbon would leak out of the system and (short of landfilling plastics) escape to the atmosphere over time. Some new carbon must therefore be added in order to supply all the plastics needed. Using bio-based sources of carbon is necessary to avoid the constant addition of fossil carbon, which would result in continuing fossil CO₂ emissions.

Biomass could also potentially be used to produce pure iron from ore, a key step in making steel, but in this instance hydrogen provides a realistic alternative. It also is a possible source of carbon for steelmaking. Biomass is already a major fuel in the cement industry, and continuing to use it with CCS could be a way to offset emissions that cannot be captured. Finally, biofuels – and biogas in particular – offer an alternative to electrification, especially for some high-temperature processes.

However, the pathways are cautious about all these uses, due to the competing claims on biomass as a resource, so the focus is on the indispensable use of biomass as a feedstock.

There are five main ways to limit the amount of biomass required:

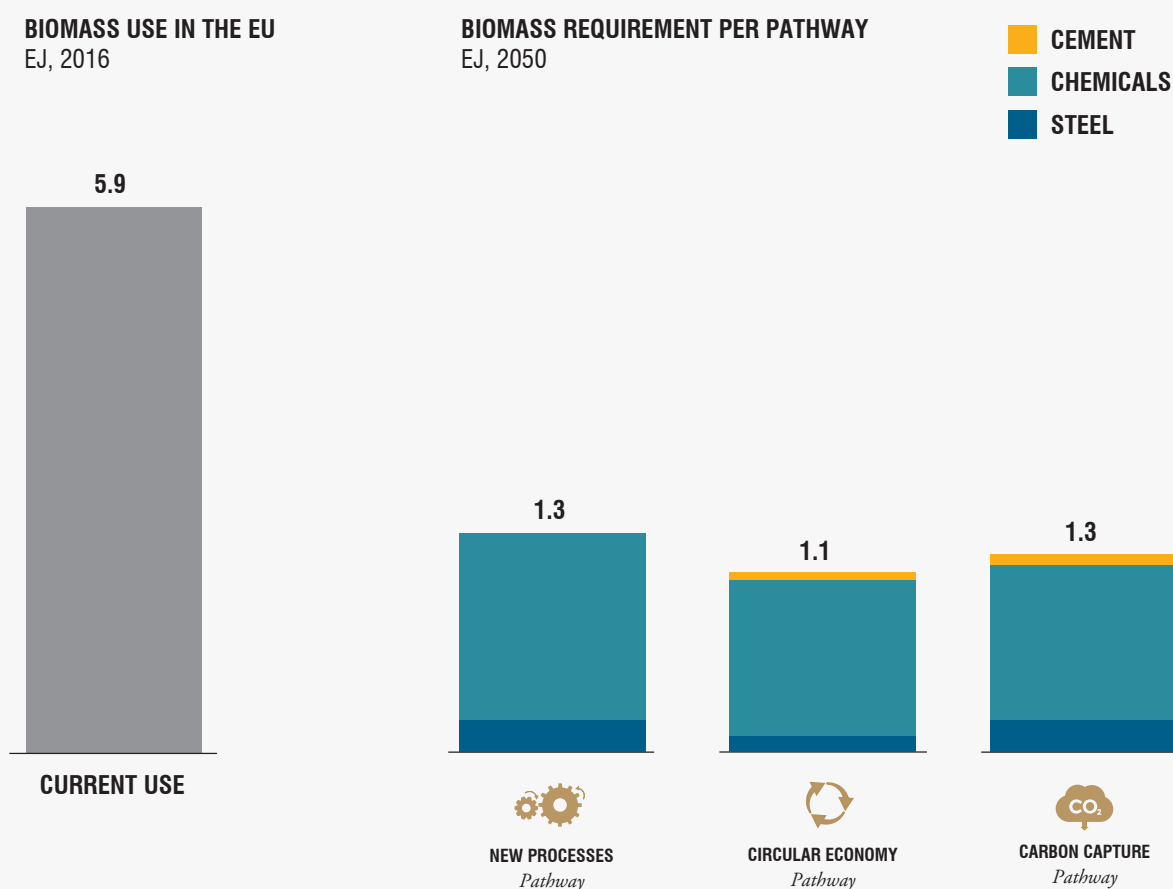
- 1. Materials efficiency:** This spans a range of strategies, from car-sharing to high-performance polymers and reduced over-packaging, and can reduce plastics use by around 20% as a cautious estimate.
- 2. Substitution with alternative materials:** Nearly half the mass of biomass is directly lost in the conversion to plastics. To avoid these losses, one option is to use polymers that are more similar to bio-based molecules in structure. Another is to use wood fibre directly as an alternative to the polymers used today. Together, these could reduce biomass requirements by 10%.
- 3. Recirculation of plastics:** The more circular the use of plastics, the less additional bio-based carbon is required. High levels of reuse and mechanical and chemical recycling are therefore key; they can supply up to two-thirds of the input needed for plastics production.
- 4. CCS:** This can enable continued use of fossil carbon instead of biomass, but only if the carbon embedded in plastics is permanently stored, which is the main approach taken in the Carbon Capture pathway. Massive CCS on waste incineration would then be required, a challenging prospect. Another option would be to store plastics permanently instead of burning them, but this would require proof that the negative effects of landfilling can be avoided.
- 5. Mobilisation of new bio-resources:** Examples include biomass now used as fuel in the pulp and paper industry, amounting to 0.5 EJ today, or half the amount required in the pathways.³⁶ Some of this is in the form of 'black liquor', which could be a very good starting point for making bio-chemicals. More widespread electrification of the pulp and paper sector would therefore free up a major source of chemical feedstock in the future – and potentially create a new, valuable use of pulp and paper industry by-products. Another potential source are various non-recycled municipal waste streams, which can have a high content of biomass and which have few other uses (indeed, it is a major source of methane emissions and thus a conundrum for climate policy). Waste can be gasified and the carbon and hydrogen recovered for use in chemical synthesis, including alongside pure-plastics streams. Major innovation and new supply chains will be required to develop such processes, and should be a high priority.

The main potential alternative to using biomass would be to use CO₂ as a building block of chemicals. However, the electricity requirements are very large. For example, to switch out 1 EJ of biomass as feedstock for plastics, some 400 TWh of electricity would be required instead to capture CO₂ from the atmosphere and produce hydrogen for synthetic chemistry. This would more than double the total

electricity requirements of the chemicals sector. In contrast, if 1 EJ of biomass were used to produce electricity (recalling that this is a major use of biomass in the EU today), it would achieve less than 100 TWh of electricity output. In this comparison, using biomass as chemicals feedstock is four times as electricity-efficient as burning it in power stations to generate electricity.

Exhibit 1.21

ACHIEVING NET-ZERO EMISSIONS FROM INDUSTRY REQUIRES 1.1–1.3 EJ OF BIOMASS PER YEAR BY 2050



SOURCES: CURRENT BIOMASS USE BASED ON IEA (2017). BIOMASS REQUIREMENT PER PATHWAY BASED ON MATERIAL ECONOMICS MODELLING AS DESCRIBED IN SECTOR CHAPTERS.³⁷

1.3 ACCELERATED IMPLEMENTATION: AN AGENDA FOR THE COMING 5-10 YEARS

A successful transition will require concerted efforts by government, industrial companies, companies in major value chains, cities, civil society, and individuals. The transition is technically feasible, but it is not economically plausible in today's markets. The next 5–10 years will be crucial in enabling EU heavy industry and major value chains to chart a low-CO₂ course.

Many EU industrial companies know that doing nothing is not viable. Indeed, EU industry has long gravitated towards increased specialisation, performance and efficiency to counter pressures ranging from energy costs, trade practices or global overcapacity. A low-CO₂ track would be a continuation and acceleration of these trends. Low-CO₂ solutions pioneered and commercialised in Europe will eventually be needed globally in a world with large unmet materials needs. Meanwhile, the EU could transition to a much more secure position: a more materials-efficient economy that relies less on imported fossil fuels and feedstock, and is more attuned to domestic sources of comparative advantage: local integration, digitisation, end-of-life resources, etc.

Nonetheless, the first steps of this transition will not occur without a step-change both in policy and in companies' strategic choices. To launch a new economic and low-CO₂ agenda for EU heavy industry, major policy innovation and entrepreneurship will be required.

The main policy in place today is the EU Emissions Trading System (EU ETS). In theory, a predictable and rising carbon price could provide incentives for many (but not all) of the actions underlying the pathways here. Achieving a cost-effective transition will be much more difficult without a high-enough carbon price.

However, it is unlikely that the EU ETS by itself could drive the strategies required for net-zero emissions from industry.

Changing the strategic direction of a company on the basis of a carbon price would require very strong assurances that future high prices are all but certain. However, such high prices in the EU but not in other markets would rapidly make these industries globally uncompetitive. Policy-makers have also demonstrated that the rules of the EU ETS are not fixed, but subject to continued revision.

Moreover, carbon prices do not enable all the activity needed. On its own, carbon pricing does not provide sufficient incentives for investment in innovation. It also does not address market failures that hold back many circular economy solutions, which instead will likely require interventions similar to those used for energy efficiency in buildings and transportation.

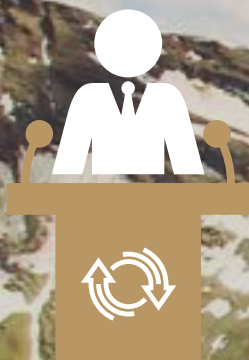
A new policy agenda is needed. While all pathways require broad policy support, each option has different requirements. Effective policy must start from a deep understanding of the change required, and the business case for different options. Just as the solution set for net-zero industry is wide-ranging, the policy agenda must have many parts, each addressing different aspects of the transition (Exhibit 1.22).

This is a new area of policy. Whereas buildings, transportation, and electricity generation all have many climate policies in place besides the EU ETS, this is not the case for industry. New interventions create a risk of unintended consequences, and each mechanism would need careful evaluation and design. This study has not evaluated which options would be best, or indeed whether the disadvantages of any one option outweigh its benefits. It therefore cannot recommend a specific policy approach or package. Instead, the aim is simply to identify the extent of 'policy gap' and to start the conversation about possible options.



Exhibit 1.22

SIX POLICY AREAS TO ENABLE A LOW-CO₂ INDUSTRIAL TRANSITION



1

ACCELERATE INNOVATION AND SCALING OF NEW SOLUTIONS

- Scale up mission-driven innovation programmes, including new approaches to piloting and demonstration support
- Ensure early deployment to create faster innovation loops

2

CREATE LEAD MARKETS AND SAFEGUARD COMPETITIVENESS OF LOW-CARBON OPTIONS

- Create the certainty required for early commitment to low-CO₂ development and investment
- Strengthen support, with options including carbon prices, subsidies, quotas, public procurement

3

ENABLE INVESTMENT AND REDUCE RISK

- Ensure an underlying future business case for higher-cost low-CO₂ solutions
- Provide direct support and de-risking through concessional finance, capital grants, public-private partnerships

4

ENABLE HIGH-QUALITY RECIRCULATION OF MATERIALS

- Create a business case for recycled materials and feedstock
- Target high collection rates and regulate for clean materials flows through targets for recycling quality, charges for landfill/incineration, and improved waste-handling infrastructure

5

INTEGRATE MATERIALS EFFICIENCY INTO EU CLIMATE POLICY

- Introduce policy to directly target the barriers holding back materials efficient solutions and business models
- Use energy efficiency policy approaches such as standards, targets, labelling, and quotas

6

MAKE AVAILABLE THE NECESSARY INPUTS AND INFRASTRUCTURE

- Ensure the availability of electricity grids, hydrogen infrastructure, public waste handling, etc. required for industrial decarbonisation
- Launch a regulatory regime to guide the early deployment of CCS transport and storage infrastructure



**LOW-CO₂
INDUSTRIES**



I. ACCELERATE INNOVATION AND SCALING OF NEW SOLUTIONS

Reaching net-zero emissions from heavy industry will require a major innovation and deployment programme, with strong public financial and other support. By the 2030s, EU companies must have gathered significant experience and started to consolidate solutions – from car-sharing and chemical recycling to new methods of making iron – that are now in early trials.

The materials system thus stands where the energy system stood in the early 2000s. There is a largely known set of emerging solutions to build upon, with significant innovation momentum, but many key options are not yet commercially viable. Their further development cannot be fuelled just by intellectual property law or the promise of near-term commercial advantage, the typical drivers of business innovation. On the contrary, innovation on this scale is risky. Companies going it alone would not only be committing significant resources, but risking disruption to production.

As a result, public support will be crucial. Indeed, given the punishingly short timescale to bring solutions to full readiness, most of the early innovation funding may need to come from public sources.

Innovation needs to happen on both the demand and supply side. On the supply side, the most urgent agenda is to accelerate the demonstration of new production processes. On the demand side, the innovation agenda is broader. A key part is new business models, including sharing business models for vehicles and other under-utilised capital assets, and new systems for reuse and re-manufacturing. New digital solutions will be important enablers, permitting the identification and tracking of materials, automation of materials handling, and dismantling of end-of-life products.

To support this innovation, government could play three major roles:

- **Mission-driven research support:** There is an urgent need to clarify the innovation agenda. One key challenge is identifying the technical and commercial pain points. Another is to create mission-driven innovation, in order to develop technologies that could significantly contribute to the transition to net-zero emissions industry, but which have little or no near-term commercial potential. These technologies could include efficient high-temperature electric heating, novel chemical recycling routes, and advances in hydrogen production. Identifying these high-priority technologies, as has been done for the energy industry in the Strategic Energy Technology (SET) Plans, could help coordinate action across the EU.
- **New approaches to piloting and demonstration:** The EU could support research and demonstration by mobilising existing tools with a stronger industry focus (e.g., the InvestEU programme, Horizon Europe, the Connecting Europe Facility and the upcoming ETS Innovation Fund). However, the short timescale means strongly directed public support will be required, de-risking and co-funding. State Aid rules may stand in the way, in which case some may need to be modified. A particular focus should be the financing of large, capital-intensive demonstrations nearing commercial scale, on which policy often has fallen short in the past.
- **Deployment for early innovation loops:** As in the power sector, early deployment will be key. It is only through real-world testing and experience that new insights can be generated to fuel further innovation. Innovation needs to be undertaken within industrial production systems, at industrial sites, and with industrial companies as the main actors. Therefore, the creation of lead markets (see below) is also a prerequisite for accelerated innovation.

2

2. CREATE LEAD MARKETS AND SAFEGUARD COMPETITIVENESS OF LOW-CARBON OPTIONS

Policy must support the introduction of new, low-CO₂ production routes and uses of materials.

The traditional approach is to set a price on carbon emissions, tilting the playing field so that low-CO₂ solutions are no longer at a disadvantage. In the long run, if ambitious climate mitigation is undertaken internationally, this solution could work, with all its advantages of ensuring the right trade-offs and letting the market choose the most cost-effective way to reduce emissions.

However, earlier in the transition, two concerns would get in the way:

1. **International competition** puts a practical limit on the carbon price. Setting the price too high will cause emissions-intensive industries to move outside of Europe – so-called carbon leakage.
2. **While early deployment** is needed to scale solutions to 2050, pioneers within the EU will be at a disadvantage relative to both international rivals and EU peers.

As a result, other mechanisms may be needed. This is tricky territory. The challenge is to strike a balance between the disadvantages of ‘picking winners’ and the risk of offering insufficient incentive for the fundamental shifts required for deep emissions cuts. The policies also need careful design to avoid distorting competition beyond what is needed to make low-CO₂ options more attractive.

With that in mind, policy-makers have a wide menu of options. All are drawn from climate policies in other sectors. They fall broadly into five categories:

- **Remove existing regulatory hurdles:** There are cases where existing standards, introduced for reasons unrelated to climate protection, need to be amended to enable important low-emissions solutions. Stakeholders have cited the current standards for a minimum cement content in concrete, as well as the specification of eligibility of binders in different cement classes. Of course, any changes to regulations must preserve safety and other requirements that drove their introduction in the first place.
- **Subsidies for low-emissions solutions:** This has been a major tool of policy in the electricity sector.

Design options include ‘feed-in tariffs’ and similar instruments; tools that provide a contract-for-difference relative to the market price for a product, or quotas and tradable certificates for low-CO₂ production. A key challenge will be handling the heterogeneity of products: one steel or chemical is not equivalent to another.

- **Product quotas and standards:** Another approach would be to create a specific low-CO₂ market in each material-using value chain. For instance, a rule might require that a specific share of the steel sold in EU markets contain iron reduced using low-CO₂ methods, or that plastics contain a specific share of non-fossil carbon. For illustration, more specific options could include requiring that the production of concrete not exceed an average maximum CO₂ footprint. Such a policy would allow all the low-emissions solutions, from clinker production to cement mixing, to compete to achieve the desired emissions cuts. The current standards regulating the CO₂ intensity of tailpipe emissions from vehicles could also be expanded to include the CO₂ from the materials footprint.
- **Public procurement:** Public authorities can directly create lead markets through their own procurement choices. Cities, regions and countries make up a large share of the market for infrastructure and construction, and for a range of materials-intensive products.
- **Border adjustments:** It would be possible to introduce taxes or tariffs for goods imported from regions that do not enforce a CO₂ price similar to that in the EU. To allay fears of revenue-raising protectionism, the taxes could be refunded to the countries of origin. The trade ramifications, including admissibility under the rules of the World Trade Organization, are complex. Furthermore, feasibility will differ significantly between products. Border adjustments also do not, on their own, address the issue of enabling first movers within the EU.

Many of these options may work best as transitional mechanisms. However, the higher cost of some low-CO₂ production routes may well persist in the long run, in which case permanent incentives will be required to overcome this disadvantage in operating expenses. CO₂ prices may well be the best long-term option, pursuing the logic already laid down in the EU ETS.

3

3. ENABLE INVESTMENT AND REDUCE RISK

Since a large volume of additional investment is needed to drive the transition to net-zero emissions heavy industry, government needs to ensure that companies can make those investments with an acceptable level of risk.

First they need to make the underlying business case. In other areas of climate policy, investment has rarely been a direct target. Instead, the approach has been to create sufficiently secure market conditions – for example, through CO₂ prices, quotas or subsidies. Governments then relied on pre-existing financing mechanisms to respond to these incentives. This has been successful in many cases, such as the creation of entirely new sets of investors in the power system, supporting the shift to renewable electricity generation. Similarly, creating a credible framework to ensure a future business case must also be the foundation for net-zero emissions heavy industry.

However, there are several reasons why this may not be enough:

- **Early investment will be key**, as EU industrial companies are already facing significant reinvestment decisions in the next 5–10 years, for assets ranging from coke ovens to steam crackers.
- **In industry, low-CO₂ assets** are rarely ‘modular’ in the way that solar or wind power are. Instead, they require large lump-sum investments in new production capacity, which then has a long lifespan.
- **Companies face large risks** if solutions are only gradually becoming technically proven. In such cases, the future business case may depend strongly on continued policy incentives.
- **Prudence may dictate** some redundancy and optionality. This could entail building up parallel, low-CO₂ capacity while also maintaining existing production capacity, until market and technical conditions are right for a full switch.
- **Many investments** in the next 5–15 years would be in ‘first of a kind’ solutions, which entail larger capital expenses than fully mature solutions. This creates a first-mover disadvantage.
- **Deploying low-CO₂** solutions at existing sites may increase complexity and induce additional adaptation costs to fit into existing wider production systems.

- **Large changes** to infrastructure and industrial sites can face significant permitting and other hurdles, creating further barriers.

As a result of these challenges, industries may need direct investment support. There are many ways to do this. For example, some Member States have provided very low-cost, concessional finance – such as shouldering some of the risk – for actions ranging from building retrofits to renewable energy projects. There are also several pre-existing mechanisms to build on. Another possibility is to change how the depreciation of assets is accounted for, reducing the tax burden during the early years of an asset and thus encouraging investment in new assets. Other options include fiscal rebates linked to new investments and European Investment Bank financing instruments.

Beyond this, capital grants are the most direct way to offset some of the challenges, but implementers will face the challenge of not distorting investment. Concessional finance or blended finance can improve the viability of some high-risk investments. As with the creation of lead markets, State Aid guidance would need to be amended to enable some of these options. ‘Low regulatory zones’ could help overcome some of the inertia and uncertainty created by permitting rules.

Finally, policy-makers must confront the risk of stranded assets. Given the short time until 2050, it will not be possible to avoid some redundancy. As a result, some high-CO₂ assets may need to be written off before the end of their technical or economic life. Such decisions will hit companies’ balance sheets and therefore also their financing capacity.

Policy could handle this dynamic in different ways. At one end, stranded assets are best prevented by avoiding any additional investment in high-CO₂ production systems, beyond what is strictly necessary. Another approach is more technical fixes, such as changing how accounting standards handle depreciation and write-downs. More directly, direct support or ‘grandfathering’-style principles (in which existing assets are exempt from new regulations that apply to newly built assets) could directly defray some stranded asset cost.

4

4. ENABLE HIGH-QUALITY RECIRCULATION OF MATERIALS

This requires two policy steps. The first is to encourage high collection rates and clean materials flows. The recirculation of materials relies on high collection rates. Once collected, the resources to be used as feedstock or raw material for new production need to be both well separated and adequately pure.

This is a broad agenda, ranging from minor adjustments to ambitious initiatives designed to redirect large waste flows. Potential examples to investigate include:

- **Targets for cutting CO₂** emissions from waste, similar to existing targets for landfill emissions.
- **Updating recycling targets** to encompass quality, not just quantity. It may be best to measure, not the quantity of material sent to recycling, but rather that material's effective capacity to replace virgin production. This is the more relevant metric.
- **Charges for less desirable** options for end-of life treatment of waste, such as landfill (already in place in many Member States) or incineration (currently often encouraged rather than discouraged by policy).
- **Removing hurdles** to cross-border trade in end-of-life flows, to enable their large-scale use as feedstock or raw materials.
- **Regulations to limit** the levels of copper and other 'tramp elements' in steel scrap, as these elements permanently downgrade the quality of the steel stock.

More indirect options include regulations for how end-of-life vehicles and other products are dismantled; design criteria for products containing copper wiring; and a requirement to keep copper-alloyed steel separate.

- **Creating public definitions** and standards for plastic sorting grades and other materials, to create more transparency.
- **New waste-handling infrastructure** to enable the new levels of separation and sorting required for chemical recycling.
- **Adequate rules** for the use of CO₂ as a feedstock for making new materials (CCU), especially if the CO₂ ultimately comes from a fossil source.

The second step is to create the business case for using recycled materials and feedstock. This means creating market incentives for the production and use of recycled materials that reflect their contribution to emissions abatement. Any specific incentive introduced on the production side must also enable recycling, if there is not to be a distortion in favour of new production rather than use of recirculated materials. Mechanisms for lead markets that are neutral in this respect are the best option. Where this is not achievable, it may be necessary to create separate markets. One example would be to explicitly target the creation of demand for plastics produced from recycled feedstock.

5

5. INTEGRATE MATERIALS EFFICIENCY INTO EU CLIMATE POLICY

By encouraging a step change in demand-side solutions, government can ease many of the challenges of the transition to net-zero emissions. In particular, a more circular economy will reduce the cost and investment needs and cut the amount of renewable electricity and biomass required. However, there are a number of barriers to the creation of a circular economy, in particular the need to coordinate actions across entire value chains.

Policy in this territory can borrow heavily from the playbook of energy efficiency policy. The motivations often are the same: a known potential for improvement that often is cost-effective, but which is held back by a range of barriers and market failures. These barriers are also familiar from the experience with energy efficiency. Incomplete contracts result in split incentives where the parties best able to avoid over-use of materials have few incentives to do so. The extent of materials use is often unknown now, due to a range of information barriers. Missing markets mean that, even if there were demand for high-quality end-of-life

materials, there are no mechanisms that this could translate all the way to the product design stage, where the issue is often easiest to address. Regulation also sometimes gets in the way, especially in trying out new business models for important services. Finally, the price of new materials often does not reflect the full cost of environmental externalities, including CO₂ emissions.

Policy to redress these can span a wide range of options. These can involve specifying targets for materials use in large product categories (such as the amounts of cement used in a category of building, or the load-bearing capacity of steel vs. requirements in buildings). Instruments such as the Eco-Design Directive could potentially be adapted to incorporate such principles for a range of products.

As with energy efficiency policy, there is a delicate balance to strike. Policy that limits choices can induce hidden costs or have unintended consequences. With that in mind, there are a range of options for the regulation of materials efficiency.

6

6. MAKE AVAILABLE THE NECESSARY INPUTS AND INFRASTRUCTURE

A final category of policy is to ensure that the inputs and infrastructure required are available.

The build-out of up to 750 TWh of additional electricity generation must be accompanied by available transmission and distribution capacity. The more this can link up cheap sources in one part of the EU with the key industrial demand centres, the more competitive European industry will be.

Waste handling also would need to change profoundly to achieve the 40–80% recirculation of plastics implied by the pathways. Vertical integration of plastics producers with the waste sector could help, but as much of waste infrastructure is publicly run, it also would be necessary to adapt public systems to mobilise waste as a major industrial resource.

On a more local scale, sector coupling offers an important way to enable some production routes. This can include linking up of pulp and paper and chemicals production, steel and chemicals, and more. Hydrogen also can become a new feedstock requirement across multiple sectors, with a need to build new infrastructure for distribution and storage.

CCS will require an entirely new infrastructure for transport and storage. To date, this has been a major impediment to the further development of CCS. Companies looking to capture CO₂ face either uncertainty that transport and storage will be available at all, or a risk of commercially unattractive dependence on a single (effectively monopolist) counterpart. One way to enable early investment and provide certainty would be to create a public regulatory regime, rather than expect companies to become dependent on private storage operators.

2. STEEL

INNOVATION LEADERSHIP FOR LOW-CO₂ STEEL

Steel is a vital material for a modern, industrialised economy. In fact, for every person in the EU, there are about 12 tonnes of steel¹, underpinning vital functions from construction and infrastructure, to transport and industrial production.

Yet, steel production is also a significant source of greenhouse gas emissions – more than 200 Mt CO₂ per year in the EU.² Thus, to meet its climate objectives, the EU must find a way to meet its steel needs while reducing emissions almost to zero.

Until recently, no emissions reduction scenario explored such deep cuts. Instead, studies left as much as half of emissions in place even in 2050. This changed with the analysis underpinning the EU Long-Term Strategy (LTS), which includes scenarios that reduce emissions by as much as 97%.

This study seeks to strengthen the evidence base for what it would take to reach such deep reductions. It confirms the finding from the LTS, that truly deep cuts to emissions from steel production are, in fact, possible. The solution set is wide-ranging,

spanning new production processes and increased recirculation of steel, as well as materials efficiency and circular economy business models.

Major and rapid change will be necessary in all cases – and there are clear needs for policies to enable the transition. Far more resources must be devoted to accelerating innovation on several fronts. Credible new policy solutions are needed to make it viable to pursue low-CO₂ production routes that are up to 20% more expensive than current routes. Barriers to many circular economy solutions must be overcome, likely through policy supports similar to those used to promote energy efficiency.

An increase in investment of up to 65% must also be made possible, starting early to develop demonstration plants and to steer the large investments that will be needed in the coming years in a low-CO₂ direction. Finally, a low-CO₂ steel sector will require large new sources of input, including 210–355 TWh of clean, affordable electricity.

In the context of a capital-intensive industry with long-lived assets, time is very short. The transition to low-CO₂ steel in 2050 is possible, but any further delay would hugely complicate the transition.



*Truly deep cuts to emissions
from steel production
are possible.*

2.1 THE STARTING POINT

EU companies have been making steel for over 150 years, and despite shifts in global markets, the EU steel sector remains large. The European steel industry produces 169 million tonnes of steel per year, meeting almost all of EU demand. It has an annual turnover of 123 billion EUR and employs 320,000 people.³

Still, the EU steel sector faces real challenges. There was a 30% drop in steel demand in the year following the 2008 financial crisis, and EU production has not fully recovered, while net imports have been growing.⁴ Large global over-capacity of as much as 540 Mt per year⁵ contributes to depressed prices, and tariffs and other challenges to international trade add further complications. For all these reasons, the profitability of most EU producers has been depressed for many years.

Efforts to reduce emissions will touch all aspects of steel: its production, use and recycling at end of life (Exhibit 2.1). In terms of production, 61% of the 169 Mt of annual production takes place through the so-called integrated route, using first a blast furnace and then a basic oxygen furnace (BF-BOF) to produce iron and then steel from iron ore and coal. The other main production route uses electric arc furnaces (EAF) to melt scrap steel. This recycling process accounts for 39% of the annual EU production.

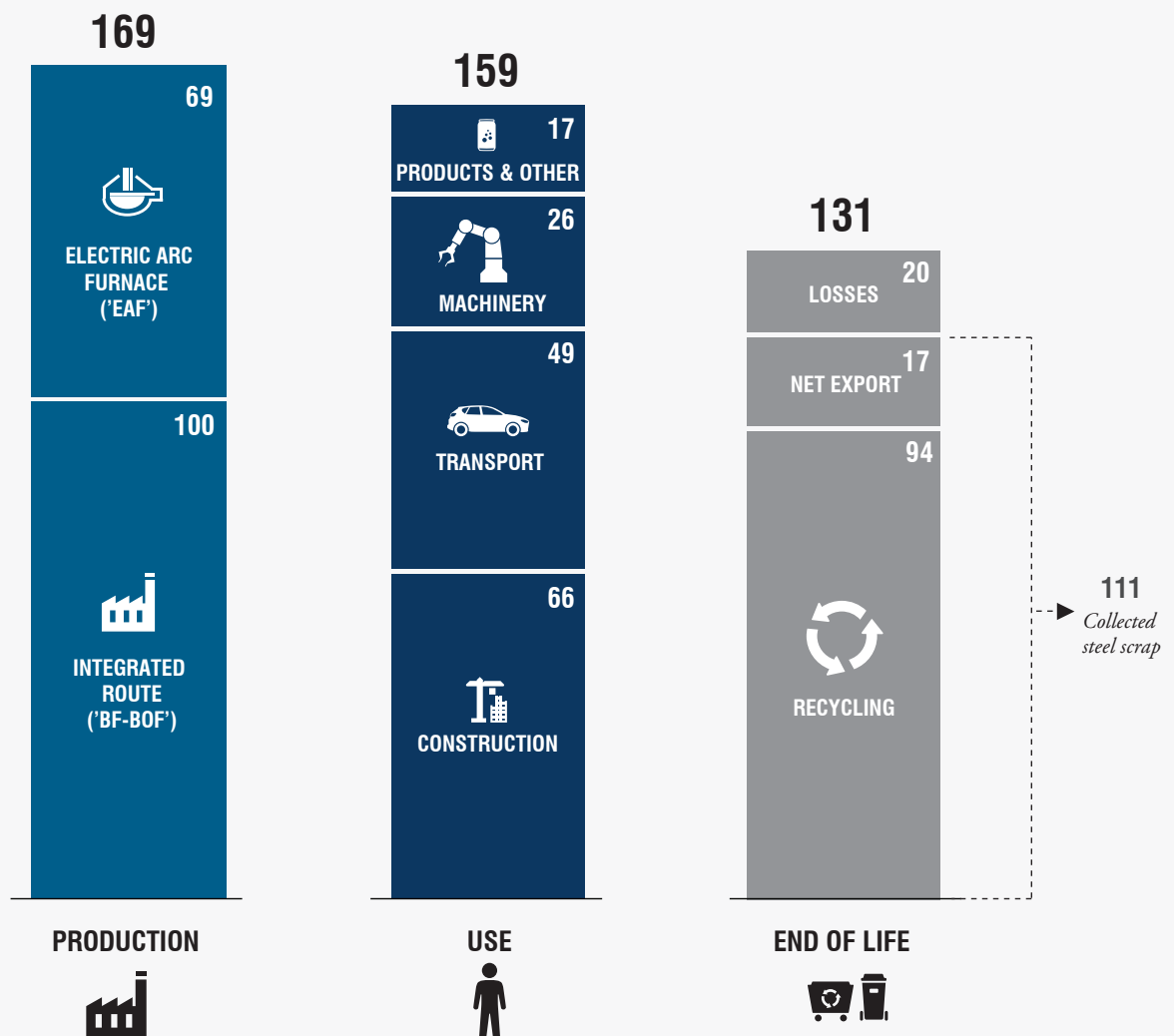
Steel users in sectors including construction and infrastructure (42% of demand), transportation (31%), industrial machinery (16%) and a range of metal products (11%) will also be touched by the efforts to reduce emissions. Likewise, the EU will need to enable high-quality steel recycling; already today, 111 million tonnes of steel scrap is collected and either remelted to make new products in Europe or exported. Once steel has been made it is processed into many different forms, so it is not a homogenous commodity. There are two major categories: long products such as rebar and drawn wire, and flat products such as slabs and heavy plate. Steels are also sorted into various grades, which specify either their chemical makeup or their mechanical properties. Different uses require different grades: for example, the automotive industry typically needs higher-quality steel than does construction.

The investment cycle of steel plants plays a major role in how a transition to net zero emissions would play out. To 2050, practically all major production assets will need substantial re-investments: blast furnaces on a cycle of 15–20 years, and most EU coke plants will also require substantial rebuilding or replacement in the same time frame. Enabling companies to direct capital towards new, lower-emissions production routes at these major investment points will be a key factor in a cost-effective transition. The alternative is lock-in to continued high emissions, or the risk of stranded assets that must be replaced ahead of the end of their technical life.

Exhibit 2.1

PRODUCTION, USE, AND END OF LIFE OF EU STEEL

ANNUAL STEEL VOLUMES
Mt, 2017

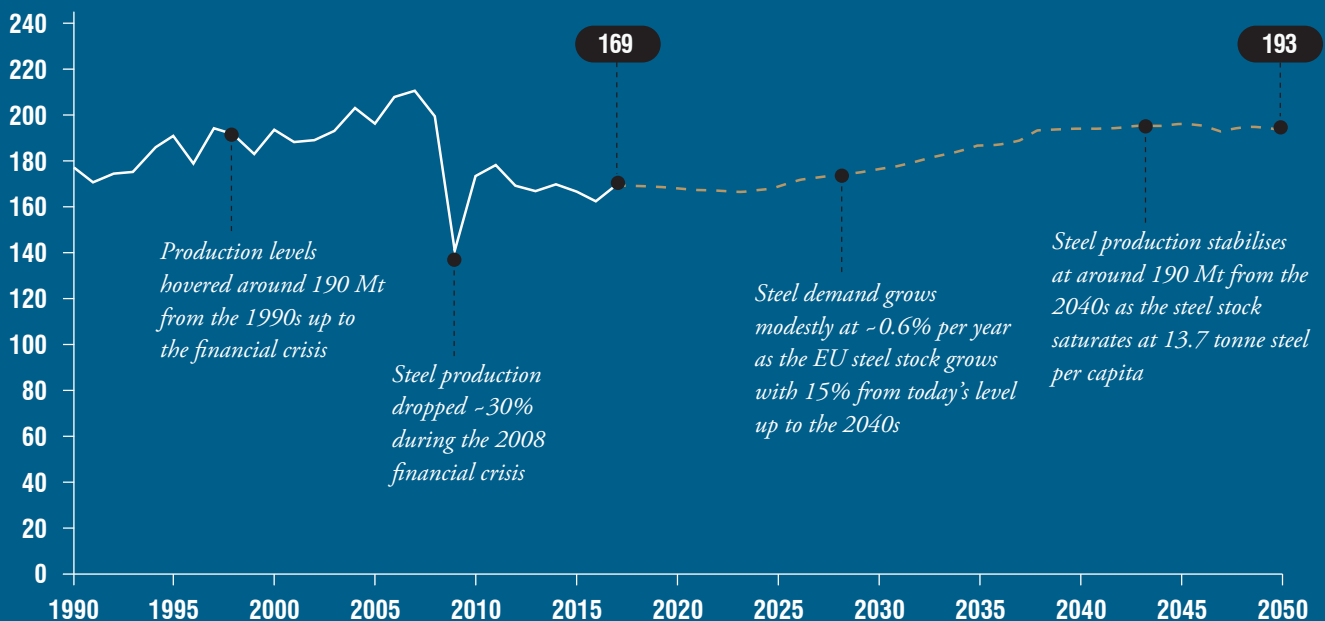


NOTES: TOTAL USE IS BASED ON EU APPARENT STEEL CONSUMPTION. INDIVIDUAL NUMBERS DO NOT SUM TO THE TOTAL DUE TO ROUNDING.
SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON EUROFER (2018) AND PAULIUK ET AL. (2013).⁶

Exhibit 2.2

EU STEEL PRODUCTION WILL STABILISE AT AROUND 190 MT PER YEAR IN THE 2040s AS THE STEEL STOCK SATURATES

EU STEEL PRODUCTION IN A BASELINE SCENARIO MILLION TONNES OF STEEL PER YEAR



NOTES: BASELINE SHOULD BE UNDERSTOOD AS "CURRENT PRACTICE", WITHOUT DEMAND REDUCTION FROM A MORE CIRCULAR ECONOMY OR REDUCED MATERIALS INTENSITY. THE MODELLING APPROACH IS A DYNAMIC MATERIALS FLOW ANALYSIS MODEL BASED ON THAT DEVELOPED BY PAULIUK ET AL. THIS INCORPORATING STOCKS (HISTORICAL STOCK FLOWS, FUTURE STOCK LEVELS), SCRAP FORMATION (PRODUCT LIFETIMES, SCRAP FORMATION, COLLECTION RATES, REMELTING LOSSES, ETC.), AND DERIVED NEW PRODUCTION REQUIREMENTS. TRANSPORTATION, MACHINERY, CONSTRUCTION, AND PRODUCTS ARE MODELLED SEPARATELY.

SOURCES: MATERIAL ECONOMICS MODELLING BASED ON EUROFER (2018), WORLD STEEL (1990-2018), AND PAULIUK ET AL. (2013), SEE ENDNOTE.⁷

The transition will take place against a backdrop of modestly growing need for steel (Exhibit 2.2). In a baseline scenario in which patterns of use are similar to today, and imports and exports remain at the same level, production in the EU would increase to around 190 Mt per year by 2050. Underlying this is a 15% increase in the total per-capita steel stock, in part to underpin the build-out of a low-emissions energy system and infrastructure.

The task ahead for policy-makers and companies is thus threefold: to ensure society continues to enjoy the benefits that steel provides, to avoid the relocation of production to other countries, and to cut CO₂ emissions.

CO₂ EMISSIONS FROM IRON AND STEELMAKING

Making steel produces a lot of greenhouse gas emissions. Globally, 2.3 tonnes of CO₂ are released, on average, for every tonne of steel produced from integrated steelmaking. European producers are more efficient than the average, but they still release 1.9 tonnes of CO₂ per tonne of steel. The total direct emissions from EU steel production are just shy of 200 Mt CO₂. This figure rises to 210 Mt CO₂ when upstream electricity is included.⁸

In the integrated route, carbon plays multiple roles. First, it is a reducing agent in the blast furnace, taking out the oxygen from iron ore to produce iron. Second, it is the energy source producing the high temperatures required to melt steel and also to drive the multitude of processes in the overall production system. Third, some carbon is in fact a necessary ingredient of steel, up to 1% for high-carbon steel.

The special role of carbon combines with other factors to make deep emissions cuts from current production processes challenging. First, the CO₂ is released from multiple sources during the steelmaking process (Exhibit 2.3), all of which must be addressed for truly deep cuts. Second, the chemical process emissions from the reduction of iron ore are significant, so just switching energy inputs will not suffice. Third, steel production requires very high temperatures, which limit the technological options and necessarily require large amounts of energy to generate. Finally, the process is highly integrated, with outputs of one step used as inputs in other parts – so changing one aspect of it often forces changes elsewhere.

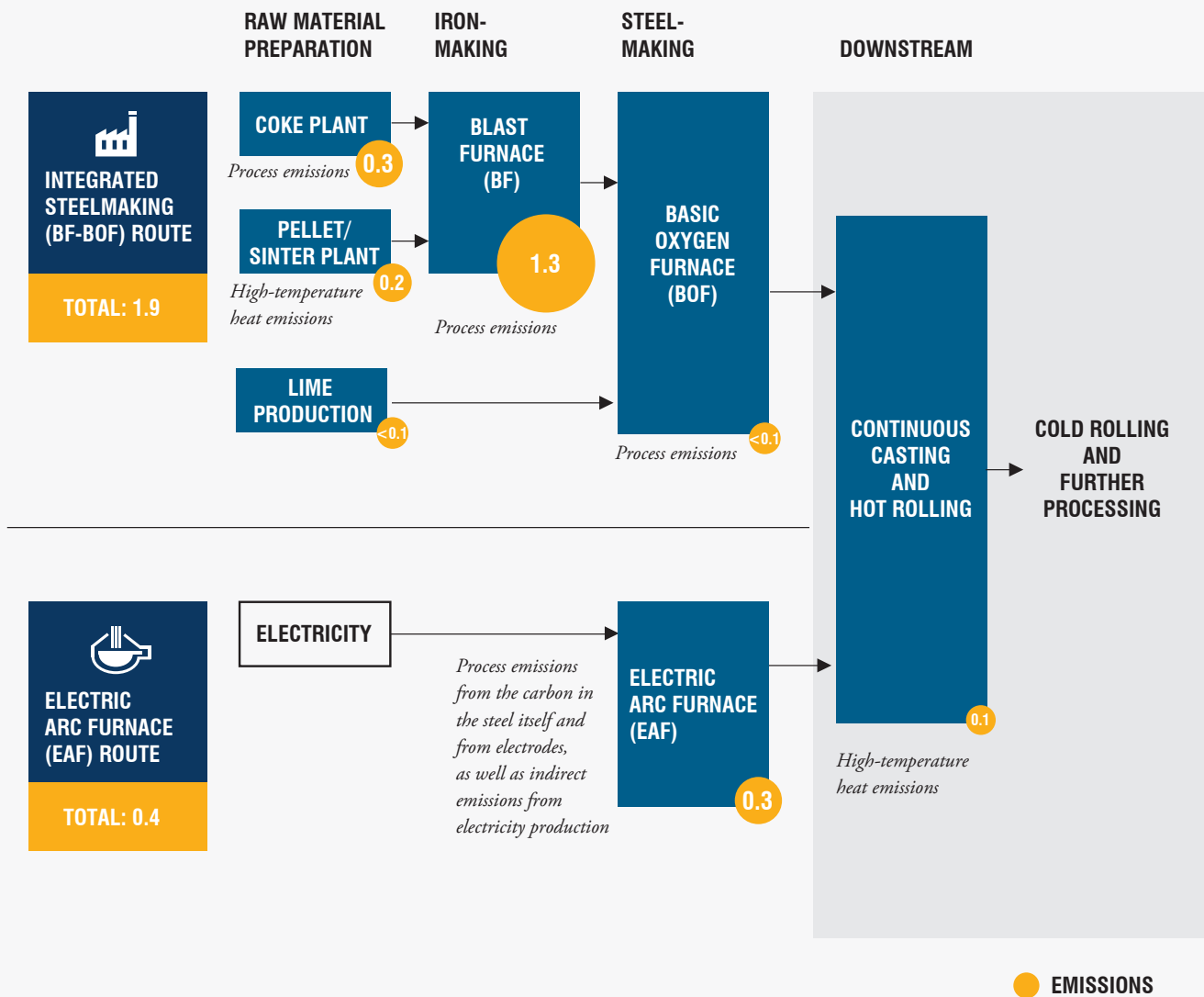
One major option for deep cuts is in fact already in use and reduces sector emissions substantially: CO₂ emissions from recycled steel are significantly lower than those from production of new steel. The energy required is only 10-15% of that required in the production of primary steel from iron ore. Direct emissions can be as low as 0.1 t CO₂ per tonne product. Another 0.1–0.3 t CO₂ arises in the production of the electricity used as input, but can be eliminated with zero-carbon electricity. However, as discussed below, relying on more scrap requires both that the scrap is available and that its quality can be controlled.

In a baseline scenario without major changes to steel use and production, emissions in 2050 would remain largely the same as today, at 208 Mt CO₂ per year. A slight increase in steel production would counterbalance marginal improvements in process efficiency and an increase in the use of recycled steel. As we discuss in the following sections, the challenges to cutting emissions from iron and steel production can be overcome. However, doing so will require major changes to how steel is produced: a sector transformation rather than marginal improvements.

Exhibit 2.3

CO₂ IS EMITTED FROM ALL STAGES OF STEEL PRODUCTION

CO₂ EMISSIONS FROM STEEL PRODUCTION
TONNES CO₂ PER TONNE STEEL



NOTES: DOWNSTREAM PROCESSES ARE THE SAME FOR ALL PRODUCTION ROUTES. THE FIGURE SHOWS WHERE CARBON EMISSIONS ARE FIRST CREATED IN THE OVERALL PROCESS. THE ACTUAL POINT OF RELEASE OF CO₂ TO THE ATMOSPHERE MAY DIFFER. INDIVIDUAL NUMBERS DO NOT SUM TO THE TOTAL DUE TO ROUNDING.

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.⁹

2.2 STRATEGIES FOR A LOW-CO₂ STEEL SECTOR

Past roadmaps have tended to conclude that some remaining emissions in steel production are all but unavoidable, even many decades from now.¹⁰ The emphasis has been on carbon capture and storage, but the challenges noted above (multiple emissions sources, low CO₂ concentration in flue gases, complex interdependencies) have led most studies to conclude that as much as half of emissions would remain even with CCS.

The analysis underlying the EU Long-Term Strategy took a first step towards moving beyond these limitations. There are vestiges of the ‘traditional’ approach, with one scenario leaving 31% of emissions in place, but also scenarios that cut emissions by up to 97%. These are arguably the first attempts to describe a steel sector consistent with the need to reach net zero emissions.

This study seeks to complement this analysis by describing in detail what it would take to reach very deep emissions reductions. It takes as broad an approach as possible to outline pathways to net zero

emissions by 2050, looking not just at production, but also at the use of steel throughout the value chains.

The study finds that there are large opportunities both to improve steel recycling and to use steel more efficiently – much more than in previous roadmaps, including the LTS. Much as energy efficiency reduces the need to mobilise new supplies of energy, materials efficiency and circular economy approaches can cut the need to make new, primary, steel.

However, even in a stretch case for circular economy solutions, it will be necessary to produce millions of tonnes of primary steel per year in the EU even in 2050 – and worldwide for most of the century or more. Therefore, this study also includes a much wider set of clean production processes than in some previous roadmaps. They span new techniques for ironmaking with fossil inputs combined with CCS; fossil-free steelmaking based on hydrogen instead of coal; and the possibility of integrating steel into circular carbon flows through carbon capture and utilisation (CCU) and coupling with chemicals production.

Exhibit 2.4

STRATEGIES FOR DEEP...

CIRCULAR ECONOMY IN MAJOR VALUE CHAINS



MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS

Reducing the amount of materials used for a given product or structure, or increasing the lifetime and utilisation through new business models



MATERIALS RECIRCULATION AND SUBSTITUTION

Using end-of-life materials as input to new production, or using low-CO₂ alternative materials that provide the same function

MATERIALS EFFICIENCY

- Reduced scrap losses in manufacturing
- Materials efficient use of steel in products and constructions, notably reduced over-specification in construction
- Higher-strength steel

MATERIALS RECIRCULATION

- Improved design, end-of-life disassembly, and scrap handling to reduce contamination with copper and other tramp elements
- Increased collection rates of end-of-life scrap

SHARING BUSINESS MODELS AND INCREASED LIFETIME OF PRODUCTS

- New business models such as car-sharing to increase use intensity and product lifetime, reducing steel needed per passenger-kilometre
- Remanufacturing and reuse of steel components to increase lifetime of products and structures

...EMISSIONS REDUCTIONS FROM STEEL

CLEAN PRODUCTION OF NEW MATERIALS



NEW AND IMPROVED PROCESSES

Shifting production processes and feedstocks to eliminate fossil CO₂ emissions



CARBON CAPTURE

Capture and permanent storage of CO₂ from production and end-of-life treatment of materials, or use of captured CO₂ in industrial processes

CLEAN UP CURRENT PROCESSES

- Incremental energy efficiency improvements
- Switch to biofuels and -feedstock in blast furnaces and downstream processes
- Natural gas-based direct reduction (DRI) as a transition step to net-zero production

CARBON CAPTURE AND STORAGE

- Carbon capture on coal-based processes
- Smelting reduction to concentrate CO₂ flows and achieve high capture rates

NEW PROCESSES AND FEEDSTOCKS

- Direct reduction using hydrogen as reducing agent

CARBON CAPTURE AND UTILISATION

- Chemicals production from carbon-rich blast furnace off gases
- Switch to recirculated / non-fossil feedstock and CCS of residual CO₂ required for net-zero solution

ELECTRIFICATION

- Hydrogen production through water electrolysis
- Electrification of ore sintering
- Electrification of reheating furnaces and other downstream processing

CIRCULAR ECONOMY AND MATERIALS EFFICIENCY IN MAJOR VALUE CHAINS

As noted, modern societies require in the range of 10–13 tonnes of steel per person to provide essential services such as mobility, infrastructure, industrial production and more.

However, there is nothing absolute about this number, and in fact there are multiple opportunities to use steel more efficiently. By reducing waste, optimising structures, increasing the utilisation of key capital goods, and increasing the lifetime of structures and products, it is possible to achieve the same end-use benefits with less steel (that is, the same amount of passenger-kilometres of transportation, built area, infrastructure availability, protection of packaged goods, etc.)

This study has carried out a bottom-up assessment of this potential (Exhibit 2.5), modelling the major opportunities in transportation, construction, machinery, and various products.¹¹ Overall, we find it is possible in an ambitious scenario to achieve the same economic benefits while using 54 Mt (28%) less steel per year in 2050.

The most important measures include:

- **A reorganisation of mobility** towards autonomous and shared vehicles, which could reduce the amount of steel required by as much as 70% for the same number of passenger kilometres.¹²
- **Digitisation and other** tools to optimise steel use in construction. This includes reduced over-specification (today's buildings often use 50% more steel than required), modular construction and reconstruction in favour of demolition, re-use of structural elements, and the use of high-strength steels.¹³
- **Reduced yield losses** in manufacturing. The amount of steel scrap generated in manufacturing can vary by as much as 50% even in mature processes. Although such scrap is not lost, it is wasteful and leads to the need for large absolute steel stock at any one point.
- **A range of materials** efficiency and circular economy principles such as lightweighting techniques, remanufacturing opportunities, product-as-a-service business models, etc. across a range of product groups.

For policy-makers and businesses, a key insight is that major contributions towards lower emissions rest not only with the steel industry itself, but with actors in entirely different sectors. Achieving these savings will mean changing practices along several of steel's major value chains. In some cases, it also entails reorganising the way basic services are provided – notably passenger transport. In others, the key is product design, business models, or digitisation to reduce transaction costs of improved construction techniques.

Although these levers result in reduced steel demand, they need not result in reduced economic activity. In some cases, they represent productivity opportunities: achieving more with the same output. Like other improvements in productivity, this can boost economic activity by freeing up resources for other use. In other cases, there is a migration of activity away from upstream steel production and into other points of the value chain. In particular, there will be greater need for labour, data and energy in construction and manufacturing.

Achieving these categories of measures can be complex. They require extensive coordination and information flows. Incentives often are poorly aligned, and current models for everything from contracts to performance management often neglect materials efficiency. In this, too, circular economy and materials efficiency opportunities are similar to energy efficiency, which often faces very similar barriers. On the other hand, digitisation is a strong driving force, reducing the transaction costs of many opportunities.

It therefore is uncertain how much of the potential can be achieved. This study explores two alternative scenarios:

In the scenario with a high level of circularity, around 75% of the identified potential is realised. This reduces the amount of steel required by 54 Mt per year in 2050, resulting in a total steel demand of 139 Mt.

The less ambitious scenario for circularity captures instead just one fourth of this amount. This would leave steel demand close to 181 Mt per year.

Exhibit 2.5

DEMAND-SIDE OPPORTUNITIES FOR MATERIALS EFFICIENCY AND NEW CIRCULAR BUSINESS MODELS

Mt STEEL PER YEAR, 2050

REDUCED SCRAP FORMATION IN MANUFACTURING.

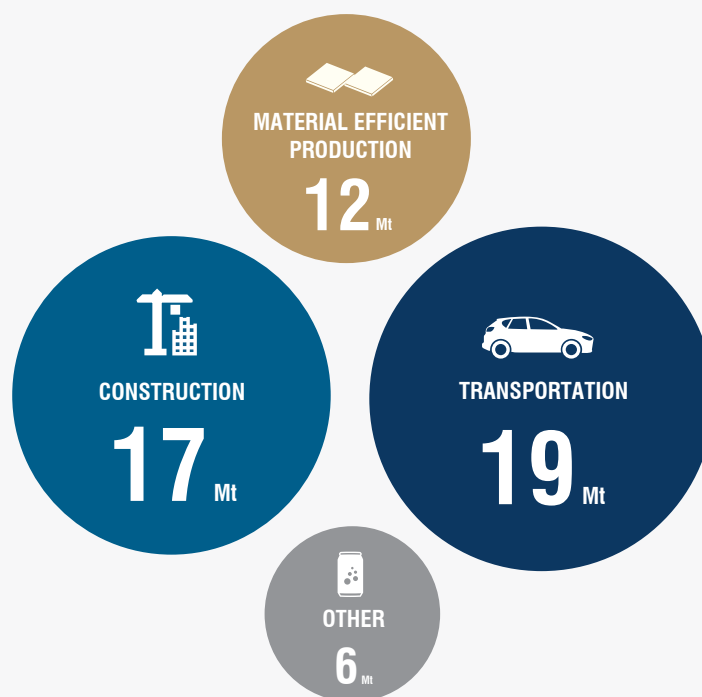
Although most steel scrap in the manufacturing process is recycled, in the meantime additional primary steel has to be made. Therefore, measures to cut the formation of scrap during manufacturing will cut overall production. This can be achieved by switching to designs that consider the production process, making semi-finished products that are closer to the final shape, and embracing technologies like 3D printing and powder metallurgy that make less scrap.

INCREASED EFFICIENCY OF STEEL USE IN CONSTRUCTION

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 higher-strength materials; and reusing buildings and building components. For example, high strength steel can reduce the amount of steel needed for a given project by 30%. Furthermore, projects often use 50% more steel than is physically necessary.

INCREASING THE USEFUL SERVICE FROM STEEL

By extending the lifetime of buildings, and/or by increasing the utilisation of floor space through sharing and other circular business models.



SHARING MODELS OF TRANSPORTATION FOR PASSENGER CARS.

Car-sharing and similar schemes ensure that each vehicle is used more intensively, reducing the need to make extra units. A shared mobility system could reduce materials use in transport by 50-70%

INCREASING THE USEFUL SERVICE OF TRANSPORTATION UNITS

By increasing utilization and by extending the lifetime through high strength steel and improved maintenance.

INCREASED EFFICIENCY OF STEEL USE IN MACHINERY AND PRODUCTS.

High strength steel applied in machinery could reduce demand with 2.1 Mt steel per year.

SHARING SCHEMES

To ensure more intensive use of steel products including sharing of domestic appliances and machinery. A system for shared products can reduce steel need with 20%.

SOURCE: MATERIAL ECONOMICS ANALYSIS, SEE ENDNOTE.¹⁴

MATERIALS RECIRCULATION: ENABLING HIGH-QUALITY STEEL PRODUCTION FROM SCRAP

Steel is already a highly circular material. On average, 85% of end-of-life steel is recovered for recycling – more than has been achieved for any other major material.¹⁵ Recycling is driven by the intrinsic economic value of steel scrap: the 131 Mt generated in the EU every year has a value of some 30 billion EUR. Of this, some 94 Mt are used in the EU, making up half of the iron input to EU steelmaking¹⁶, while 17 Mt are exported, with Turkey the largest destination.

In coming decades, the availability of scrap in the EU will increase, as the EU steel stock saturates (Exhibit 2.6). There are also opportunities to increase the collection rate for end-of-life steel (which already varies depending on steel prices, as well as country by country). By the 2050s, the amount of scrap available could be as large as total EU annual steel needs, raising the intriguing prospect that EU steel needs could be met largely by recycling steel already made. Steel could become the first, and by far largest, flow of a nearly fully circular material.

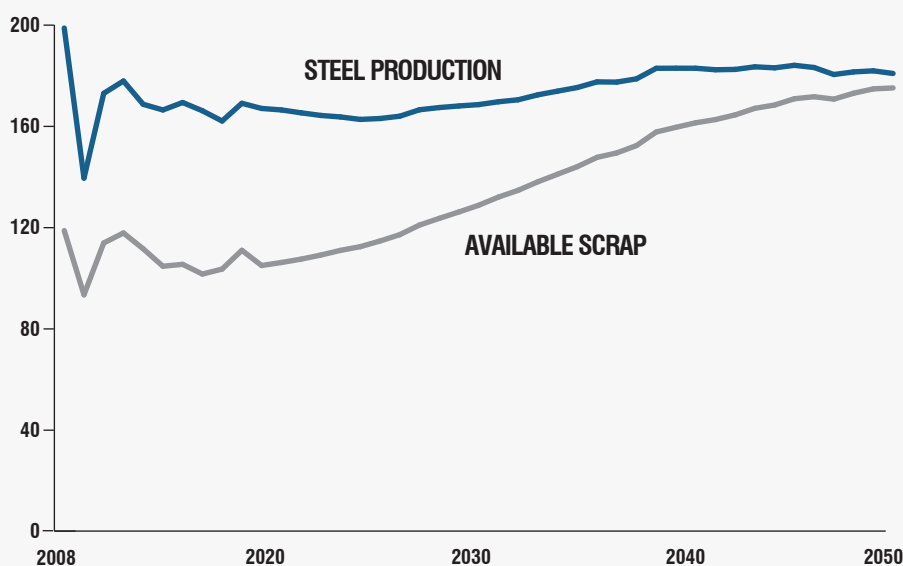
The EU steel industry and wider economy face a fundamental choice over whether to use this scrap in the EU or to export it. The impacts on global greenhouse gas emissions, and on the economics of the industry, are complex. On the one hand, if primary production of steel was maintained at current levels, the scrap exports could increase three- to fourfold, to 80 Mt per year. This in turn would reduce the need for primary production in other regions. Especially if EU primary production became less emissions-intensive, this would contribute to global CO₂ reductions.

On the other hand, using the scrap generated in the EU would mean EU producers needed fewer resources. The EAF route to steel production uses only 10-15% of the energy of integrated production and is significantly less capital-intensive. Direct CO₂ emissions are also much smaller, at 0.1 t CO₂ per tonne coil with best practice. Using these resources less would directly cut EU emissions. It could also pioneer models for a highly circular steel system that would ultimately be beneficial at the global level.

Exhibit 2.6

EU COULD FULFIL MOST OF ITS STEEL DEMAND USING SCRAP-BASED PRODUCTION

STEEL SCRAP AVAILABILITY AND STEEL PRODUCTION
MILLION TONNES PER YEAR



NOTES: PRODUCTION AND SCRAP VOLUMES IN THIS EXHIBIT REFER TO A SCENARIO WITH 'MEDIUM CIRCULARITY', REPRESENTED IN NEW PROCESSES AND CARBON CAPTURE PATHWAYS.
SOURCES: MATERIAL ECONOMICS MODELLING BASED ON EUROFER (2018) AND PAULIUK ET AL. (2013).¹⁸

If the EU steel industry does opt to significantly increase its use of scrap, major changes will be necessary. There is some limited potential to increase the amount of scrap used in the BF-BOF route, but the main step would be to gradually switch towards a higher share of EAF-based steelmaking.¹⁹ Today EAFs are used almost exclusively for long products, but some flat products (62% of EU finished steel production²⁰) would need to come from this route (as is already the case in the United States). As noted, emissions from EAFs can be reduced to very low levels if electricity is generated using zero-emissions sources.

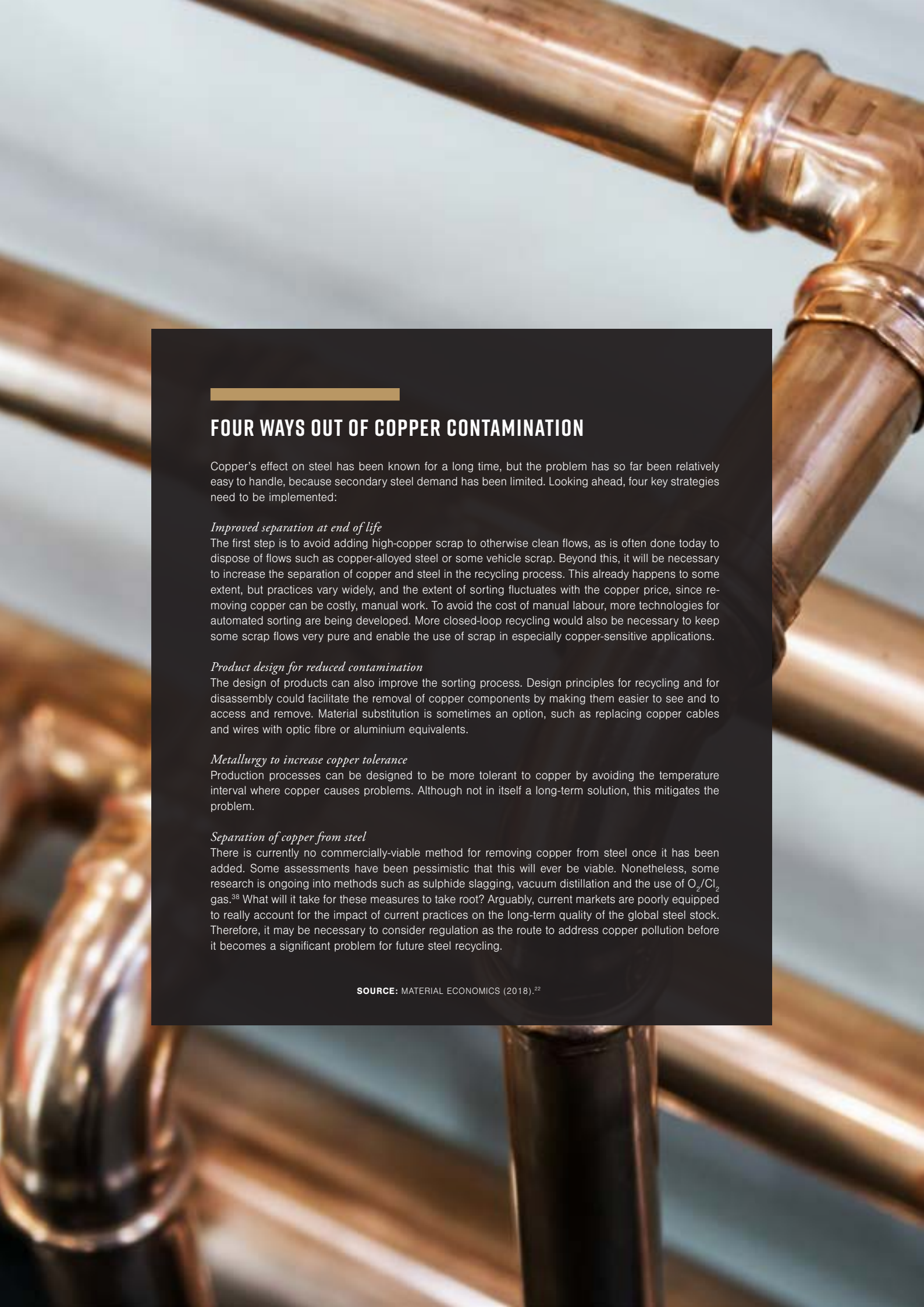
Increasing the share of scrap input above around 60% in total EU production also is possible, but would require a concerted push to improve control over the quality of steel scrap. The most important step is to reduce the contamination of steel scrap by undesired 'tramp elements', especially copper, which is introduced during the steel lifecycle and recycling (for example, copper wiring from other components often attaches to the steel from the chassis and frame of an end-of-life car). Even small levels of copper adversely affect the quality of some steel products. Unlike many other elements, copper cannot be removed to slag when scrap is re-melted.

There are concrete steps that can be taken to drastically reduce the inmixing of copper in scrap, notably more carefully sorting out scrap metal before it is recycled, replacing copper with other metals where possible, and designing products that can be easily disassembled for recycling (see Box, next page).

Keeping the steel stock clean for future recycling is not just desirable for EU resource efficiency – it also affects global steel production. Unless practices are changed, the recycling of steel would be constrained by copper already by 2050, and more steel would have to be made from iron ore.²¹ Given the higher resource use and emissions from primary production it would result in additional CO₂ emissions, eventually reaching several hundred million tonnes of CO₂ per year. Therefore, downgrading steel and selling it outside the EU is not a long-term solution. Efforts to improve the collection rate and reduce the contamination of steel scrap should be high up the list of priorities for reducing emissions from steel production.

To capture these considerations, this study considers two different scenarios for the share of scrap metal input to steel production. In a high recycling scenario, the scrap share of steel production would reach 70%. This is technically possible given total scrap availability, product mix, the potential to reduce scrap contamination, and the more widespread use of EAFs – but would require changes to scrap handling as well as the structure of production. In a low-scrap scenario, scrap-based inputs would stay between 50% (today's level) and 60%. Depending on how demand develops, the EU would then export as much as 38-63 Mt of scrap per year by 2050.





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 has been 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 making 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. Although not in itself a long-term solution, this mitigates the problem.

Separation of copper from steel

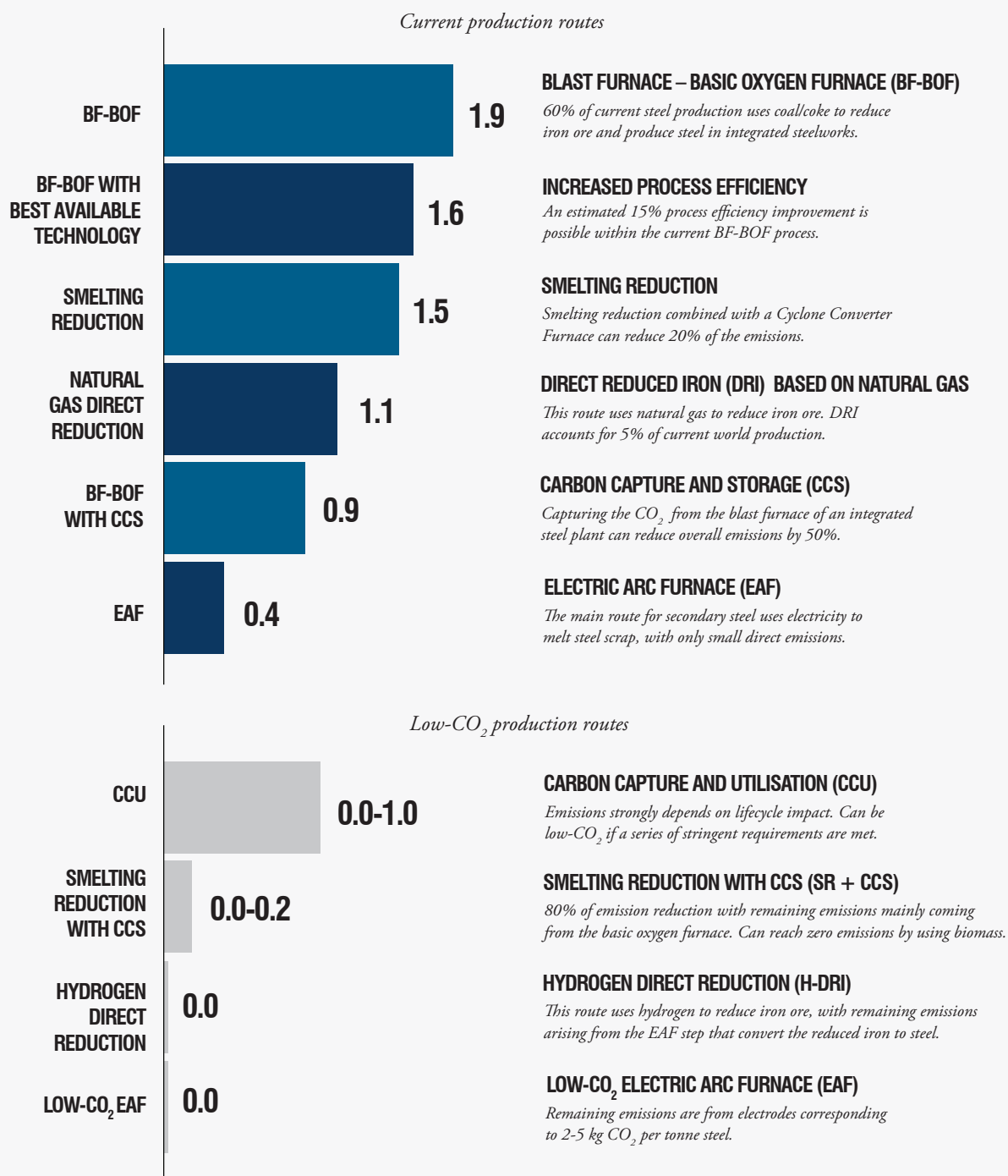
There is currently no commercially-viable method for removing copper from steel once it has been added. Some assessments have been pessimistic that this will ever be viable. Nonetheless, some research is ongoing into methods such as sulphide slagging, vacuum distillation and the use of O_2/Cl_2 gas.³⁸ What will it take for these measures to take root? Arguably, current markets are poorly equipped to really account for the impact of current practices on the long-term quality of the global steel stock. Therefore, it may be necessary to consider regulation as the route to address copper pollution before it becomes a significant problem for future steel recycling.

SOURCE: MATERIAL ECONOMICS (2018).²²

Exhibit 2.7

FOUR PRODUCTION ROUTES ARE COMPATIBLE WITH NET-ZERO EMISSIONS

CO₂-INTENSITY OF EU STEEL PRODUCTION
TONNES CO₂ PER TONNE STEEL



NOTES: ALL PRODUCTION ROUTES ASSUMING ZERO-CARBON ELECTRICITY IN 2050. CURRENT PRODUCTION PROCESSES INCLUDE DOWNSTREAM EMISSIONS FROM CONTINUOUS CASTING AND HOT ROLLING. THESE DOWNSTREAM EMISSIONS ARE ASSUMED TO BE FULLY DECARBONISED BY 2050 IN THE LOW-CO₂ PRODUCTION ROUTES.

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.²³

CLEAN PRODUCTION OF PRIMARY STEEL

Increased materials efficiency and recycling can significantly reduce long-term need for primary steelmaking. However, new primary production from iron ore will be required in any scenario. Globally, some 1 billion tonnes per year of new, primary production will be necessary for the foreseeable future to build up the amount of steel in the global economy.²⁴ In Europe, some share of primary steel will be needed to enable the full production mix required. Therefore, clean production processes will be necessary, in Europe as well as globally.

The scope for easy cuts has already been all but exhausted. Today's integrated production emits just 50% of the CO₂ compared to steelmaking in the 1970s and is now close to its theoretical limits. The scope for further energy and process efficiency improvement in integrated plants is on the order of 5-10%. Other options, such as using a larger share of bio-ba-

sed inputs in production, can realistically provide only marginal CO₂ reductions within the current production system.²⁵

This leaves two main routes to deeper cuts from steel production. The first is to use direct reduction, replacing the carbon in fossil fuels with electricity (for energy) and with hydrogen (for the reduction of iron ore). The second is to capture nearly all of the carbon, and reprocess or store it in ways that permanently prevent release to the atmosphere. However, unlike in energy processes (such as power generation), carbon capture in the steel sector is far from straightforward. Rather than an 'end of pipe' solution that can be fitted to existing production, it will require major modifications to the core process of iron and steelmaking.

In either case, low-CO₂ iron and steel production therefore requires a major transformation.

LOW-EMISSIONS PROCESSES WITH HYDROGEN-BASED DIRECT REDUCTION

Nearly all CO₂ emissions from steelmaking arise in two core processes: producing the heat energy to melt steel and drive the processes, and the reduction of iron ore to iron. Thus, a major candidate for deep cuts is to replace these two steps. The energy part is in fact already proven, as the EAFs used in scrap-based steelmaking are widely used. Eliminating carbon from reduction would require further development of the Direct Reduction of Iron (DRI) process to replace carbon with hydrogen.

DRI is a proven process, accounting for 5% of steelmaking globally²⁶ (but only 0.4% in the EU). It uses natural gas instead of coal as the 'reducing agent' to produce iron, which in turn can be further processed into steel in much the same ways that scrap is: an electric arc furnace (EAF) followed by several downstream steps. This process is less emissions-intensive than the BF-BOF route, with CO₂ emissions around 40% lower.²⁷ In the EU, the economics of current DRI production have been unfavourable, as it depends strongly on access to cheap natural gas.

Swapping in hydrogen for natural gas is technically entirely plausible. Even in a natural gas-based DRI process, some 50% of the reduction of iron is done by the hydrogen contained in the natural gas, with the remainder done by carbon, which then creates CO₂. There is thus no question that hydrogen can reduce iron ore. However, there has never been any commercial reason to increase the share of hydrogen, and further development is required to bring this option to industrial scale. Several EU steel companies now have plans to start piloting H-DRI including Salzgitter, SSAB, ThyssenKrupp, and Voestalpine.²⁸ These companies foresee a sequence of piloting and demonstration spanning some 10–15 years before the technology is fully proven and ready to operate at large capacities.

The shift to hydrogen creates entirely new resource demands. The hydrogen production must itself be CO₂-free, either by capturing the CO₂ from production or by using zero-emissions electricity – otherwise it would simply cre-

ate new emissions elsewhere (see Box, next page). If hydrogen is produced from water via electrolysis, some 3-4 MWh of zero-carbon electricity is required for every tonne of steel produced. If the same hydrogen is instead produced from natural gas via today's dominant production route (steam methane reforming, SMR), it would be necessary to capture and permanently store 0.5 tonnes of CO₂ for every tonne of steel. In either case, replacing today's coal and coke ovens with electrolyzers and electricity or SMR and CCS and its infrastructure is a major change. One major aspect of this is large-scale hydrogen storage. A large steel plant may require five days worth of storage both to safeguard continuous operation, and to ensure flexibility in electricity use to benefit from lower electricity prices.

Using hydrogen for reduction and EAFs for heating already would take care of most of the emissions. However, for truly deep cuts it would also be necessary to further develop other steps in the iron and steel production chain. First, an alternative source of energy is needed for preparing (sintering and pelletising) iron ore. This requires high temperatures in excess of 1,000°C, with electricity and biofuels both possible candidates. Second, the EAF process must be made largely fossil-free. Although direct emissions are already low today (around 0.1 t CO₂ per tonne of steel), they can be cut further. Additional process development will be required to combine very low CO₂ emissions with high yields and efficiency. Finally, as with all other steel routes, the downstream forming processes must be either electrified or use biogas. The largest energy use is in reheating furnaces that require heat of 1,200°C prior to rolling and other processes, but there also are a range of electric power, steam generation, and other processes that need zero-carbon energy inputs.²⁹

This study explores scenarios of 28–63 Mt of primary steel made every year by H-DRI by 2050 – a significant fraction of the baseline production of 193 Mt. Actual steel made at plants using H-DRI would be significantly larger, as nearly all production would benefit from using a significant share of steel scrap as well.

CARBON CAPTURE AND STORAGE

Carbon capture and storage (CCS) has long been explored as an option for steel production. The main thrust has been to explore how it could be fitted to existing blast furnaces. However, the multiple sources of emissions and integrated nature of steel plants means that only a small share of emissions would be addressed if carbon capture was applied to the process as currently configured. By modifying the blast furnace to recycle its exhaust gases ('top gas recycling'), this could increase to a 50% reduction.³⁰ In past roadmaps, this has been mooted as a maximum feasible reduction level.³¹ No study appears to have deemed it feasible to fit all the major emissions sources within an integrated steel plant with carbon capture.

These are stark findings. They amount to saying that major changes to steel production processes will be required for carbon capture to achieve deep emissions cuts. There are two main options now actively explored in Europe. One is to replace the current blast furnace route with smelting reduction. The other is to take the top gas recycling concept several steps further, to heavily reprocess gases from both blast furnace and coke oven through a combination of CCU and CCS. The pathways explored in this study show up to 54 Mt of steel per year produced through these routes by 2050.

HYDROGEN BECOMES A KEY INPUT IN A NUMBER OF CLEAN PRODUCTION ROUTES

Today, hydrogen is produced through steam reforming of methane from natural gas, and used predominantly in ammonia production and petroleum refining. In a net-zero economy, large-scale, clean production of hydrogen will be a necessary enabler for many low-GHG routes across industrial and other sectors.

- In steel production, hydrogen can replace coal as a reducing agent (removing unwanted oxygen from iron ore to produce pure iron), avoiding CO₂ emissions from steelmaking and coking processes.
- In plastics, hydrogen becomes a key building block in a range of new production processes, including to increase yields in gasification, in the production of methanol, and potentially as a reactant in the synthetic production of plastics from CO₂.³²
- In the cement industry, hydrogen is one option among several to achieve carbon-free high-temperature heat. Hydrogen is also an energy carrier (or fuel), enabling energy storage and distribution that could facilitate the use of intermittent renewable energy sources.³³
- Hydrogen is already a key input in ammonia production – but changing how it is produced could dramatically reduce or eliminate CO₂ emissions in the sector.

There are two main routes for the production of hydrogen without large CO₂ emissions. One is to eliminate carbon entirely, and make hydrogen through the electrolysis of water. The most mature technology is alkaline electrolysis, which can turn yield hydrogen output corresponding to 70–75% of the electrical energy input.³⁴ Other options under development (proton-exchange membrane electrolysis, solid oxide electrolysis) could achieve still higher efficiency. Electrolysis already has high technology readiness, but it is only cost-competitive with SMR if the electricity is very cheap, so it has rarely been used at scale. Many assessments expect the cost of electrolyzers to fall by as much as half when they start to be manufactured and deployed at scale.

The other main low-CO₂ production route is continued use of SMR, but with capture of the CO₂ produced. The challenge is to achieve high capture rates: while the feedstock CO₂ is concentrated and easy to capture, CO₂ from fuel combustion in the reformer is harder to reach. One option is to electrify the heat instead. While carbon capture technology is relatively mature, it has not been applied to SMR in practice, so additional demonstration and development is needed. Other options also are being explored, including methane pyrolysis, where the carbon is concentrated to a solid instead of being released as CO₂ gas. If the solid can be safely stored, this offers another potential route to CCS. The route chosen for clean hydrogen production has a range of knock-on effects and requirements. For CCS, infrastructure for carbon transport and permanent storage is a current major roadblock. Production is best carried out at scale, as both SMR and CCS are most cost-effective at large units. Further technology development is required for the high capture rates of 90% or more required for a net-zero economy.

Technologies for electrolysis are much more modular and can operate at smaller scale. The key requirement is large amounts of essentially CO₂-free electricity, which also becomes a major part of the cost of production. In addition, electrolyzers are capital-intensive. Large-scale hydrogen storage (another development priority) also has major benefits, as it can enable electrolyzers to operate flexibly. In an electricity system with large shares of variable renewable electricity, this can drastically reduce the cost of electricity and therefore also the levelised cost per tonne of hydrogen (even accounting for the greater capacity required).

SMELTING REDUCTION WITH CARBON CAPTURE

Smelting reduction has been a candidate for iron and steel production since the 1980s. Medium-scale operation has been proven, but the technology has never reached a major share of production. In the EU, the HIsarna project run by Tata Steel is the main ongoing effort to develop smelting reduction further.

In direct smelting, the coking plant, sinter plant and blast furnace are all dispensed with. Instead, iron ore is injected into a reactor alongside powdered coal. The ore is liquified in a cyclone converter furnace and drips to the bottom, and the coal reduces the ore to iron in a molten state. The molten metal can then be reprocessed to steel in a basic oxygen furnace, as in the standard BF-BOF route.

The underlying motivations for smelting reduction have been to reduce energy consumption by up to 20%, to replace expensive coke with much cheaper coal, and to find a production route with lower capex requirements. However, direct smelting also has features that make it a good match with carbon capture. By replacing several processing steps with a single reactor, it creates a single point source of CO₂ for nearly all the emissions from ironmaking. Moreover, in the HIsarna case, the use of pure oxygen creates a very CO₂-rich gas that is much cheaper to capture than are the low-concentration CO₂ streams resulting from traditional processes. In total, some 90% of emissions could be eliminated. The fuel flexibility of the process also makes it possible to introduce a share of biomass instead of coal, for a fully net-zero solution. As with all other routes, for very deep cuts it also would be necessary to adapt downstream steel processing steps to electricity or other fossil-free energy.

Large-scale deployment of smelting reduction and CCS would be a transformation on a similar magnitude to a switch to H-DRI: a wholesale change of the core ironmaking process of primary steelmaking, with a need to first demonstrate industrial-scale operations. Assessments by industry experts interviewed for this study diverge on the prospects of achieving this. In practical terms, the further development of HIsarna will now take place not in the EU, but in India. It also would face the challenges of brownfield conversion, and of parallel investment to enable continuous production during the switch from one production system to another.

The other major requirement is feasible options for transporting and storing large volumes of CO₂. This has been a major stumbling block for past efforts to develop CCS in Europe. Escaping the chicken-and-egg dynamic of capture-and-storage is an indispensable step on the way to large-scale use of direct smelting or any other CCS concept.

BLAST FURNACE-BASIC OXYGEN FURNACE WITH CARBON CAPTURE, UTILISATION AND STORAGE

The final option for nearly CO₂-free production is to substantially modify the operation of the current blast furnace route, combining it with both carbon capture and utilisation and carbon capture and storage. This builds on the top gas recycling concept but takes it much further. The core idea is to combine the gases produced from the main carbon sources (coke oven, blast furnace, and basic oxygen furnace) with hydrogen to produce syngas for chemicals production (instead of burning them for energy generation, as is done today). Companies exploring this option include Thyssen-Krupp (Carbon2Chem) and ArcelorMittal (Steelanol, IGAR).

The main advantage of this route would be to find a way to continue using the blast furnaces that are at the heart of current steelmaking. However, for this to be compatible with net-zero CO₂ emissions, very major additional industrial processes and strict criteria would be required. Specifically:

- 1. The majority of inputs must be circular or bio-based carbon.** Today, advanced operation of blast furnaces can allow the share of coke to be as low as 50%, with the remainder typically coal or petcoke. Industry experts hypothesise that the share of coke could be reduced to as low as 25%, and the remaining 75% could then consist of end-of-life plastics or biomass as alternatives to (new) fossil carbon.
- 2. Integration of all main processes.** For deep CO₂ cuts, the gases from the coke oven, blast furnace, and basic oxygen furnace must all be diverted for reprocessing to chemicals.
- 3. Large-scale carbon capture to offset fossil carbon input.** The residual CO₂ would have to be permanently stored (not used), in order to offset the fossil carbon used. This could amount to 25% of the total, depending on how much hydrogen is added, but it may need to be more.
- 4. Outputs restricted to circular products.** The chemicals produced would need to be used exclusively for products that themselves are nearly fully recycled. If used for single-use chemicals or fuels, or if plastics were only partially recycled as happens today, emissions would only be postponed briefly until end-of-life plastics were incinerated (almost half of plastic has a lifecycle of just one year).³⁵
- 5. Other inputs must be fossil-free:** The processes would rely heavily on hydrogen, which must come from a CO₂-free source.

If all of these five conditions are met, the concept is similar to the chemical recycling concepts for plastics described in Chapter 3. In a case of sector coupling, the steel sector would then become the process for recirculating plastics to high-value chemicals, from which new plastics could be made. Given the large amounts of carbon required for iron- and steelmaking, the quantity of chemicals produced would rapidly grow very large (in the millions of tonnes).

These are exacting requirements. The CO₂ emissions savings would be very different if, say, fossil-derived coke continued to be the main input, if CCS was not applied, or if the outputs were not fully circular. There thus are very narrow parameters within which CCU could be part of a net-zero economy.

Low-CO₂ iron and steel production requires a major transformation.



2.3 LOW-EMISSIONS PATHWAYS FOR THE EU STEEL SECTOR

A major conclusion of this study is that there are many technologies and strategies that could contribute to a net-zero emissions steel industry in the EU. Another is that all options require major transformations: from how steel is used in major value chains, to the organisation of mobility and other sectors, and to the fundamental production routes for iron- and steelmaking.

With so many options in play, and so much uncertainty over costs and risks, no one pathway can give all the answers and policy insights required to enable these transitions. To guide discussions, this study explores three pathways to a net-zero emissions EU steel industry in 2050 (Exhibit 2.8). Each pathway incorporates all the solutions identified above, but with different degrees of emphasis:

New processes pathway. In this pathway, there is only modest success in capturing the potential for increased materials efficiency (12 Mt steel equivalent per year by 2050). Instead, production remains at 181 Mt in 2050, and is concentrated in processes that rely on extensive use of electricity. The core production process is H-DRI, which amounts to 63 Mt of steel production in 2050. This is combined with increased scrap use of 29 Mt, which can be combined with iron from H-DRI in EAF production. This pathway has the largest gross amount of steel scrap being used, but not the highest share of steel production. In contrast, in this scenario CCS and CCU options are limited to just 9 Mt per year, corresponding to a few large plants in favourable locations.

Circular economy pathway. In this scenario, Europe relies on materials efficiency and circularity to meet much of its need for steel. The need for new steel production is reduced by 54 Mt per year through increased materials efficiency and widespread adoption of new business models in mobility and construction. Steel production in 2050 thus stands at 139 Mt. Much of this, in turn, is met through steel recycling, as drastically improved product design, dismantling, scrap handling and advances metallurgy enable the EU to derive 70% of its need for iron from scrap. The remaining 28 Mt of primary production takes place via a mix of H-DRI and CCS/CCU options.

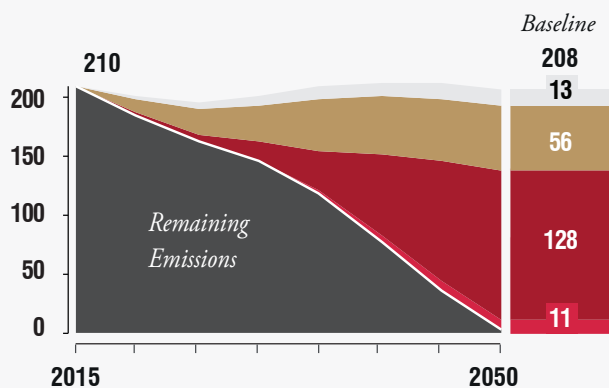
Carbon capture pathway. This pathway sees the same amount of steel production as in the ‘New Processes’ pathway, but less use of scrap, which remains at the same share as today (50% of iron input). Primary production of iron therefore stands at 91 Mt in 2050, similar to today’s levels. As in the New Processes pathway, new production routes are rapidly scaled up in the 2030s, but the emphasis is on CCS rather than on extensive use of electricity. Smelt reduction with CCS plays a major role. H-DRI also finds a place, but half the hydrogen input is produced from steam reforming of natural gas with CCS rather than from electrolysis. CCU also plays a role, but is tightly bound by the requirements to ensure permanent sequestration of carbon in products. In total, some 72 Mt of CO₂ per year is permanently stored via these processes in 2050.

Exhibit 2.8

PATHWAYS TO NET-ZERO EMISSIONS FOR STEEL

CO₂ ABATEMENT
Mt CO₂ PER YEAR

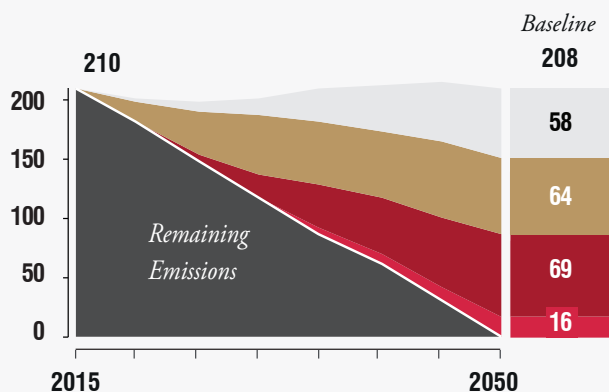
NEW PROCESSES
Pathway



PATHWAY BASED ON ELECTRIFICATION OF STEEL PRODUCTION PROCESSES

- Focus on primary production using hydrogen-based direct reduction (H-DRI) and indirectly electrifying the steel production process by using hydrogen produced by electrolysis.
- The share of steel produced through the electric arc furnace route increases to 60% by 2050.

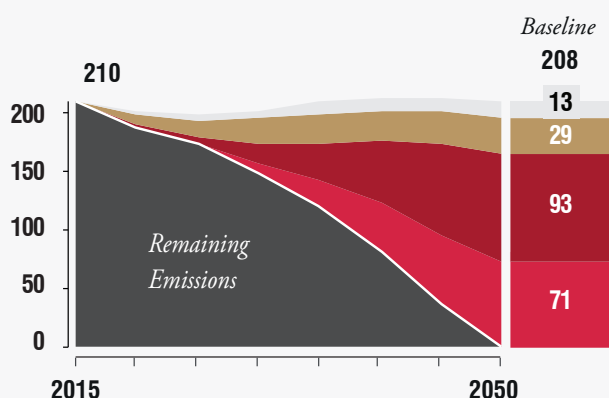
CIRCULAR ECONOMY
Pathway



EMPHASIS ON ACHIEVING MORE WITH STEEL ALREADY MADE AND PRODUCTION BASED ON RECYCLED STEEL

- Concentration on demand-side opportunities for materials efficiency and new circular business models for steel, such as car sharing, and material efficiency in construction.
- Increase in scrap-based production and recirculation of steel within EU. The share of steel produced through the electric arc furnace route increases to 70% by 2050.

CARBON CAPTURE
Pathway



PATHWAY FOCUS ON CAPTURING CO₂ FROM STEEL AND HYDROGEN PRODUCTION PROCESSES

- Emphasis on using CCS/U on primary steel production. In this pathway, 50% of the primary production in 2050 is equipped with CCS/U.
- Producing 50% of the hydrogen required for the Hydrogen direct reduction route (H-DRI) with steam methane reforming combined with CCS.

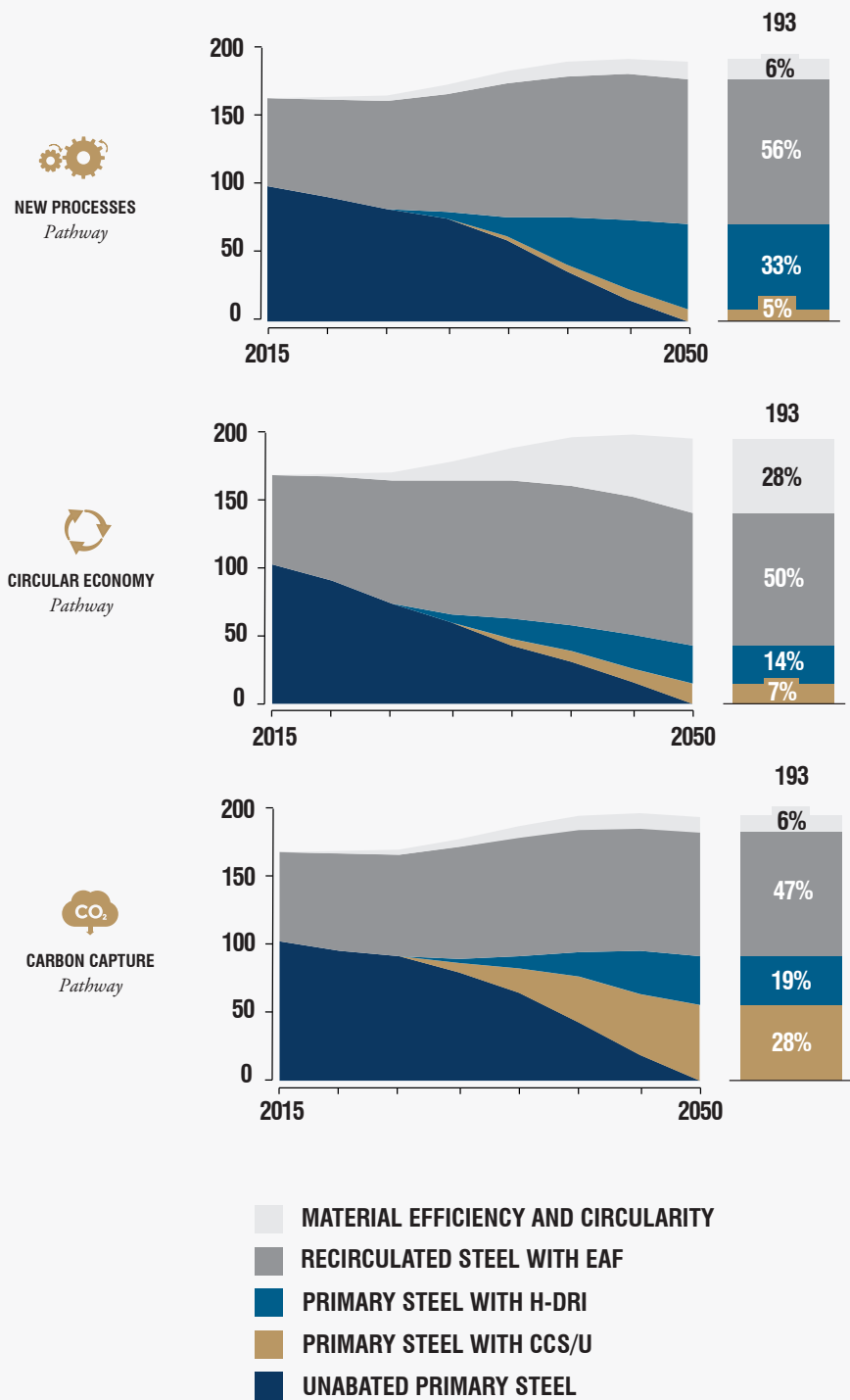
- MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS
- MATERIALS RECIRCULATION AND SUBSTITUTION
- NEW PROCESSES
- CARBON CAPTURE AND STORAGE
- REMAINING EMISSIONS

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

Exhibit 2.9

PRODUCTION ROUTES IN NET-ZERO PATHWAYS

EU IRON AND STEEL PRODUCTION MIX TO ACHIEVE NET ZERO EMISSIONS IN 2050
Mt STEEL PRODUCED PER YEAR AND ROUTE



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.



While the three pathways are designed to be strikingly different, several elements are inescapable and recur across all three. These cross-cutting elements offer crucial clues for the design of a net-zero emissions steel industry.

All pathways entail very major shifts in the production structure of the sector. Simply put, there is no path to truly deep emissions cuts in the steel sector that does not entail a major transition in fundamental technologies and processes. This presents a formidable challenge, but also an opportunity to develop new solutions.

Likewise, while the emphasis in these pathways is on truly net-zero options, transitional solutions will play an important role for early emissions reductions. These can include continued process efficiency solutions, early shifts towards increased use of steel scrap, increased use of biomass, a range of materials efficiency improvements, and early decarbonisation of the electricity sector. The risk otherwise is that deep cuts can be achieved only from the mid-2030s, presenting a challenge to near-term emission reduction goals.

Another cross-cutting insight is that all pathways depend on significant acceleration of solutions that are promising but nonetheless emerging – car-sharing systems, materials-efficient construction, scrap handling, hydrogen DRI, smelt reduction, and carbon storage

business models. Which of these prove the easiest is still uncertain, but the strategy now must be to pursue as wide a portfolio as possible, and to immediately find ways to significantly increase the resources dedicated to their development. Several ongoing projects developed by companies are expected to be ready in the 2040s, but this could probably be pushed to an earlier date, given a suitably strong policy push.

Also, while such rapid changes are undeniably challenging, the transition to net-zero emissions will be significantly easier if more circular economy solutions can be mobilised. These buy time for technology development, and as we discuss below can reduce cost, investment needs, and input requirements. They deserve special emphasis, as they currently do not form part of either industrial strategy or climate policy.

Finally, in all pathways, both the steel industry and new materials-efficient or circular business models will become heavily reliant on new outside actors. These include new infrastructure and inputs, whether for CO₂ transport and storage, or for electricity supply. Likewise, policy will become a major determinant of the decisions made in the sector. It will be a requirement for innovation, but also for the sector to bear the increased costs and investments that reduce barriers to circular economy and materials efficient solutions, and that enables the required infrastructure and inputs.

DEEP CUTS TO EMISSIONS WILL INCREASE THE COST OF PRODUCING STEEL BY UP TO 20%

Producing steel without CO₂ emissions will come at a cost. By 2050, the additional costs range between 3.5 and 5.0 billion EUR per year, implying an average abatement cost between 17-24 EUR / t CO₂. There are differences between the pathways, with the circular economy pathway the most cost-effective – provided the major materials efficiency levers can be successfully pursued – and little difference between the other two pathways.

A closer look at the different production routes shows the key parameters that determine the costs of different options (Exhibit 2.10). In particular, the new low-emissions production routes remain more expensive than existing production routes even after full deployment, adding 0-20% to the cost of steel products. These costs are estimates for fully developed processes, once some key components have travelled down the cost curve. Early deployment is likely to be more expensive.

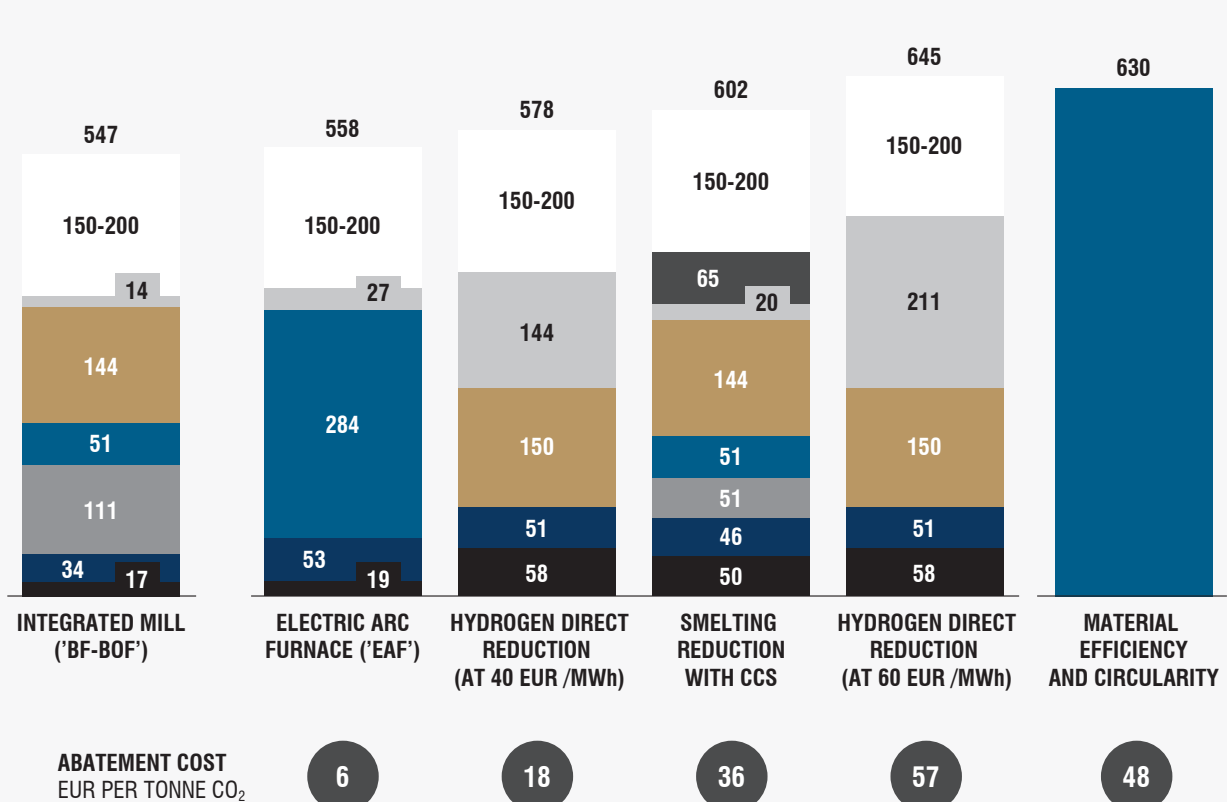
Exhibit 2.10

COST OF PRODUCTION IS HIGHER FOR LOW CO₂ PRODUCTION ROUTES

COST BREAKDOWN OF PRODUCTION ROUTES
EUR PER TONNE STEEL

COST INCREASE OF 0-20% FOR LOW-CO₂ PRODUCTION ROUTES
RELATIVE TO EXISTING INTEGRATED MILLS

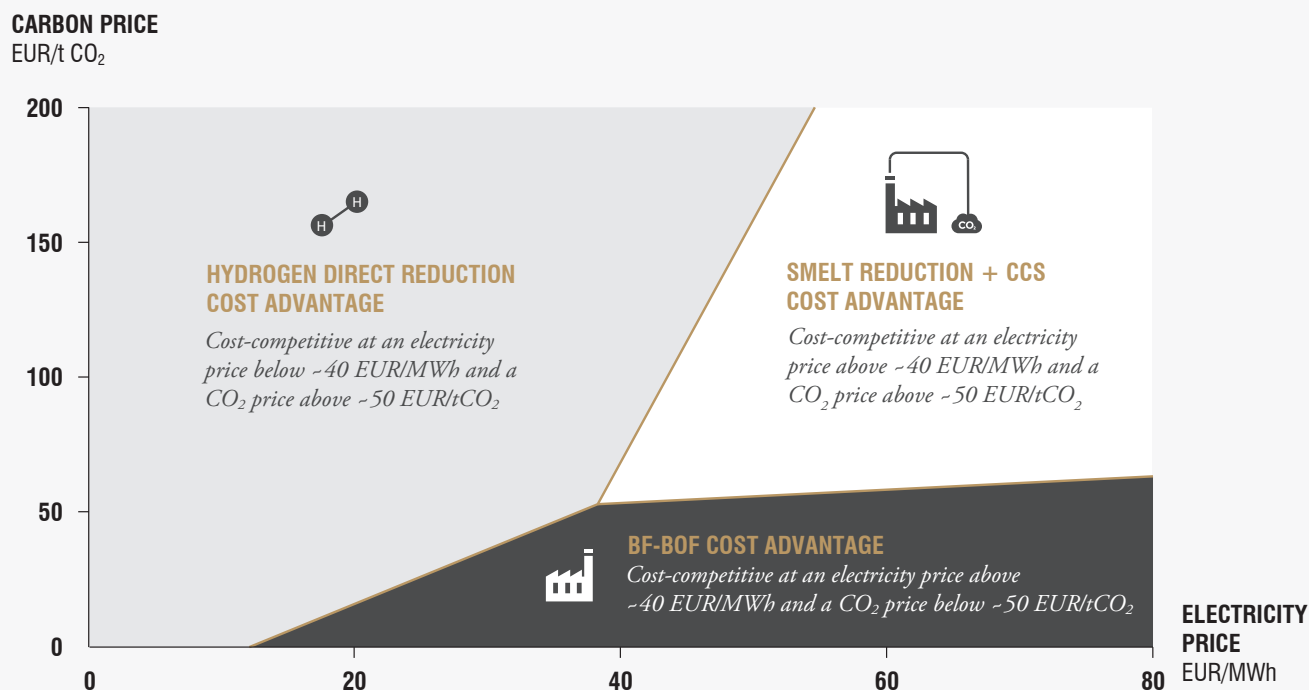
DOWNSTREAM
CCS
ELECTRICITY
IRON ORE/PELLETS
STEEL SCRAP
COKE/COAL
OTHER
CAPEX



NOTE: ABATEMENT COST CALCULATED ASSUMING ZERO-CARBON ELECTRICITY. CO₂ PRICES NOT INCLUDED IN THE PRODUCTION COSTS.
SOURCES: MATERIAL ECONOMICS MODELLING BASED ON MULTIPLE SOURCES, SEE ENDNOTE.³⁶

Exhibit 2.11

THE CARBON PRICE AND COST OF ELECTRICITY WILL DETERMINE THE BEST WAY TO MAKE NET-ZERO EMISSIONS STEEL



Given this picture, policy will play an indispensable role in making low-CO₂ steel production viable, both to keep European producers competitive relative to steelmakers abroad who continue to use high-CO₂ processes, and to enable pioneers to move ahead within Europe. Either the low-emission routes will have to be given an opex advantage of some form, or the EU will need to establish separate markets for low-emissions steel.

Another conclusion is that cost alone does not provide a basis for choosing one route over another, except to suggest that omitting circular economy strategies from the solution set would lead to higher aggregate costs. The advantage of one route over another will depend strongly on parameters that will vary within Europe and over time: notably the electricity price, the ultimate efficiency achieved for direct smelt reduction, the viability of CCU, and the cost of developing large-scale CO₂ storage.

The costs of increased materials efficiency and improved circularity are among the hardest to estimate. Surveying a range of levers, they range from potentially very cost-effective (such as improvements to mobility), to potentially expensive options (such as extensive optimisation of steel use in buildings). Many levers depend on changing regula-

tion and digitisation to reduce the transaction costs of their implementation. Overall, however, the finding is that circular economy levers are likely to be as cost-effective as those for low-CO₂ production.³⁷

Cost also will depend strongly on how some key parameters develop. Electricity is especially important for the H-DRI route, where it can make up one-third or more of total production cost. The modelling is based on an electricity cost assumption of 40 EUR per MWh for the production of hydrogen. Achieving this level would likely depend on flexibility of use, so that production can benefit from periods of lower electricity prices (the modelling includes the capex for five days of hydrogen storage). However, if electricity prices were higher, costs would rapidly increase. A comparison of electricity and CCS options shows that CCS can be more cost-effective once the price of electricity starts reaching 50 or more EUR per MWh (Exhibit 2.11). The analysis also shows that abatement costs in the steel sector need not be very high: for any electricity price, there are options that cut emissions almost to zero at less than 50 EUR per tonne CO₂. However, this comparison, like others, depends on many other assumptions, including that H-DRI, smelt reduction, and large-scale CO₂ transport and storage are all viable technical options.

INVESTMENT IN THE STEEL SECTOR WILL NEED TO RISE BY 25-65%

The transition to a net-zero emissions steel sector will require a new wave of investment in the industry. Investment levels will need to be up to 65% higher than in the baseline scenario. Instead of an average of 1.6 billion EUR per year, the amount required could reach 3-4 billion EUR per year in some periods in the 2030s and 2040s.

The amount of investment varies significantly by pathway. In particular, circular economy solutions are less capital-intensive, so they reduce the amount of investment required.

Exhibit 2.12

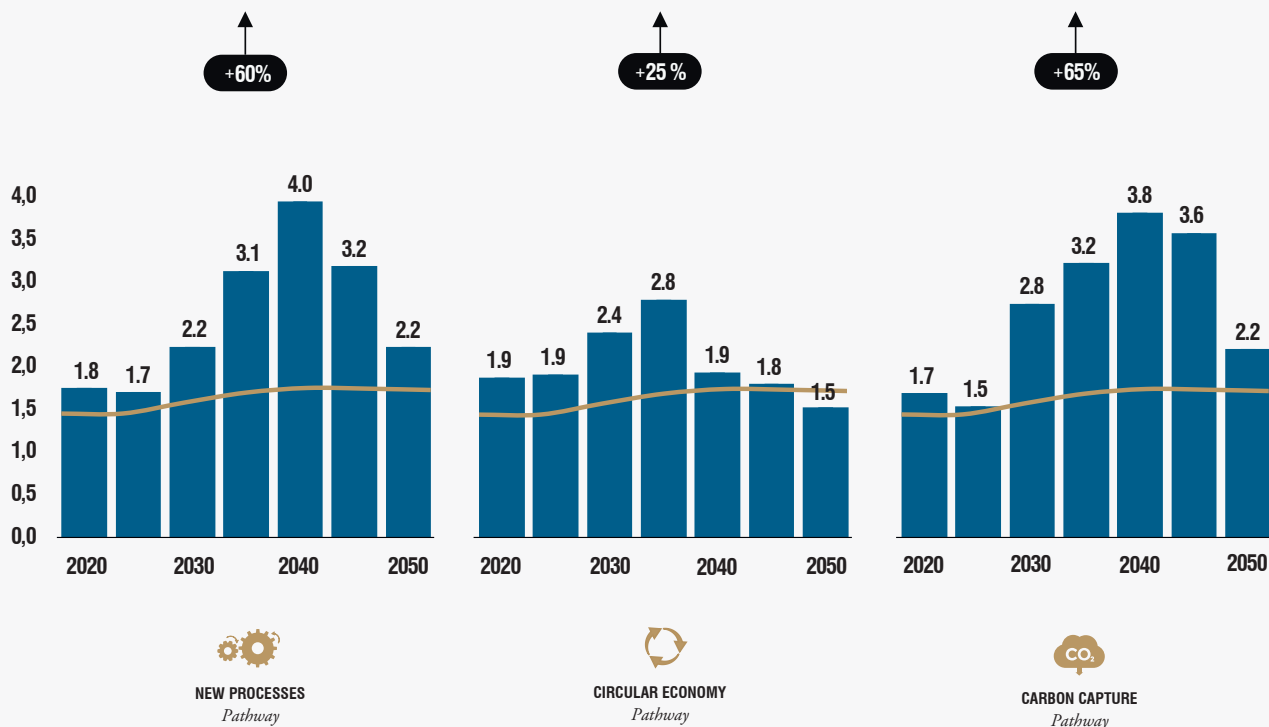
NEW CAPACITY FOR LOW-CO₂ PRODUCTION INCREASES INVESTMENT NEED, WHILE CIRCULARITY BRINGS DOWN TOTAL INVESTMENTS

INVESTMENT IN PRODUCTION CAPACITY OF CRUDE STEEL
BILLION EUR PER YEAR

INCREASE RELATIVE TO BASELINE

+ X%

■ PATHWAY
— BASELINE



NOTE: INVESTMENT INCLUDE NEW PRODUCTION CAPACITY AS WELL AS REGULAR RETROFITS OF EXISTING ASSETS. INVESTMENTS DO NOT INCLUDE DOWNSTREAM INVESTMENTS OF CONTINUOUS CASTING AND HOT ROLLING OR DEVELOPMENT COSTS OF BRINGING NEW TECHNOLOGIES TO MATURITY.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

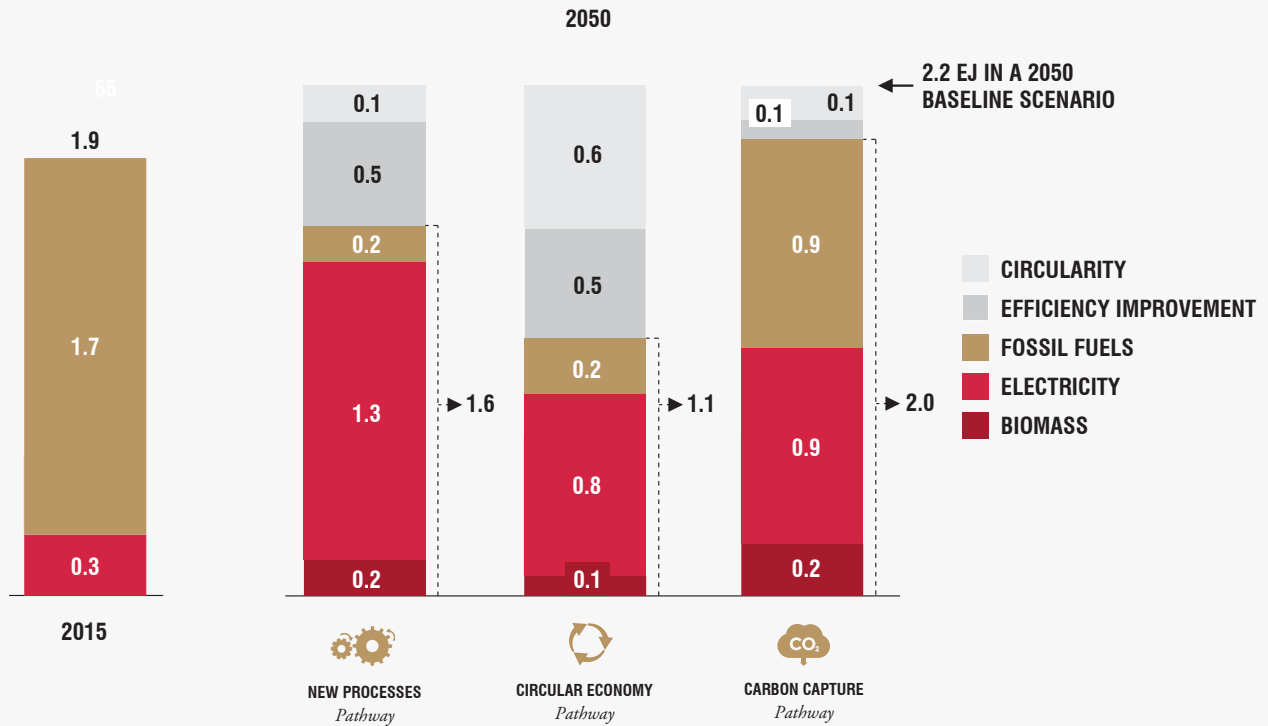
The background image is a wide-angle, high-angle shot of the interior of the Oculus at the World Trade Center. The structure's iconic white, ribbed exterior is visible, creating a series of converging lines that draw the eye towards the top. The interior is a vast, open space with a light-colored floor. Numerous people are seen walking and standing throughout the atrium, providing a sense of scale. In the distance, a mezzanine level with a glass railing is visible. The lighting is bright and even, highlighting the architectural details.

The transition to a net-zero emissions steel sector will require a new wave of investment in the industry.

Exhibit 2.13

CURRENT FOSSIL ENERGY USE CAN BE REPLACED WITH RENEWABLES IN 2050

ENERGY MIX TODAY AND IN 2050
EJ ENERGY PER YEAR



NOTES: FOSSIL FUELS INCLUDE NATURAL GAS USED TO PRODUCE HYDROGEN IN THE CARBON CAPTURE PATHWAY. INDIVIDUAL NUMBERS DO NOT SUM UP TO THE TOTAL DUE TO ROUNDING. SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

The main reason for the higher investment need is not in fact that the low-CO₂ production routes all are inherently more capital-intensive. Smelt reduction, once fully developed, could require less capital. Once CCS is included, it is around 10% more capital-intensive than current production routes. Hydrogen DRI also is some 20–30% more capital-intensive, depending on how the capital cost of electrolyzers develops.

Instead, the higher investment needs arise due to several other requirements. First, there is a need for pilot and demonstration plants to accelerate the development of low-CO₂ production routes. This is not the largest cost in absolute terms, but is among the more difficult to mobilise for companies. The capex is always additional to what is required just to keep production going, and it has little likelihood of a commercial return on its own terms.

Second, much of the new low-CO₂ capacity will be brownfield conversion, which entails additional capex. Switching existing integrated production to new processes will be a complex undertaking. The new production processes will have implications for large integrating infrastructure such as raw materials storage and processing, utility supply, power distribution, gas collection and storage, steam and power generation, transport infrastructure, etc. that together can amount to half the capex of an integrated plant. Additionally, a new plant energy system will be needed to replace the energy currently derived from coke oven and blast furnace gases.

Third, there will likely be some need for double investment in capacity. Companies will need to ensure continuous production, and therefore to build the new production capacity alongside that already in place. Risk means that some redundancy

is a prudent strategy. As many of the low-CO₂ technologies will not be available at scale until the 2030s, there is some need for continued investment in existing BF-BOF plants, some of which would then be retired early as the new, low-CO₂ capacity is built out. This creates a risk that some assets must be written off ahead of the end of their useful life, with impacts on balance sheets and therefore investment capacity.

Finally, the sector will take on substantial additional risk in going from tried-and-tested solutions to ones with uncertain performance, and is dependent on policy support that has not yet been articulated. Higher risk will, all other things being equal, entail higher financing costs.

Policy will thus play an indispensable role into enabling these increases in investment. Early commitment is particularly important to minimise the need for double investment. The upcoming reinvestment in coking plants will be one important opportunity to avoid this. Many existing coking plants will need to be substantially rebuilt in the next 20 years. These plants constitute massive investments and are the cornerstone of the current production system. To enable the transition to low-emissions production, it will be essential to make the business case for companies to direct the required capital towards low-emissions technologies instead.

Exhibit 2.14

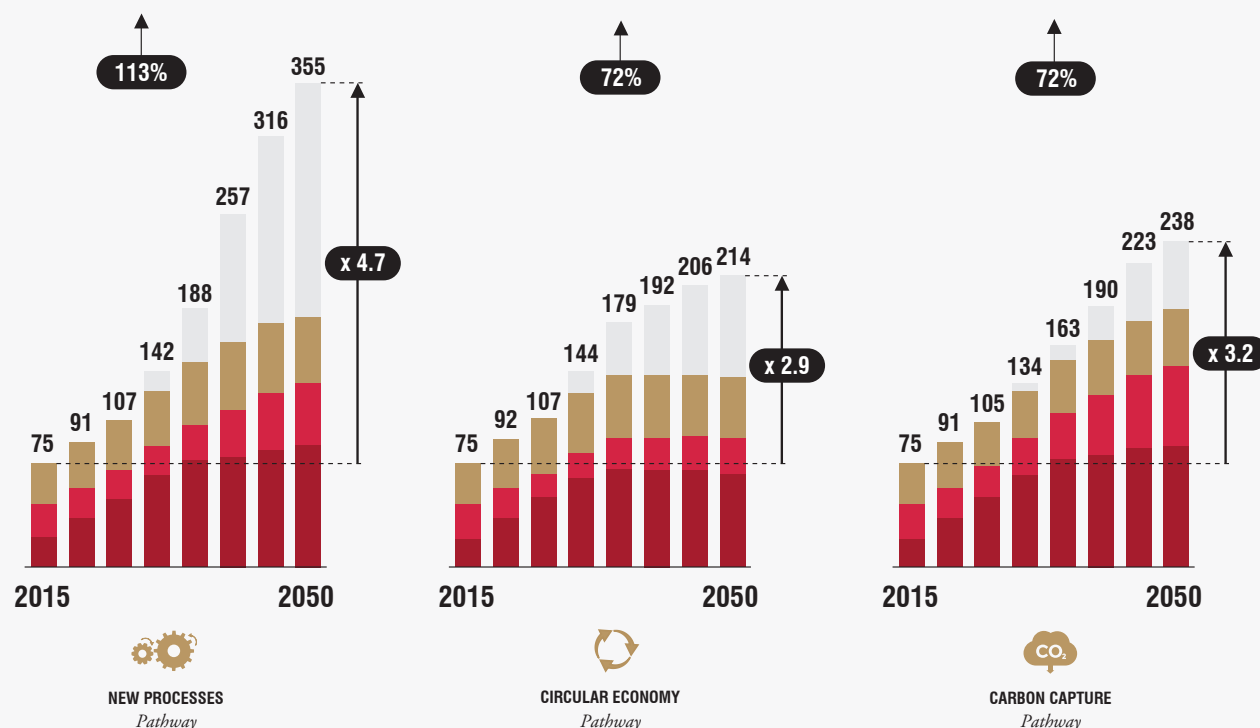
A NET-ZERO STEEL SECTOR REQUIRES 3-5 TIMES MORE ELECTRICITY

ELECTRICITY INPUT TO EU STEEL PRODUCTION TWh PER YEAR

- HYDROGEN PRODUCTION
- ELECTRIC ARC FURNACE PROCESSES
- PRIMARY PRODUCTION PROCESSES
- DOWNSTREAM PROCESSES

INCREASE RELATIVE TO BASELINE

+ X%



NOTE: PRIMARY PRODUCTION PROCESSES INCLUDE ELECTRICITY FOR CARBON CAPTURE IN THE SMELTING REDUCTION WITH CCS ROUTE.

SOURCES: MATERIAL ECONOMICS MODELLING BASED ON MULTIPLE SOURCES, SEE ENDNOTE.³⁸

A NET-ZERO EMISSIONS STEEL INDUSTRY WILL NEED NEW AND DIFFERENT INPUTS

Compared with the current steel industry, a future net-zero emissions industry will require a substantially different set of energy and feedstock inputs (Exhibit 2.13). Overall, there is a marked reduction in total energy use, reflecting the higher overall energy efficiency of the new production processes, an increased reliance on scrap instead of primary steel production, and savings of energy from improved materials efficiency and circularity.

The amount of electricity required is large, between 210–355 TWh per year. The highest electricity demand is in the ‘New processes pathway’, in which the steel industry requires 355 TWh per year in 2050. The ‘Carbon Capture’ and ‘Circular Economy’ pathways require less electricity, just above 200 TWh. While these are substantial electricity requirements, they are much lower than in some pathways presented in the LTS, where electricity use explodes to 700–1,000 MWh for the scenarios that have very deep cuts. The main reason for this is that the pathways in this study do not require either reliance on synthetic fuels, or extreme shares for hydrogen-based production.

The main drivers of electricity demand are the production of hydrogen and the increased use of EAFs (Exhibit 2.14). However, the elimination of CO₂ emissions from iron ore sintering and from downstream processes also represent substantial loads if carried out through electrification. With high dependence on electricity, the industry will likely need new sourcing arrangements for power. It also remains to be seen whether hydrogen production will be ‘captive’ or supplied through wider infrastructure. Either way, all this electricity must be derived from net-zero emissions sources, if the EU is to meet its proposed target of net-zero greenhouse gas emissions by 2050.

Overall, the EU industry would rely less on imports of coal, and more on indigenous resources. Likewise, the availability of inputs will vary geographically within the EU, and this will exert a major influence on viable production. Areas with early access to abundant, low-carbon power may be best placed to switch to hydrogen-based routes. Meanwhile, regions with early access to carbon transport and storage infrastructure may have better enablers for CCS-based routes.

Biomass is not a major input in the pathways, but it does have a role in achieving fully net-zero emissions, and in achieving early cuts. Torrefied biomass could be used in blast furnaces, or to further reduce emissions from smelt reduction with CCS (e.g. in the Hlsarna process). Gasified biomass also can be used for DRI processes. However, sustainable domestic biomass will be a scarce resource, and may find priority uses in other sectors (such as feedstock for chemicals, or for heavy-duty transport). Therefore, it does not feature heavily in the pathways for the steel industry.

Some non-energy inputs also will need to change. The amount of steel scrap used varies between 110 and 125 Mt per year. As noted, a high share of scrap-based production would require a much more tightly-controlled supply chain, with cleaner scrap flows and less contamination by tramp elements.

Finally, certain inputs are a decarbonisation challenge in themselves. One example is lime, which is used to remove impurities during steel production. Lime is responsible for about 40 kg of CO₂ in BF-BOF and about 20 kg of CO₂ in H-DRI.³⁸ The emissions from lime manufacture can be abated in the same way as those from cement, as described in Chapter 4.



3. CHEMICALS

CLOSING THE SOCIETAL CARBON LOOP

Plastics

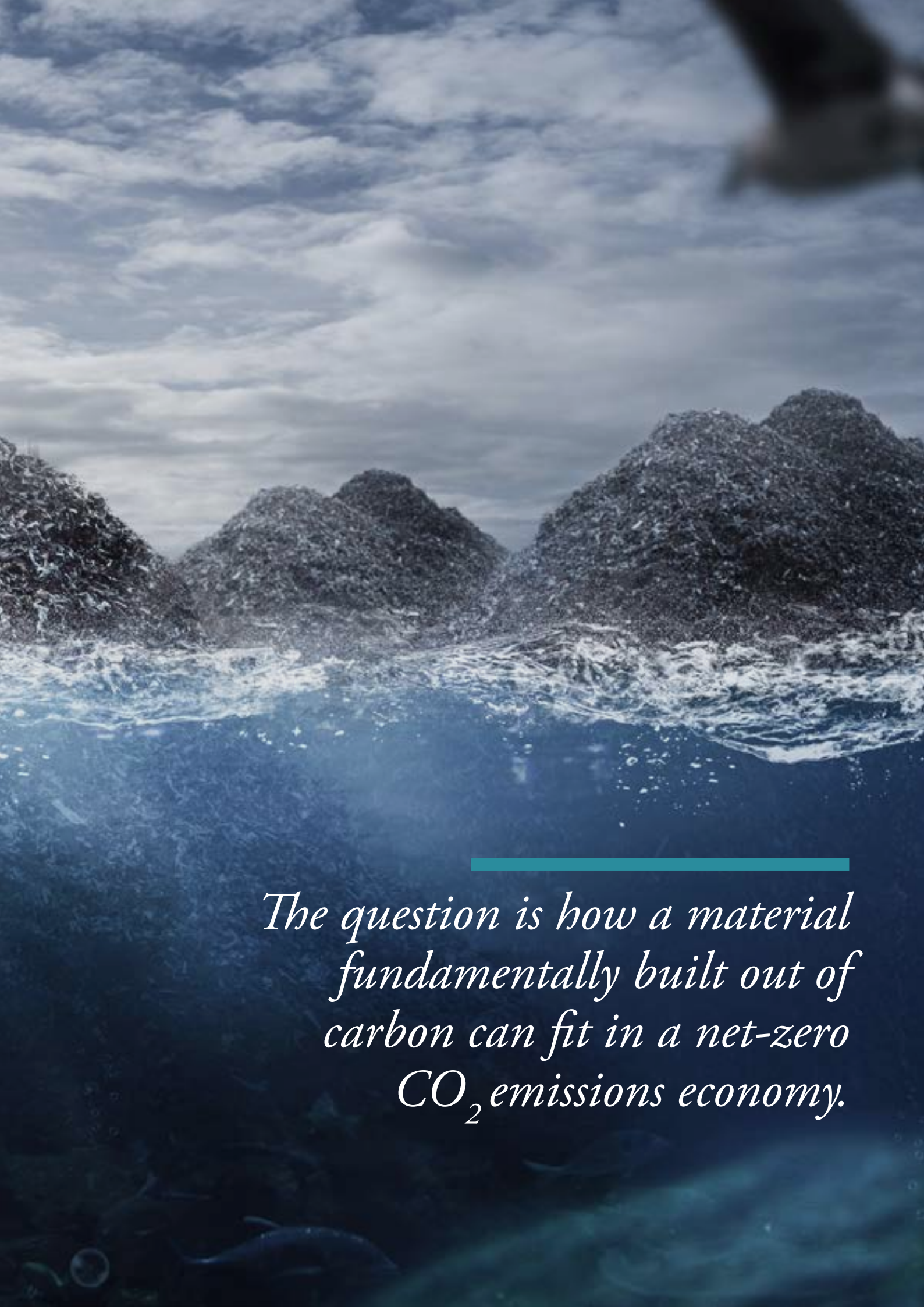
Plastics are versatile, cheap and durable materials that play many essential roles in the EU economy, from packaging to transport. Some 100 kg of plastics are used per person and year in the EU, most of which is produced by EU companies.

Today's plastics are made from fossil oil and gas. As much as 5 kg of CO₂ emissions result for each kg of plastics produced: both from their production, and from the carbon built into the material and released if plastics are burnt at end of life. These emissions are set to grow by 2050.

This study examines how a material literally built from carbon could fit into a net-zero economy. It finds that a transformation is needed in how plastics are produced, used, and handled at end of life. Using plastics more efficiently is

key, as is innovation for more plastics recycling. New feedstock will also be required: switching from fossil oil and gas and towards end-of-life plastics and biomass. This in turn requires new production processes and systems, with electricity and hydrogen as major inputs. There can also be a role for carbon capture and storage, both on production and on waste incineration.

All these solutions are available or emerging, but extensive policy support is needed to bring them to the scale where they jointly provide a net-zero solution. The change needed spans the entire value chain, from product design to end-of-life disposal. Production costs will increase by 20-43%, so companies need policy to create a business case. A 122–199% increase in investments will be required, with no time to lose if the transition is to succeed by 2050.



*The question is how a material
fundamentally built out of
carbon can fit in a net-zero
CO₂ emissions economy.*

3.1 THE STARTING POINT

Plastics are versatile, lightweight and low-cost materials with functional properties that have made them key building blocks in some of our largest value chains. Despite being relatively new materials, plastics have increasingly moved into domains that previously belonged to more traditional materials such as wood, metals, glass, and cotton.

The EU used 51 million tonnes plastics in 2017, or 100 kg per person per year (Exhibit 3.1). The largest use of plastics is in packaging, which accounts for around 40% of all plastics use. Plastics packaging is an integral part of how we transport and consume products. As packaging has a short lifetime, packaging accounts for as much as 60% of all recorded plastic

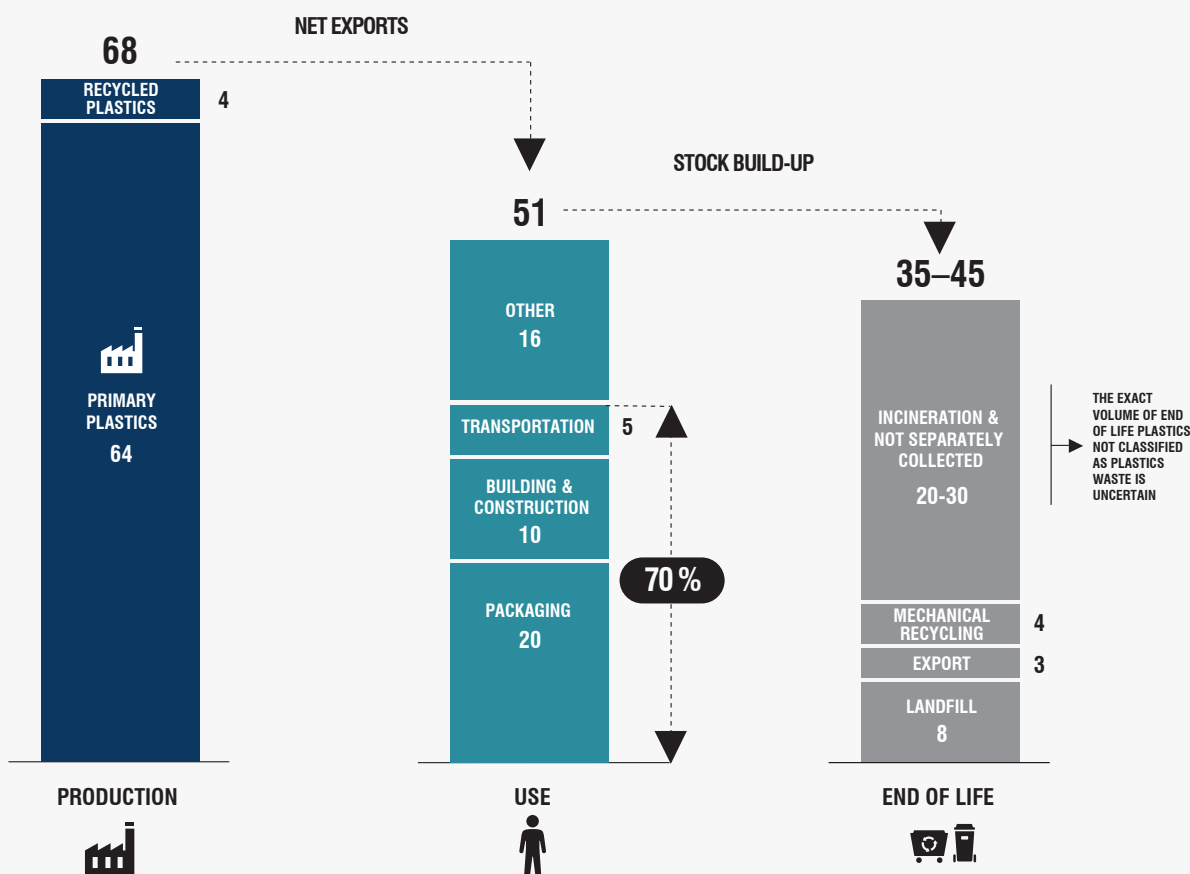
waste. A further 30% of plastics are used in building and construction, and in the automotive sector.¹ Today, plastics account for around 10-15% of the weight of an average car, and more still in terms of volume.² In the building and construction sector, plastics are used for thermal insulation, pipes, floors, and finishing, among other purposes.³ The remaining 30% of plastics are used in a range of products, from electronics to agriculture, medical equipment, and household products.⁴

Europe is also a major producer of plastics. At 64 million tonnes in 2017, 19% of world production was made in the EU, with a net export of 13 million tonnes.⁵

Exhibit 3.1

PRODUCTION, USE AND END-OF-LIFE OF EU PLASTICS

ANNUAL PLASTICS VOLUMES
Mt, 2017



NOTE: END-OF-LIFE NUMBERS ARE LATEST AVAILABLE DATA (2016).

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.⁶



Because so many plastics are used in short-lived applications like packaging, the average lifetime of plastics in the economy is only about 10 years.⁷ There are no firm estimates of the total volume of end-of-life plastics in the EU (as waste statistics are notoriously incomplete), but analysis for this study puts the amount at around 40 million tonnes per year. The 9 Mt that are sent to mechanical recycling replace around 4 Mt of virgin production (given losses in recycling process and less than one-to-one replacement, so recycled plastics remains a very small share of total production).

The term plastics comprises a wide range of different materials, with different properties and end-uses. For example, PET is used primarily for packaging, and most PVC is used in construction. Despite the great variety of plastics, the five polymer types PE, PP, PS/EPS, PVC and PET, account for some 75% of use (Exhibit 3.2). The recyclability also varies between different plastics types. However, all five major types are thermoplastic polymers that can, in principle, be mechanically recycled.

Plastics are built from a backbone of carbon. Today, plastics are dominantly produced through steam cracking of naphtha and ethane, which are respectively obtained by refining crude oil and from natural gas. In the EU, naphtha is the by far dominant route, constituting three-quarters of the feedstock. The steam cracking produce High Value Chemicals (HVCs), which are the key building blocks of the petrochemical industry. HVCs can be divided into two main categories; olefins (including ethylene, propylene and butadiene) and aromatics (mainly benzene, toluene and xylene).⁸ Added to these, there are a number of other petrochemical processes in plastics production such as production of chlorine and styrene.⁹ Many of these chemicals are also carbon-based and therefore are ultimately derived from fossil fuels, albeit by several steps. The assembled HVCs and other components are then polymerised into plastics with the use of energy for processes such as cooling, heating and pressure.

The early stages of the plastics production value chain is carried out in large, integrated chemical complexes. The production of colouring or additive masterbatches for mixing with the polymers to obtain the right properties is also a concentrated market. After that point, however, the value chain is more fragmented. The plastic granules are processed into finished products through manufacturing processes such as injection moulding, blow moulding and extrusion, depending on the design of the final product. This process is done in a more localised way by small- and medium-sized plastic converters.

The transition of this sector to low CO₂ emissions will take place against continued growth in many uses of plastics. In a baseline scenario, plastics use would grow by 18% to 62 Mt per year by 2050, assuming a slow average demand growth rate of 0.5% per year. Provided that the EU can maintain its position as a net exporter, production would then grow to 72 Mt per year in 2050.¹⁰ Worldwide growth in plastics production will be much larger, potentially doubling from 2015 to 2050.¹¹ However, on current trends much of that growth is likely to be captured by other regions where production costs are significantly lower.¹²

CO₂ EMISSIONS FROM PLASTICS

The production of plastics gives rise to on average 2.3 tonnes of CO₂ for each tonne of product.¹³ The key sources of emissions are refining, steam cracking and other foreground processes, and polymerisation, adding up to 1.7 tonnes of CO₂ per tonne plastics. In addition, upstream emissions from feedstock production and electricity are on average 0.6 tonnes per tonne plastics (Exhibit 3.3).

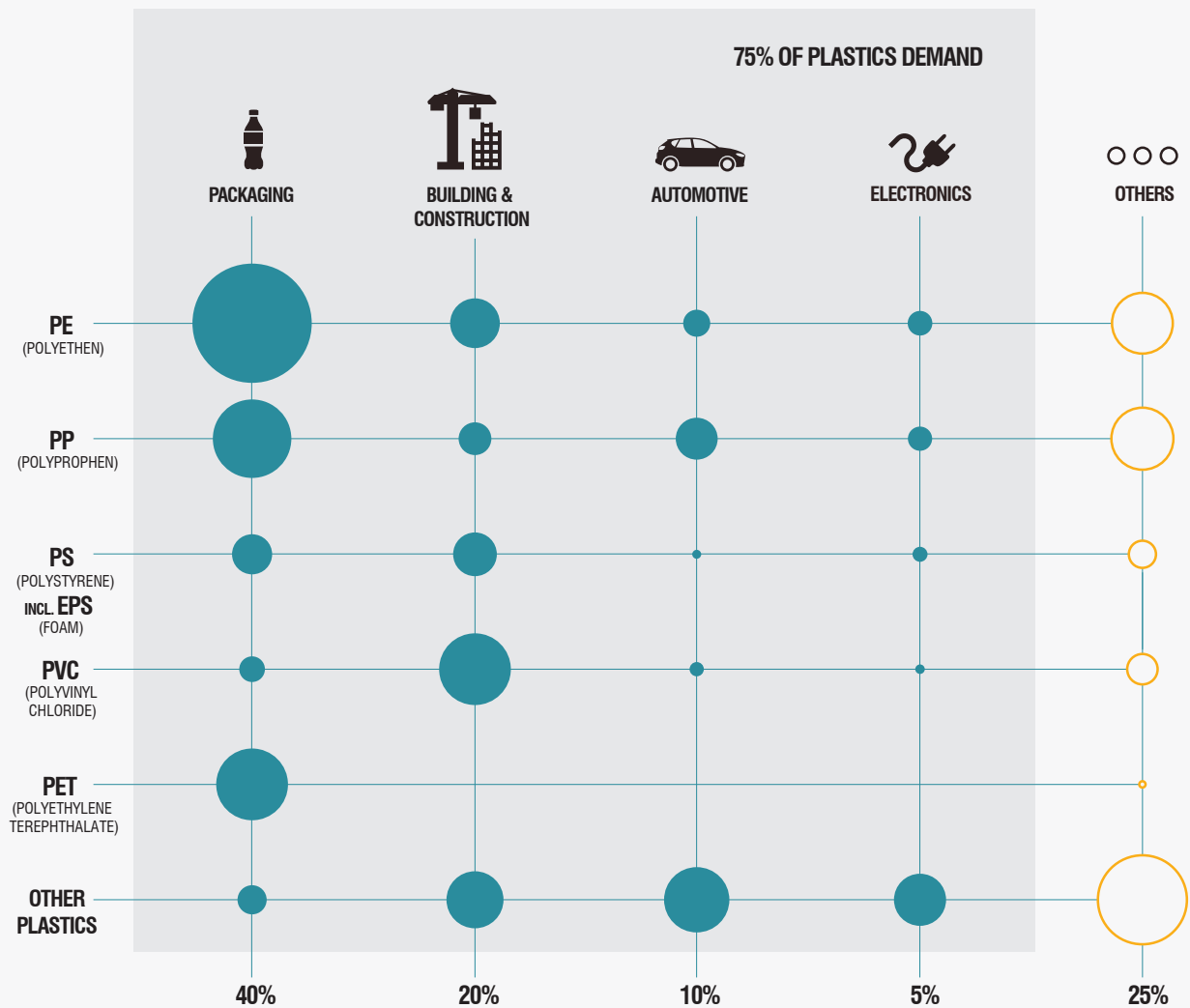
The integrated use of fossil hydrocarbons as fuel and feedstock make some of these production emissions difficult to eliminate. One obstacle is that crackers require large amounts of energy to produce high temperatures of 850-1100°C. Another is that the cracking process results in fossil hydrocarbon byproducts that are used as fuel in the process. In fact, an efficient steam cracker can be driven entirely by the energy from its own byproducts. Even if the cracker were run on external, low-carbon fuel, these fossil byproducts must be accounted for. If they are simply burnt for fuel in other processes, fossil CO₂ emissions have just migrated from the cracker to other parts of the energy system.

Moreover, these production emissions are only half of the story. An even larger amount of carbon is embedded into the product itself, corresponding to 2.7 t CO₂ for every tonne of plastics.¹⁴ As long as plastics are made from new, fossil feedstock, the total fossil CO₂ baggage of a tonne of plastics therefore amounts to as much as 5 tCO₂ per tonne of product. The timing of end-of-life emissions depends on how plastics are handled upon being discarded. The current trend is towards increased incineration, which releases the entire stock of fossil carbon immediately into the air. If the plastics are landfilled instead, emissions could, in theory, be postponed. However, the EU has adopted a zero-landfill target for recyclable waste, including plastics, to be achieved by 2030. The options for discarded plastics are therefore either recycling or incineration.¹⁵

Exhibit 3.2

FIVE PLASTICS TYPES ACCOUNT FOR 75% OF DEMAND

SHARE OF EUROPEAN PLASTICS DEMAND (51 Mt)
%, 2017



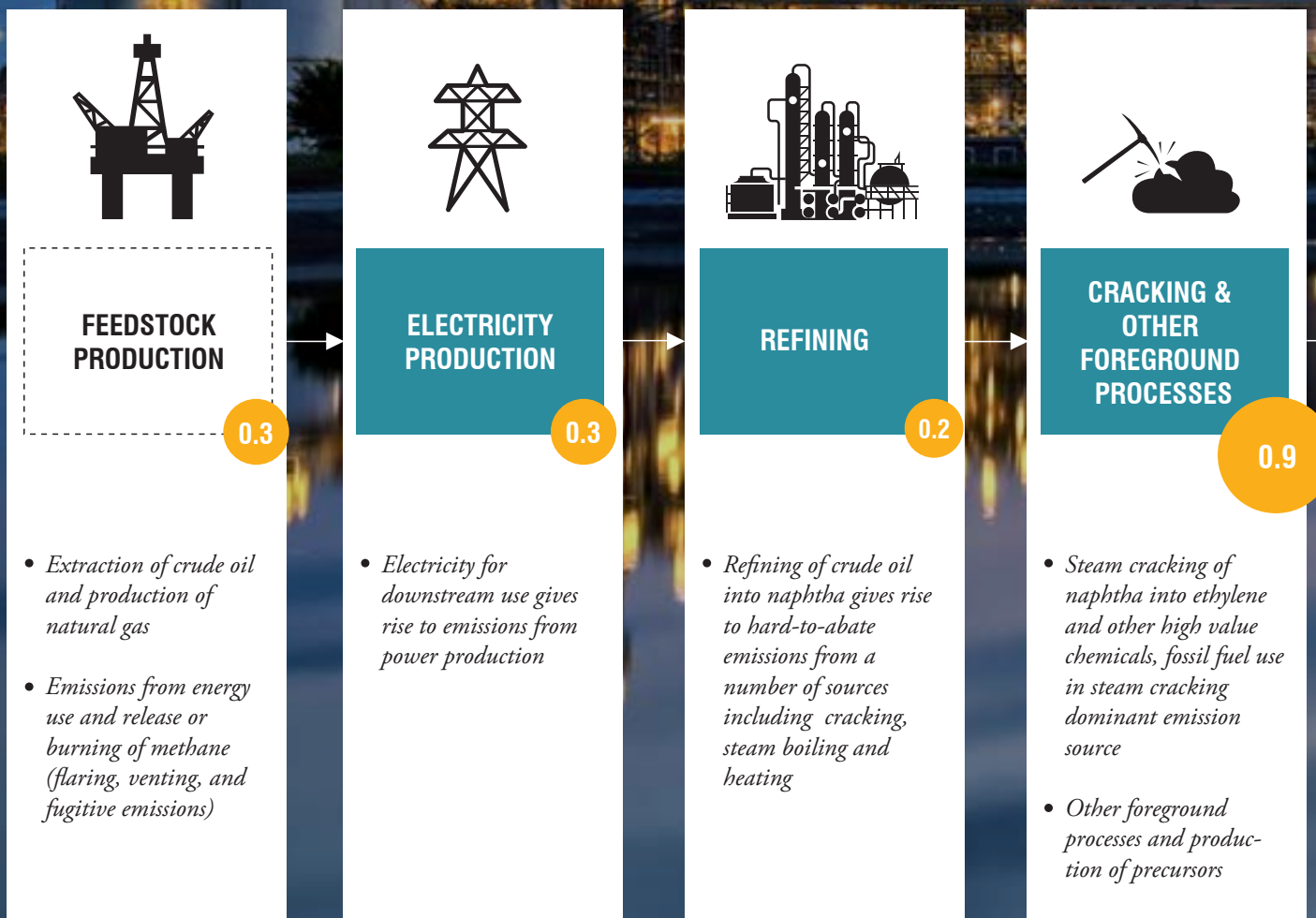
SOURCE: ADAPTED FROM PLASTICS EUROPE (2018).¹⁶

Exhibit 3.3

THE PLASTICS VALUE CHAIN AND SOURCES OF CO₂ EMISSIONS FROM PLASTICS

PLASTIC PRODUCTION AND EMISSIONS (5 TONNE CO₂/TONNE PLASTIC)¹⁷
TONNES CO₂ PER TONNE PLASTIC

● EMISSIONS
■ SCOPE
□ NOT IN SCOPE





POLYMERISATION AND BLENDING

0.6

- Polymerisation of monomers and mixing with additives to produce plastics, emissions form e.g. steam and heat



PROCESSING INTO PLASTIC PRODUCTS

- Manufacturing into finished plastics products through e.g. injection moulding, compression moulding and extrusion



USE PHASE

- Use in major value chains such as packaging, automotive, and building and construction



END OF LIFE TREATMENT

2.7

- Mechanical recycling, incineration, or landfill of end-of-life plastics
- Emissions dominantly from incineration of plastics waste

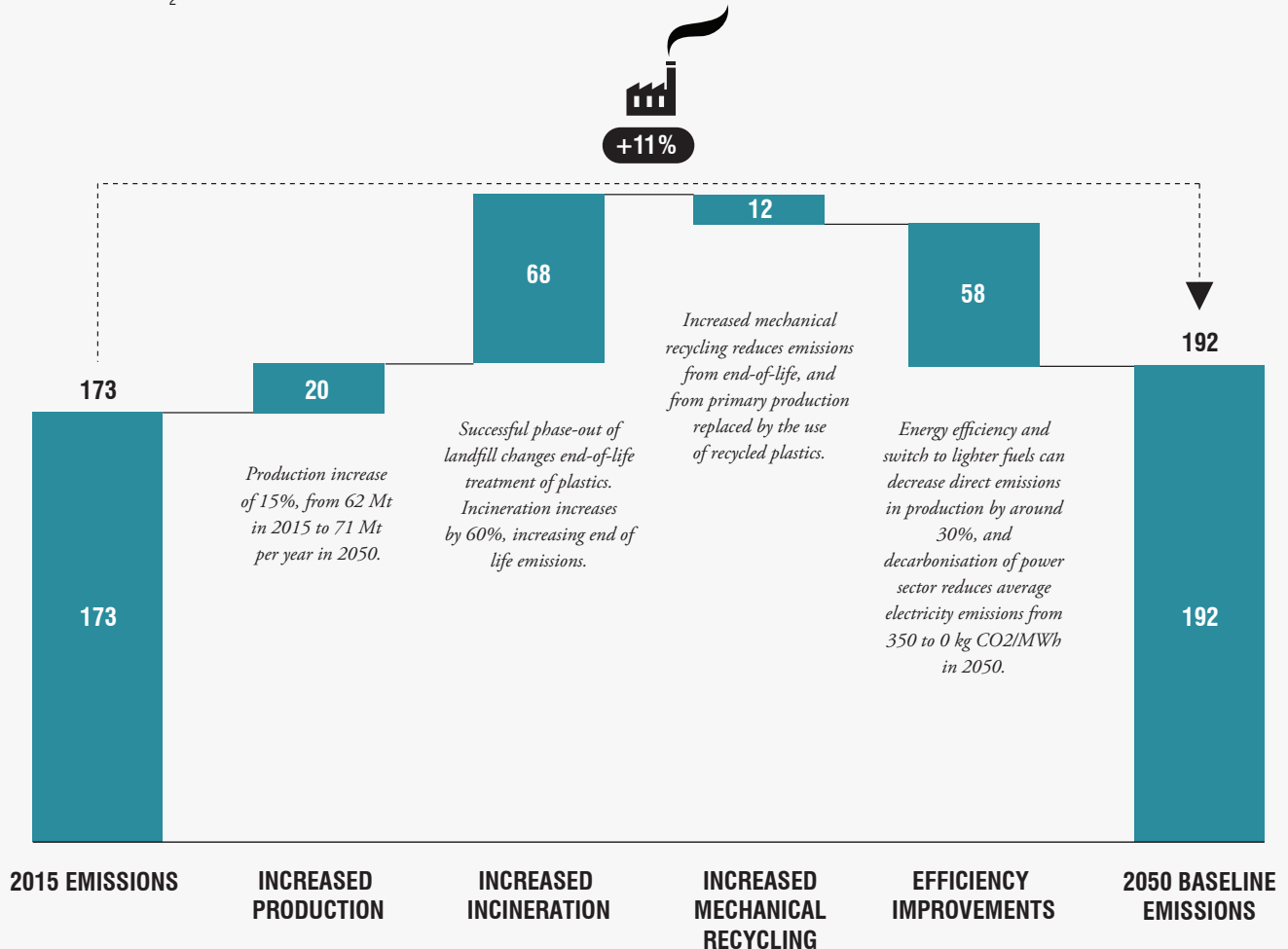
A black PlayStation 5 DualSense wireless controller is shown from a top-down perspective. The controller features glowing buttons: a red circle at the top, a cyan triangle to the left, a blue X to the right, and a purple square below the triangle. The touchpad is visible in the center, and the DualSense sensor bar is at the bottom. The background is dark and textured.

*End-of-life emissions
from plastics become
increasingly important*

Exhibit 3.4

WITHOUT CHANGE, CO₂ EMISSIONS FROM THE EU PLASTICS INDUSTRY WILL INCREASE UNTIL 2050

EMISSIONS FROM PLASTICS PRODUCTION AND END OF LIFE TREATMENT
Mt CO₂ PER YEAR, 2015



NOTE: INDIVIDUAL NUMBERS DO NOT SUM UP TO TOTAL DUE TO ROUNDING.
SOURCES: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

End-of-life emissions become increasingly important the more the rest of the economy transitions towards low CO₂ emissions (Exhibit 3.4). Increased volumes of plastics, on their own, leads to only a modest increase of 20 Mt CO₂ to 2050. They could be counterbalanced by some 58 Mt of emissions reductions through increased energy efficiency improvements, the decarbonisation of electricity used as inputs, and some degree of fuel switching. However, end-of-life emissions increase much more due to two effects. First, the amount incinerated increases as landfill is phased out. Second, every tonne burnt leads to much higher net CO₂ emissions in a low-carbon economy than it does today.

Today, plastics have only modestly higher CO₂ emissions than other fossil fuels, but in a net-zero economy, every tonne of fossil CO₂ emissions militates against the target to eliminate emissions. With no net-credit from replacing other fossil fuels, increased incineration would lead to an increase of as much as 68 Mt CO₂ by 2050. Unlike most of the economy, plastics thus sees a significant increase in emissions in a baseline scenario. A major effort therefore is required to make the production and use compatible with a net-zero economy.



3.2 STRATEGIES FOR A LOW-CO₂ PLASTICS SECTOR

The complexity of carbon and CO₂ in plastics requires special criteria for a pathway to net-zero emissions. The question is not how emissions can be reduced gradually, but how a material fundamentally built out of carbon can fit into an economy that produces no net CO₂ emissions.

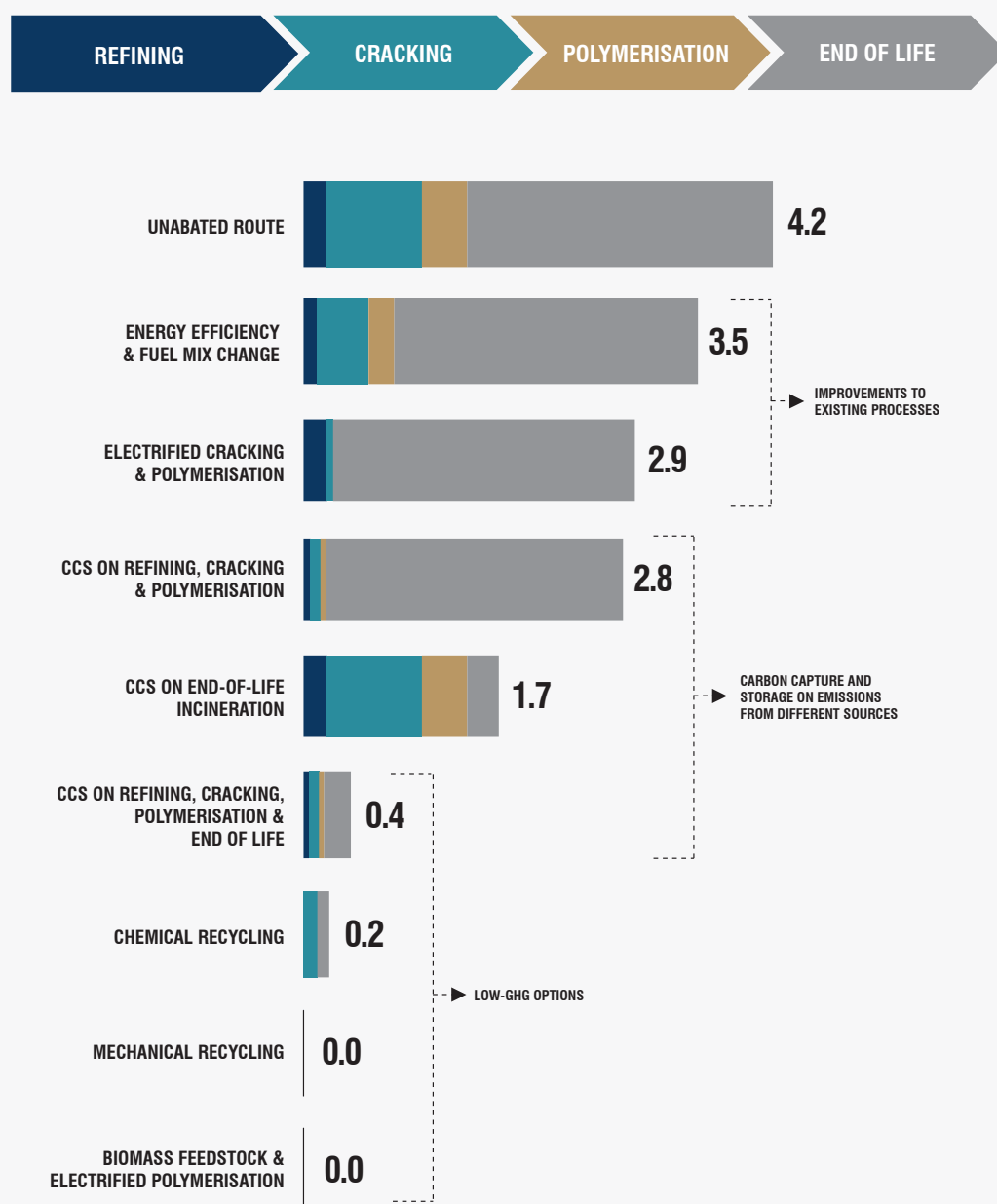
The major solutions of current roadmaps go a long way towards addressing production emissions¹⁸, but they all take

a 'cradle-to-gate' perspective that would leave up to 127 Mt of end-of-life emissions unaddressed in 2050. Exhibit 3.5 illustrates the dilemma. Options such as improved energy efficiency and fuel switching can cut emissions a fair amount in production, and more ambitious changes such as electrification of crackers and CCS on production processes can achieve deeper cuts still.

Exhibit 3.5

RECYCLING AND PRODUCTION FROM BIOMASS FEEDSTOCK ARE LOW-GHG OPTIONS

CO₂ INTENSITY OF PLASTIC PRODUCTION AND END-OF-LIFE ROUTES
t CO₂/t PLASTIC



NOTES: NOT INCLUDING EMISSIONS FROM FEEDSTOCK PRODUCTION, AND ASSUMING ZERO-CARBON ELECTRICITY AND TRANSPORT IN 2050. CRACKING INCLUDES STEAM CRACKING AND OTHER FOREGROUND PROCESSES. POLYMERISATION STEP IS ASSUMED TO BE DECARBONISED IN LOW-GHG OPTIONS IN 2050, MAINLY THROUGH ELECTRIFICATION.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.



However, end-of-life emissions then rapidly become by far the dominant source of emissions. To address end-of-life emissions, much deeper change will be necessary. One approach is to switch much of the feedstock away from fossil hydrocarbons and towards recirculated plastics and bio-based alternatives. The use of these new feedstocks in turn makes it necessary to adopt new production routes and platform chemicals. The other main approach is to extend carbon capture to all relevant sources. The requirements for net-zero are then very exacting: CO₂ must be captured not just from production, but also from upstream refining and from end-of-life incineration.

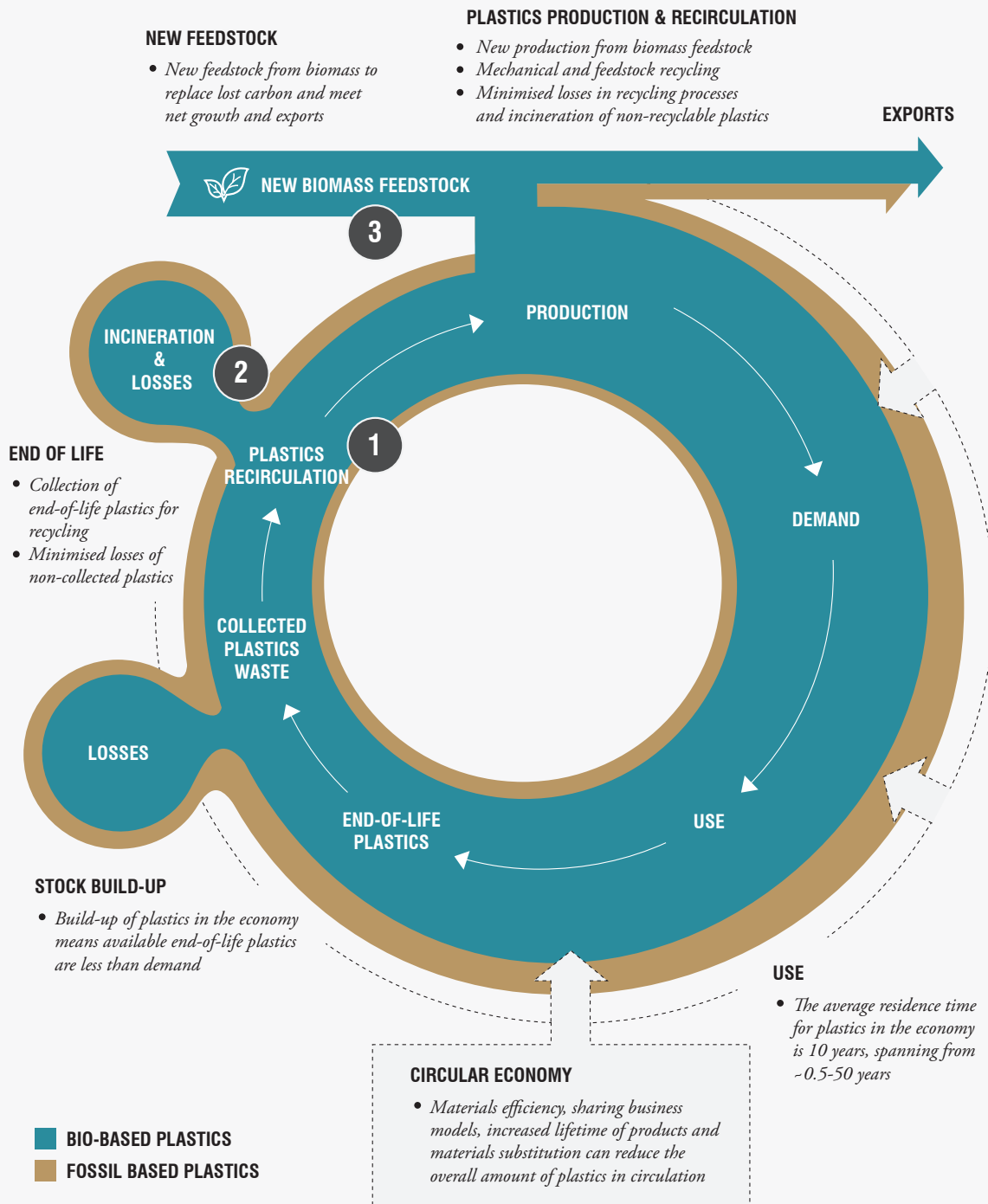
Overall, these solutions can create a 'societal carbon loop' (Exhibit 3.6), where no or very little fossil carbon escapes as new, fossil CO₂ emissions.

To complement these solutions in the production, recirculation, and end-of-life handling of plastics, there also are opportunities to change the ways plastics are used. Such opportunities span changed product design, materials efficiency, new sharing business models, and ways to increase product lifetimes.

The key to any plausible pathway will be to translate these rather abstract objectives into concrete business opportunities.

Exhibit 3.6

CLOSING THE SOCIETAL CARBON LOOP FOR PLASTICS



The first step is to achieve very high recycling rates from end-of-life plastics (1). This requires both mechanical and feedstock recycling of plastics, so that most of carbon in the plastic produced comes from recirculated material. However, 100% recycling is not a realistic target, for plastic or any other material. Achieving even an 80% rate would require a major reorganisation of the waste sector.

Realistically, some 20-30% of plastics would therefore be incinerated after an average residence time in the economy of 5 years. (2)

Some new feedstock therefore is also required to replace the carbon that is lost, as well as any net growth in the amount of plastics (3). If this is derived entirely from biomass, the total plastic stock will eventually consist of biogenic carbon, and end-of-life emissions taken care of. The main way to keep total biomass demand manageable is to ensure recycling rates are as high as possible.

If, on the other hand, new fossil carbon is used, an equivalent amount of carbon must be captured permanently and stored. CCS on end-of-life incineration can achieve this. Another option would be to permanently store solid plastics.

Exhibit 3.7

STRATEGIES FOR DEEP...

CIRCULAR ECONOMY IN MAJOR VALUE CHAINS



MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS

Reducing the amount of materials used for a given product or structure, or increasing the lifetime and utilisation through new business models



MATERIALS RECIRCULATION AND SUBSTITUTION

Using end-of-life materials as input to new production, or using low-CO₂ alternative materials that provide the same function

MATERIALS EFFICIENCY

- Reducing over-use in packaging and other products and components
- Design principles for reduced materials use
- Switch to high-performance polymers

MATERIALS RECIRCULATION

- Innovation in product design and materials choice for efficient and high-quality mechanical recycling
- Technology and infrastructure for collection and sorting systems
- Large-scale collection of end-of-life plastics as feedstock for new production (when mechanical recycling not possible)

SHARING BUSINESS MODELS AND INCREASED LIFETIME OF PRODUCTS

- New business models such as car-sharing to increase intensity of use and shift innovation focus
- Increased product lifetimes including through reuse and remanufacturing of products and components

MATERIALS SUBSTITUTION

- Switch to low-CO₂ materials such as sustainably sourced fibre alternatives where they can provide equivalent functionality

...EMISSIONS REDUCTIONS FROM PLASTICS

CLEAN PRODUCTION OF NEW MATERIALS



NEW AND IMPROVED PROCESSES

Shifting production processes and feedstocks to eliminate fossil CO₂ emissions



CARBON CAPTURE

Capture and permanent storage of CO₂ from production and end-of-life treatment of materials, or use of captured CO₂ in industrial processes

CLEAN UP CURRENT PROCESSES

- Increase process- and energy-efficiency (steam crackers)
- Switch to lower-CO₂ fuels and electricity
- Increased use of lighter feedstock

CARBON CAPTURE AND STORAGE

- Carbon capture and storage (CCS) on steam cracker furnaces and refinery processes
- CCS on waste-to-energy plants

NEW PROCESSES AND FEEDSTOCKS

- Plastics from bio-feedstock
- Chemicals recycling of end-of-life plastics (depolymerisation, solvolysis, pyrolysis + steam cracking, gasification)
- Reprocessing of by-products (e.g., through methanol-to-olefins)
- New polymers and catalysts

CARBON CAPTURE AND UTILISATION

- 'Synthetic chemistry' to produce new chemicals from CO₂ ('power to X') using non-fossil sources of carbon

ELECTRIFICATION

- Electrification of steam crackers
- Electrification of cooling, heating, compression, and steam
- Electrification of hydrogen production

Exhibit 3.8

FITTING PLASTICS INTO A NET-ZERO ECONOMY WILL REQUIRE A SYSTEM REDESIGN





*The EU currently uses
100 kg of plastics per
person per year.*

MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS

The EU currently uses 100 kg of plastics per person per year, which would increase to close to 120 kg if current trends continue.

However, the amount of plastics required depends heavily on how it is used, and there are in fact numerous opportunities to use plastics more efficiently without compromising on functionality or end-user benefits (Exhibit 3.9).

A bottom-up assessment finds that there are significant opportunities to make products more materials efficient. Because plastics are cheap and lightweight, their specification has not been optimised, leading to significant overuse. Experts in the food and consumer goods industry indicate that continuous innovation could reduce the plastics in packaging by 20% or more without compromising functionality. Product designs can also be made more materials-efficient, both by applying new design

principles that reduce the amount of materials, and by using higher-strength plastics to reduce the mass required.

Sharing business models in major value chains provide another major opportunity to reduce the amount of materials required. Car-sharing is a prominent example, with potential to reduce total materials demand by half or more. Combined, materials efficiency and sharing business models could reduce the EU's annual plastics demand by 13 million tonnes by 2050.

The potential for materials efficiency and circular business models is fragmented along long value chains, and therefore overlooked. There are significant barriers that must be overcome, but also strong innovation and new solutions enabled by digitisation. To capture the uncertainties about future developments, this study explores scenarios for the potential of materials efficiency and circular business models corresponding to 7-13 Mt of plastics use per year.

SUBSTITUTION OF PLASTICS WITH OTHER MATERIALS

The substitution of plastics with other materials offers another way to reduce CO₂ intensity. This is a thorny topic: materials always compete, and product designers make their choices based on numerous criteria. Also, the choice of one material over another affects lifecycle emissions in complex ways.¹⁹ Nonetheless, the requirement to fully eliminate CO₂ emissions adds another dimension to this discussion.²⁰ Some other materials are much easier to render CO₂-free than are plastics; for example, some paper and board products are already produced virtually without fossil CO₂ emissions. Moreover, as we discuss below, the cost of producing plastics may need to increase substantially to fully eliminate emissions, changing plastics' competitiveness vis-à-vis other materials.

For this study, we used a detailed analysis of all major packaging segments to investigate the potential to use fibre-based materials instead. The finding was that up to 25% of current plastics used in packaging could, in principle, be substituted with fibre-based alternatives without compromising on the unique properties of plastics (barrier properties, formability, transparency, etc.).²¹⁺ For other plastics applications, such as buildings, automotive and electrical or electronic equipment, similarly detailed assessments are not available. However, biocomposites offer a drop-in solution for many structural elements, with at least 5% aggregate substitution potential.

All in all, the pathways explored in this study range from a modest 4 Mt of substitution of plastics, to 6 Mt.

Exhibit 3.9

MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS COULD REDUCE PLASTICS DEMAND BY 13 MILLION TONNES BY 2050

DEMAND REDUCTION POTENTIAL Mt, 2050



EFFICIENT USE OF PLASTICS...

...by reducing overuse and over-specification. Innovation and materials efficient design could reduce plastics in packaging by 20% or more without compromising functionality.

MATERIALS-EFFICIENT DESIGN...

...and production can reduce mass required in plastics products and components by using new design principles, high-strength plastics, and optimised production processes.

SHARING BUSINESS MODELS...

...can reduce the materials required per service and in some cases also per product. Car-sharing for example could reduce overall materials use by 50%, as a shared mobility system enables a smaller average size car to cater to the average 1.5 passengers per car. Moreover, higher intensity of use in a shared system could reduce the number of cars per passenger-kilometre, further reducing materials demand.



REUSE OF PLASTICS PRODUCTS...

...to extend their lifetime. Reuse of up to 5% of end-of-life plastics products can reduce demand for new plastics, the biggest potential is in business-to-business applications such as transport packaging, but a decreased reliance on single-use plastics products in the consumer category also holds potential to reduce demand.

MECHANICAL RECYCLING...

...of up to one-third of end-of-life plastics can reduce demand for primary production as well as avoid end-of-life emissions from incineration.



SUBSTITUTION OF PLASTICS WITH OTHER MATERIALS...

...that provide similar functionality but are easier to render CO₂-free. Up to 25% of current plastics used in packaging could be substituted with fibre-based alternatives without compromising functionality. For other plastics applications such as components in buildings, automotive and electrical or electronic equipment, biocomposites could provide around 5% aggregate substitution potential.

SOURCES: MATERIAL ECONOMICS ANALYSIS, SEE ENDNOTE.²²

PLASTICS RECIRCULATION (REUSE AND MECHANICAL RECYCLING)

Plastics recycling is perhaps the most familiar of circular economy strategies for plastics, with long-standing targets and regulation. This study finds that mechanical recycling, in which the plastics are sorted, shredded, cleaned, melted and reprocessed into new plastics products, will have a major role in any low-CO₂ plastics system. Up to a third of end-of-life plastics could be reused or mechanically recycled by 2050.²³

Mechanical recycling leads to significant CO₂ savings. Even today, the emissions are just 0.5 tonnes of CO₂ per tonne recycled plastics, compared with 2.3 tonnes for primary production. Mechanical recycling also avoids the 2.7 tCO₂ equivalent of emissions from end-of-life incineration. Moreover, manufacturing plastics products through mechanical recycling means a move from what are today intrinsically fossil-based processes with high temperatures and new oil and gas as feedstock towards processes focused around logistics, low heat, mechanical power, and data-driven sorting and automation that are much easier to decarbonise.

To assess the potential for mechanical recycling, it is necessary to first understand the starting point. Perhaps surprisingly, the amount of effective displacement of new plastics production through mechanical recycling is in fact less than 10%. Official statistics often quote higher numbers, but do not account for all plastics, for losses in the recycling process, and for recycled plastics that displace non-plastics, leading to a potential rebound effect on plastics demand.²⁴

It is possible to dramatically increase this, by at least a factor of three.²⁵ Such a significant boost to mechanical recycling would require a significant shift in focus: away from waste management, and towards a wholesale push of innovation, large-scale operation, and adaptation of designs across the plastics value chain (Exhibit 3.10). Mechanical recycling thus can be an indispensable contribution to emissions reductions in the plastics sector. However, for plastics to reach the very high recirculation rates required to close the societal carbon loop, other forms of recycling will also be required, as discussed below.

The pathways span recycling rates that can replace between 15 and 25% of new plastics production that would otherwise be required.

A push for increased reuse of plastics products before being discarded as waste could provide another 3 million tonnes of emissions cuts per year by 2050. Currently, around 40% of plastics could be categorised as ‘single-use’, meaning the product is disposed of after a very short useful life.²⁶ While there is some potential to adapt consumption patterns for increased reuse of single-use consumer plastics such as bags and bottles, the biggest potential is found in plastics used by businesses, such as business-to-business packaging.²⁷

Exhibit 3.10

MECHANICAL RECYCLING AND REUSE HAS THE POTENTIAL TO SUPPLY 30% OF PLASTICS DEMAND

MECHANICAL RECYCLING AND REUSE OF END OF LIFE PLASTICS Mt, SHARE OF PLASTICS DEMAND



SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.²⁸

REDUCING EMISSIONS FROM THE CURRENT PRODUCTION SYSTEM

Materials efficiency, circular business models, mechanical recycling, and reuse can significantly reduce the need for new plastics production in the long run. However, even in an ambitious scenario, some new plastics will be required, which means that new cleaner production methods are needed.

The most immediate starting point is to reduce the CO₂ footprint of current production processes. There is considerable scope to do so through improved energy efficiency, switching to lower-CO₂ fuels, lighter feedstocks, and electrifying steam crackers.

The scope for energy efficiency improvements is considerable, because there is a large difference in energy efficiency between the ‘best’ and ‘worst’ steam crackers in Europe today, with additional potential in other processes. Direct emissions could be cut by 20-40% depending on how much of this potential can be mobilised.²⁹

Switching from naphtha to lighter feedstocks such as ethane can result in significant emissions reductions for some products. For ethylene, the increased yield reduces direct

emissions by up to 50% per tonne of ethylene.³⁰ Changing from liquid naphtha to gaseous ethane feedstock requires upgrades and alterations to existing assets, but provides flexibility to change between feedstocks depending on current prices.

A more significant step would be to switch to electricity as the source of heat in steam crackers, potentially eliminating direct CO₂ emissions almost entirely. This contrasts with the current practice of generating heat from by-products or natural gas. While electrification will require technology development, most experts deem it feasible. The challenge is more one of commercial viability: it will require significant investment and requires competitive electricity prices.

Electrifying crackers does not on its own lead to net-zero emissions, if the feedstock continues to be fossil hydrocarbons. However, it is a crucial component of a net-zero chemicals sector. Crackers will continue to play an important role, for example in some chemical recycling or bio-based processes, as described below.



*Chemical recycling will
play an indispensable
role in a future net-zero
emissions plastics system.*

FEEDSTOCK RECIRCULATION (CHEMICAL RECYCLING)

A major finding of this study is that chemical recycling will play an indispensable role in a future net-zero emissions plastics system. It is a complement to mechanical recycling, which is more resource-efficient. Together, the two approaches could bring the recirculation of plastics to as much as 62% of production. Plastics would then be as circular as the major metals (steel is 85% recycled, and aluminium around 70%).³¹

Chemical recycling breaks down plastics into monomers, oligomers or simpler molecules, creating new feedstocks for plastics production. The key benefit is that it ‘erases the memory’ of the material. Unlike other materials (such as wood fibre or metals), there need be no downgrading of quality, the output can hold just as high a quality as new plastics production. For this reason, chemical recycling is an attractive option for plastics that are not suitable for mechanical recycling. These include mixed polymer flows, aged or contaminated plastics, and thermosets or fibre-reinforced plastics.³²

Recirculating end-of-life plastics as feedstock is a form of recycling, in that the same molecules are used again for new products. But in many ways it is more akin to a new production route: requiring large-scale infrastructure, secure and large-scale feedstock supply, integration with other chemicals processes, and substantial energy inputs.

Chemical recycling has a long pedigree, with large-scale trials already in the 1990s, but it fell out of fashion during periods of lower oil prices. It is far from a mature and large-scale production route, but several European companies are now investigating multiple options for future production. There are a range of emerging technologies that are suitable for different types of plastics waste. For instance, depolymerisation breaks plastics down into monomers or oligomers, whereas feedstock recycling by pyrolysis or gasification yields even simpler molecules. Meanwhile, solvolysis is a ‘lighter treatment’ that separates the polymer from additives and contaminants before it is reprocessed into plastics.³³

This study explores two largely-proven processes: gasification and pyrolysis, both of which convert plastics into simpler molecules (Exhibit 3.11). These routes should be understood as representative, and not in any way an attempt to provide the final answer for chemical recycling. On the contrary, there is ample opportunity for in-

novation to achieve resource-efficient routes with high yields, and that are amenable to mixed polymer streams.

The energy demand can vary in the range of 1–7 MWh of input required, depending on the process and product produced. For gasification, zero-CO₂ hydrogen from either electrolysis or steam methane reforming with CCS is a major input. For pyrolysis, the central part is the electrification of the cracker stage.

For low emissions, the overall carbon mass balance must be very high, so that the amount of CO₂ released is minimal. To make chemical recycling commercially viable today, mass balance is often sacrificed (and some of the plastics input in effect used as fuel input). In a net-zero system, however, nearly all of the carbon in the inputs must be transformed into outputs. For gasification, this comes at the price of needing to add more hydrogen. For pyrolysis, the main implication is the need to add another process step, so that the fuel-grade by-products from cracking (in large part methane) are not burnt, releasing CO₂, but further processed into HVCs. If this is done, the carbon escaping as CO₂ could be below 5% of the total.³⁴

Finally, the above implies that chemical recycling likely will require adaptation of chemical production systems, with processes and new platform chemicals. One candidate is methanol, which can be further processed to olefins with established catalysts. Methanol also enables the production of plastics from a large variety of biomass feedstocks.³⁵

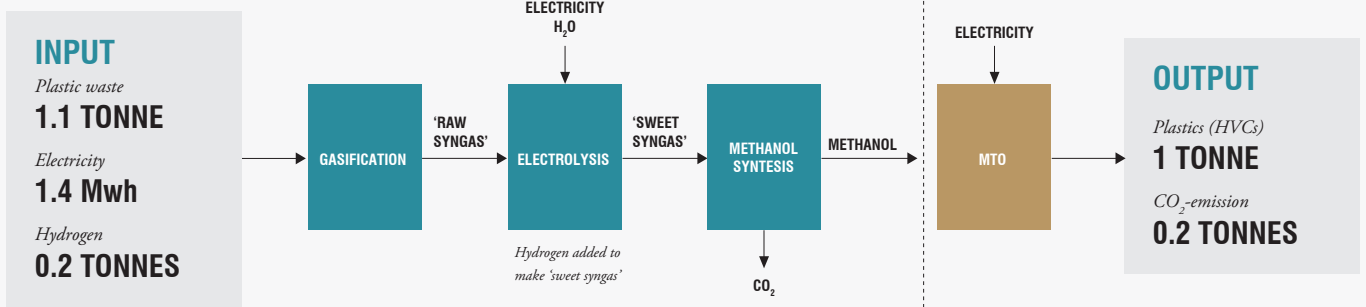
If these conditions are met, chemical recycling can achieve very low emissions to the atmosphere of around 0.2 tCO₂ per t plastics – compared to the 2.3 tCO₂ from de novo production from fossil feedstock. On the other hand, if some or all the conditions were not met, the outcome could be drastically different: chemical recycling with poor carbon mass balance, high-CO₂ energy inputs, or where the output is used to produce transportation fuel could easily have a CO₂ footprint approaching that of an existing current cracker.

For the pathway analysis, this study explores one option where as much as 65% of end-of-life plastic is sent for chemical recycling, and a less ambitious scenario with 20% chemical recycling.

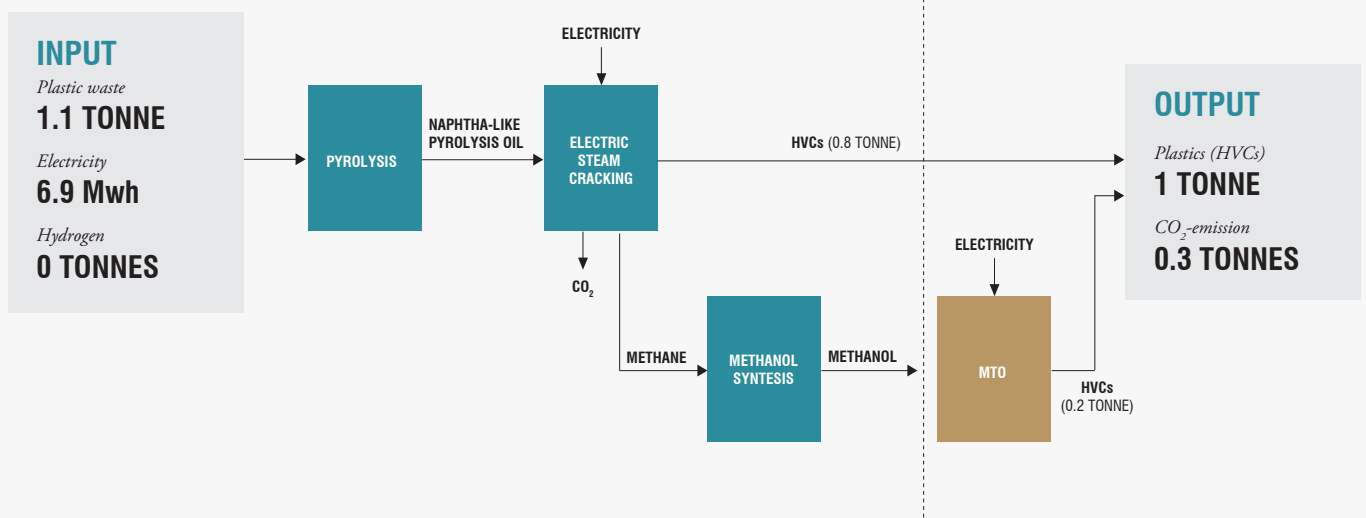
Exhibit 3.11

CHEMICAL RECYCLING OF END-OF-LIFE PLASTICS THROUGH TWO REPRESENTATIVE ROUTES

GASIFICATION



PYROLYSIS & STEAM CRACKING



NOTES: THE METHANE STREAM IS THE MAIN BY-PRODUCT FROM STEAM CRACKING. ELECTRICITY FOR PRODUCTION OF 0.2 KG HYDROGEN REQUIRES AROUND 8 MWH OF ADDITIONAL ELECTRICITY. THE PATHWAYS USE A COMBINED ROUTE WITH A 50/50 SHARE BETWEEN THE GASIFICATION AND THE PYROLYSIS & STEAM CRACKING ROUTES.

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON RESEARCH INSTITUTES OF SWEDEN (RISE) AND DECHEMA (2017), SEE ENDNOTE.³⁶

BIO-BASED PLASTICS PRODUCTION

It is not possible to meet 100% of a modern society's demand for plastics through mechanical and chemical recycling. New carbon needs to be added to build up stocks, to meet any increase in demand, and to offset losses both in collection and in recycling processes. Even in a stretch scenario, therefore, at least 38% of plastics must be made from new rather than recirculated feedstock – and a much larger share if systems are less circular, or if demand is higher.

If plastics are made from new fossil feedstock, the overall plastics works like a slow-burn combustion system: oil is extracted, it is turned into plastics, it circulates through the economy with some losses in every cycle, and anything that is not recirculated is burnt at the end of life. The cumulative impact on CO₂ is large: even with a high recycling rate of 70% (against less than 10% today), some two-thirds of the carbon would be released as CO₂ to the atmosphere within 15 years. In other words, a net-zero plastics system cannot rely entirely on recirculation – it must also find a way to avoid CO₂ from all the new carbon that must be added.

One solution is to switch from fossil to renewable feedstock – much like energy systems switch from fossil to renewable energy. For plastics, this means using carbon from biomass, or 'biogenic' carbon. (The other option would be to use CO₂ captured from air and synthesised to chemicals, but as discussed later in this chapter, this is much more resource-intensive.) A range of biomass feedstocks can be processed into bio-ethanol, bio-methanol, biogas or bio-naphtha, which can then be used to produce conventional plastics. The biogenic carbon emitted at end-of-life incineration of plastics produced from biomass does not lead to net emissions, as they are offset by the carbon sequestered during the growth phase of the biomass.

There are several possible ways to produce conventional plastics from biomass. Two options illustrate the range of potential feedstocks and uses: anaerobic digestion and gasification, which both use methanol as a platform chemical (Exhibit 3.12). Both are established processes, and gasification in particular is developing fast. In both routes, it is possible to produce methanol, which in turn can be turned into olefins via the MTO route. The resource requirements are substan-

tial. The gasification route requires as much as 3.5 tonnes of dry biomass input for every tonne of HVCs produced. The route based on anaerobic digestion requires much less biomass, 1.9 tonnes, but it also requires large amounts of electricity – 13 MWh per tonne – to produce hydrogen instead.³⁷

Sustainable biomass resources are scarce, with competing and growing demands from the power, transportation, heat and other sectors. A major finding of this study is that 'biofeedstock' nonetheless needs to be considered a high priority in the overall transition to a net-zero economy. The use of biomass for chemicals feedstock is not recognised in today's climate policies and discussions, which tend to equate 'biomass' with 'biofuel'. Yet there are few alternatives if we are to achieve truly deep emissions cuts from plastics. The main option would be to use renewable electricity to capture CO₂ for further synthesis, but as we discuss below, this comes with still much higher resource requirements.

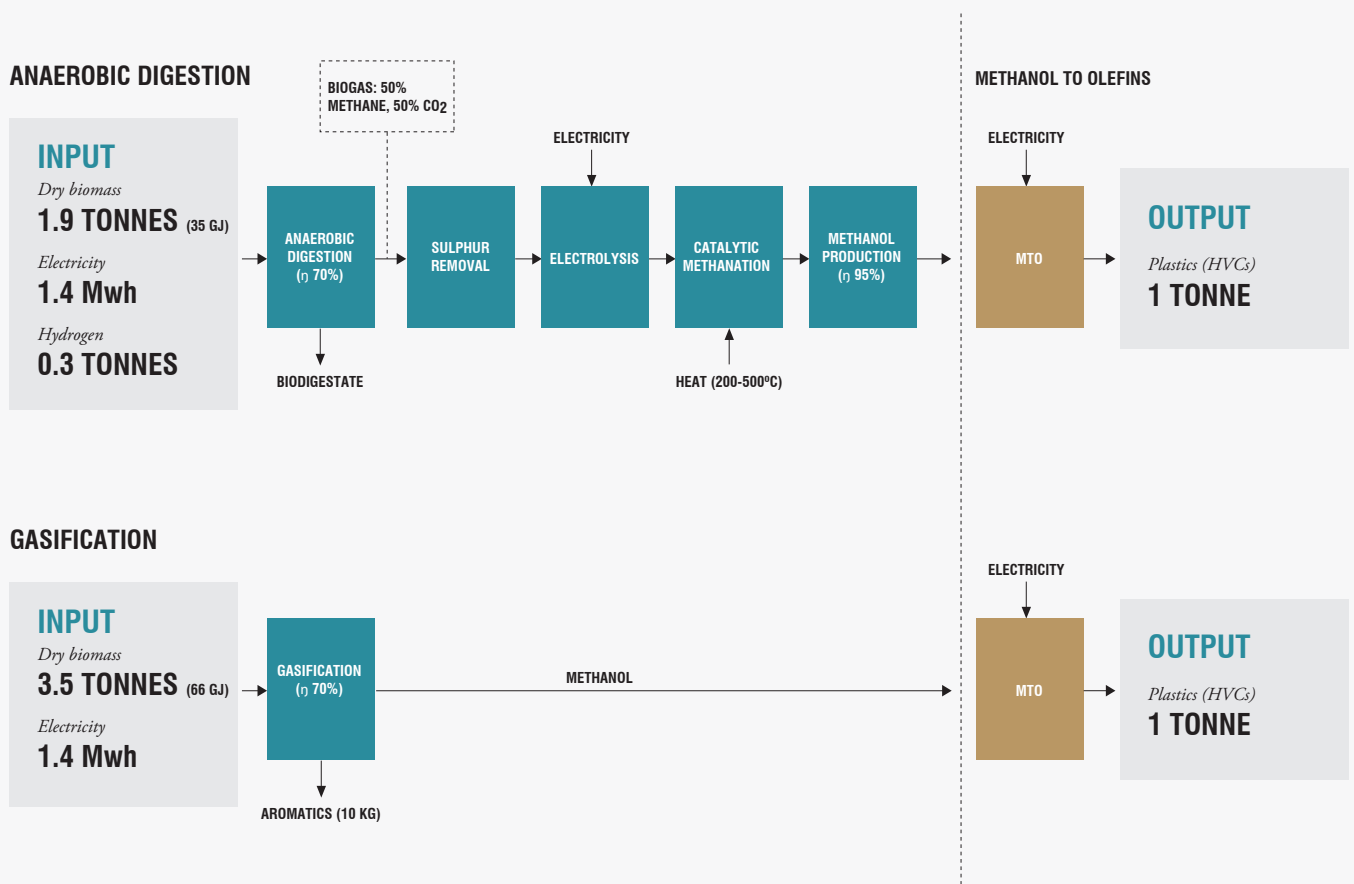
At the same time, it is crucial to reduce biomass requirements for plastics as much as possible. In no scenario will it be feasible to simply use bio-based production as a drop-in replacement for today's fossil-based system. Instead, bio-based plastics must be used strategically as a solution within an overall production system of increased materials efficiency, circular business models, some degree of substitution, high levels of plastics recycling, and flexible processes capable of using the biomass streams with the least opportunity cost.

The routes used here arguably are conservative, as they investigate how today's polymers could be produced from entirely different feedstock that in molecular terms is often a poor match. Further development of other polymers, such as polylactic acid (PLA), with a closer affinity to the original composition of various bio-molecules could significantly reduce the resource claims. There is a lot of scope for innovation into efficient routes for production of bio-based plastics.

The pathways explored in this study produce between 20 and 24 Mt of plastics derived from bio-feedstock in 2050, with the volume largely dependent on how successful other strategies to reduce CO₂ from plastics turn out to be.

Exhibit 3.12

BIO-BASED PLASTICS PRODUCTION WITH METHANOL AS A NEW PLATFORM CHEMICAL



NOTES: ELECTRICITY FOR PRODUCTION OF 0.3 KG HYDROGEN REQUIRES AROUND 13 MWh OF ADDITIONAL ELECTRICITY. THE PATHWAYS USE A COMBINED ROUTE WITH A 50/50 SHARE BETWEEN THE ANAEROBIC DIGESTION AND GASIFICATION ROUTES. BIOMASS IS ASSUMED TO CONTAIN 30% MOISTURE AND HAVE AN ENERGY VALUE OF 18.5 MJ/KG.

SOURCES: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

CARBON CAPTURE

The final strategy for reducing CO₂ emissions from plastics is to capture the carbon and store it in ways that prevent release into the atmosphere on the timescales relevant for climate change.

There are three major CO₂ sources at different parts in the value chain: petroleum refining, steam cracking, and waste incineration. All can in principle be done. Carbon capture and storage is in principle possible from steam crackers, using either post-combustion or oxyfuel options. Costs would likely be higher than for some applications often mooted for CCS, given the lower carbon intensity of fuels used in crackers and higher resulting oxygen needs.³⁹ Above all, there is little practical experience, as CCS has not been applied on steam crackers to date. Waste to energy also is being explored, with a trials starting at the Klemetsrud waste-to-energy facility in Oslo, Norway.

Still, there are several reasons why CCS could be challenging to apply in the case of plastics. The ideal scenario for CCS is a single, large-scale emissions source, preferably with a high concentration of CO₂. In contrast, in the case of plastics, three separate emissions sources at different points in the value chain would have to be addressed. Waste incineration is also typically small-scale, with more than 500 waste-to-energy plants across the EU.⁴⁰ Universal coverage would therefore be difficult to achieve.

CCS could also have a role in the production of hydrogen, which is used in several of the low-carbon routes in significant volume. CCS with steam methane reforming can be preferable to production via water electrolysis when electricity prices are high.

A final theoretical option for CCS is to use solid plastics directly as a form of CO₂ storage. A major concern with plastics is that they are long-lived, so they present challenges for waste management. However, if plastics could be safely stored, without the disadvantages of standard landfilling, then it might be possible to use such storage as a form of CCS. The feasibility of such an approach is far from clear: it would require a U-turn on current EU policy to phase out landfilling; there would need to be strict safeguards against pollution (such as the risk of escaping microplastics); and the permanence of the CO₂ sequestration would need to be assessed. As this is highly speculative, it is not included in the pathways explored in this study, which instead build on current EU policy to phase out landfilling.

The pathways explored in this study span a wide range of possible uses of CCS. At one extreme, some pathways use no CCS, but instead achieve CO₂ neutrality through recirculation and biomass inputs. In other pathways, CCS is used across refineries, steam crackers, incineration plants, and hydrogen production, alongside other options. In this scenario, CCS leads to emissions cuts of 59 Mt CO₂ per year.

CARBON CAPTURE AND UTILISATION AND ‘POWER-TO-X’

A final option for CO₂ reductions to use CO₂ as a feedstock for chemicals production (carbon capture and utilisation, CCU). As discussed in Chapter 2, this has been proposed as a way to handle the significant CO₂ and carbon monoxide (CO) generated from core processes in the steel sector. By combining CO₂ with hydrogen, it is possible to synthesise a wide range of chemicals.

At one extreme, it is possible to capture CO₂ from the air and combine it with hydrogen from water electrolysis using renewable energy. In this case, the CO₂ reductions relative to fossil feedstock are immediately apparent. Much like sustainable biomass, it provides a source of new carbon supply for chemicals that requires no fossil hydrocarbons. However, the energy resources required are phenomenal: as much as 27 MWh of zero-carbon electricity is required to produce one tonne of HVCs.⁴¹ For comparison, deriving the same amount of HVCs from biomass requires 1.5-14 MWh of electricity. Viewed through this lens, using biomass for chemicals production saves as much as 25.5 MWh of electricity per tonne HVCs.

The other option is to capture CO₂ from another industrial or energy process and use this as a building block of chemicals. This already takes place in some cases: for example, urea is produced using CO₂ from ammonia production. However, as the CO₂ is of fossil origin, and it is released into the air once urea is used as fertiliser, it delays rather than prevents the release of the fossil CO₂. The same applies to other uses of CO₂ where the origin is fossil, and the product is short-lived.

The exception is where the product itself displaces some other fossil CO₂; for example, CO₂ from one fossil-based process could in principle be captured to make a transportation fuel that, in turn, displaces standard fossil-based transportation fuels, somewhat reducing overall CO₂ emissions. As long as the energy system as a whole is fossil-based, CCU based on fossil CO₂ sources may thus be able to reduce CO₂ emissions, although there is a lively debate about the extent of savings. In a net-zero economy, however, the release of CO₂ from fossil sources is not possible without some offset mechanism, even if the CO₂ is ‘used twice’ before it is released.

Fuels are an extreme example of a short-lived product, but the same logic applies in cases with longer lifetimes. Few carbon-based products have lifetimes and recycling rates that, combined, make them comparable to permanent sequestration of carbon (the chief potential exception may be some mineral-based construction materials). Specifically, plastics do not offer an opportunity for long-term sequestration. As noted, even if recycling rates were 70%, as high as those for aluminium today, some two-thirds of the carbon would be released as CO₂ after 15 years.⁴²

As noted in Chapter 2, these considerations do not rule out the use of CO₂ or CO from one process for the production of chemicals in a net-zero economy. However, the conditions that must apply are very strict. In brief, any fossil CO₂ used in the process must be offset by permanent storage through CCS; and any CO₂ that leaks during the product lifetime must be replenished by a non-fossil source such as biomass. The overall viability of CCU as a zero-emissions solution is therefore inextricably linked to the use of non-fossil sources of CO₂.

3.3 PATHWAYS TO A NET-ZERO CO₂ PLASTICS SECTOR

We have seen that a range of complementary strategies are required to achieve deep emissions cuts for the EU plastics sector. By successfully deploying these strategies, the EU can transition to a net-zero emissions plastics sector by 2050. The revamped plastics sector would have a renewed production base, new patterns for the use and reuse of materials, and new sources of value.

Clearly this is a major transformation agenda, spanning the entire plastics value chain. While many of the core technologies and business models are already developed, they are either optimised for other end products such as fuels, and/or need accelerated commercialisation and upscaling. There are also many costs and risks associated with developing and deploying these strategies.

Given the many uncertainties, there is a need to explore many different pathways to a net-zero emissions EU plastics sector in 2050. Together, the pathways are intended to span the full set of strategies, but each pathway has a different focus, and not all strategies are employed in all pathways:

New processes pathway: This pathway emphasises new processes and feedstocks for new plastics production. A range of routes for the production of HVCs from biomass feedstock and end-of-life plastics are rapidly scaled up during the 2030s, and production from new fossil feedstock is entirely phased out by 2050. By this time, these routes produce the same amount of plastics as is made in the EU today. These processes both rely heavily on electricity: for heat input to pyrolysis and cracking, the production of hydrogen, methanol synthesis, and various other processes such as MTO. This pathway has the highest share and largest amount of plastics produced

through chemical recycling, and thus requires significant improvements in the collection of end-of-life plastics.

Circular economy pathway: This pathway entails heavily restructuring the use of plastics in all major value chains, so that a third of the baseline demand for plastics is met through materials-efficient products and production, sharing-economy options, and materials substitution. There is a large migration of value towards these new economic activities. In addition, plastics become highly circular materials, with mechanically recycled plastics meeting 26% of demand, and chemical recycling another 47%. The need for production from new feedstock is the lowest of any of the pathways, making smaller claims on biomass resources.

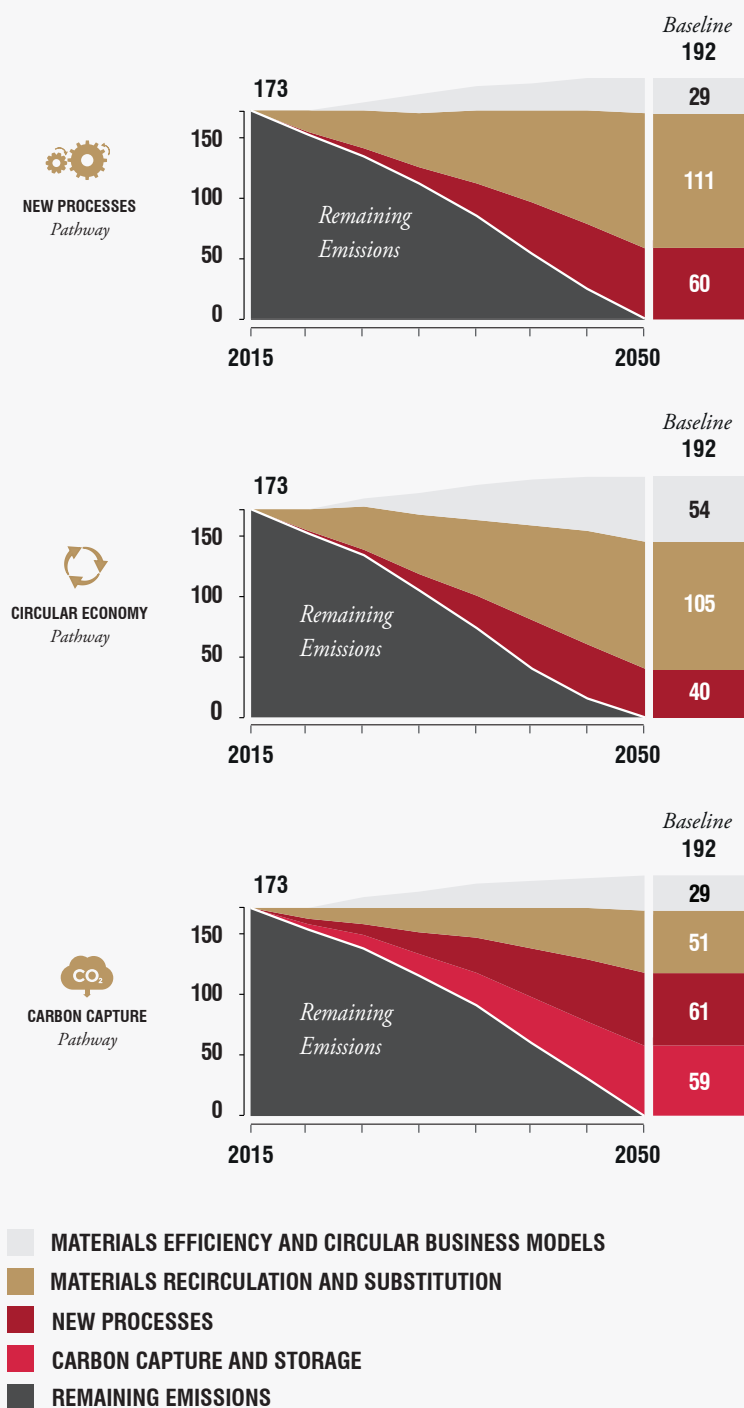
Carbon capture pathway: This pathway pushes the potential to use CCS the farthest. Circular economy opportunities play a relatively minor role. 40% of production uses fossil feedstock via routes largely similar to today's, but with crackers either electrified or equipped with CCS, so there are no 'unabated' steam crackers left in 2050. CCS is also fitted on refineries and on two-thirds of waste incineration plants for any plastics that are not recycled. Mechanical and chemical recycling also play a significant but smaller role in this pathway. Biomass is used as feedstock as well, to provide the compensating 'negative emissions' from incomplete carbon capture (a capture rate of less than 100% at individual plants, but above all the challenge of equipping every facility with CCS) through capture of biogenic CO₂.

All three pathways assume the same total underlying services from plastics in 2050 (packaging, mobility, etc.), but they fulfil these in different ways (Exhibit 3.14).

Exhibit 3.13

PATHWAYS TO NET-ZERO EMISSIONS FOR PLASTICS

CO₂ ABATEMENT
Mt CO₂ PER YEAR



EMPHASIS ON NEW PRODUCTION ROUTES THROUGH RECYCLING AND PRODUCTION FROM BIOMASS FEEDSTOCK

- 62 percent of production from end-of-life plastics by 2050 through a combination of mechanical and chemical recycling, hinging on a significant increase in collection rates of end-of-life plastics
- Remaining 38 percent of production from biomass feedstock, using methanol as new platform chemical
- Increased reliance on electricity for hydrogen production and in production processes

EMPHASIS ON DEMAND-SIDE MEASURES TO ACHIEVE A MATERIALS EFFICIENT AND CIRCULAR PLASTICS SECTOR

- Emphasis on demand-side opportunities for materials efficiency, materials substitution and new circular business models for plastics, resulting in the decreased production volume to 52 Mt by 2050
- Highly circular scenario with 62 percent produced through mechanical and chemical recycling, and remaining 38 percent from biomass feedstock

EMPHASIS ON CARBON CAPTURE AND STORAGE/UTILISATION ALLOWS FOR A CONTINUED ROLE FOR PRODUCTION FROM FOSSIL FEEDSTOCKS

- Emphasis on using CCS/U on plastics production from fossil feedstocks as well as CCS on end-of-life incineration, and electrification of steam crackers to reduce direct emissions
- 32 percent of production from biomass feedstock to enable offsets from incomplete fossil CO₂ capture through capture of biogenic CO₂ from incineration of bio-based plastics

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

While the three pathways are significantly different, a number of cross-cutting lessons emerge from them.

All pathways rely on significant innovation and technology development. The solution set included in the pathway is largely proven in principle, but absent commercial incentives, it is still far from large-scale deployment. To achieve deep emissions cuts by 2050, new solutions must be proven by the 2030s, so the next decade is key. These pertain not just to the production of chemicals, but also to a range of innovation in business models and product design to enable reuse, recycling, and materials efficiency. On the other hand, there is a large upside: if innovation effort can be redirected, it is all but certain that new solutions, catalysts, and processes will emerge.

All pathways entail deep and pervasive change. Current chemical production systems are highly optimised and integrated. All pathways entail disruptive and large-scale change in feedstocks, processes, platform chemicals, and energy sources. For EU companies, the strategic ramifications could hardly be larger. On one hand, current production faces structural challenges of more expensive feedstock and energy than many other regions. On the other, striking out to embrace entirely new production systems and inputs is a ‘bet the company’ level of commitment. Enabling such non-marginal change through policy is notoriously difficult, and will require early, robust, and credible policy signals.

The CCS pathway may seem less disruptive in some ways, as it continues to use well-established processes with fossil feedstock at its core. However, the flip-side is that this would arguably be the most challenging CCS effort in the economy. Fitting CCS to a substantial share of the 50 steam crackers in the EU is a significant undertaking in its own right, but there are also 90 petroleum refineries providing much of the feedstock (and facing much-diminished demand for fossil transport fuels in a low-carbon transition), and 500–1000

waste incineration plants that would be the destination for the carbon embedded in plastics products in this pathway.

In all pathways, early action to pursue of ‘traditional’ CO₂ reduction strategies would ease the transition. Energy efficiency and electrification can provide early cuts, before new production routes can be scaled up, and also limit the total amount of new feedstock and energy required. Electrification of crackers and other high-temperature heat (e.g. for pyrolysis) will be needed in all routes.

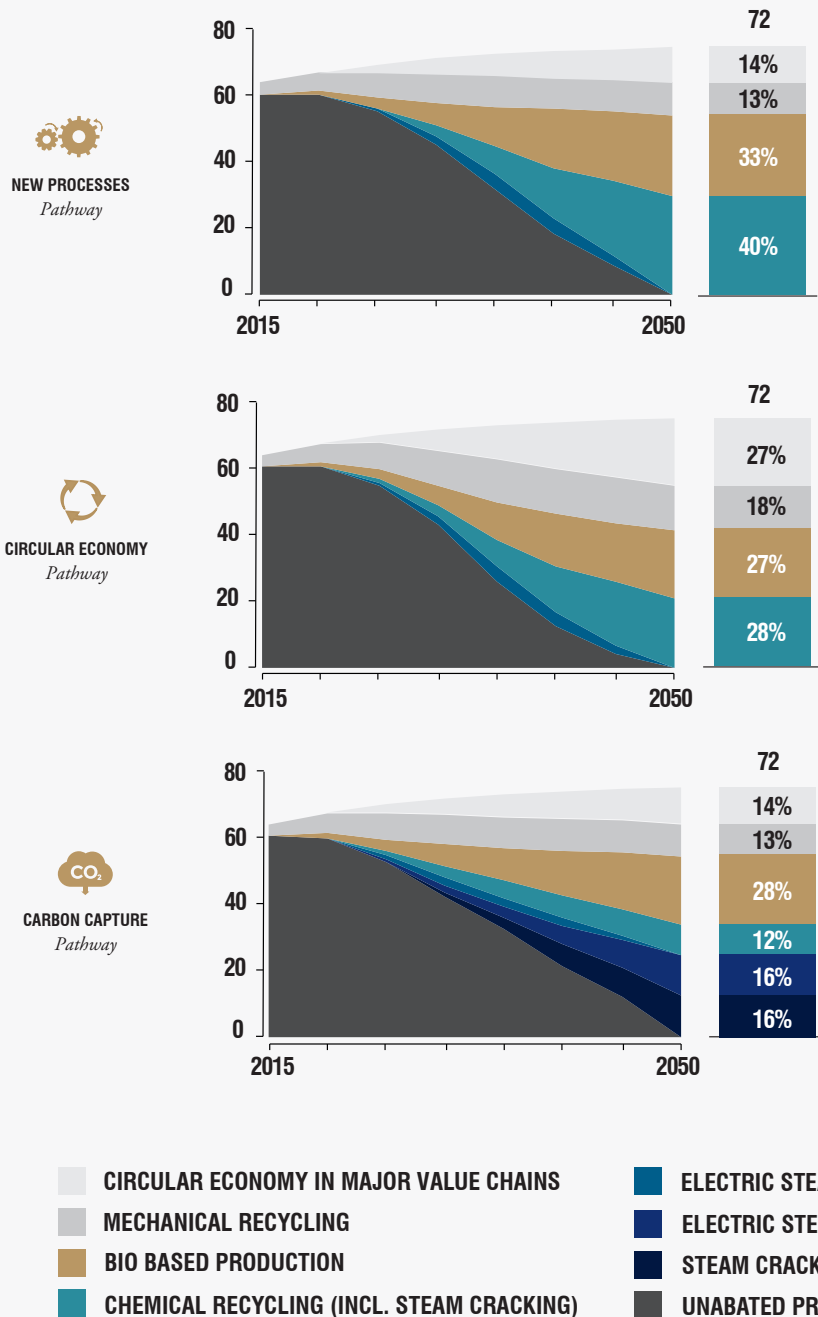
Just as important, achieving the potential for mechanical recycling and reuse, materials efficiency, and circular business models further helps the transition to fit plastics use into a net-zero economy. Together, they hold the potential to provide the same benefits as the production of 25 Mt of plastics by 2050. Tapping into this potential eases many of the transition challenges, reducing costs and investment needs, the amount of electricity and biomass required, and the pace at which new production technologies must be deployed. To unlock this potential, ‘upstream’ innovation will be key: changing product design, materials choice, and business models. In terms of policy, it may require a program of ‘energy efficiency-type’ interventions.

Finally, the chemicals sector will need to become more integrated and tightly linked to other sectors in this transition. One reason is an increase in the number of processing steps. To achieve truly deep cuts to emissions, it will be necessary to transform a fuller range of feedstock flows that today are burnt as fuel, or to capture the CO₂ and store it. Likewise, mobilising new feedstocks will require industrial symbiosis to use byproducts from other sectors (such as pulp and paper or food and drink), or join forces with other parts of the economy to mobilise feedstock (notably, hydrogen). Tight integration of chemicals and the waste sector is another potential enabler, especially in the more circular pathways.

Exhibit 3.14

PRODUCTION ROUTES IN NET-ZERO PATHWAYS

EUROPEAN PLASTICS PRODUCTION MIX TO ACHIEVE NET ZERO EMISSIONS IN 2050
Mt PLASTICS PRODUCED PER YEAR AND ROUTE



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

DEEP CUTS TO CO₂ EMISSIONS WILL INCREASE THE COST OF PLASTICS PRODUCTION OR USE BY 20-43%

Most of the routes to eliminating emissions from plastics production and end-of-life flows come at a cost. By 2050, the additional costs in the pathways range between 27 and 34 billion EUR per year. The average CO₂ abatement cost lies in the range 140-177 EUR / tCO₂. The differences in costs are not large enough that one set of solutions is obviously more attractive than another, and all face major non-financial barriers that may be at least as important (whether mobilising very high levels of end-of-life collection, producing the electricity required, or finding acceptance and commercial logic in large-scale CCS infrastructure). Overall, the circular economy options have the potential to be more cost-effective, provided that the major materials efficiency levers can be successfully pursued.

A closer look at the different production routes indicates the cost drivers for different solutions (Exhibit 3.15). Overall, options that eliminate not just production but also end-of-life emissions add 20-43% to the cost of bulk plastics. These are estimates of fully demonstrated processes at scale; early deployment is likely to be more expensive.

As this shows, all major solution levers will depend on some form of policy support if they are to compete against current, incumbent solutions. EU producers are already heading more towards specialisation than bulk production, but much of the plastics volume is still a commodity business where systematic cost disadvantages are not feasible. A solution will therefore be necessary to level the playing field of these new production routes, both relative to competitors outside Europe who continue to rely on high-CO₂ processes, and to allow early movers in Europe to move ahead of local competitors. Either the OPEX disadvantage has to be offset, or markets must be separated depending on their emissions profile of products (e.g. the degree of recycled or non-fossil feedstock they contain).

The additional costs are driven primarily by four factors: electricity, feedstock switching, CCS, and the cost of materials efficiency and circular economy solutions. Electricity is a major driver of the increased costs of the new production routes. It is used in large quantities both to produce hydrogen and as a source of heat. The electricity accounts for 27% of the cost of chemical recycling, and 23% of the cost of production by electric steam cracking.

The switch to new feedstocks means the cost of plastics production will now be heavily determined by the prices of biomass and end-of-life plastics, instead of oil and gas prices. Competition for biomass from other sectors, notably energy, could drive up prices. At present, there are also policies that favour the use of biomass in other sectors, such as transportation and power generation. Therefore, further policy action will be needed to ensure that the plastics industry can compete for access to this biomass.

CCS also becomes a major potential cost driver. Fitting CCS onto plants that incinerate end-of-life plastics will be particularly challenging, because the plants are typically small, which leads to higher costs per tonne of CO₂ captured. They also are widely dispersed, which drives up transport and storage costs.

As for other materials and value chains, the costs of increased materials efficiency and improved circularity are among the hardest to gauge. Levers span the full range from genuine productivity improvements to potentially expensive options to optimise plastics use. Digitisation is a major enabler to reduce transaction costs across the board. Overall, the finding is that circular economy levers are likely to be as cost-effective as those for low-CO₂ production.

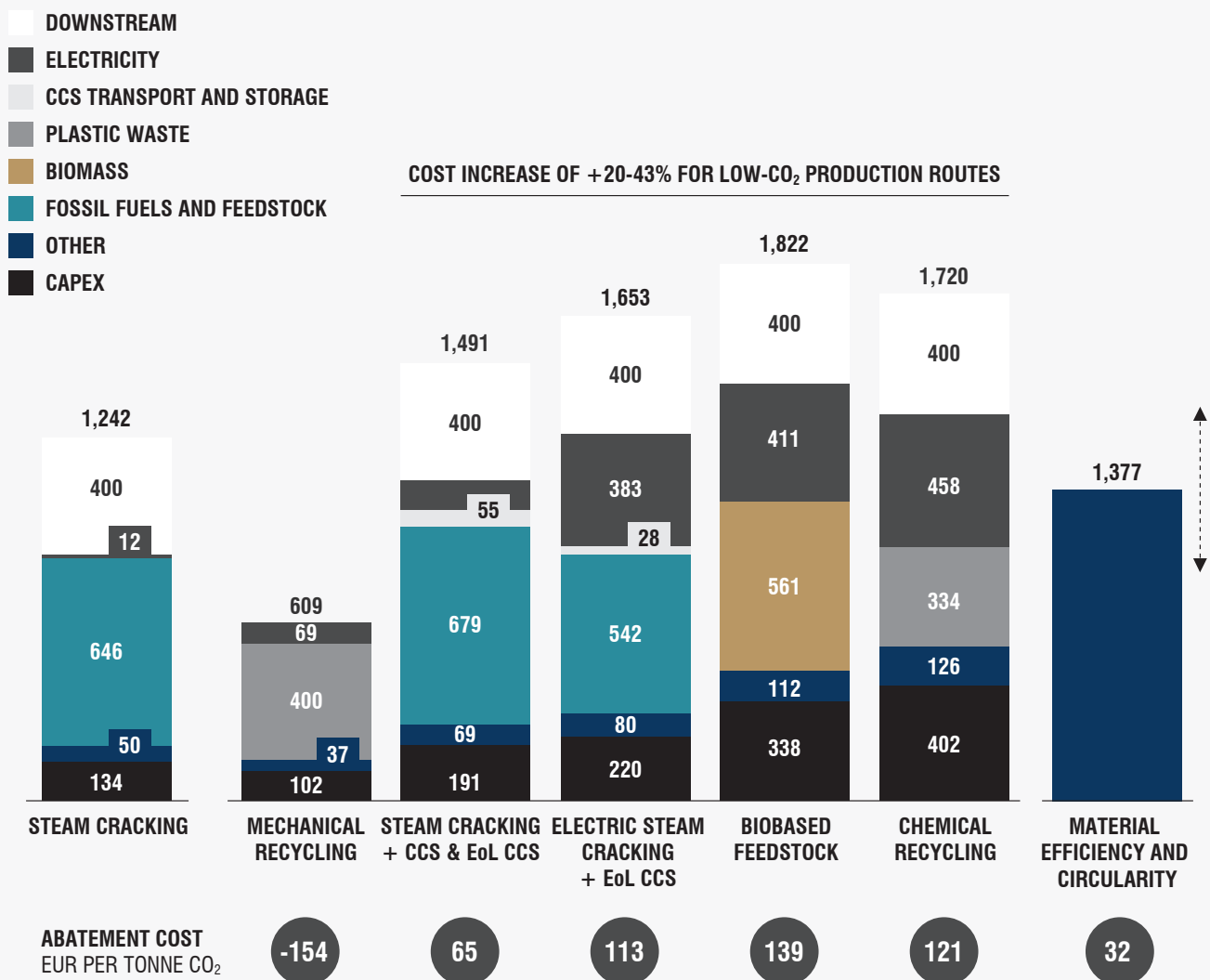
All of these are likely also to vary across Europe – with local renewable energy resources, carbon transport and storage infrastructure, availability of industrial clusters, and other circumstances. This adds another reason to pursue a portfolio of solutions.

While these cost estimates have various uncertainties, they arguably are on the side of caution by not including the potential upsides of innovation. The approach in this study has been to use processes that are as near tried-and-tested as possible, and to use today's efficiencies and yields for the quantitative estimates.⁴³ Many of the building blocks of a low-CO₂ sector – large-scale gasification, highly automated sorting technology, methanol-to-olefins, new circular economy business models, carbon capture technologies suitable for steam crackers, etc. – are emerging but only early in their journey towards industrialisation. There is therefore a significant potential for costs to fall as they are deployed.

Exhibit 3.15

COST OF PRODUCTION IS HIGHER FOR NEW LOW-CO₂ PRODUCTION ROUTES

COST BREAKDOWN OF TECHNOLOGIES EUR PER TONNE PLASTICS



NOTES: ABATEMENT COST CALCULATED ASSUMING ZERO-CARBON ELECTRICITY. CO₂ PRICES NOT INCLUDED IN THE PRODUCTION COSTS.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

INVESTMENT IN PLASTICS PRODUCTION AND VALUE CHAINS WILL NEED TO INCREASE BY 122-199%

Enabling a new production and consumption system for plastics will require a wave of investment. Total capex rises by an estimated 122–199% depending on the pathway, to the tune of 3-4 billion EUR per year on average to 2050. The variation between pathways is thus relatively large, with lower costs the more prominent the role of circular economy solutions. These rely less on large-scale and capital intensive infrastructure, and more on logistics, data, business model adaptation, and labour.

Much of the increase in investment is due to the increased complexity of production. Mobilising end-of-life plastics as feedstock requires greater capital investment in waste handling. Many of the production routes go from a single step of steam cracking to produce HVCs from naphtha or ethane, to also include secondary steps (such as methanol synthesis and methanol-to-olefins) to process by-products that otherwise result in CO₂ emissions. Carbon capture in all cases requires new capital assets. Similarly, routes based on pyrolysis, digestion or gasification involve more process loops before HVCs can be produced, each with additional capital requirements. Overall, the new routes are as much as 45-200% more capital-intensive.

The need for early development of new technologies through piloting and demonstration further increases the investment requirements, as do costs of brownfield conversion of existing complexes. The additional capital requirements will also depend heavily on whether new solutions can be put in place at the point when existing assets need retrofitting or upgrading anyway. A major objective of the transition must be to avoid double investment: first in maintaining current, fossil-based production capacity, and then in abandoning this in favour of new, low-CO₂ production routes. The more policy can enable a single fork in the road, the less of an investment penalty there will be.

This additional investment will take place only if the EU becomes an attractive destination for investment in chemicals production overall. Globally, most recent investment has taken place outside the EU, in regions with strongly growing home markets or with favoured access to cheap feedstock. The EU will need a different investment model to realise a net-zero transition in chemicals. Pioneering low-carbon solutions within an overall enabling policy environment may well have as much claim to likelihood of success as any other strategy.

Exhibit 3.16

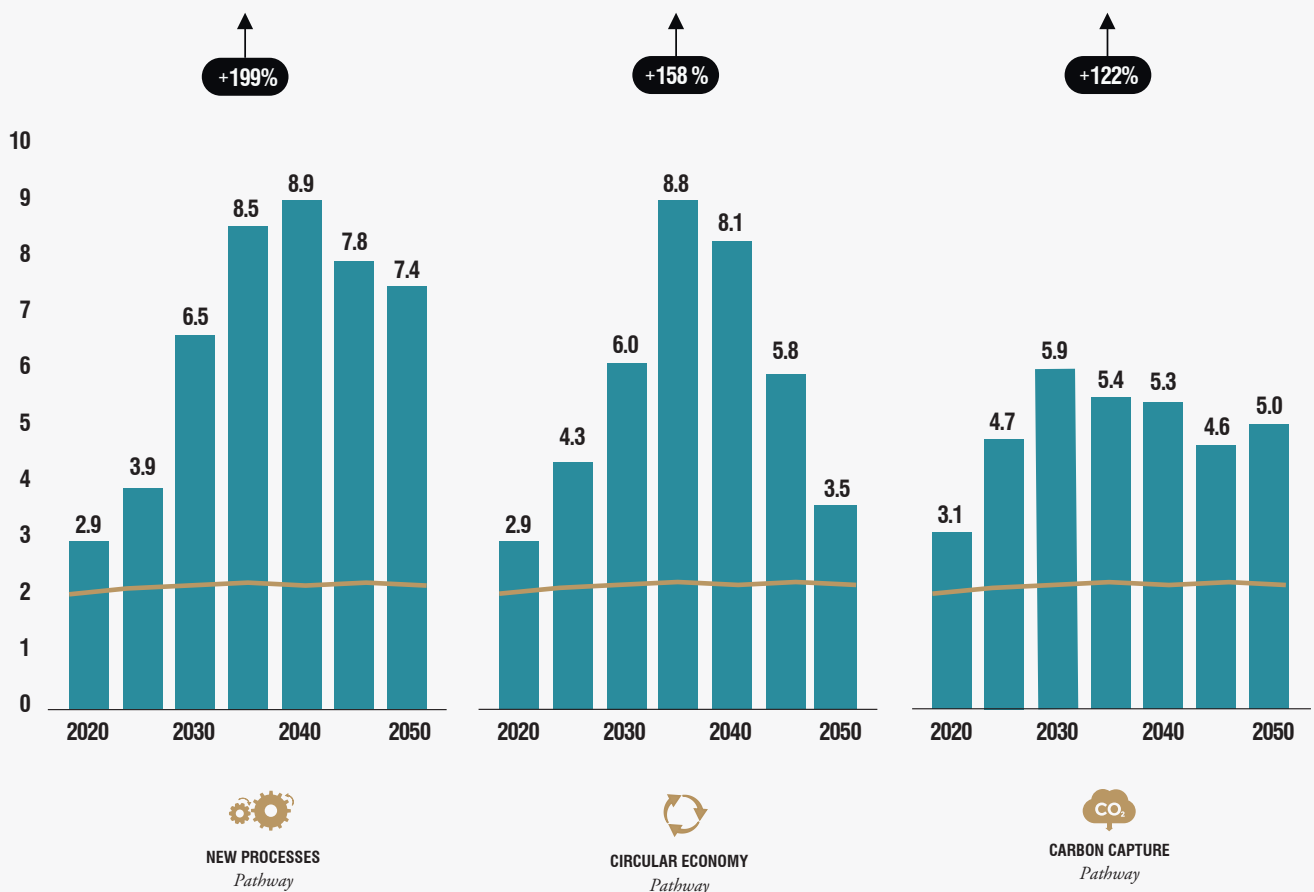
LOW-CO₂ PRODUCTION CAPACITY INCREASES THE INVESTMENT NEED

INVESTMENT IN PLASTICS PRODUCTION CAPACITY
BILLION EUR PER YEAR

INCREASE RELATIVE TO BASELINE

+ X %

■ PATHWAY
— BASELINE



NOTES: INVESTMENT NEEDS DO NOT INCLUDE DOWNSTREAM PRODUCTION. INVESTMENTS IN POWER GENERATION OR CARBON TRANSPORT AND STORAGE INFRASTRUCTURE ARE NOT INCLUDED.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

A NET-ZERO EMISSIONS PLASTICS INDUSTRY WILL EXCHANGE FOSSIL OIL AND GAS FOR ELECTRICITY, BIOMASS, AND CIRCULAR RESOURCES

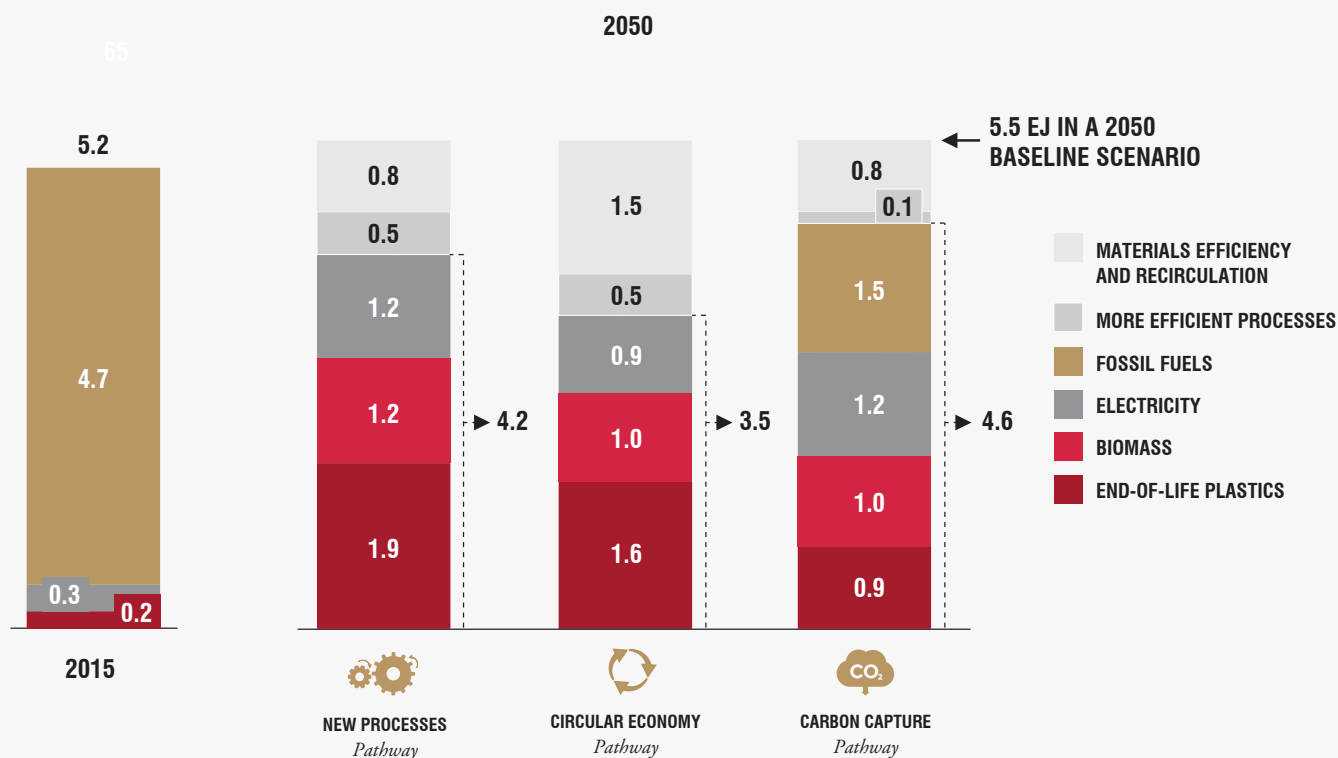
Today's plastics production system is integrated to the wider petrochemicals and fossil fuel supply chain. Naphtha, by far the dominant feedstock for plastics production in the EU, is an intermediate stream in the refining of fossil hydrocarbons to fuels. Ethane, used in most remaining production, is a component of natural gas. Natural gas and various fuel-grade products are also used in steam generation and in furnaces. All in all, some 1000-1500 TWh of oil and natural gas are used in the production of HVCs and in downstream processes.

In the low-carbon pathways, these fossil sources are either replaced, or used in contexts with CCS (Exhibit 3.17). The main replacements are 0.9–1.2 EJ of electricity for hydrogen, heating and process thermal energy, 1-1.2 EJ of biomass and 0.9–1.9 EJ of end-of-life plastics, for use as feedstock. In the CCS pathway, 1.5 EJ of oil and gas continue to be used, but with CCS in the production of hydrogen, in steam cracking, and at end of life.

Exhibit 3.17

INPUTS CHANGE FROM FOSSIL SOURCES TO ELECTRICITY, BIOMASS, AND END-OF-LIFE PLASTICS

ENERGY AND FEEDSTOCK MIX TODAY AND IN 2050
EJ ENERGY PER YEAR



NOTES: 0.9-1.2 EJ OF ELECTRICITY CORRESPONDS TO 238-332 TWh.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

ELECTRICITY

In all three pathways, the plastics industry needs an abundant supply of affordable low-emissions electricity. The additional electricity is necessary for thermal energy in cracking and pyrolysis, for steam generation, and to power a range of additional processes. Around 75% of the electricity will be needed to produce hydrogen. The electricity requirements could be reduced by alternative hydrogen production methods, whether steam methane reforming with CCS or emerging options such as methane pyrolysis (see Box in Chapter 2).

The cost of electricity also becomes a major determinant of the cost of production. With a degree of storage and over-capacity, hydrogen production can be flexible and benefit from periods of lower electricity prices, which becomes especially important in energy systems with a high share of variable renewables such as wind and solar power. In contrast, the core thermal loads of cracking and related processes will depend on much more continuous operation, and likely also face higher prices. Electrification can be done gradually on an existing steam cracking complex, for instance by first replacing one or two furnaces, or by using hybrid system switching between fossil fuel and electrical heating depending on prices.

END-OF-LIFE PLASTICS

Meanwhile, the focus on production from recycled plastics creates a need for collected and sorted end-of-life plastics. The share varies by pathway, but is always major: 35-41 Mt per year. This boost in recycling would require significant changes across the value chain. High-quality mechanical recycling requires very pure plastics flows with little contamination to achieve high-quality recirculation. Chemical recycling is less exacting, but also requires some pre-processing, and above all collection and processing of large volumes matching those of large-scale chemicals production.

These changes also require significant change to the current waste handling sector. In all cases, it needs to rapidly break the current trend towards large amounts of fossil CO₂ emissions from end-of-life plastics. In a more circular pathway, the disruption will be the need to collect, separate and centralise much more of end-of-life plastics as feedstock for new production. Vertical integration of waste handling and chemicals production may well be the most reliable way to organise this. In a CCS pathway, the driver of change would instead be to fit carbon capture to waste incineration plants – which in turn may require that end-of-life incineration is scaled up and centralised to a smaller number of sites in a significantly reorganised sector. Either way, the status quo for waste handling is not an option for net-zero emissions from plastics.

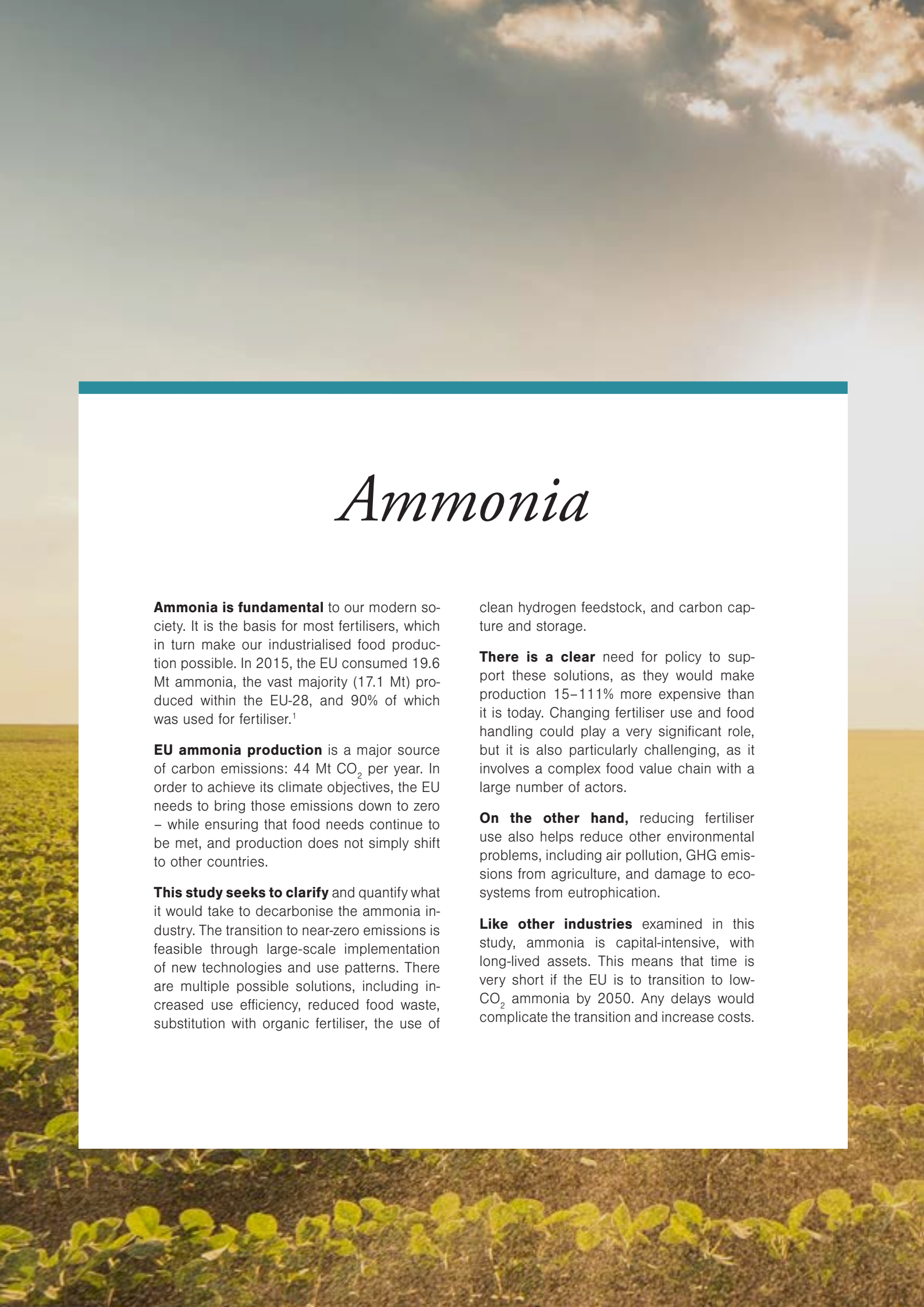
BIOMASS

The final major change is the need to mobilise large volumes of biomass for use as feedstock. Supplying 32-38% of the EU's plastics demand through production with biofeedstock in 2050 would require 75-95 million tonnes of biomass.

There is no doubt that this will be a scarce and valuable resource. This study nonetheless finds that using biomass for chemicals feedstock is a high priority: it is high time that EU climate and energy policy avoided directing biomass towards relatively low-value uses where there are other viable options (such as the generation of bulk electricity), and prioritised uses where few other options are available. The use of biomass as feedstock for chemicals is one such use. On average, the routes included in the pathways require 19 MWh of biomass and electricity for every tonne of HVC produced. For illustration, if instead 'power-to-X' methods were used (direct air capture of CO₂, combined with synthesis of chemicals from CO₂ and hydrogen from electrolysis), the electricity required would be as much as 27 MWh of electricity for one tonne of HVC.

Nonetheless, the amount of biomass used for chemicals must be limited. The most important strategy is to use other options to bring down the total amount of new carbon from biomass that is required. In the pathways, this is achieved through a balanced portfolio of materials efficiency, mechanical recycling, chemical recycling, and carbon capture. That way, bio-based production never need to meet more than 38% of underlying demand in the pathways. Another strategy is to mobilise waste streams that compete as little as possible with biodiversity targets, food and feed production, or other high-priority uses for biomass. One such source is the bio content of mixed waste, which can be used in gasification. Others could include various current energy uses of biomass, such as byproduct streams in the pulp and paper industry or bioenergy used for basic heat generation, that could be freed up if some processes were electrified instead. A final option is to gradually switch to polymers that have closer affinity to the biomass inputs, and which therefore require less biomass per tonne produced.

All of these changes to inputs point to a chemicals sector much more closely integrated with other parts of the economy. This includes energy (electricity), transportation (hydrogen), waste (end-of-life flows, biomass), pulp and paper, and food and drink (biomass), as well as providers of carbon transport and storage.



Ammonia

Ammonia is fundamental to our modern society. It is the basis for most fertilisers, which in turn make our industrialised food production possible. In 2015, the EU consumed 19.6 Mt ammonia, the vast majority (17.1 Mt) produced within the EU-28, and 90% of which was used for fertiliser.¹

EU ammonia production is a major source of carbon emissions: 44 Mt CO₂ per year. In order to achieve its climate objectives, the EU needs to bring those emissions down to zero – while ensuring that food needs continue to be met, and production does not simply shift to other countries.

This study seeks to clarify and quantify what it would take to decarbonise the ammonia industry. The transition to near-zero emissions is feasible through large-scale implementation of new technologies and use patterns. There are multiple possible solutions, including increased use efficiency, reduced food waste, substitution with organic fertiliser, the use of

clean hydrogen feedstock, and carbon capture and storage.

There is a clear need for policy to support these solutions, as they would make production 15–111% more expensive than it is today. Changing fertiliser use and food handling could play a very significant role, but it is also particularly challenging, as it involves a complex food value chain with a large number of actors.

On the other hand, reducing fertiliser use also helps reduce other environmental problems, including air pollution, GHG emissions from agriculture, and damage to ecosystems from eutrophication.

Like other industries examined in this study, ammonia is capital-intensive, with long-lived assets. This means that time is very short if the EU is to transition to low-CO₂ ammonia by 2050. Any delays would complicate the transition and increase costs.



*The transition to near-zero emissions
is feasible through large-scale
implementation of new technologies
and use patterns.*

3.4 THE STARTING POINT

Large-scale ammonia production took off after World War I, when the Haber-Bosch process was invented.² Today, the nitrogen captured in ammonia production is an integral part of modern agriculture, and it remains a cornerstone of food production for a growing global population.

In the EU, annual production of ammonia amounts to 17 million tonnes per year. Of this, 90% is used to produce nitrogen fertilisers, and the rest in various industrial applications. The EU produces 75% of the N fertilisers and imports the remaining quarter.^{3, 4} The EU ammonia and fertiliser industry has annual turnover of €11 billion, and it employs 78,500 people.⁵ Production takes place at more than 40 plants, with typical capacity of half a million tonnes per year.⁶

The ammonia production process combines nitrogen (taken out of the air) with hydrogen; indeed, more than half the hydrogen produced industrially around the world is used to make ammonia.⁷ The hydrogen, in turn, is derived from natural gas through a process called steam methane reforming. The natural gas input makes up the vast majority of the cost of ammonia production, often 80% or more.⁸ As in other processes heavily dependent on natural gas, European producers face a substantial cost disadvantage. Cash costs can be less than half in regions with cheap gas, notably the Middle East, the United States, and Russia.⁹

Mineral fertilisers (largely derived from industrially produced ammonia) are used in combination with organic fertiliser, including manures. Mineral fertiliser provides around 45% of nitrogen input, and organic fertiliser 40%.¹⁰ Total use of mineral fertiliser in the EU is increasing, both in absolute numbers and in kg per hectare.¹¹

CO₂ EMISSIONS FROM AMMONIA PRODUCTION

The production of each tonne of ammonia in the EU results in emissions of 2.5 tonnes of CO₂¹⁷ (see Exhibit 3.18). At current production levels, the total CO₂ emissions are 44 Mt. European producers are already more CO₂-efficient than some of their global counterparts. For example, in China ammonia is often produced with coke/coal rather than natural gas as a source of energy and hydrogen, and average CO₂ emissions are more than 4 tonnes per tonne of ammonia.¹⁸

CO₂ arises from two separate sources in ammonia production. First, steam methane reforming creates CO₂ as a by-product.¹⁹ The resulting stream of CO₂ is around 70% of the direct emissions of CO₂ from ammonia production (or half if CO₂ from electricity generation is also counted). It also is very pure, and

Much of the nitrogen applied as fertiliser is not actually absorbed by the plants, but rather is lost to the environment. Reducing the so-called 'nitrogen balance' has long been a priority for EU and individual Member States' environmental policies, due to the large negative effects that excess nitrogen has on ecosystems.¹² Indeed, some argue that the degree of disturbance of the nitrogen cycle from current practices is approaching a 'planetary boundary' that, if crossed, could cause irreversible damage.¹³ Still, despite governments' efforts, the nitrogen balance in the EU is not declining. However, there are large differences between countries in the nitrogen lost per hectare of agricultural land, and numerous studies confirm that there is potential for large improvements in the efficiency of fertiliser application.¹⁴ As discussed in more detail below, many have pointed to digitisation as a major opportunity to increase nitrogen efficiency in agriculture.

Other than use efficiency, the amount of fertiliser required is largely determined by agricultural production. However, there is no simple relationship with calories consumed. The composition of diets is a major factor, as different foodstuffs have very different nitrogen requirements. In addition, the amount of food that is wasted determines how much production is needed to satisfy demand.

Future ammonia requirements depend on a balance of all of these factors. Demand in the EU is largely stable. In a baseline scenario, this study follows other analyses that see a slight increase, with ammonia use growing somewhat less (3%) than the projected increase in EU population to 2050 (4%).¹⁵ For the purposes of analysis, the baseline scenario assumes no change in imports, although as noted, current input markets strongly favour production in lower-cost regions.¹⁶

therefore easy to capture. For example, it is used in the production of urea, a major precursor to fertilisers, which requires both ammonia and CO₂ in its production.²⁰

The remaining emissions come from the energy inputs to the process steps. In the EU, natural gas is typically used for heating, and the process also requires electricity for compressors.

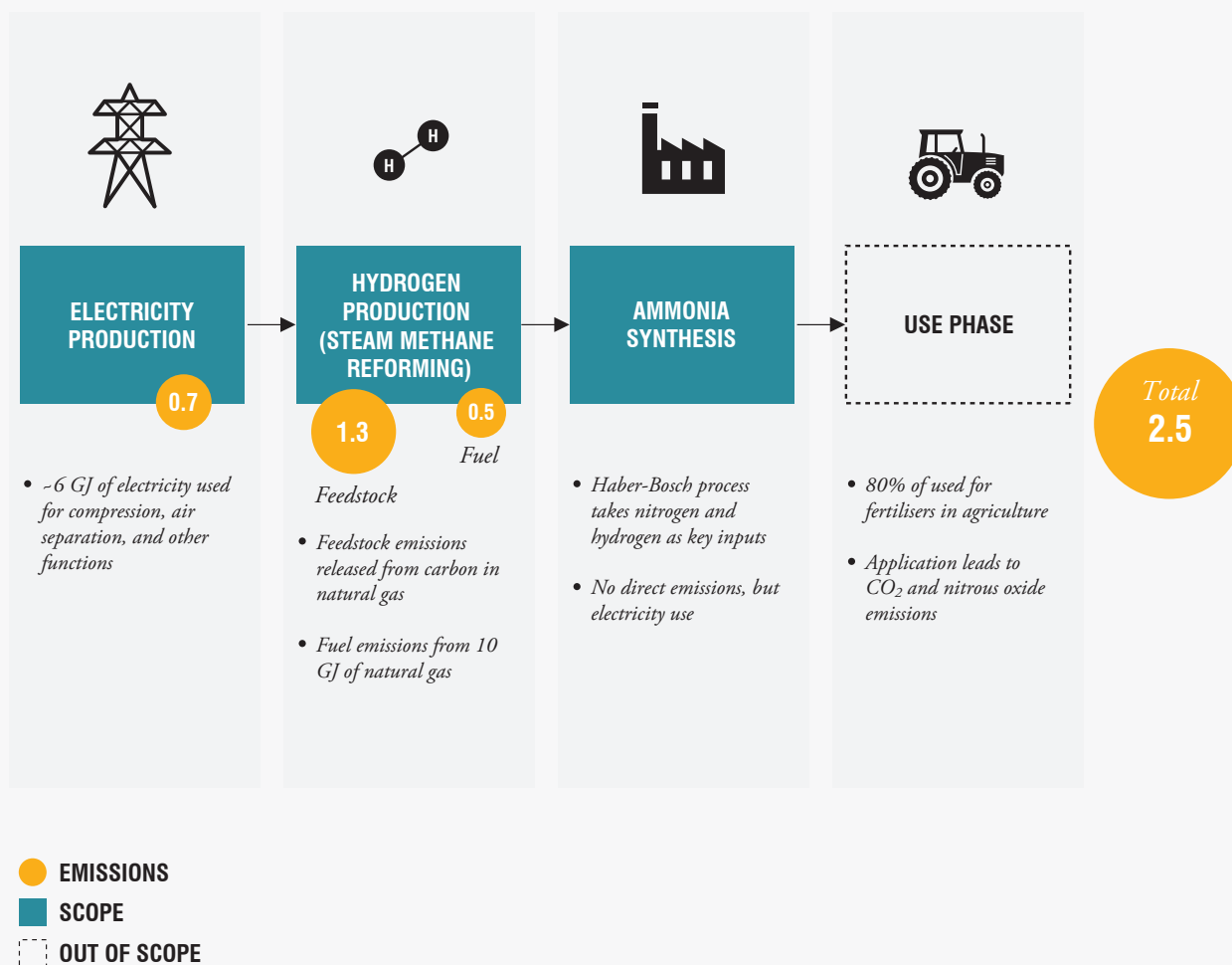
In addition to emissions from production, the use of fertiliser gives rise to very considerable emissions in the agriculture sector. The smaller impact is from the CO₂ used to produce urea, which is released into the air when urea-based fertilisers are applied in the field. While urea therefore is arguably a case of 'carbon capture and use' (CCU), it is not an application of CCU that has any net climate benefit.

Exhibit 3.18

CO₂ EMISSIONS FROM AMMONIA PRODUCTION ARISE IN THE PRODUCTION OF ELECTRICITY AND HYDROGEN INPUTS

CO₂ EMISSIONS

TONNE CO₂ PER TONNE AMMONIA



SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON DECHEMA (2017)

The far larger climate impact comes from the release of nitrous oxides, greenhouse gases which trap more than 300 times more heat than does CO₂. Nitrous oxides from agriculture are also a major precursor to air pollution, with adverse health effects. The more excess fertiliser is used, the more nitrous oxides are released. This study looks only at CO₂, so it does not consider ways to reduce nitrous oxide emissions, but these are a key part of any strategy to cut GHG emissions from agriculture.

The baseline scenario sees only a slight reduction in the amount of CO₂ released per tonne of ammonia produced, mostly due to a reduction in CO₂ produced in electricity generation. However, as ammonia production would increase slightly, emissions in 2050 would be in parity to today. Concretely, the scenario sees 32 Mt CO₂ per year in 2050, compared with 44 Mt CO₂ today.

Exhibit 3.19

STRATEGIES FOR DEEP...

CIRCULAR ECONOMY IN MAJOR VALUE CHAINS



MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS

Reducing the amount of materials used for a given product or structure, or increasing the lifetime and utilisation through new business models



MATERIALS RECIRCULATION AND SUBSTITUTION

Using end-of-life materials as input to new production, or using low-CO₂ alternative materials that provide the same function

USE EFFICIENCY AND REDUCED WASTE

- Increase uptake efficiency of fertilisers and reduce leakage to water and air by controlling conditions, improving timing of application, using additives, increasing precision of application, etc.
- Reduction of food waste, especially in processing and by consumers, reduces the amount of food production required and subsequently fertiliser needs

SUBSTITUTION WITH ORGANIC FERTILISERS

- Switch a greater share of nitrogen input to organic fertilisers (40% today)

...EMISSIONS REDUCTIONS FROM AMMONIA

CLEAN PRODUCTION OF NEW MATERIALS



NEW AND IMPROVED PROCESSES

Shifting production processes and feedstocks to eliminate fossil CO₂ emissions



CARBON CAPTURE

Capture and permanent storage of CO₂ from production and end-of-life treatment of materials, or use of captured CO₂ in industrial processes

HYDROGEN FROM WATER ELECTROLYSIS

- Electrolysis using CO₂-free electricity can fully eliminate CO₂-emissions from ammonia production process

CARBON CAPTURE ON STEAM METHANE REFORMING

- Capture of 90% of CO₂ emissions from hydrogen production through steam methane reforming. For high capture rates, both fuel and feedstock emissions must be captured

3.5 STRATEGIES FOR REDUCED CO₂ FROM AMMONIA PRODUCTION

Technically, CO₂-free ammonia production is feasible using the same Haber-Bosch process as is used today. The crux is the inputs. Hydrogen would need to be produced without release of CO₂, as would electricity.

The production of low-CO₂ hydrogen could take place through two main routes: water electrolysis using zero-carbon electricity, or the use of carbon capture and storage

(CCS) in steam methane reforming (SMR) plants.

In addition to CO₂-free production, it is possible to reduce ammonia requirements in agriculture without reducing food production. The key measures are to reduce food waste, increase the efficiency of fertiliser use, and switch from mineral fertiliser to organic fertiliser.²¹

CIRCULAR ECONOMY AND USE EFFICIENCY

In 2015, 64 kg of mineral fertiliser was used per hectare of utilised agricultural area in the EU.²² This corresponds to 21 kg per tonne of food, on average.²³

This study has made a top-down estimate of how the same amount (and composition) of food could be provided with less fertiliser input, and therefore ammonia production. The most important measures identified are:

- **Reduction of food waste:** An estimated 90 Mt of food is wasted yearly in the EU.²⁴ Reducing this already is a major EU policy goal, with a target to halve per-capita food waste in the retail and consumer level by 2030.²⁵ Grocery-store food handling holds some of this potential, but most sits in how consumers use the food they purchase, and in how food is processed and handled in the supply chain prior to arriving in stores.²⁶

- **Increased use efficiency and precision agriculture:** The large nitrogen balance gives a sense of the degree of over-use of nitrogen fertilisers in current practice. In ad-

dition, some fertilisers produced from ammonia, such as urea, also causes large CO₂ emissions, as much as 97% of the bounded C in urea evaporates within the first eight days corresponding to 0.7 ton of CO₂ per kg urea applied.²⁷ A long list of small changes to practice can increase efficiency substantially: ensuring sufficient availability of other nutrients such as sulphate and phosphate, controlling soil acidity, switching to nitrate fertiliser, timing application to weather conditions, using additives that stop volatilisation of urea, using cover crops, varying rates of application with conditions, using more frequent and varied application, and improving application accuracy.²⁸

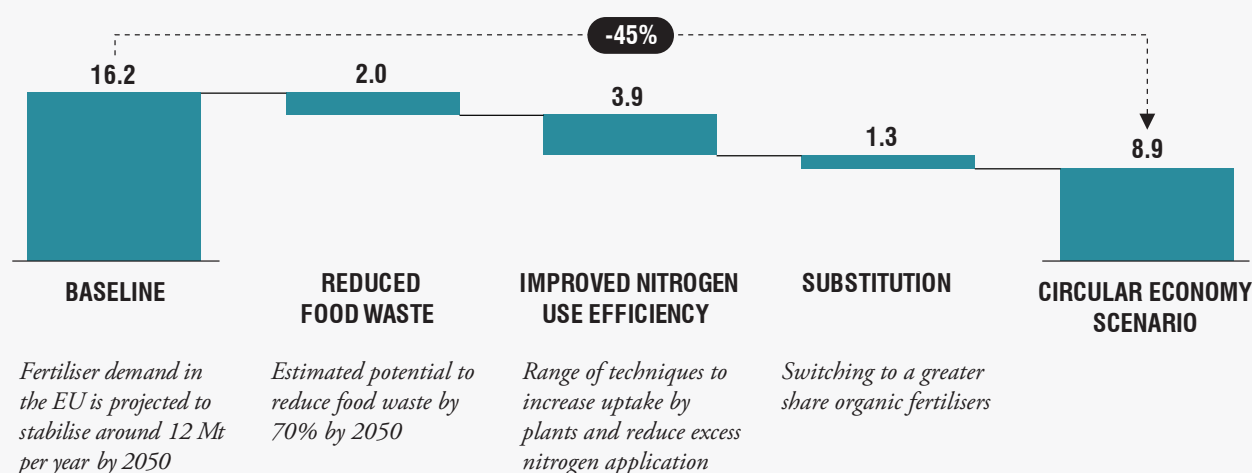
Many of these measures are challenging to work into standard agriculture. However, digitisation and automation can make it easier. As technology improves, costs will fall.

Substitution of mineral fertilisers with organic fertiliser: As noted, organic fertilisers already are widely used in EU agriculture. It is possible to achieve still-higher shares, thus

Exhibit 3.20

A STRETCH CASE FOR EFFICIENCY AND SUBSTITUTION REDUCES N-FERTILISER DEMAND BY 45% BY 2050 WHILE MEETING FOOD DEMAND

AMMONIA DEMAND REDUCTION FROM IMPROVED VALUE CHAIN EFFICIENCY AND SUBSTITUTION
Mt AMMONIA PER YEAR USED FOR FERTILISERS, EU (2050)



SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES.²⁹

reducing the need for mineral fertiliser production. Major obstacles are logistics and the unpredictability of supply.

In an ambitious scenario, reduced food waste could cut ammonia requirements by 12%, precision agriculture and use efficiency by 24%, and substitution with organic fertiliser by 8%. This results in a total of 45% less ammonia demand in 2050 – a 7.3 Mt decrease – relative to the baseline scenario that largely continues current practice (Exhibit 3.20).

Although these measures result in reduced ammonia demand, they need not result in reduced economic activity. Some would be genuine productivity improvements (such as the reduction of food waste); others would shift economic value from the production of inputs, to activities that achieve more precise and efficient use, or that put waste from related sectors (livestock) to a good use.

Added to this, reduced fertiliser use would have a range of co-benefits. The largest are the reduction of ammonia

and nitrous oxide emissions to air (the latter having major GHG reduction benefits as well as benefits for clean air), and reduced leakage of nitrogen to water, with reduced eutrophication as a result.

Nonetheless, achieving these measures can be complex. They require systemic changes involving a large number of actors within the food supply chain, from farmers to wholesalers, retailers, and producers. It is therefore uncertain how much of the potential can be achieved. This study explores two alternative scenarios:

- **In a high scenario**, three-quarters of the identified potential is realised. This reduces the amount of ammonia required by 5.5 Mt per year in 2050, resulting in a total ammonia demand of 12 Mt.
- **In the less ambitious scenarios**, just 40% of the potential is achieved. This would leave ammonia demand close to 15 Mt per year in 2050.

LOW-CO₂ PRODUCTION OF AMMONIA

Fertilisers will always play an important role in ensuring that agriculture is productive enough to feed a growing population. Finding ways to produce low-emissions ammonia will therefore be necessary even with very efficient use or with substitution with organic fertilisers. The need will be even larger in regions of the world where incomes are rising as the population grows.

EU production already is highly efficient, with CO₂ emissions within 10% of the theoretical minimum for the current technology.³⁰ Efficiency improvements thus have only limited potential to further contribute to reduced CO₂ emissions. It is possible in principle to reduce fossil CO₂ emissions by switching from natural gas to biogas. However, the analysis carried out for this study found this much more expensive in the long run than other options.³¹ Biomass is a very expensive source of hydrogen, and there are many other, high-priority uses of biomass resources that would take precedence in an overall net-zero transition.

This leaves two main technologies for very deep emissions cuts: either to capture emissions from the current steam methane reforming and permanently store it, or to produce ammonia using hydrogen derived from water electrolysis.

A. Zero-emission ammonia with water electrolysis

Emissions from an SMR plant arise for two reasons: i) when natural gas is split into 'syngas' (a mix of carbon monoxide and hydrogen), and ii) when natural gas is burnt in the SMR furnace used to heat the process.³²

In contrast, water electrolysis involves no carbon, as long as electricity production is carbon-free. The most mature technology for doing so is alkaline electrolysis, but there are many other processes at various stages of development.³³

Electrolysis switches inputs from natural gas and electricity, to just electricity. Total energy requirements are broadly similar. Whereas today's process uses 8.9 MWh of natural gas for fuel and feedstock plus 2.1 MWh of electricity, electrolysis uses around 9.1 MWh electricity per tonne of ammonia, depending on the efficiency of electrolysis.

For electrolysis to cut emissions, electricity generation needs to be less emissions-intensive than it is in the EU today. Whereas the average CO₂ emissions from electricity production in the EU are 350 g CO₂ per kWh, they would need to be less than 210 g CO₂/kWh for electrolysis to result in less emissions than SMR per tonne hydrogen (see Exhibit 3.24, further below).

The technology to produce the hydrogen through electrolysis and nitrogen through air separation is already established, although there is significant scope to improve the efficiency of electrolysis. There also is a need to develop efficient ways of storing hydrogen at scale. This in turn can enable flexible operation that capitalises on the variability of electricity supply in an electricity system with a high share of solar and wind power.

Overall, however, the main challenge with switching to 'green' ammonia from electricity is financial rather than technical. Key considerations are the need to replace current production units, the availability of electricity at attractive prices, and infrastructure for hydrogen storage and transportation.³⁴

Given uncertainties, this study explores scenarios with 4–15 Mt of ammonia production through this route.

B. Carbon capture and storage

Hydrogen production through SMR has significant potential for carbon capture and storage. The larger the point source of CO₂ emissions, and the more concentrated the flow of CO₂, the easier it is to use CCS. In the case of ammonia, emissions typically are around 1 million tonnes per year, allowing for good economies of scale. More importantly, the process emissions are a nearly pure stream of CO₂ that can be captured at very low cost. Indeed, more than one-third of this CO₂ is already captured today, used in the production of urea, for enhanced oil recovery, and in food production.³⁵

For genuinely low-CO₂ production, however, two additional things are needed. First, as noted, the process CO₂ is only around half of the total. The emissions from combustion must also be addressed. One option is to fit the furnace, too, with CCS. The other would be to electrify the source of heat input. The second requirement is infrastructure to compress, transport, and store the CO₂.

The main way to achieve high CO₂ capture rates from ammonia production is to use chemical absorption technologies. These can achieve capture rates between 55%–90%, where the 90% rate requires also capturing the CO₂ in the flue gas of the furnace, which raises energy requirements substantially.³⁶

The acceptance of CCS and availability of transport infrastructure and suitable storage are all uncertain. This study explores up to 10 Mt of ammonia production through SMR with CCS, but also considers scenarios where no CCS is used.



*Improving the efficiency of
ammonia use has many benefits
beyond GHG reductions.*

3.6 LOW-EMISSIONS PATHWAYS FOR EU AMMONIA PRODUCTION

To guide discussions, this study explores three pathways to a net-zero emissions EU ammonia production in 2050 (Exhibit 3.21), each emphasising a different approach to CO₂ emissions reductions:

- **New Processes pathway:** In this pathway, only 40% of the potential to reduce fertiliser demand is captured. Ammonia production in 2050 stands at 15 Mt, but all of it uses water electrolysis for hydrogen production.
- **Circular Economy pathway:** In this pathway, 75% of the potential for demand reduction is captured, through a concerted push to reduce food waste, increase the efficiency of fertiliser use, and a switch to organic fertiliser. Ammonia production is reduced to 12 Mt annually in 2050, substantially lower than today. The remaining production all uses water electrolysis.
- **Carbon Capture pathway:** This pathway sees the same amount of ammonia production as in the 'New Processes' pathway. However, production continues to use predominantly SMR, which is gradually fitted with CCS from the 2030s. By 2050, 20% (4 Mt) is produced with completely CO₂-free technology and 11 Mt through SMR and carbon capture. Remaining emissions are 2 Mt CO₂ in 2050, while 17 Mt CO₂ is stored annually.

Similar to the pathways outlined for other sectors, the three ammonia pathways result in very different outcomes, illustrating key options for how the ammonia industry can achieve near net-zero emissions. More than in other sectors, however, the ammonia industry clearly faces a major choice:

prioritise large-scale deployment of CCS, or switch to a new production technology.

Ammonia has the advantage of technically being relatively easy to make CO₂-free or with drastically reduced emissions. The way ahead becomes a strategic choice where technology is only one consideration: should CCS resources be used on a product that could instead be produced completely CO₂-free by using electricity? Or should R&D resources and electricity be saved for sectors that are far more challenging for CCS?

Once the emission intensity of electricity allows for it, and water electrolysis-based ammonia is ready to scale up significantly, the industry could be transformed. The new technology is not as dependent on large-scale plants, but is rather modular. Ammonia can in fact also be used as a 'fuel', so entirely new sources of demand could arise.

In all pathways, both the ammonia industry and materials-efficient or circular business models will depend heavily on new outside actors. They, in turn, require new infrastructure and inputs, whether for CO₂ transport and storage or for electricity supply.

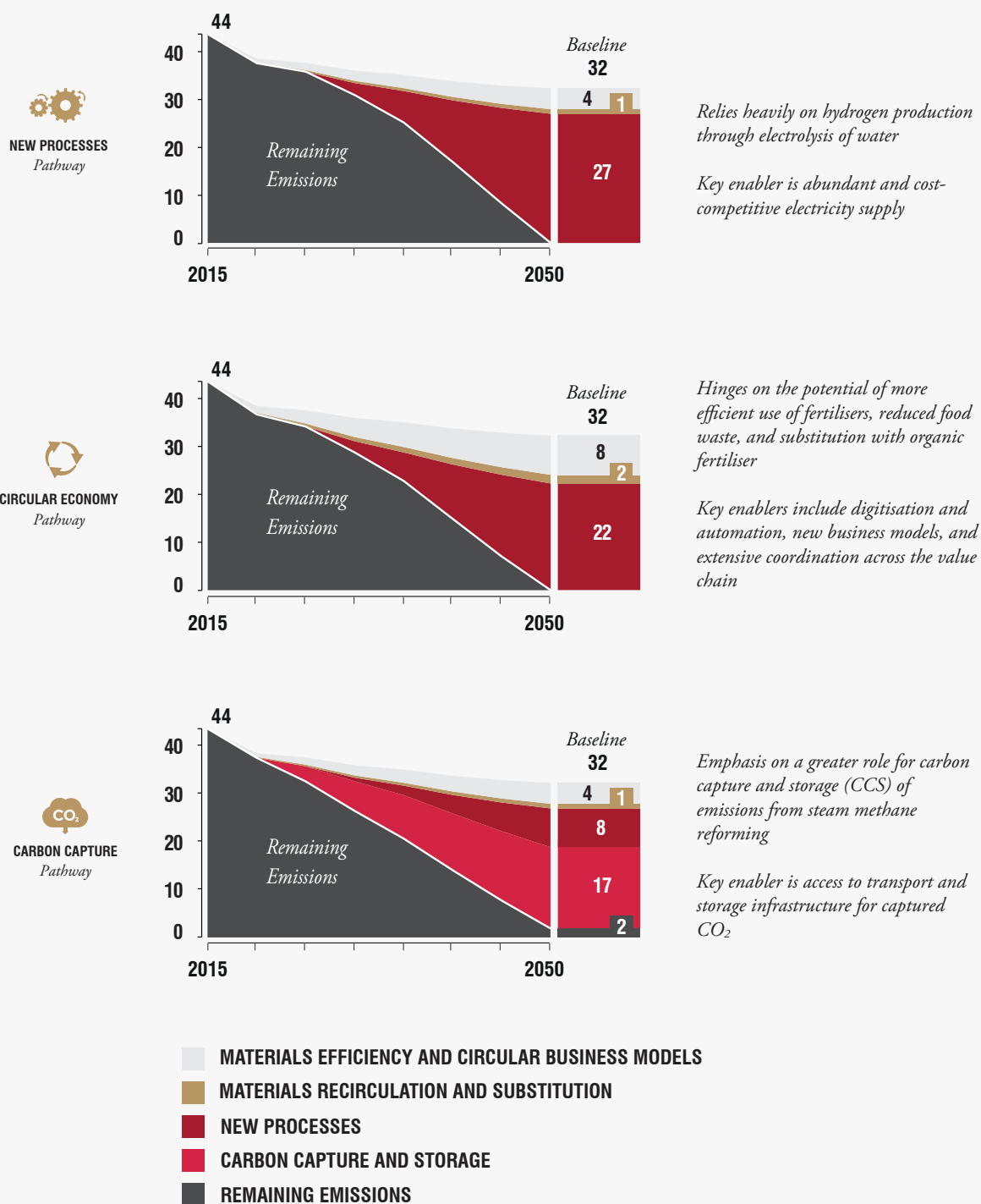
Finally, in all pathways, the use of fertilisers will be the largest influencer of demand, but it is outside the control of the ammonia industry. Instead it is dependent on the development of a more efficient food industry and the adoption of new methods within agriculture. Any improvement would not only reduce emissions from ammonia production, but also have positive consequences for the future of sustainable food production.

Exhibit 3.21

PATHWAYS TO NET-ZERO EMISSIONS FOR AMMONIA

EMISSION REDUCTIONS IN AMMONIA PRODUCTION, 2015-2050

Mt CO₂/YEAR



SOURCES: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

DEEP CUTS TO EMISSIONS WILL INCREASE THE COST OF PRODUCING AMMONIA

Producing ammonia without CO₂ emissions will come at a cost (Exhibit 3.22). Fitting CCS to ammonia production adds €39 per tonne of CO₂ captured, or €64 per tonne of ammonia, an increase of 15% on the standard SMR process without carbon capture.

The water electrolysis route is costlier under most electricity prices. In a scenario with highly flexible use of electricity (some 5,000 load hours per year), electrolyzers could likely access electricity at a cost similar to the levelised cost of electricity production from a mix of solar and wind power, estimated at around €40 per MWh by 2050.³⁷ This comes with higher costs for electrolyser capacity and hydrogen storage. The estimated cost of ammonia production is €553 per tonne, an increase of 55% on the standard SMR process.

In contrast to these, the cost of reducing food waste and increasing use efficiency may be significantly lower, potentially coming at no additional cost (or even at a cost saving), if digitisation and automation develop as many stakeholders expect.

At these values, the additional cost of production ranges between €0.5 and 2 billion per year in 2050, implying an average abatement cost of €39–215 / tCO₂. The carbon capture pathway is 25% cheaper than one reliant exclusively on water electrolysis for the same volume of production. However, the circular economy pathway could potentially cost even less.

Overall, cost alone is not a robust metric for choosing one approach over another. Instead, different solutions will be required, depending both on local conditions (availability of CO₂ storage, price of electricity), and on how technology develops.

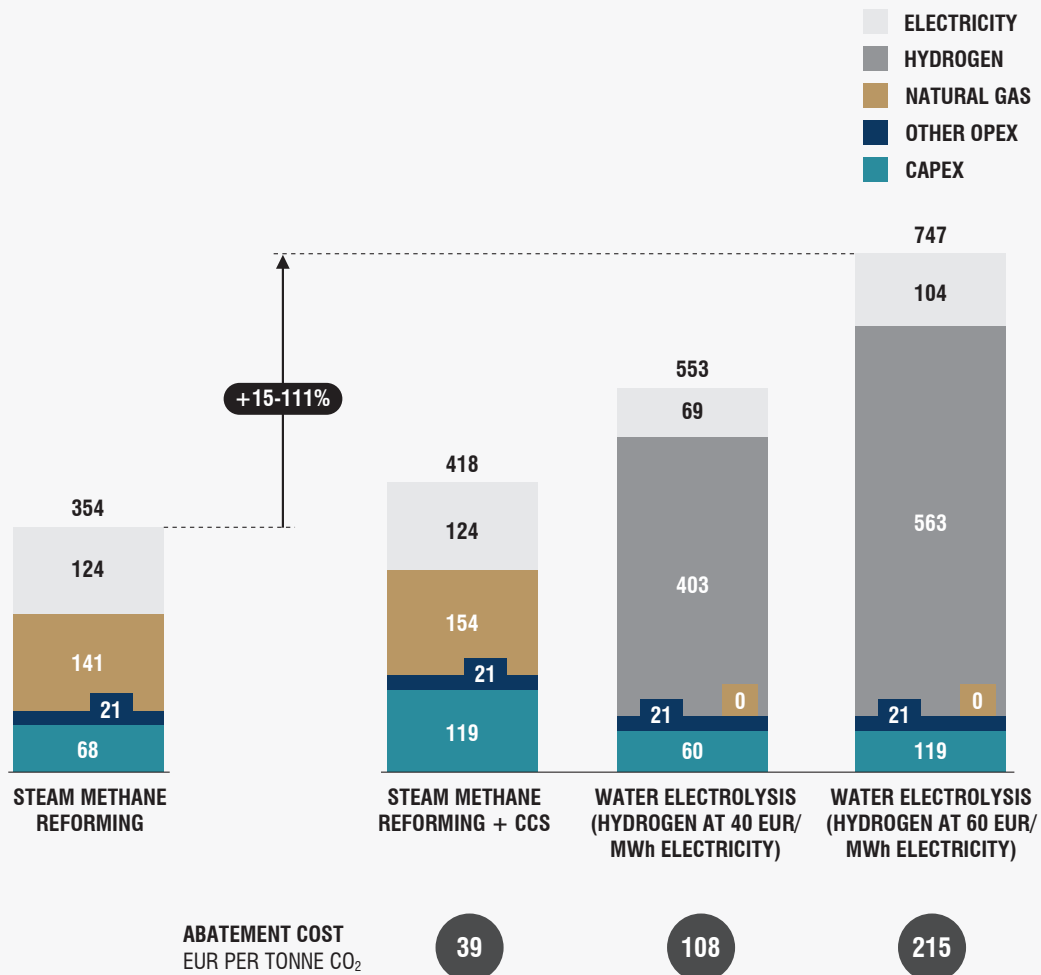
Finally, this study assumes continued production in the EU as a basis for the analysis. However, hydrogen and therefore ammonia production could very well be one of the sectors where access to cheaper renewable electricity make for a substantial cost advantage (much like cheaper natural gas does today). If so, it would be more cost-effective for the EU to import CO₂-free ammonia than to produce it.

Exhibit 3.22

LOW-CO₂ PRODUCTION ROUTES COST 15-111% MORE THAN THE CURRENT SMR PROCESS

PRODUCTION COST BY ROUTE

EUR PER TONNE AMMONIA, EUR PER TONNE CO₂ ABATED



NOTES: ABATEMENT COST CALCULATED ASSUMING ZERO-CARBON ELECTRICITY. CO₂ PRICES NOT INCLUDED IN THE PRODUCTION COSTS.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

INVESTMENT IN AMMONIA PRODUCTION WILL NEED TO INCREASE BY 6-26%

The transition to a net-zero ammonia sector will require investments, but not necessarily higher than in the base case (Exhibit 6). Although the production costs of the water electrolysis route are higher overall than those for steam methane reforming, the investment costs are lower than SMR with CCS. Added to this, circular economy solutions are less capital-intensive, and therefore bring down total investment costs relative to a baseline scenario.

The amount of investment thus varies significantly by pathway. The base case has an average of €0.6 billion per

year, while the circular economy scenario has just above €0.6 billion per year, and the carbon capture pathway has €0.7 billion per year.

The sector would take on substantial additional risk in going from tried-and-tested solutions to ones with uncertain performance and higher total production costs. Policy will therefore play an important role in enabling these investments, not least by providing some certainty about a future business case.

Exhibit 3.23

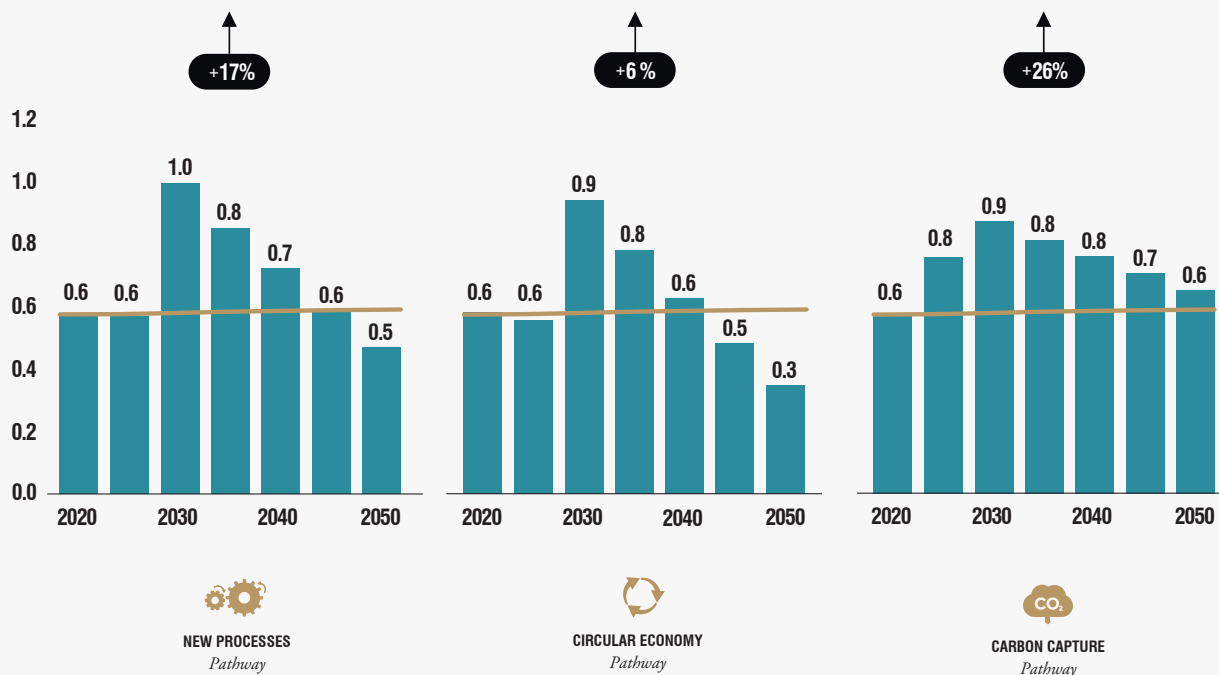
INVESTMENT REQUIREMENTS INCREASE BY 6-26% IN LOW-CO₂ PATHWAYS

INVESTMENT REQUIREMENTS
BILLION EUR PER YEAR

INCREASE RELATIVE TO BASELINE

+ X %

■ PATHWAY
— BASELINE



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

NET-ZERO EMISSIONS AMMONIA PRODUCTION WILL REQUIRE NEW AND DIFFERENT INPUTS

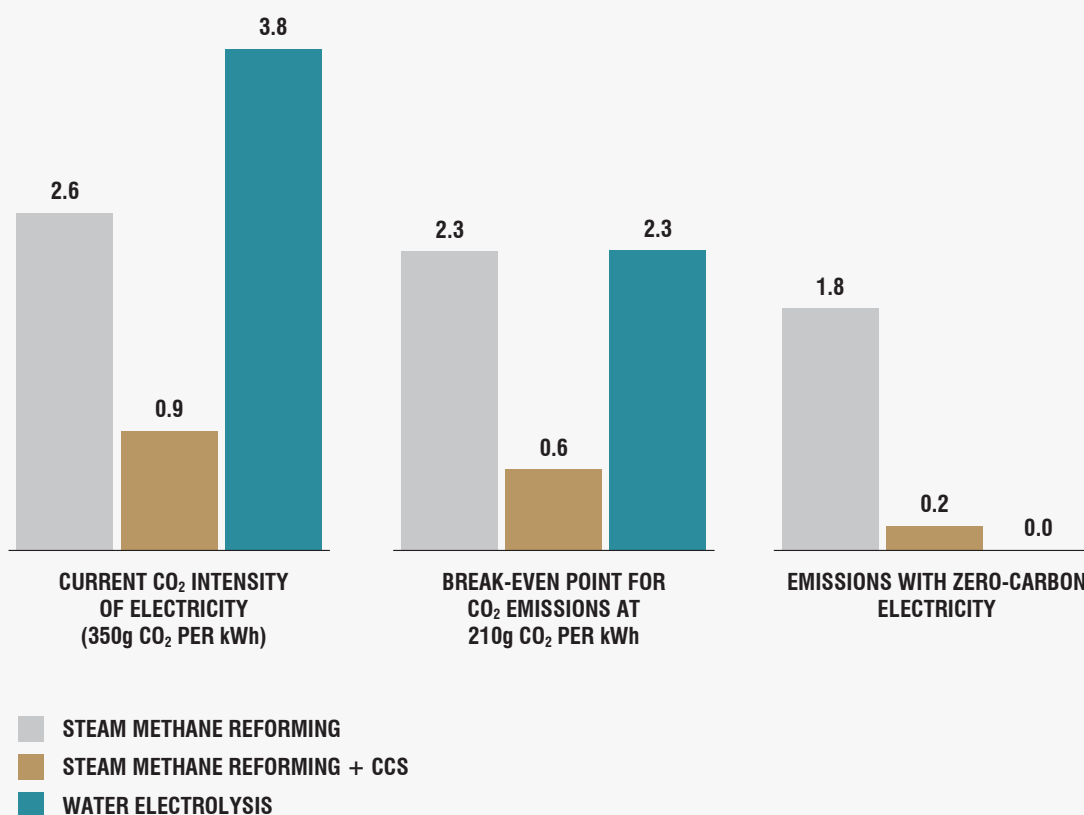
The main shift in inputs is from today's natural gas to electricity, depending on the amount of production based on water electrolysis. In the new processes pathway, as much as 160 TWh of electricity is required to replace the approximately 35 TWh of electricity and 151 TWh natural gas used today. The carbon capture pathway uses less than half as much electricity (69 TWh), but instead sees 99 TWh of remaining natural gas consumption. In addition, there is a need in this pathway for infrastructure to transport and store 17 Mt CO₂ per year by 2050.

The new processes and circular economy pathways rely on production that does not involve carbon at all, and they can thus achieve zero CO₂ emissions. However, this depends on electricity production being carbon-free (Exhibit 3.24). As noted, water electrolysis reduces emissions only once the CO₂ emissions from electricity generation fall below 210 g CO₂/kWh.

Exhibit 3.24

ELIMINATING EMISSIONS FROM ELECTRICITY WILL BE CRUCIAL FOR DEEP EMISSION CUTS

CO₂-INTENSITY OF AMMONIA PRODUCTION ROUTES WITH DIFFERENT CO₂-INTENSITY OF ELECTRICITY
TONNE CO₂ PER TONNE AMMONIA



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

4. CEMENT & CONCRETE

REINVENTING A FUNDAMENTAL MATERIAL

Concrete is ubiquitous in our modern society. It is the most widely used construction material for both buildings and infrastructure. Currently, the EU uses more than two tonnes of concrete per person per year, of which 325 kg is cement.

Concrete production is also a major source of CO₂ emissions. Up to 95% of these come from the production of cement – some 109 Mt of CO₂ per year. These emissions are hard to cut: 60% are an unavoidable result of the process chemistry of production, and the remaining 40% arise from the need to produce very high-temperature heat.

Until recently, no emission reduction scenario had explored how to achieve the deep cuts needed to fit concrete production into a net-zero society. Indeed, studies left as much as two thirds of emissions in place even in 2050, with further reductions dependent on the degree of carbon capture and storage.

This study evaluates what it would take to achieve truly deep reductions by 2050. It finds

that net-zero emissions are possible, and the solution set is wide-ranging. It includes changes to cement production – notably carbon capture and storage, electrification, and switching to new raw materials. It also involves changes to how concrete is made and used: optimising the use of cement in its production, efficient use of concrete in structures, and new circular economy business models.

Many different pathways to net-zero emissions are possible, and all require major changes to current practices. Policy will be crucial to enable coordination along the value chain and to support low-CO₂ production routes that are 75–115% more expensive than the current routes. Moreover, substantial resources need to be devoted to innovation, while investments need to increase by up to 50%.

In the context of a capital-intensive industry with long-lived assets, time is very short. The transition to low-CO₂ concrete in 2050 is possible, but it needs to begin promptly to avoid escalating costs later on.

*As much as half of the solution may
be changes to how concrete
is specified and used.*



4.1 THE STARTING POINT

Of all building materials, concrete is the by far most widely used. In 2015, the EU used 2.2 tonnes per person, or more than a billion tonnes in total.¹ For comparison, the second-largest volume of material in construction was steel, at 66 Mt.²

Concrete is aggregates (sand, gravel, crushed stone), water and cement. Cement has a key role: it is the ‘glue’ that gives concrete its structural stability. Although cement makes up just 7–20% of concrete, from a climate perspective it is the key constituent, with 95% or more of the CO₂ footprint.

A climate scenario for cement and concrete must therefore take two perspectives. On the one hand, cement use depends chiefly on how concrete is used: how much construction, using how much concrete, with how much cement. On the other hand, for low-CO₂ production, the focus needs to be on cement itself.

The European cement industry produced 167 million tonnes (Mt) of cement in 2015.³ Construction activity is highly correlated with economic cycles, so the production of cement varies accordingly. The EU cement sector saw a 35% drop in demand after the 2008 financial crisis, and volumes remain at similar levels since 2013.

The cement sector contributes €4.5 billion to direct added value in the EU, and employed 38,000 people.⁴ There are around 200 active cement kilns, and another 100 plants that perform grinding of cement.⁵ In recent years, there has been a consolidation of plants, concentrating production in fewer and larger facilities. Industry stakeholders expect a continuation of this trend, so that the average size could increase from today’s roughly 1 million tonnes per plant per year to as much as a 2.5 million tonnes.

Production is highly capital-intensive. A new integrated plant producing 2.5 million tonnes costs up to €500 million to build.⁶ Once built, variable costs are much lower – sometimes as low as €15–20 per tonne, especially if low-cost waste fuel is used. The large number of plants across the EU reflects the need to co-locate production near a suitable limestone source, and the high cost of transportation. Transporting cement can cost €10–15 per 100 km⁷, and with sale prices in the range of €60–80 per tonne, large distances quickly become uneconomic. This also means that Europe is largely self-sufficient in cement production, although trade can occur across the Mediterranean.

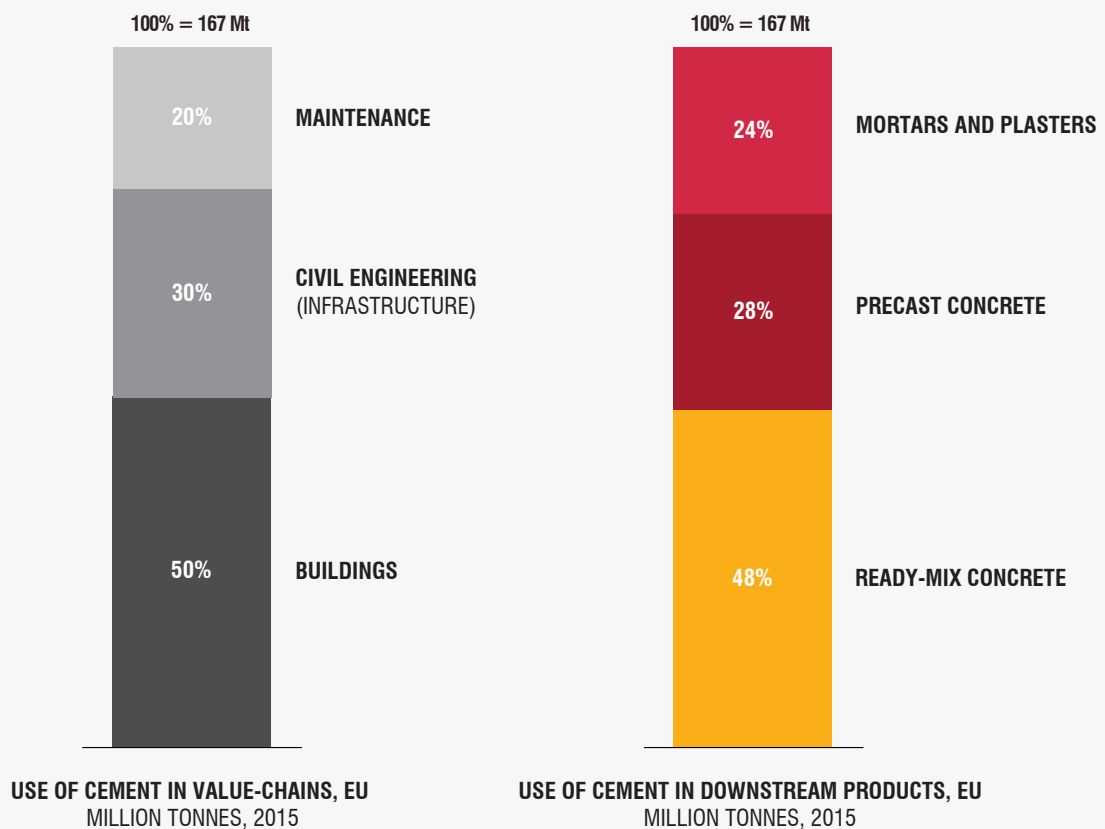
Half of European cement is used in the construction of new buildings, and 30% in infrastructure (Exhibit 4.1). The remaining 20% are used for various forms of maintenance and repair work across these two categories. As noted, the large majority of cement is used for concrete. Most of this, in turn, is sold as ready-mix concrete, produced at a batch plant. These need to be highly local, to minimise transport distances and times between mixing and use. Most of the remaining concrete is in the form of pre-cast elements that are used whole in construction. Pre-cast production allows for greater control over on-site casting. Finally, just over 20% of cement is used for mortar (to hold together bricks, cinder blocks, etc.).

Whereas cement production is concentrated among a few large companies in the EU, concrete is a highly fragmented business. It is also larger, with 350,000 employees and a contribution to GDP of 16 billion per year.

There are also multiple categories of both cement and concrete. Concrete is divided into ‘exposure classes’, each with different resistance to risk of corrosion, chemical exposure, tolerance for wet environments, or resistance to temperature variation. Likewise, cements are classified in 27 common types, in five main groups (CEM I–VI), depending on their specific composition and properties.

Exhibit 4.1

**CEMENT IS PRODUCED FOR CONCRETE AND MORTAR
AND USED IN BUILDINGS AND INFRASTRUCTURE**



SOURCES: MATERIAL ECONOMIC ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.⁹



CO₂ EMISSIONS FROM CEMENT AND CONCRETE

Nearly all the emissions from concrete production (95%) result from the production of cement, and specifically the production of cement clinker, the main binder component (Exhibit 4.2).

Clinker is produced through the calcination of limestone, whereby the rock is crushed and combined with a small amount of clay and other ingredients and heated to temperatures of 1,450°C or more. CO₂ arises from two distinct sources in this process. One is the fuel used in the kiln. Each tonne of clinker requires some 3.7 GJ of energy. Although the cement industry uses a range of fuels, the large majority (54%) is coal or petcoke, which is suitable for the very high temperatures of 1,400°C or more required for calcination, but also has high emissions intensity.¹⁰

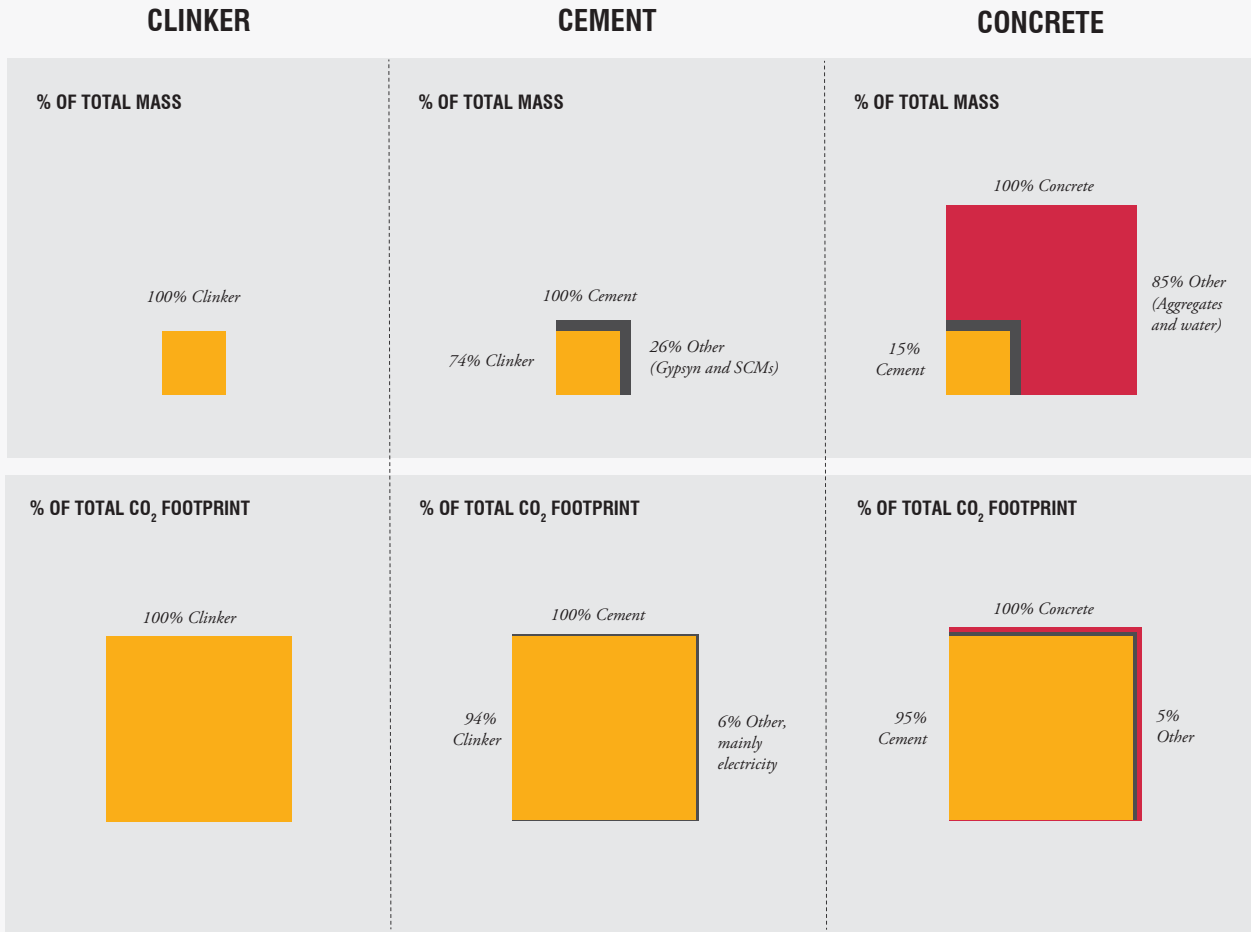
The second source is process emissions. The chemical process of calcination releases carbon

contained in the rock itself. The resulting CO₂ is all but irreducible. Clinker production therefore inevitably results in 0.54 tonnes of CO₂ for every tonne of clinker. These emissions are among the hardest to address. They cannot be avoided except by reducing production or by switching the raw material. Once produced, they must be captured if they are not to be released to the atmosphere.

The emissions from all other steps in the production of concrete are minor by comparison. In the EU, cement consists of 74% clinker. The other major constituents are i) filler materials (normally, limestone), ii) other materials required to obtain the right chemistry and properties of cement, and iii) so-called supplementary cementitious materials (SCMs). SCMs can fulfil much the same binder role as clinker, up to a point. The two main sources are slag from blast furnaces in the steel sector, and fly ash produced in coal-fired power plants.

Exhibit 4.2

CLINKER MAKES UP ~10% OF CONCRETE BY MASS, BUT MORE THAN 90% OF THE CARBON FOOTPRINT



Clinker is made by calcining a mixture of approximately 80% limestone (to provide calcium) and 20% aluminosilicates. Raw materials are heated up to 1,450 °C, transforming limestone to calcium oxides and sintering the mixture. The carbon dioxide released in this chemical reaction accounts for 65% of the clinker CO₂ footprint. The remaining 35% arise from the burning of fossil fuels to provide heat for the kiln

The purpose of cement is to bind fine sand and coarse aggregates together in concrete and mortar. It acts as hydraulic binder, meaning it hardens when water is added.

Cement is made by grinding clinker with a small amount of gypsum and other materials. Ordinary Portland Cement contains 95% clinker, but other cement types substitute some share of clinker with other, supplementary cementitious materials. The average clinker content in EU cement is 26%.

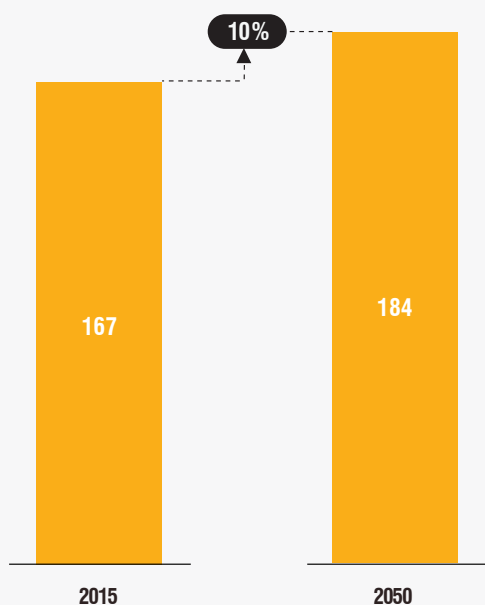
Concrete is the fundamental structural component of many buildings and a large amount of infrastructure. It is a mix of cement, water and aggregates and can also contain small quantities of chemical admixtures. The cement content in concrete varies between 7-20%, depending on the compressive strength and other characteristics required.

NOTES: 'OTHER' CO₂ EMISSIONS FROM CONCRETE INCLUDE THE MANUFACTURING OF CONCRETE AND EMISSIONS FROM OTHER MATERIALS THAN CEMENT. TRANSPORT EMISSIONS ARE EXCLUDED FROM THESE FIGURES.
SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.¹¹

Exhibit 4.3

IN A BASELINE SCENARIO, CEMENT PRODUCTION WOULD INCREASE BY ~10%, WHILE EMISSIONS REMAIN AT TODAY'S LEVELS

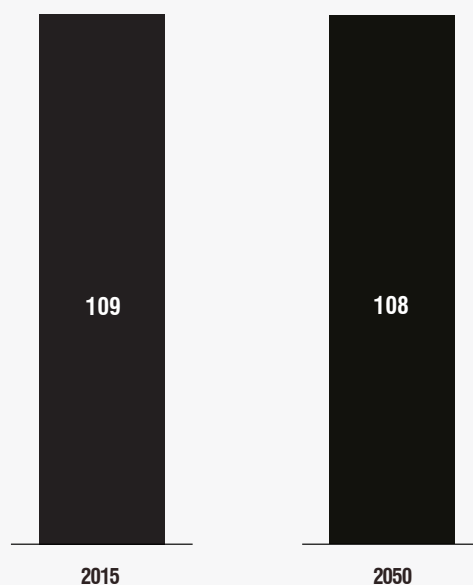
PRODUCTION VOLUME
MILLION TONNES CEMENTITIOUS MATERIAL PER YEAR



10% INCREASE IN CEMENT USE

- Increase in built area of 7% by 2050
- Recovery of infrastructure built-out
- Maintained market share with other building materials

CARBOND DIOXIDE EMISSIONS
MILLION TONNES CO₂ PER YEAR



EMISSIONS INTENSITY FALLS FROM 0.65 TO 0.59 KG PER TONNE CEMENT, MEANING EMISSIONS STAY CONSTANT

- 10% improvement in energy efficiency
- Full decarbonization of power inputs
- Constant share of SCMs
- No increase in biomass uses

NOTES: INCLUDES DIRECT AND INDIRECT EMISSIONS.

SOURCES: MATERIAL ECONOMIC ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.¹²

As a basis for comparison, this study uses a baseline scenario for future production. The baseline scenario reflects what would occur if concrete continued to be specified and used largely as it is today, while cement production techniques improved its efficiency, but did not adopt any dramatic changes to production.

In such a scenario, cement emissions in 2050 would be about 108 Mt CO₂ per year, similar to today's level of 109 Mt CO₂ (Exhibit 4.3). Production of cement is projected to

increase by some 10%, reflecting a recovery of construction activity as well as ongoing urbanisation and build-out of new infrastructure (in part related to a new low-CO₂ energy and transport systems). This would be counterbalanced in part by reduced emissions from improved energy efficiency (~10%), and from decarbonisation of electricity supply (~6% reduction in emissions). In contrast, the baseline sees no change in the share of SCMs used (if anything, supplies of current SCMs may fall in the future – see next section).

4.2 STRATEGIES FOR LOW-CO₂ CEMENT AND CONCRETE

To date, roadmaps for the future of the cement sector have tended to conclude that some of the industry's emissions are virtually unavoidable, even in 2050. In the EU, some analyses have suggested that two-thirds of emissions would remain in 2050, with further reductions depending on how many cement kilns were fitted with carbon capture and storage (CCS).¹³ The European Commission's A Clean Planet for All was more ambitious, tackling this problem for the first time. Most of its scenarios foresaw reductions of around 60%, so still far from all emissions, but the two most ambitious ones went up to 85% reductions in emissions.¹⁴ On a global level, the International Energy Agency (IEA) has proposed 24% as a possible target.¹⁵

As these analyses indicate, eliminating all emissions in this sector is challenging, so it is particularly important to consider the full set of possible solutions (Exhibit 4.4). This study differs from prior analyses in two main ways. First, it

considers cement in the context of the overall value chain of construction and infrastructure. The analysis presented here is thus as much a 'concrete' roadmap as it is a 'cement' roadmap. This builds on other recent studies that have highlighted the wealth of opportunities across the cement value chain: both in how cement is used to make concrete, and in the use of concrete to help create buildings and other infrastructure.¹⁶

The second step is to consider additional innovations in the production of cement. CCS is a major part of low-CO₂ production of cement, but past analyses have highlighted that near-universal CCS will be difficult to achieve, so it is necessary to consider a range of options. These include supplementary cementitious materials and alternative binders to traditional cement clinker, the use of electricity for heat, and novel approaches to CO₂ capture.

Exhibit 4.4

STRATEGIES FOR DEEP...

CIRCULAR ECONOMY IN MAJOR VALUE CHAINS



MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS

Reducing the amount of materials used for a given product or structure, or increasing the lifetime and utilisation through new business models



MATERIALS RECIRCULATION AND SUBSTITUTION

Using end-of-life materials as input to new production, or using low-CO₂ alternative materials that provide the same function

LESS CEMENT IN CONCRETE

- Reduce intensity in concrete by using advanced fillers and admixtures
- Reduce overspecification of ready-mix concrete
- Optimise concrete exposure classes to reduce

cement intensity

RECYCLING OF CEMENT FINES

- Separation of pure concrete fines as raw material for new cement production
- Recovery and separation of unhydrated cement for direct reuse

LESS CONCRETE PER STRUCTURE

- Reduce waste in construction
- Optimise structure design to limit over-specification
- Advanced construction techniques including 3D-printing
- Increased use of pre-cast elements
- Post-tensioning for increased strength
- Use of high-performance concrete

SUBSTITUTION OF CLINKER WITH OTHER CEMENTITIOUS MATERIALS

- Use of natural pozzolans and calcined clays
- Development of alternative binders and novel cements

SUBSTITUTION WITH WOOD

- Increased use of cross-laminated timber and engineered wood products as alternatives to steel and cement

MORE BENEFIT FROM EACH STRUCTURE

- 'Build to last' principles and modularity to increase lifetimes and flexibility
- Re-construction and refurbishment to reduce demolition
- Re-use of structural elements
- Space sharing to reduce need for additional built area

...EMISSIONS REDUCTIONS FROM CEMENT & CONCRETE

CLEAN PRODUCTION OF NEW MATERIALS



NEW AND IMPROVED PROCESSES

Shifting production processes and feedstocks to eliminate fossil CO₂ emissions



CARBON CAPTURE

Capture and permanent storage of CO₂ from production and end-of-life treatment of materials, or use of captured CO₂ in industrial processes

CLEAN UP CURRENT PROCESSES

- Increased energy efficiency through pre-calciners, preheating, waste heat recovery, and other techniques
- Switch to biofuels (and in the short term, waste fuels)

CARBON CAPTURE AND STORAGE

- Separation of process and combustion emissions
- Oxyfuel or other CCS options for integrated combustion and process emissions

ELECTRIFICATION OF PROCESS HEATING

- Plasma, microwave energy, hydrogen, or other technologies

CARBON CAPTURE AND UTILISATION

- Capture of CO₂ and incorporation into cement

CIRCULAR ECONOMY AND MATERIALS EFFICIENCY IN MAJOR VALUE CHAINS

The EU economy currently uses 325 kg of cement and 2.2 tonnes of concrete per person per year. These materials provide important services, such as housing and infrastructure – but there are multiple opportunities to use them more efficiently.

It is possible to achieve the same end-use benefits (that is, the same amount of built area and infrastructure availability) with less cement in concrete, and less concrete per structure or service. This can be done by optimising concrete recipes with advanced fillers, reducing over-specification, reducing waste, optimising structures, reusing elements, and increasing the lifetimes of buildings and infrastructure.

Materials efficiency can never reduce emissions to zero. However, it eases many of the challenges of transitioning

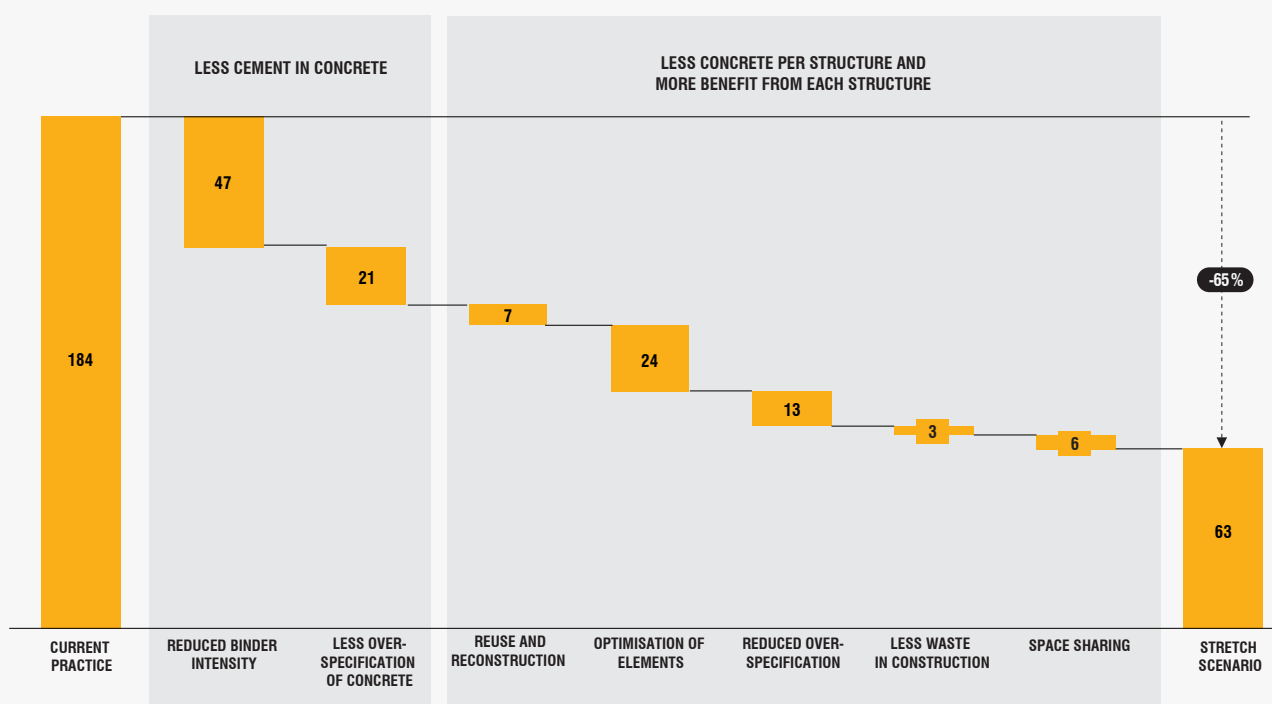
to net-zero emissions. It can reduce costs and investment needs, the amount of electricity or carbon storage required, and the speed at which new production technologies would need to be deployed.

The theoretical potential is surprisingly large. In a stretch scenario with end-to-end optimisation of cement use, it is possible to achieve the same economic benefits while using 121 Mt (65%) less cementitious material per year in 2050 (Exhibit 4.5). For policy-makers and businesses, a key insight is that major contributions towards lower emissions rest not with the cement industry itself, but with actors in entirely different sectors. Achieving these savings will mean changing practices along the cement and concrete value chain. Climate policy instruments must therefore be able to also create incentives and overcome barriers for these actors.

Exhibit 4.5

A STRETCH SCENARIO FOR MATERIALS EFFICIENCY CAN REDUCE THE NEED FOR CEMENT BY 65%

MILLION TONNES CEMENTITIOUS MATERIAL PER YEAR, 2050



SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.¹⁷

A photograph of a modern building with large glass windows and a dark overhang. The view through the windows and from the balcony shows a vast, hazy mountain landscape under a cloudy sky. A thick orange horizontal line is positioned above the text.

Major contributions towards lower emissions rest not with the cement industry itself, but with other actors in the construction value chain.

LESS CEMENT IN CONCRETE

Today, concrete typically contains 300 kg or more of cement for every cubic metre (m^3) of concrete. This practice is based on widely established practices to ensure sufficient concrete strength, corrosion resistance, and other properties for a given application (with different ‘exposure classes’ defining what is required). The minimum cement content for a given class of concrete is in fact directly regulated via standards, with little variation across the EU.¹⁸

However, there is now a large body of research and practical experience to show that the same requisite strength, reliability and durability can be achieved with significantly lower cement content. In fact, there are opportunities to reduce the amount of cement in concrete by as much as half (Exhibit 4.6).

These opportunities fall in two categories. The first is to reduce over-specification of the concrete compared with what is needed for the intended application, which occurs for two major reasons:

- Concrete manufacturers have an incentive to over-specify the product by adding more cement than necessary – for instance, to make it robust against incorrect use at the building site. Ready-mix concrete often contains 20% more cement than is required by standards.¹⁹
- The concrete’s exposure class is often higher than the situation demands. Logistics and procurement are easier when using the same, high-level class throughout,

which leads to overuse of cement. By one estimate, it might be possible in theory to cut cement requirements by as much as one-third if it were possible to perfectly match exposure class to the actual needs of each structural component.²⁰

- In practice a perfect matching is very unlikely to be achievable, but these estimates illustrate the potential size of the opportunity.

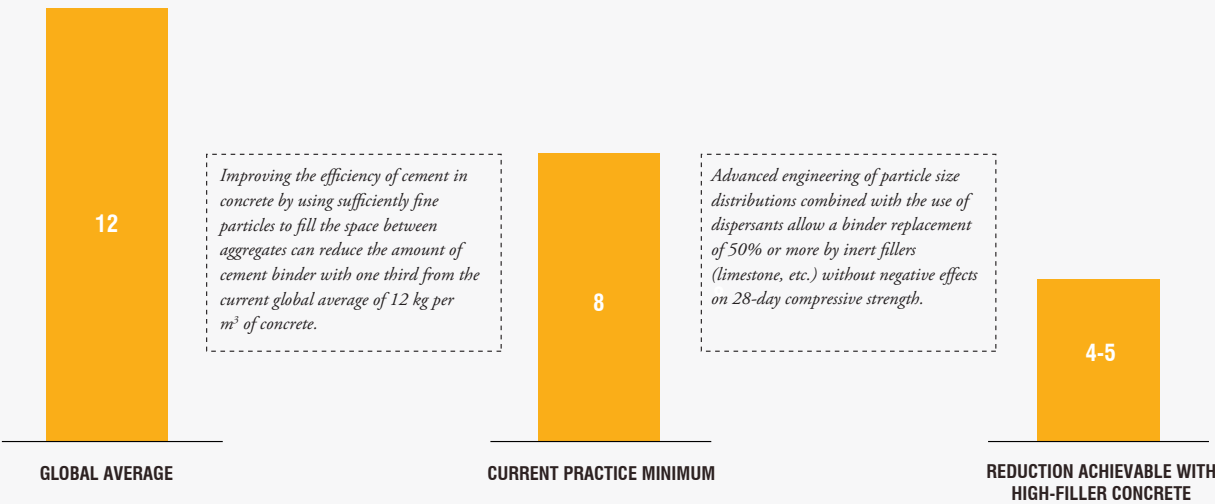
The second opportunity is to modify production to achieve the same strength of concrete with a much lower cement content. The key concept is that of ‘binder intensity’: how much cement is used for every unit of concrete (cubic metre, m^3), to generate a given compressive strength of (1 Megapascal, MPa) at the industry standard of 28 days.²¹ Today, the average binder intensity globally is 12 (kg of cement per m^3 and MPa).²² With good current practice, a binder intensity of 8 is achievable. For a strength of 30-40 MPa, a typical target in many applications, this corresponds to over 300 kg cement per m^3 of concrete.

However, a range of experience shows that it is possible to achieve the same strength with much less binder: in principle, it is possible to substitute up to as much as 70–75% of the binder with advanced filler materials, while achieving the strength required.²³ By a more cautious estimate, binder content could be reduced by 50% (Exhibit 4.6).²⁴ In other words, it is possible in principle to reduce the amount of cement used by half.

Exhibit 4.6

**THE USE OF ADVANCED FILLERS ENABLE A 50% REDUCTION
IN CEMENT CONTENT WITHOUT SACRIFICING CONCRETE STRENGTH**

BINDER INTENSITY OF CONCRETE
Kg CEMENT PER m³ OF CONCRETE AND MPa COMPRESSIVE STRENGTH



NOTES: THE DATA CONTRAST CURRENT PRACTICE WITH 'HIGH FILLER LOW WATER' APPROACHES. CURRENT PRACTICE LEADS TO A MINIMUM BINDER INTENSITY OF 8 kg PER m³ CONCRETE AND MPa COMPRESSIVE STRENGTH. ASSUMPTIONS ARE ASSUMED TO BE FULLY DECARBONISED BY 2050 IN THE LOW-CO₂ PRODUCTION ROUTES.
SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.²⁵

Reducing the binder intensity of concrete requires changes to production, adopting more advanced techniques in the blending and processing of concrete.

The approach of ‘high filler, low water’ concrete has several steps. First, it is necessary to add an ultrafine filler that allows for very high packing density. This can often be ordinary limestone, which is widely available and easy to grind, but would need to be ground much more finely than today. Second, high-quality aggregates must be used. And third, various admixtures are needed to reduce water requirements while preserving workability. While these jointly represent a significant shift in practices, the techniques themselves are all relatively standard industrial methods. Grinding requires no special equipment, although larger capacities would be required for more extensive grinding. Similarly, admixtures of various sorts are already used in 80% of ready-mix and precast concrete.

Nevertheless, industry practices would need to change considerably. For example, it may be necessary in some cases to accept longer hardening times, even if the same 28-day strength is achieved. Furthermore, action would be required by all actors in the supply chain, from producers of ready-mix concrete to construction companies. Digitisation of construction would be a crucial tool to allow for more variation in the class of concrete used, and to track the intensity of cement used.

For these techniques to become widespread, incentives must also be changed. Today, there is little measurement or reporting of materials efficiency in construction. Instead, practices remain unchanged due to a combination of current technical standards and protocols, entrenched practice, and risk distribution along the value chains. In fact, current industry standards all but bar the use of advanced techniques to reduce binder content, specifying a minimum amount. Denmark is a significant exception, allowing concrete with half the amount of cement of other Member States.²⁶

Given the extent of the changes required, we do not consider any scenario that captures the full potential.

Less concrete per structure and service

As well as cutting the amount of cement in concrete, it is possible to significantly reduce the amount of new concrete required for a given structure or service.

The first lever is to extend the lifetime of existing structural elements, including through reuse. Buildings are rarely demolished because the fundamental structure is unsound. On the contrary, the shell can often last another 50 years.²⁷ Instead, demolition is chosen because areas change their character or because refurbishing the building is considered too expensive. The most resource-efficient approach in such situations is to avoid demolition and instead refurbish. Where this is not possible, the next-best solution is to reuse structural elements, either in the new building or in a nearby development. This is being trialled at several places in the EU, including Denmark, Belgium and Germany, but only at an experimental scale.²⁸ As with many other circular economy opportunities, reusing structural elements saves resources but increases complexity, and often depends on the ability to match supply with requirements. However, stakeholders interviewed for this project indicate significant interest, and many see increased potential if building processes are digitised to a greater extent.

The second option is to optimise structures so that they require less input of new concrete. This is a relatively unexplored area, but it is known that the potential for materials efficiency of construction has not been exploited. For example, various studies have documented that 35–45% of steel in construction is in excess of what is necessary to achieve the desired structural strength.²⁹ There are fewer similar published estimates of concrete overuse, but there does seem to be a similar lack of optimisation with respect to materials efficiency.³⁰ Stakeholder interviews for this study support this, but emphasise that the potential varies significantly by end-use segment. Civil engineering projects are often carefully designed, with much less overuse of concrete, whereas several stages of buildings construction are prone to overuse.

A range of levers could reduce the amount of concrete for a given structure, likely by as much as 45%.³¹ These include: 3D printing; increased use of pre-fabricated elements, which generally use less material due to optimisation of shape; post-tensioning; and reduced waste in construction, which cuts the amount of concrete needed.

Achieving the full potential in this area would be a major undertaking. Some aspects, such as greater use of pre-fabricated elements, could be achieved with relatively minor modifications. However, more fundamental changes would require that the current Eurocode framework for safety criteria in construction be revisited, in itself a major undertaking.

RECIRCULATION OF CONCRETE AND SUBSTITUTION WITH ALTERNATIVE MATERIALS

Unlike plastics or metals, cement is not easily recycled by re-melting or similar processes, and the original chemical process cannot be reversed. Nonetheless, there are opportunities to recover useful constituents from end-of-life cement to reduce requirements for new production. The other major opportunity is to replace the clinker in cement with other cementitious materials, or novel forms of cement binder.

Cement and concrete recycling

End-of-life concrete is typically either not recycled at all and instead sent to landfill, or downcycled into aggregates for use in low-value applications such as road base. However, it is possible to recycle concrete fine particles ('fines') as a source of calcium for new cement. This has immediate CO₂ benefits, as the 0.54 t CO₂ of process emissions from producing new clinker can be avoided.

Recycling of fines requires regrinding and medium-temperature heating, both of which are substantially easier to render low-CO₂ than the high-temperature heat of calcination or the production of clinker from limestone.³² Furthermore, technologies are being developed that could recover the roughly 30–40% of end-of-life cement that is unreacted.³³ This cement can then be used as raw material for new concrete production.

The main obstacle is common to many forms of recycling: ensuring that the end-of-life stream is not contaminated by other materials that downgrade quality. Specifically, concrete must be separated from other building materials such as plaster or bricks. Therefore, demolition practices would need to change in many cases. It is also necessary to further develop advanced technologies for crushing, sensors, and thermal reactivation (which is needed to bring back the binding properties).

Substitution with wood construction

Given the challenges of cutting emissions from cement production from zero, an alternative is to consider the use of other materials that can more easily be rendered zero-CO₂.

Wood provides a potential alternative for many structures that currently use cement and steel. Cross-laminated timber (CLT) and other Engineered Wood Products (EWP) can provide additional structural strength that enable use in a wider range of building components and higher buildings. There

are now many examples of new, large buildings using advanced wood products instead of traditional steel and concrete structures, such as Light House Joensuu in Finland and the planned London Google HQ.

Substitution is only a viable low-CO₂ strategy if the replacement material is genuinely zero-CO₂. For wood products, the main prerequisite is sustainable forestry. Although sustainable forestry has many facets, from a CO₂ perspective, the basis for wood as a climate solution is that the managed forest must capture more CO₂ per year and area than does an equivalent standing, old-growth forest. Provided that forestry is conducted so that as much forest regrows as is harvested, a managed forest can then capture more CO₂ than an unmanaged or 'natural' forest.

Given this, the CO₂ savings can be substantial. By one estimate, to support one square meter of floor space, the required wooden floor beams emit 4 kg CO₂, while an equivalent concrete slab floor emits 27 kg of CO₂.³⁴ However, precise estimates will vary from building to building. Additionally, as construction products are long-lived, they can in themselves provide a source of CO₂ storage on timescales of several decades.

There currently appear to be no good estimates of the potential to switch to wood, either as main construction material or in hybrid solutions. As an indication of the potential, the European building stock is currently made up of 48% single-family homes and 27% multi-family homes.³⁵ The potential for wood construction is relatively high in these segments, while the current market share is low (8–10% and 1–5%, respectively).³⁶ On the other hand, the availability of sustainably sourced wood is uncertain, given many competing claims on the resource.

This study therefore takes a conservative approach of assuming that up to 5% of concrete used for buildings could be substituted with wood. Many stakeholders interviewed for this study expressed the view that this was a highly conservative assumption.

For wood to be a realistic alternative, regulations must allow it. Construction materials use is highly regulated by building codes. These often include limitations on the number of floors that can be timber-based, due to fire safety and acoustic performance.³⁷ Many stakeholders argue that these are outdated, not accounting for advances in wood products.

Increased use of supplementary cementitious materials

Some of the clinker in cement can be replaced with other materials with the binder properties required for concrete. These typically are referred to as ‘supplementary cementitious materials (SCMs)’. Use of SCMs has immediate CO₂ benefits, as they typically only require grinding without heating, and do not release any CO₂ as process emissions.

The use of SCMs already is established practice. Since the 1980s, the use of SCMs has reduced CO₂ emissions by 20–30%.³⁸ SCMs now make up 26% of cement in the EU, with clinker making up the remaining 74%.³⁹ The largest categories are limestone, fly ash, and blast furnace slag.

The potential to increase the use of the current main SCMs is limited. Limestone is already used near its maximum, while 90% of coal fly ash and 80% of blast-furnace slag are already directed towards use in construction.⁴⁰ Moreover, the supply of fly ash and blast-furnace slag is likely to fall substantially in a scenario where climate targets are met. Fly ash is largely a by-product of coal-fired power generation, which may be all but eliminated in a low-emissions scenario.⁴¹ Similarly, Chapter 2 (Steel) shows that the volume of blast-furnace slag may be substantially in 2050 than it is to date, due to technology shifts in steel production.

Therefore, to continue the use of SCMs, significant new sources will be required. This is desirable not only for climate reasons, but also because SCMs can improve cement properties, for instance achieving increased resistance to sulphur and chlorine.

The main contenders for alternative SCMs are pozzolans, which can be either natural or calcined. A pozzolan is a siliceous material that possesses little cementitious value by itself. However, if finely divided in the presence of moisture, it reacts with calcium hydroxide to form cementitious compounds like calcium silicate hydrate. In this form, they can be used directly in concrete.

Natural pozzolans exhibit this pozzolanic behaviour with minimal processing. They chiefly consist of volcanic ash, but can also include other ashes and volcanic glasses like pumicite or obsidian. They are extensively used in cement production in EU countries with convenient deposits, such as Greece and Italy.

A second set of minerals require heat treatment to transform them into pozzolans. These include clay and shale, both of which become pozzolans if calcined, and metakaolin. Calcined clays can be combined with limestone to reduce the clinker content of to 50%.⁴² Though thermal energy is needed, the temperatures are lower than in the production of clinker and thus easier to switch to low-CO₂ sources, including electricity.

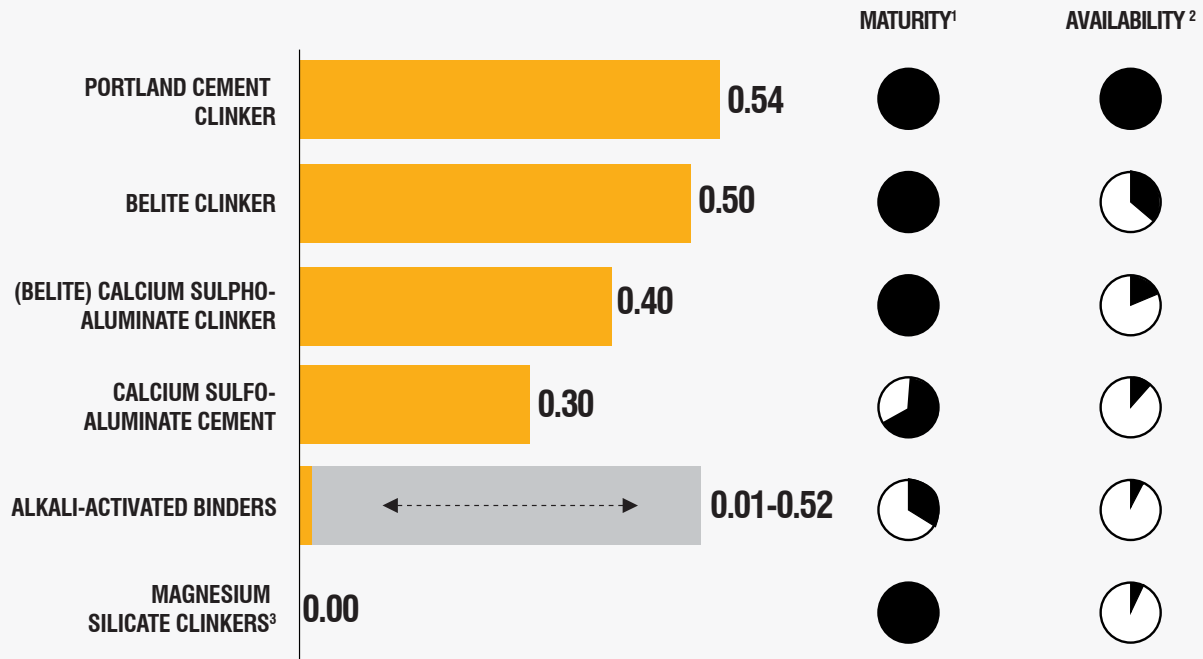
A major limiting factor for both natural pozzolans and calcined clays is the local availability of raw materials. A major attraction of Portland cement is that the main constituent is ordinary limestone, which is widely available. Deposits of calcined clays and of natural pozzolans such as volcanic ash are also available across the EU, but not nearly as uniformly distributed. Extensive use of these SCMs would thus require additional transportation, such as supply chains from the Mediterranean basin to the wider seaboard of Europe. However, such medium-distance sea freight has small emissions per tonne compared to cement production (and can also be rendered much lower-CO₂ by 2050).

This study examines two scenarios for the future use of SCMs. In a stretch scenario, SCMs could replace 40% of cement clinker in 2050 (compared with 26% today). In a more conservative scenario, they increase only slightly, to 30%. Depending on how much cement is produced, these scenarios require 41–56 Mt of SCMs in 2050, compared with 43 Mt today.

Exhibit 4.7

MOST ALTERNATIVE BINDERS REDUCE PROCESS EMISSIONS ONLY SLIGHTLY, AND ARE ALSO LIMITED BY THE AVAILABILITY OF MATERIALS

EMISSION INTENSITY PER BINDER TYPE (EXAMPLES)
TONNES PROCESS CO₂ EMISSIONS PER TONNE BINDING MATERIAL



NOTES: ¹MATURITY LEVELS: 1/3 R&D PHASE, 2/3 DEMONSTRATION-PILOT PHASE, 3/3 COMMERCIAL ,
²AVAILABILITY ON A GLOBAL LEVEL, ³MAGNESIUM OXIDES DERIVED FROM MAGNESIUM SILICATES.
SOURCES: BASED ON MULTIPLE SOURCES, SEE ENDNOTE.⁴³

Other binder alternatives and novel cements

There has long been a search for new cement chemistries that can substitute for Portland cement. From a CO₂ perspective, the chief attraction is the potential to reduce the process emissions in cement manufacture. Some also absorb CO₂ when they are cured. Many such binders and cements are in development, and it seems likely that at least some of them will play a role in the transition to net-zero emissions. However, the current candidate options face a number of obstacles that limit their realistic role in a net-zero transition by 2050. Exhibit 4.7 shows the most prominent alternative binders and novel cements currently being developed.

The chief limitation role of alternative clinkers in a net-zero scenario is the extent of emissions reductions they offer and the limited availability of raw materials. For example, belite clinker reduces emissions by only 10%, while clinkers from calcium sulphoaluminate or carbonisation of calcium silicates achieve emissions reductions of 20–40%. The general rule is that those substances with the most potential to cut emissions are also the least available.

Notably, alkali- and geopolymer-based cements could in principle eliminate nearly all process emissions, and cement based on magnesium silicate could eliminate them entirely, but the required minerals are not widespread. In many cases, reported emissions savings are measured by comparing the new chemistries with pure Portland cement, rather than cement that uses a degree of SCMs, so the true savings will be smaller than shown. Added to this, there are obstacles to adoption, including technical parameters such as hardening time or final strength, or the need for lengthy or highly specialised curing processes.

Research and development of new cement chemistries should be a high priority, as it may ultimately be possible to achieve significantly greater emissions cuts than are presented here. Nevertheless, in common with many other studies, we see a restricted role by 2050, corresponding to 5% of Portland cement in 2050.⁴⁴ Given the premise of this study to achieve net-zero emissions, the chief effect is to somewhat reduce the amount of CO₂ that needs to be captured and stored via CCS.



Any net-zero roadmap for concrete must consider options to achieve close to zero CO₂ emissions from cement kilns.

CLEAN PRODUCTION

Even with full use of materials efficiency, recirculation, and substitution options, there will still be a need for conventional cement clinker production in 2050. Any net-zero roadmap for concrete therefore must consider options to achieve close to zero CO₂ emissions from cement kilns, as well as ways to cut emissions in the near-term.

Exhibit 4.8 provides an overview of the main options and their representative CO₂ reduction potential. Remaining energy efficiency potential is relatively limited, following widespread adoption of highly efficient processes among EU companies. The key technologies are a switch from wet kilns to dry kiln

technology, fitting preheaters and precalciners, and recovery of process waste heat. By 2050, it is expected that current cement kilns can become 10% more efficient relative to today by further spreading these technologies.⁴⁵ Fuel switching can provide some further emissions reductions, though as discussed below, the role of alternative fuels will change in a 2050 perspective.

Fully eliminating CO₂ emissions is restricted to two main routes: either full carbon capture from both combustion and process emissions, or a combination of replacing the energy used for heating with a zero-CO₂ source, and capturing process emissions.

Exhibit 4.8

NET-ZERO CO₂ PRODUCTION OF CEMENT AND CONCRETE REQUIRES SOME DEGREE OF CARBON CAPTURE



SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTE.⁴⁶

CARBON CAPTURE AND STORAGE

The main challenge with clinker production are the CO₂ emissions from the limestone. These are irreducible, and will arise as long as clinker is produced from this raw material. This is a rare example of carbon capture being all but indispensable if emissions to the atmosphere are to be avoided.

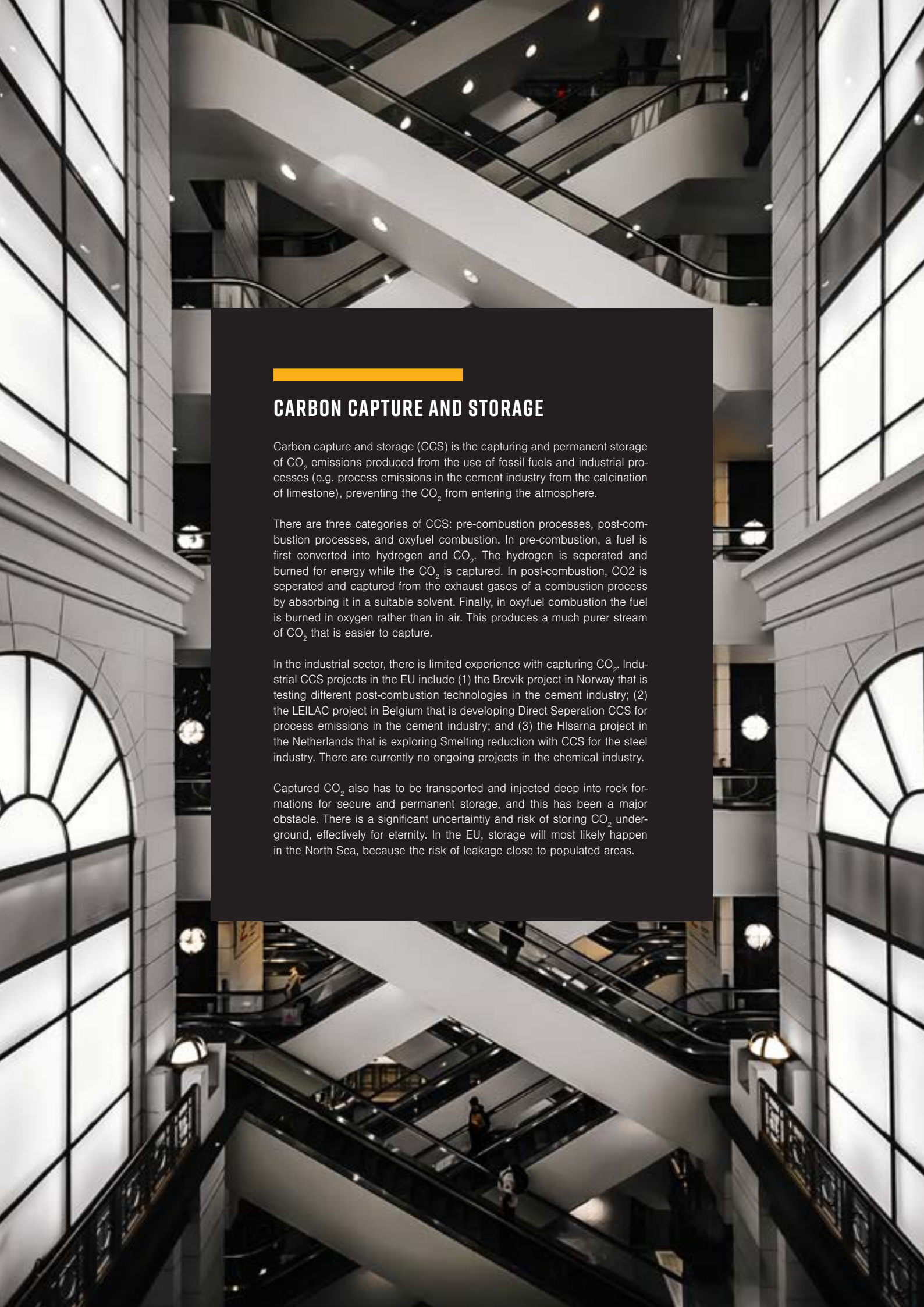
There are two main ways that CCS can be applied in cement production. One is to capture CO₂ emissions from both the burning of fuels and from process emissions from limestone. The fuel emissions are the most challenging. They contain many other gases than CO₂, making high capture rates difficult to achieve. There is only limited practical experience of real-world trials of CCS on cement production, with one active demonstration plant in the EU.⁴⁷

While there are many potential CCS technologies (see Box to the right), most industry stakeholders and experts interviewed for this study saw oxyfuel CCS as the likeliest long-term option to capture both fuel and process emissions. When fully developed, oxyfuel CCS could achieve a capture rate of up to 95%. The last few tonnes of emissions could then be abated through continued use of biomass in cement kilns, effectively creating some ‘negative emissions’ to offset the CO₂ that is not captured.

The other main approach is to handle fuel and process emissions separately.⁴⁸ In today’s kiln designs, the two streams are mixed. If they can be separated, the very pure flow of process CO₂ could be relatively easily captured at rates close to 100%. Such separation of CO₂ would require modification to kiln design (to indirectly heat the limestone), but it has the major attraction that no other capital expenditure would be necessary, except for equipment to compress the CO₂ before it is transported and stored. With process emissions captured, fuel emissions could be eliminated through electrification.

Regardless of which approach is used, CCS faces major obstacles. The 200 cement kilns in the EU are widely dispersed, located near limestone deposits and serving local markets to minimise transportation costs. Costs per tonne of CO₂ captured increase the smaller is the size of the facility, while transport costs would be particularly high for plants sited far from storage locations. The cost of CCS therefore is likely to increase sharply from the most to the least suited kilns.

In this study, we consider penetration of CCS on 90% of the production capacity. In combination with some biomass use and high capture rates, this provides a net-zero solution for the sector.



CARBON CAPTURE AND STORAGE

Carbon capture and storage (CCS) is the capturing and permanent storage of CO₂ emissions produced from the use of fossil fuels and industrial processes (e.g. process emissions in the cement industry from the calcination of limestone), preventing the CO₂ from entering the atmosphere.

There are three categories of CCS: pre-combustion processes, post-combustion processes, and oxyfuel combustion. In pre-combustion, a fuel is first converted into hydrogen and CO₂. The hydrogen is separated and burned for energy while the CO₂ is captured. In post-combustion, CO₂ is separated and captured from the exhaust gases of a combustion process by absorbing it in a suitable solvent. Finally, in oxyfuel combustion the fuel is burned in oxygen rather than in air. This produces a much purer stream of CO₂ that is easier to capture.

In the industrial sector, there is limited experience with capturing CO₂. Industrial CCS projects in the EU include (1) the Brevik project in Norway that is testing different post-combustion technologies in the cement industry; (2) the LEILAC project in Belgium that is developing Direct Separation CCS for process emissions in the cement industry; and (3) the Hlsarna project in the Netherlands that is exploring Smelting reduction with CCS for the steel industry. There are currently no ongoing projects in the chemical industry.

Captured CO₂ also has to be transported and injected deep into rock formations for secure and permanent storage, and this has been a major obstacle. There is a significant uncertainty and risk of storing CO₂ underground, effectively for eternity. In the EU, storage will most likely happen in the North Sea, because the risk of leakage close to populated areas.

Electrification of heat input

Using electricity for heat input to cement production poses a considerable challenge, because the production processes requires temperatures up to 1450°C. There are no commercially available solutions so far, but stakeholders interviewed for this project ascribe this more to a lack of a business case for their development, than to any intrinsic technical obstacle.

Developing solutions applicable for cement kilns would have wider applicability as well, not just in including in lime and ceramics production. Potential options include plasma energy, microwave energy, and indirect heating using hydrogen (see Box for an overview).

Alternative fuels

As noted, EU cement production already derives 15% of its energy from biomass. However, increasing this share significantly could prove challenging, chiefly because of the many competing claims on this resource. Despite the challenges of electrification, it may be a more viable option.

More generally, cement kilns can supplement their core fuels of coal and petroleum coke with a range of others. Over the last 20 years, the cement sector has invested heavily in the use of alternative energy sources, especially waste-derived fuels. These now make up 30% of the sector's energy input.⁴⁹ As a result, cement plants are an integral part of waste handling in several parts of the EU. They are the destination of end-of-life flows such as tyres, end-of-life plastics and mixed wastes. The main motivation behind the use of alternative fuels has been economic. Cement plants often pay very little for waste streams, or even get paid to accept them, as it helps avoid landfilling.

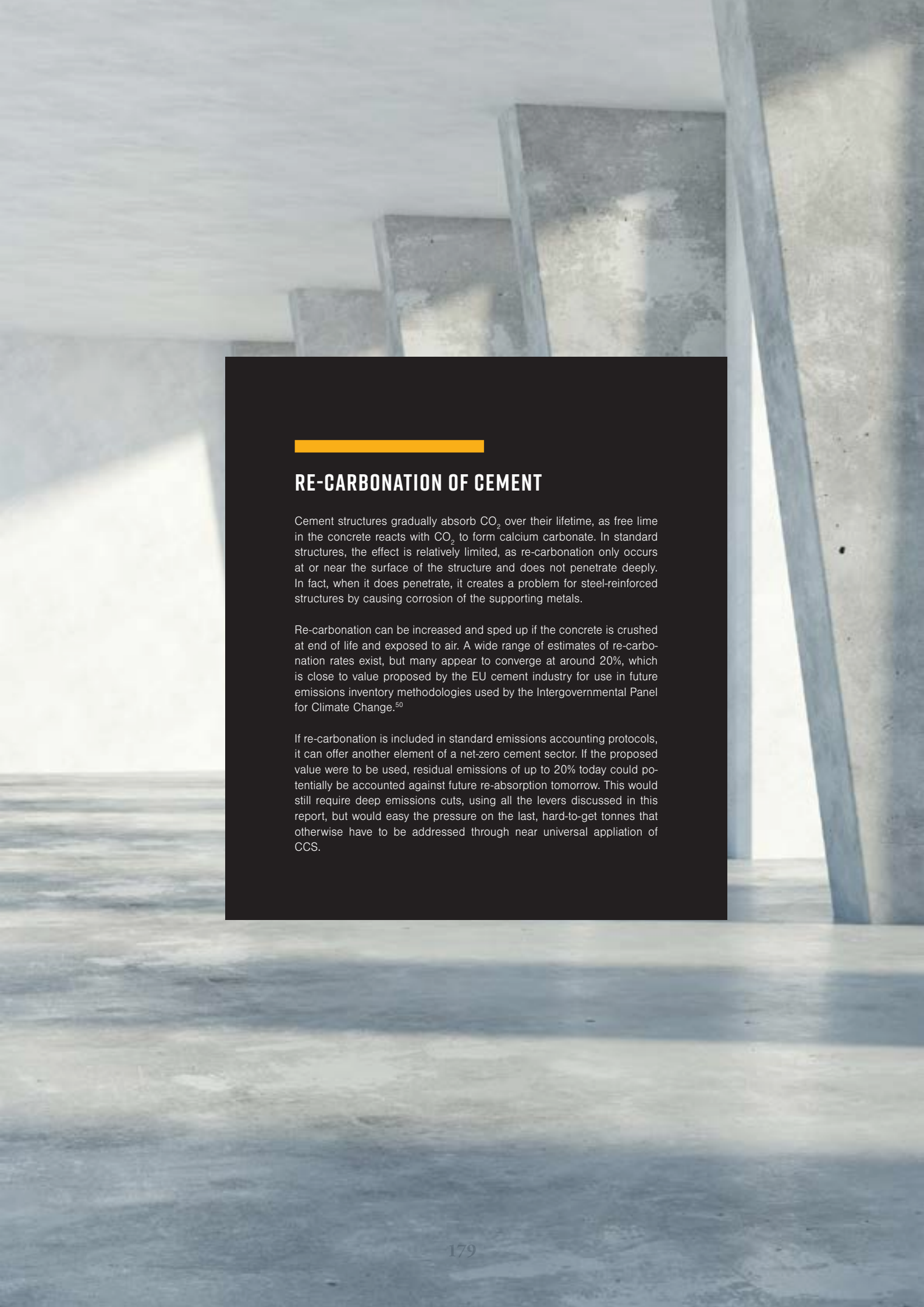
However, the CO₂ consequences of these alternative fuels are complex. Much of the energy content in waste fuels comes from fossil carbon, so the emissions are fossil CO₂ emissions. As discussed in Chapter 3 (Plastics), the incineration of end-of-life plastics and other fossil carbon sources will tend to become a major source of CO₂ in a net-zero emissions economy. These energy sources therefore are not a low-CO₂ solution in a net-zero economy by 2050.

OPTIONS FOR ZERO-CO₂ HIGH-TEMPERATURE HEAT IN CEMENT PRODUCTION

Plasma generators can generate the very high temperatures needed for some of the steps in cement production, with an efficiency of 85–90%. These generators are available at suitable output ranges and are already proven in industrial contexts. While no single commercial plasma generator can output more than 7 MW, it is possible to run several generators in parallel to supply higher power levels. However, one disadvantage is that the generators are sensitive to dust, so they tend to require maintenance every 200–300 hours. There is also the question of how to maintain heat transfer within the kiln. Plasma energy has been studied by CemZero, a project run in partnership by the Swedish state-owned utility company Vattenfall and Cementsa, a subsidiary of HeidelbergCement.

Using microwave energy for heating has the potential to reduce energy consumption by up to 40%. This is because microwaves can be uniformly absorbed throughout the entire volume of an object, whereas traditional fuels warm an object gradually from the outside inwards. To date, high-temperature microwave heating has not been used at scale in industrial processes, although microwaves are routinely used at lower temperatures. However, a lab-scale prototype and a semi-industrial prototype has been developed in Europe through the EU-sponsored DAPhNE project (2012–2015). Using microwaves for heating offers many other advantages for the industry, relative to traditional fuels. These include shorter processing times, the possibility of modular production facilities, lower annual maintenance costs for kilns, and the option to operate kilns much more flexibly.

Hydrogen offers a dense source of energy that does not emit CO₂, provided the hydrogen is made using a net-zero emissions technology. It has a higher technology readiness than microwave energy, so electrification through hydrogen could be deployed at an earlier date. However, it would require substantial modification of existing cement plants. Furthermore, hydrogen would entail much higher production costs, as it requires nearly twice as much energy as the microwave option.



RE-CARBONATION OF CEMENT

Cement structures gradually absorb CO_2 over their lifetime, as free lime in the concrete reacts with CO_2 to form calcium carbonate. In standard structures, the effect is relatively limited, as re-carbonation only occurs at or near the surface of the structure and does not penetrate deeply. In fact, when it does penetrate, it creates a problem for steel-reinforced structures by causing corrosion of the supporting metals.

Re-carbonation can be increased and sped up if the concrete is crushed at end of life and exposed to air. A wide range of estimates of re-carbonation rates exist, but many appear to converge at around 20%, which is close to value proposed by the EU cement industry for use in future emissions inventory methodologies used by the Intergovernmental Panel for Climate Change.⁵⁰

If re-carbonation is included in standard emissions accounting protocols, it can offer another element of a net-zero cement sector. If the proposed value were to be used, residual emissions of up to 20% today could potentially be accounted against future re-absorption tomorrow. This would still require deep emissions cuts, using all the levers discussed in this report, but would ease the pressure on the last, hard-to-get tonnes that otherwise have to be addressed through near universal application of CCS.

4.3 LOW-EMISSIONS PATHWAYS FOR THE EU CEMENT SECTOR

Clearly there is a very wide range of solutions that could contribute to a net-zero emissions cement industry. These solutions would address everything from how the basic binding material is produced, to how concrete is used in construction, to what is done with end-of-life concrete.

Shifting to a net-zero system will require changes along the whole value chain, and reaching the full potential of any of these opportunities is a considerable challenge. The good news is that all can be pursued in parallel: there are no major conflicts between low-CO₂ clinker production, the substitution of clinker with other materials, or changes to concrete composition, or to the use of concrete in structures. At the same time, no single solution can achieve all the necessary emission reductions.

This study lays out three pathways to a net-zero emissions EU concrete industry in 2050, with different degrees of success and adoption of each measure (Exhibits 4.10 and 4.11). Each incorporates all the solutions identified above, but with different degrees of emphasis:

- **New Processes pathway:** In this pathway, there is modest success in capturing the potential for increased materials efficiency. Cement demand is reduced by 44 Mt per year by 2050, requiring production of 140 Mt, which is somewhat lower than that in 2015 (167 Mt). The key technology choice is widespread electrification of that input, in combination with separate capture of process CO₂. With 90% of cement production using carbon capture, a total of 35 Mt CO₂ is captured in 2050. 15% of energy input is biomass, thus achieving net-zero emissions from the sector overall. A major driver of emission reductions is the rapid development of the underlying electrification and CCS technologies, with widespread investment since the 2030s and plenty of clean electricity available.
- **Circular Economy pathway:** In this scenario a large share of the circular economy potential is captured, reducing the need for production of cementitious materi-

als by 44% or 81 Mt through widespread adoption of material efficiency, recirculation and substitution. This corresponds to 65% of the technical potential identified, so while the pathway does not require 'perfect' implementation of any one strategy, most need to be pursued to some degree. Production of cement is 103 Mt in 2050, split between electrified heat without CCS (10 Mt), electrified heat with and carbon capture and storage (46 Mt) and fossil fuel-fired processes with oxy-fuel carbon capture and storage (46 Mt). This scenario means 31 Mt of CO₂ per year is captured and stored from cement production in 2050. The key enabler for this scenario is the widespread adoption of new practices by concrete companies, architects, constructors, building companies, demolition companies, and others in along the construction value chain. While the core technologies for electrification and carbon capture are required, they can be introduced later.

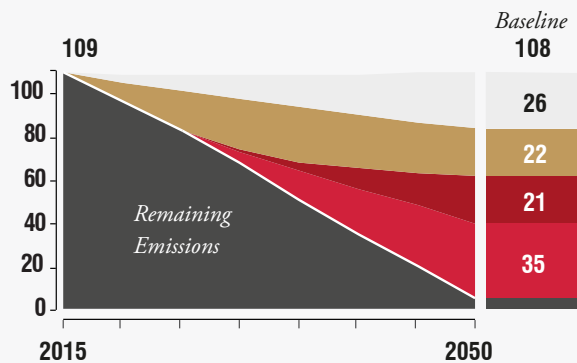
- **Carbon Capture pathway:** This pathway is the one most similar to existing cement 'roadmaps'. Only 15% of the potential for cement demand reduction is achieved, and patterns of use are largely similar to today. Materials efficiency and substitution reduce demand by 19 Mt by 2050 and barely offsetting growth in activity. Production of cement in 2050 therefore is similar to that today, at 165 Mt. The emphasis is on integrated CCS on fuel and process emissions. 16 Mt is produced with electrified heat with carbon capture and storage, but as much as 148 Mt using oxyfuel or other integrated CCS. As a result, 85 Mt of CO₂ per year is captured and stored from cement production in 2050. This pathway sees an all-out effort on CCS, which must be fitted across the EU on a large number of kilns. It shows what it would take to reach net-zero emissions if either electrification or value-chain measures proved very hard to achieve, whereas CCS gained widespread acceptance and momentum, becoming a standard feature of industrial production, supported by extensive infrastructure across the continent.

Exhibit 4.9

PATHWAYS TO NET-ZERO EMISSIONS FOR CEMENT & CONCRETE

CO₂ ABATEMENT
Mt CO₂ PER YEAR

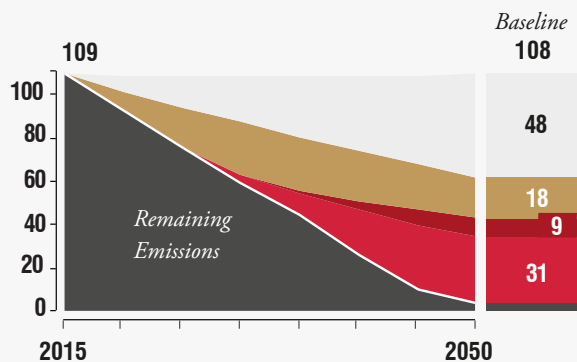

NEW PROCESSES
Pathway



EXTENSIVE ELECTRIFICATION OF CEMENT PRODUCTION PROCESSES

- The pathway sees some adaptation of the concrete value chain, but more emphasis on changing the composition of cement and the inputs to cement production
- Key enablers are i) abundant and affordable electricity, with near complete electrification of production, and ii) innovation and investment in processes to enable separate capture of process CO₂

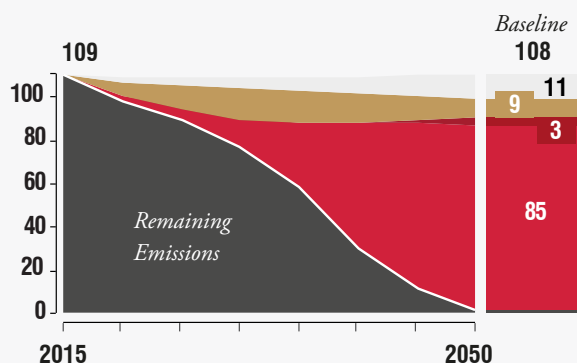

CIRCULAR ECONOMY
Pathway



EMPHASIS ON MATERIALS EFFICIENCY, NEW BUSINESS MODELS, AND SUBSTITUTION

- The pathway sees concerted effort by actors throughout the value chain including cement producers, concrete manufacturers, architects, construction companies, demolition companies to jointly capture two-thirds of the materials efficiency and substitution potential
- Key enablers include revision of standards to enable new practices, behavior change and diffusion of new practices across the value chain, and digitisation and introduction of new construction processes


CARBON CAPTURE
Pathway



MINIMAL CHANGE TO VALUE CHAIN AND EXTENSIVE CAPTURE OF CO₂ FROM CEMENT PRODUCTION

- The pathway sees only minor change to the cement production process and to the use of cement and concrete.
- Instead the emphasis is on CCS at nearly all cement plants

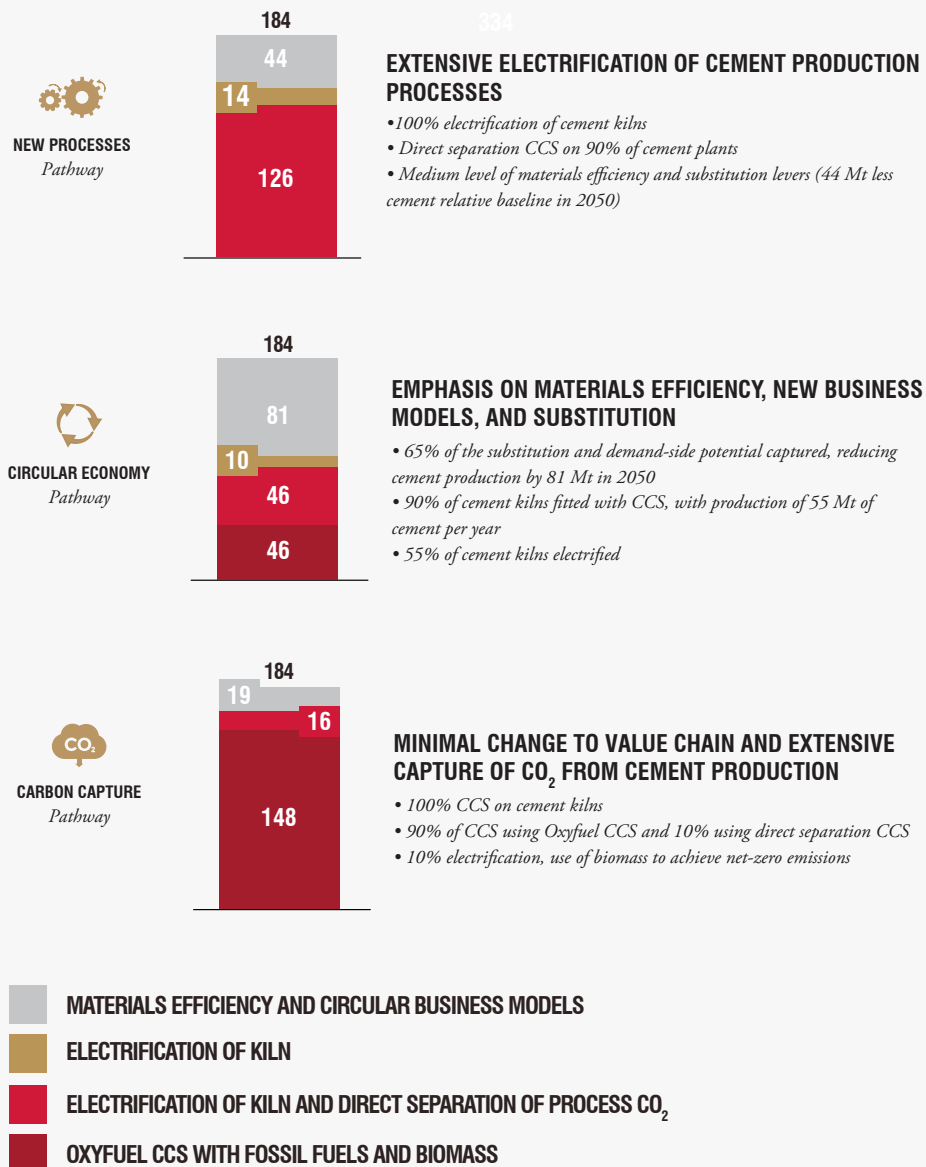
-  MATERIALS EFFICIENCY AND CIRCULAR BUSINESS MODELS
-  MATERIALS RECIRCULATION AND SUBSTITUTION
-  NEW PROCESSES
-  CARBON CAPTURE AND STORAGE
-  REMAINING EMISSIONS

SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

Exhibit 4.10

PRODUCTION ROUTES IN NET-ZERO PATHWAYS

EUROPEAN CONCRETE PRODUCTION MIX TO ACHIEVE NET ZERO EMISSIONS IN 2050
Mt CEMENTITIOUS MATERIAL PRODUCED PER YEAR AND ROUTE



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.



The transition to net-zero emissions will be significantly easier if more circular economy solutions can be mobilised.

The three pathways are designed to be substantially different, but there are recurring themes. Carbon capture and storage is used in all three. However, the amount of CO₂ captured varies significantly, between 31 and 85 Mt. This reflects the considerable uncertainty about the cost and the availability of storage capacity that is situated nearby and socially accepted. In all pathways, all production is shifted away from the current production route. There is no pathway that does not entail major investment and transformation, either in cement kilns or in other steps of the value chain.

Likewise, while the emphasis in these pathways is on truly net-zero options, a range of solutions play an important role in early emissions reductions, including fuel switch to biomass and energy/electrical efficiency improvements. They enable deeper cuts before the mid-2030s, when other solutions can be deployed at larger scale.

Another cross-cutting insight is that all pathways depend on significant acceleration of solutions that, while prom-

ising, are only at an emerging stage today – not least of them CCS. Increased demonstration is needed in all three cases, but especially in the Carbon Capture pathway. Electrification, the mobilisation of new sources of supplementary cementitious materials (SCMs), high-filler concrete, a change towards more pre-cast structures, and new construction techniques will all take time and require technical innovation, behavioural change, new business models, and in some cases regulatory change. In all cases, early policy guidance will be required, as options are rarely viable in today's market conditions.

The transition to net-zero emissions will be significantly easier if more circular economy solutions can be mobilised, which have a very substantial potential in this sector. These buy time for technology development, and as we discuss below, can reduce cost, investment needs, and input requirements. They deserve special emphasis, as they are currently not part of industrial strategy or of climate policy, and have not been recognised in most 'roadmaps' for future cement production.

DEEP CUTS TO EMISSIONS WILL INCREASE THE COST OF PRODUCING CEMENT BY 70–115%

The new ways of producing cement come at a substantial cost relative to today's practices. By 2050, the additional costs range would be €6–9 billion per year, implying an average abatement cost of €60–83 per tonne CO₂.

There are differences between the pathways, with the circular economy pathway the more cost-effective (€6.3 billion per year). At an electricity price of €60 per MWh, the New Processes pathway appears more expensive (€6.8 billion per year in 2050) than the Carbon Capture pathway (€8.6 billion per year), but the difference is negligible if electricity is available at €40 per MWh or less.

The new production routes add significant costs to cement production (Exhibit 4.11). Electricity becomes a major part of production cost for any electrified route of production, but increased capital costs and the cost of carbon transport and storage also make up significant elements.

The cost of increased materials efficiency and improved circularity are among the hardest to estimate. Surveying a range of levers, however, they appear relatively more cost-effective compared with the high cost of electrification and CCS. In particular, the techniques underlying increased use of SCMs and high-filler cement are much less resource-intensive, and could see a cost advantage once they reach industrial scale. Others (such as reuse or optimisation of structural elements, or variation in concrete exposure class-

es) face coordination costs that are high today, but which could fall significantly in a more digitised construction industry that also employs more advanced techniques, including 3D printing.

This leads to three main conclusions. First, the most cost-effective solution will vary across markets and with local circumstances, notably electricity prices and the cost of carbon storage and transport. However, cost alone is not a robust basis at this stage in the transition for choosing one approach over another. It is likelier that the barriers – of innovation and rapid deployment, mobilisation of measures in the value chain, and acceptance and infrastructure for CCS – will determine which solution is most promising in a given setting.

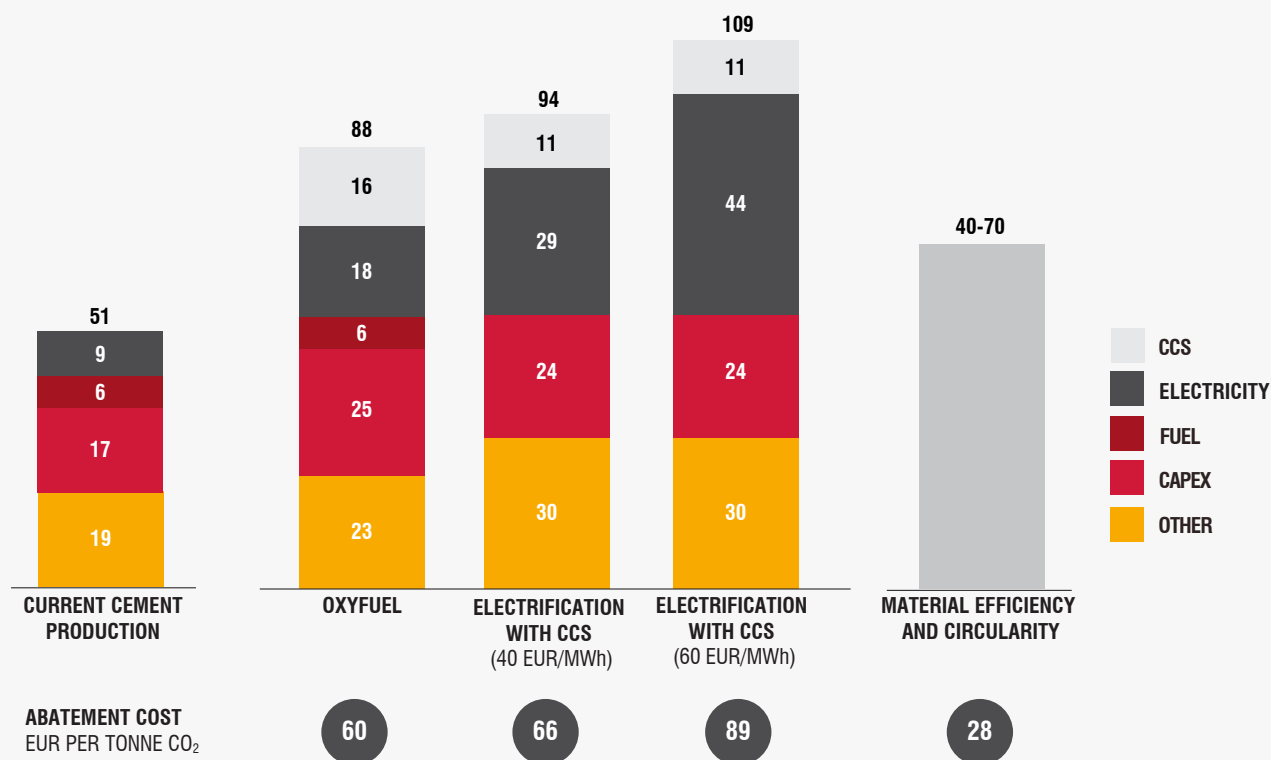
Third, the level of cost increase could drive very substantial change in the industry. Of particular concern is the significant risk of carbon leakage. A cost increase of €40 or more per tonne of cement is more than enough to offset transportation costs from a range of geographies. Even if carbon leakage has not occurred on a large scale today, it would become a very real prospect with this large an increase in the price of cement.

Given this picture, policy will play an indispensable role in making low-CO₂ cement production viable, and to support a transition that otherwise will raise many challenges.

Exhibit 4.11

THE PRODUCTION COST OF NET-ZERO CO₂ CEMENT IS 70-115% HIGHER THAN CURRENT PRODUCTION

CEMENT PRODUCTION COSTS PER ROUTE OR COST OF MATERIALS EFFICIENCY AND SUBSTITUTION PER TONNE CEMENT AVOIDED
EUR PER TONNE OF CEMENT



NOTE: HIGH ESTIMATE FOR MATERIALS EFFICIENCY AND CIRCULARITY IS USED TO CALCULATE ABATEMENT COST.
SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

INVESTMENT IN THE CEMENT SECTOR WILL NEED TO RISE BY 20-50%

The transition to a net-zero emissions cement sector will require a new wave of investment in the industry, with substantially higher investment levels than in the baseline scenario. Total investment needs increase by one-third in the New Processes pathway, but by half in the more capital-intensive Carbon Capture pathway. The Circular Economy pathway sees a lower overall increase of 22%, as many of the underlying opportunities are much less capital-intensive than is cement production. Overall, the total additional capital requirements are an additional €150–350 million per year, on average, until 2050.

The main reason why investment needs increase is that the underlying processes are more capital-intensive. CCS always entails significant investment either in adaptation of the kiln or in capture equipment. Electrification uses more capital-intensive methods than standard combustion methods of heating.

Companies will also need to invest more for a range of other reasons. The amounts required for early investment in pilot and demonstration plants are not large compared with a full industry roll-out. However, they can be among the most difficult for companies to undertake, as there often is little direct commercial benefit.

Another source of investment is the need for one-off conversion of brownfield sites to use new raw materials and

energy sources, or to adapt sites for carbon capture and onward transport and storage. Replacing current energy systems also has a range of knock-on effects.

These investment estimates are based on a gradual re-investment and replacement in current production facilities, and the gradual build-up of alternative solutions for SCMs and for concrete. However, given the size of cost differences between low-CO₂ and current production routes, it is possible that much more drastic change will be required.

Cement production today is organised for local supply, from facilities with low incremental cost per tonne but substantial capital outlay. With much higher marginal cost, or with large changes to demand patterns, several other changes are possible. One possibility is that it would push towards further consolidation of the industry, a development that some industry stakeholders anyway expect. New factors would then become relevant, including access to carbon storage, access to new sources of raw materials (calcined clays and natural pozzolans, in addition to limestone), or other local advantages. Such a consolidation scenario is not represented in these pathways, but would require additional investment.

Either way, policy will play an indispensable role, both in creating the underlying business case and in reducing risk.

Exhibit 4.12

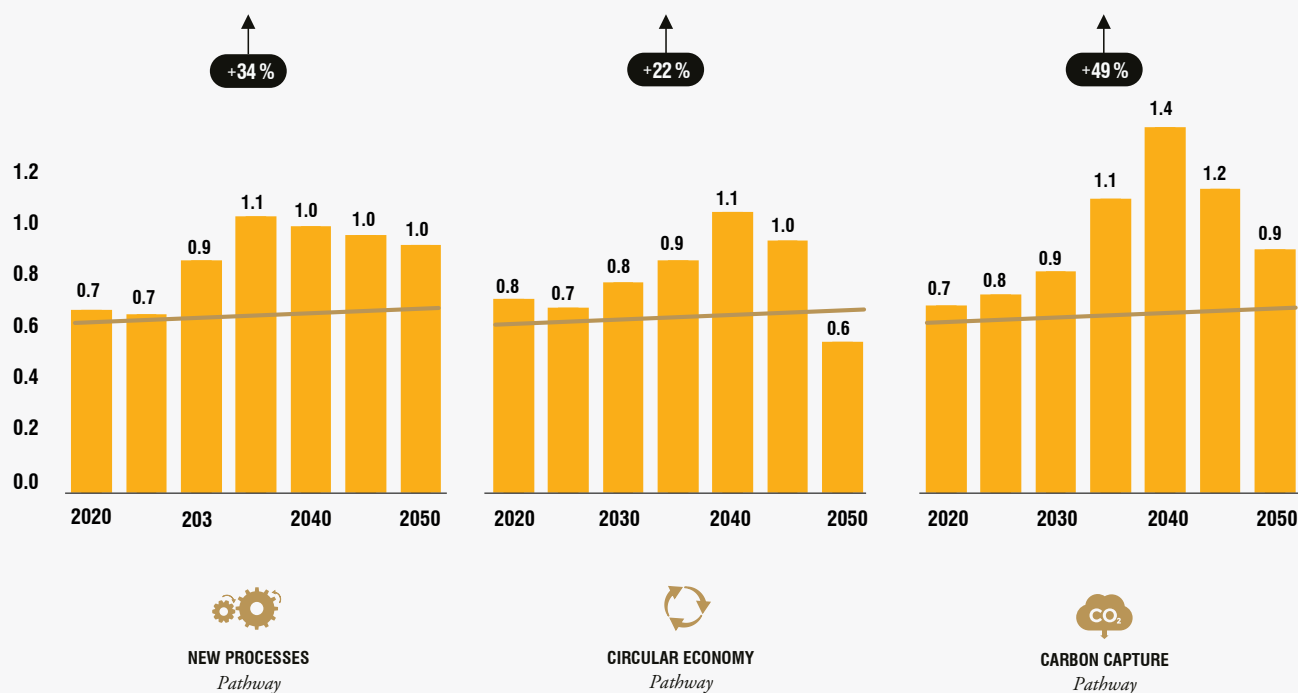
INVESTMENT REQUIREMENTS IN A NET-ZERO TRANSITION INCREASE BY 22-49% ON BASELINE LEVELS

INVESTMENT IN CEMENT PRODUCTION CAPACITY
BILLION EUR PER YEAR

INCREASE RELATIVE TO BASELINE

+ X %

■ PATHWAY
— BASELINE

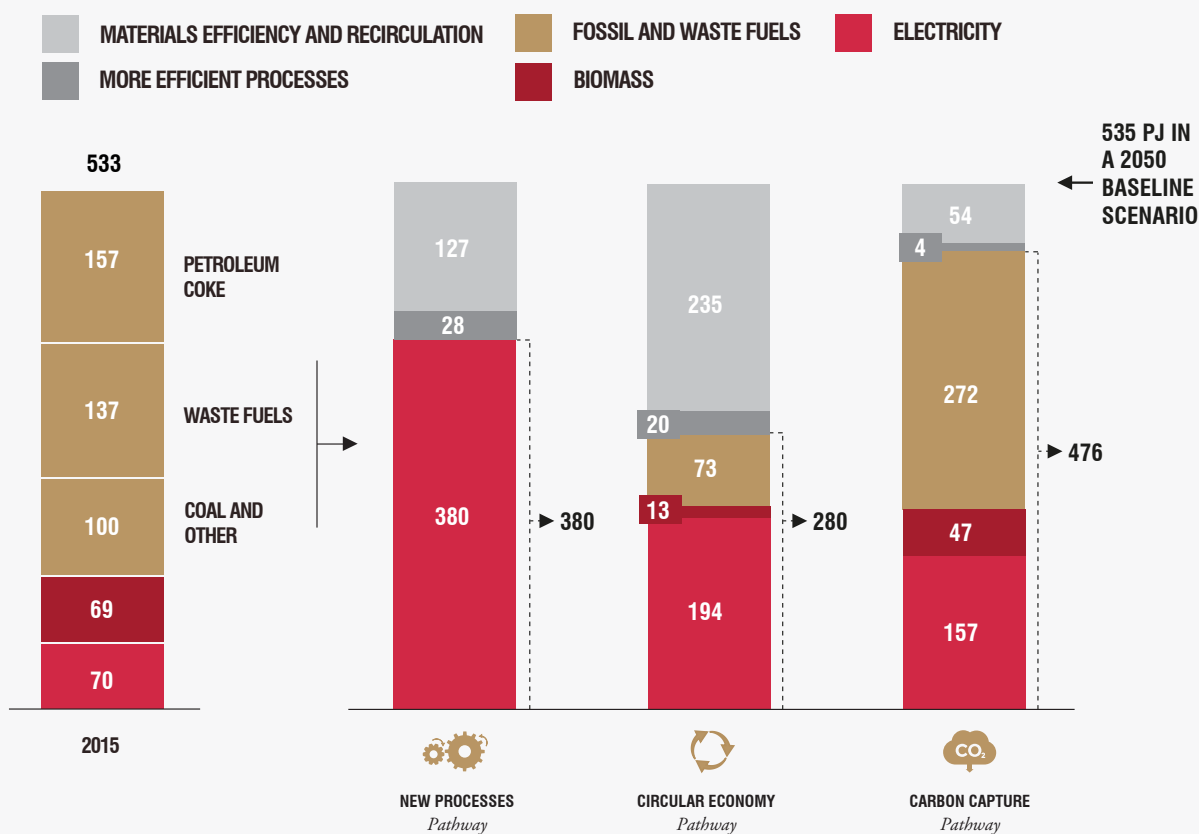


SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

Exhibit 4.13

THE LEVEL AND MIX OF ENERGY SOURCES CHANGES SIGNIFICANTLY IN A NET-ZERO TRANSITION

ENERGY MIX FOR CEMENT PRODUCTION, 2050
PJ ENERGY PER YEAR



SOURCE: MATERIAL ECONOMICS ANALYSIS AS DESCRIBED IN TEXT.

A NET-ZERO EMISSIONS INDUSTRY WILL NEED NEW AND DIFFERENT INPUTS

A net-zero emissions concrete industry will potentially see a very major change in the inputs used (Exhibit 4.13). In a baseline scenario, total energy use in 2050 would be similar to today, as increased efficiency largely offset an increase in production. The major changes to concrete use in the Circular Economy pathway sees a very major reduction in energy requirements, as the large energy needs of cement production are replaced by measures with much lower energy intensity (despite transportation, grinding, and other requirements).

The other major shift is towards electricity, which increases most in the maximal electricity use represented by the New Processes pathway, but increases also in the Carbon Capture pathway, in part to drive the carbon capture process. The Carbon Capture pathway otherwise maintains much more use of fossil and waste fuels. The biomass required to achieve full net-zero emissions is relatively small, lower than the sector uses today, but with less CCS penetration, requirements for deep cuts from the sector as a whole would rise rapidly.



Policy will play an indispensable role, both in creating the underlying business case and in reducing risk.

ENDNOTES

CHAPTER I

¹ The carbon budget for materials production is estimated to 300 Gt CO₂ (Material Economics, 2018), based on the average of available scenarios in the IPCC AR5 database (Intergovernmental Panel on Climate Change, 2014). The overall carbon budget is estimated to 800 Gt for the period 2015-2100 (Material Economics, 2018), based on Mercator Research Institute on Global Commons and Climate Change (2018).

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² Prominent existing industrial roadmaps include analyses published by CEMBUREAU and the International Energy Agency for Cement (CEMBUREAU, 2013 and International Energy Agency, 2018), EUROFER for steel (EUROFER, 2013), and CEFIC and DECHEMA for chemicals industry (CEFIC, 2013 and DECHEMA, 2017), and the International Energy Agency for integrated scenarios including industry (International Energy Agency, 2017). More recently, the most prominent update is the analysis by the European Commission (European Commission, 2018c).

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DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

European Commission (2018c). A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy.

The European Steel Association (EUROFER) (2013). A Steel Roadmap for a Low Carbon Europe 2050. Steel Industry.

International Energy Agency (IEA) and The World Business Council for Sustainable Development (WBCSD) (2018). Technology Roadmap - Low-Carbon Transition in the Cement Industry. <http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf>.

³ This refers to direct employment in the production cement, steel, and plastics in primary form. Adding the next step in the value chain (concrete production, manufacturing of plastics products, and indirect and induced GVA from steel), the numbers are 5 million employees and a €362 billion addition to GDP.

CEMBUREAU (2017b). Key facts & figures. <https://cembureau.eu/cement-101/key-facts-figures/>.

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

The European Steel Association (EUROFER) (2018). European Steel In Figures 2018. <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

⁴ CEMBUREAU (2017a). Activity Report 2017. <https://cembureau.eu/media/1716/activity-report-2017.pdf>.

The European Steel Association (EUROFER) (2018). European Steel In Figures 2018. <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

⁵ Eurostat (2019b). Trade statistics (Comext data code: DS-018995).

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

The European Steel Association (EUROFER) (2018). European Steel In Figures 2018. <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

⁶ OECD (2018b). Recent Developments in Steelmaking Capacity. DSTI/SC(2018)2/FINAL.

⁷ CEFIC (2018). Landscape of the European Chemical Industry 2018. <http://www.chemlandscape.cefic.org/wp-content/uploads/combined/fullDoc.pdf>.

⁸ Eurostat (2018). Packaging waste statistics - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics.

⁹ Steel scrap export volumes are given by the Bureau of International Recycling (BIR, 2018) and by Eurofer (Eurofer, 2018). The value is based on recent steel scrap prices as published by the London Metal Exchange (The London Metal Exchange, 2019).

The London Metal Exchange (2019). LME Steel Scrap. London Metal Exchange: LME Steel Scrap, 27 February. <https://www.lme.com/Metals/Ferrous/Steel-Scrap#tabIndex=2>. Proice.

Bureau of International Recycling (BIR) (2018). World Steel Recycling In Figures 2013 – 2017. Brussels, Belgium. https://www.bdsbv.org/fileadmin/user_upload/180222-Ferrous-report-2017-V07.pdf.

The European Steel Association (EUROFER) (2018). European Steel In Figures 2018. <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

¹⁰ Production volumes: 163 Mt of cement (WBCSD Cement Sustainability Initiative, 2016), 17 Mt of ammonia (International Fertilizer Association, 2016), 169 Mt of Steel (Eurofer, 2018, and Bureau of International Recycling, 2018), 64 Mt of primary plastics (Plastics Europe 2018) and around 4 Mt of recycled plastics (see Plastics chapter). Use categories have been broadly divided into construction, infrastructure, transportation, machinery, packaging, agriculture, and other based on steel, plastics, and cement sector chapter analyses. 80% of ammonia is used for fertilizers, based on Dechema (2017). End-of-life volumes for steel and plastics are found in the sector chapter analyses. No authoritative statistics quantifying annual cement waste exist. Estimate is based on Material Economics analysis assuming all EU construction waste to be waste, the share of concrete in waste to be 42% and cement share of concrete to be 16%.

Bureau of International Recycling (BIR) (2018). World Steel Recycling In Figures 2013 – 2017. Brussels, Belgium. https://www.bdsbv.org/fileadmin/user_upload/180222-Ferrous-report-2017-V07.pdf.

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

The European Steel Association (EUROFER) (2018). European Steel In Figures 2018. <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

Eurostat (2019a). Generation of waste by waste category, hazardousness and NACE Rev. 2 activity (env_wasgen). http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wasgen&lang=en.

International Fertilizer Association (IFA) (2016). Ammonia production and trade statistics.

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

WBCSD Cement Sustainability Initiative (2016). Getting the Numbers Right (GNR) Project, Emission Report 2016. <http://www.wbcsdcement.org/GNR-2016/index.html>.

¹¹ Based on energy and industry CO₂ emissions of 3,536 million tonnes in 2014 (international Energy Agency, 2017) and consistent with data reported by the European Environment Agency.

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

European Environment Agency (2019). Total greenhouse gas emission trends and projections. February. <https://www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-6/assessment-2>.

Total emissions estimate for the sectors are based on European Union Transaction Log (European Commission, 2017), electricity consumption data from Eurostat (Eurostat, 2017), plastics end-of-life treatment data based on previous analyses (Material Economics, 2018), and bottom-up data of process CO₂ emissions based on multiple sources as given in the sector-specific chapters.

European Commission (2017). Climate Action - European Union Transaction Log. 11 October. <http://ec.europa.eu/environment/ets/>.

Eurostat (2017). Electricity production, consumption and market overview - Statistics Explained. Eurostat - Statistics Explained, June. http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview.

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

¹² It would be possible in principle to prevent the release of this CO₂ by storing plastics instead of burning them. However, landfilling has many other disadvantages, which has led the EU to set ambitious landfill-reduction targets. The options for end-of-life treatment of plastics going forward therefore are either recycling or incineration.

¹³ Emissions from materials production and end-of-life treatment (for plastics) has been categorised into 'easier-to-abate' emissions (electricity and low- and mid-temperature heat) and 'hard-to-abate emissions' (process emissions, high temperature heat, and end-of-life treatment). For steel, 40% of direct emissions from BF-BOF and all direct emissions from EAF are allocated to process emissions, and the remaining 60% of direct emissions from BF-BOF allocated to high-temperature heat. For cement, emissions from fuel use are allocated to high-temperature heat, and remaining direct emissions are process emissions. For plastics, 100% of refinery emissions and 50% of direct emissions from steam cracking and polymerisation are allocated to process emissions. Remaining 50% of direct emissions from steam cracking are allocated to high-temperature heat and remaining 50% of direct emissions from polymerisation are allocated to low- and mid-temperature heat. Emissions from end-of-life incineration and transport emissions from mechanical recycling (negligible) are allocated to end-of-life emissions. For ammonia, 1/3 of the direct emissions have been allocated to low- and mid-temperature heat, and the remaining 2/3 of the direct emissions to process emissions. All electricity use is categorised into emissions from electricity.

¹⁴ CO₂ and nitrous oxide emissions from fertiliser application are not included in the analysis. In keeping with current inventory methodologies, the analysis also does not include the potential for cement to absorb CO₂ through recarbonation.

¹⁵ Material Economics (forthcoming). Industrial Transformation 2050 - Appendix.

¹⁶ See references in Endnote 2.

¹⁷ See the detailed chapters on each sector for discussion. In brief, important examples include the electrification of steam crackers, which leaves in place the process emissions from the 35-45% of by-products that are not HVCs, and also does not solve the issue of end-of-life emissions from plastics; non-fossil input to cement kilns, which leaves the process emissions from calcination that constitute 60% of the total; capture of the pure CO₂ stream from ammonia process emissions is cheap, which leaves the 40-50% of CO₂ emissions that stem from fuel use; and CCS on blast furnaces in steel production, which typically leaves other emissions sources that constitute 40% of the total emissions from steel production.

¹⁸ Allwood, J. M., Ashby, M. F., Gutowski, T. G. and Worrell, E. (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling*, 55(3). 362–81. DOI:10.1016/j.resconrec.2010.11.002.

International Energy Agency (IEA) (2019). Material Efficiency in Clean Energy Transitions. OECD. DOI:10.1787/aeaaccd8-en.

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

¹⁹ European Commission (2018b). Energy efficiency first: Commission welcomes agreement on energy efficiency. [www.europa.eu](http://europa.eu), 19 June. http://europa.eu/rapid/press-release_STATEMENT-18-3997_en.htm.

²⁰ Many of these opportunities are described in more detail in the report The Circular Economy – a Powerful Force for Climate Mitigation (Material Economics, 2018).

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²¹ See The Circular Economy – a Powerful Force for Climate Mitigation (Material Economics, 2018) and the sector chapters in this report for details about the underlying opportunities.

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²² See The Circular Economy – a Powerful Force for Climate Mitigation (Material Economics, 2018) and the forthcoming appendix to this report (Material Economics, forthcoming).

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

Material Economics (forthcoming). Industrial Transformation 2050 - Appendix.

²³ Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²⁴ The widely reported numbers for plastics recycling refer to the share of reported plastics waste that is collected for recycling. Thus, this number only account for the collected plastics waste (there are also other streams of plastics waste that is part of e.g. the municipal waste stream). Moreover, there are significant sorting and recycling losses, meaning that the volumes of plastics waste collected for recycling is significantly larger than the volumes of plastics produced through recycling that can replace the production of primary plastics. See the sector chapter on Chemicals in this report as well as for example Van Eygen et al. (2018).

Van Eygen, E., Laner, D. and Fellner, J. (2018). Circular economy of plastic packaging: Current practice and perspectives in Austria. *Waste Management*, 72. 55–64. DOI:10.1016/j.wasman.2017.11.040.

²⁵ However, this study does not find that it is necessary to use still more energy intensive ‘power-to-X’ technologies at large scale. These synthesise fuels or chemicals directly from CO₂ and hydrogen, and are three times more electricity-intensive than the bio-based and chemical recycling routes used in this study.

²⁶ The cost increase of a soft drink has been calculated for a 1.5 EUR bottle weighing 26 grams. The current cost of plastics raw-materials are based on average polymer prices from OECD (2018). The cost increase of a building has been calculated using a total cost for buildings of 5,994 EUR/m² and an average of 3 tonnes of materials per m² (Material Economics, 2018). The composition of materials in a building is based on Ecorys et al. (2014), resulting in on average 74 kg of steel, 15 kg plastics, and 206 kg of cement per m². The cost increase of a car is calculated for an average car with a sales price of 20,661 EUR with a tax rate of 21% (based on European Automobile Manufacturers Association, 2013) weighing 1.4 tonnes (ICCT, 2012). The composition of materials in a car is based on Material Economics (2018), resulting in on average 916 kg steel and 130 kg plastics per car. The material cost increases in 2050 is calculated using the modelled average production cost in 2050 in the pathway with the highest production cost for each material, respectively, compared to current costs for each material.

Ecorys, Copenhagen Resource Institute, Herczeg, Dr. M., McKinnon, D., Milios, L., Bakas, I., Klaassens, E., Svatikova, Dr. K. and Widerberg, O. (2014). Resource Efficiency in the Building Sector. Rotterdam.

European Automobile Manufacturers’ Association (ACEA) (2013). The Automotive Industry Pocket Guide. https://www.acea.be/uploads/publications/POCKET_GUIDE_13.pdf.

International Council on Clean Transportation (ICCT) (2012). European vehicle market statistics - Pocketbook 2012. 107.

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

OECD (2018a). Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses. OECD Publishing, Paris. <http://dx.doi.org/10.1787/9789264301016-en>.

²⁷ See The Circular Economy – a Powerful Force for Climate Mitigation (Material Economics, 2018) for a detailed discussion of the cost of different measures. The Appendix to this report provides additional detail of the cost estimates underlying these calculations.

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

Material Economics (forthcoming). Industrial Transformation 2050 - Appendix.

²⁸ Specifically, the prices are based on commodity prices in the International Energy Agency's SDG scenario (International Energy Agency, 2018), complemented with data on end-use costs to industry from Material Economics experience with working with industrial companies.

International Energy Agency (IEA) (2018). World Energy Outlook 2018. <https://www.iea.org/>.

²⁹ See, for example, Öko-Institut (2017) and Agora Energiewende (2015)

Agora Energiewende (2015). The Integration Cost of Solar and Wind Power.

Öko-Institut (2017). Renewables versus fossil fuels – comparing the costs of electricity systems. https://www.agora-energiewende.de/fileadmin2/Projekte/2016/Stromwel-ten_2050/Agora_Gesamtkosten-Stromwelten-EN_WEB.pdf.

³⁰ Specifically, all cost estimates for hydrogen are based on a load profile of 5000 hours' operation per year. This results in higher electrolyser capacity as well as hydrogen storage costs, which are account for in the cost modelling, but on the other hand allows for electricity costs that are closer to the levelized cost of a combination of offshore and onshore wind in combination with solar photovoltaics.

³¹ Assuming an average turbine of 2.2 MW producing 4.7 GWh annually.

³² DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

³³ See sector chapters for details of the underlying analysis.

³⁴ A large plant is estimated to have an annual production of 4.5 Mt steel and a total electricity need of 3.5 MWh/t produced steel.

³⁵ Elbersen, B., Startisky, I., Hengeveld, G., Schelhaas, M.-J., Naeff, H. and Böttcher, H. (2012). Atlas of EU Biomass Potentials. https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/biomass_futures_atlas_of_technical_and_economic_biomass_potential_en.pdf.

³⁶ CEPI (2017). Key Statistics 2017 - European Pulp & Paper Industry.

³⁷ See endnote 35.

CHAPTER 2

¹ Material Economics analysis based on Pauliuk et al (2013). In 2017, the EU steel stock was 11.92 tonne steel per person with 73% of the steel stock being in the construction sector.

Stefan Pauliuk, Tao Wang and Daniel B. Müller (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.

² Material Economics analysis, calculated bottom-up based on EU production volumes and emission factors of the BF-BOF and EAF route. EU production volumes in 2015 was 101 Mt for the BF-BOF route and 65 Mt for the EAF route based on Eurofer (2018). Emissions factors include direct and indirect emissions for crude steel production and include emissions from some downstream processes (continuous casting and hot rolling) but not all downstream processes such as cold rolling. Total downstream emissions in 2015 is estimated to be 0.11 tCO₂ / t steel. Direct emissions of the routes are based on a wide literature study and conversations with industry experts while indirect emissions are based on electricity use for the two production routes and an average CO₂ emission factor of 0.35 tCO₂ / MWh for the EU electricity grid based on the IEA (2017). Electricity use has been checked with multiple sources and industry experts and the calculated indirect emission factor has been verified with literature. Based on Eurofer (2013) and expert interviews, it has been assumed that the BF-BOF route produces all of its electricity use and the emission factor for direct emissions has therefore been adjusted for this assumption.

The European Steel Association (EUROFER) (2013). A Steel Roadmap for a Low Carbon Europe 2050. Steel Industry.

Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

Fischedick, M., Marzinkowski, J., Winzer, P. and Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. Journal of Cleaner Production, 84. 563–80. DOI:10.1016/j.jclepro.2014.05.063.

Doug Zuliani, Vittorio Scipolo and Carsten Born (2009). Opportunities to reduce costs and lower GHG emissions in EAF and BOF steelmaking. Stahl und Eisen, 129.

EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

International Energy Agency (2017a). Energy Technology Perspectives 2017. www.iea.org/etp2017.

³ EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

⁴ EU steel production dropped from 199 Mt crude steel per year in 2008 to 139 Mt crude steel per year in 2009 according to

EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

⁵ European Commission (2018). Steel: Global Forum takes important steps to tackle overcapacity. http://europa.eu/rapid/press-release_IP-18-5865_en.htm.

⁶ Losses are calculated from an 85% effective recovery rate based on Pauliuk (2013) and World Steel Association (2009). Production volumes, demand, and end-of-life volumes are based on Eurofer (2018). Steel use per sector from Eurofer (2018) have been categorized by Material Economics in four major groups, 'Transportation', 'Construction', 'Products', and 'Other', which means that the data cannot be looked up directly. Metalware and tubes have been split among several of these categories.

EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

Stefan Pauliuk, Rachel L. Milford, Daniel B. Müller and Julian M. Allwood (2013). The Steel Scrap Age. *Environmental Science & Technology*, 47(7). 3448–54. DOI:10.1021/es303149z.

Stefan Pauliuk, Tao Wang and Daniel B. Müller (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.

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

⁷ The modelling approach is a dynamic materials flow analysis model based on that developed by Pauliuk et al (2013). This incorporates stocks (historical stock flows, future stock levels), scrap formation (product lifetimes, scrap formation, collection rates, remelting losses, etc.), and derived new production requirements. Transportation, Machinery, Construction, and Products are modelled separately. Four factors drive this demand for steel produced in the EU:

1. The need to build up the stock of steel to supply demand for new structures and product. The EU's steel stock has increased from around 6.1 tonnes per capita in 1970 to 11.8 tonnes per capita in 2015. During the same period, the EU's population grew by 69 million people.

2. The need to replace end-of-life products and structures. The lifetime of steel varies a lot depending on use, from less than 10 years for some consumer products, to many decades for infrastructure. On average, some 2–3% of the EU's steel stock is turned over every year.

3. The need to cover steel that is lost as scrap during manufacturing. This amounts to around 27% of steel. This steel is not permanently lost, as almost 100% of it is recycled. Nonetheless, these process losses mean more steel production is needed in any given year.

4. The economic need to export steel to other regions. Net imports now stand at 3.2 Mt per year (exports are 22.9 Mt and imports 26.1 Mt).

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.

EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

World Steel Association (worldsteel) (2018). World Steel in Figures 2018. <https://www.worldsteel.org/en/dam/jcr:f9359dff-9546-4d6b-bed0-996201185b12/World%2520Steel%2520in%2520Figures%25202018.pdf>. Steel industry statistics.

International Iron and Steel Institute (2000). Steel Statistical Yearbook 2000. <http://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook-.html>. Informatics(Statistical Yearbook).

⁸ Emissions for the steel industry depend on scope of emissions and different assumptions and the value is therefore hard to look up directly. Values used in this report have been calculated bottom-up by Material Economics using production volumes from Eurofer (2018) and emissions factors for the BF-BOF and EAF route. It has furthermore been assumed that the BF-BOF route produces all its electricity and therefore is self-reliant on electricity use based on Eurofer (2013). Direct emissions from the BF-BOF route has therefore been adjusted after this assumption and is based on multiple sources and expert interviews. Indirect emissions of 18 Mt CO₂ have been calculated by multiplying the production volume of EAF based on Eurofer (2018) with the average emission factor of EU electricity based on the IEA (2017).

International Energy Agency (2017b). World Energy Outlook 2017. www.iea.org.

The European Steel Association (EUROFER) (2013). A Steel Roadmap for a Low Carbon Europe 2050. Steel Industry.

⁹ Emission factors represent average values across the EU since emission factors of the two production routes vary depending on factors such as the age of the steel plant, energy mix, and external factors such as emissions from the power grid. An extensive analysis of multiple sources have been analysed in order to create a representative production routes, and sources include:

Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

LKAB (2016). 100% LKAB Pellet Steel vs. Average European Primary Steel. Info on Steel Industry.

The European Steel Association (EUROFER) (2013). A Steel Roadmap for a Low Carbon Europe 2050. Steel Industry.

EUROFER (2019). Eurofer Reporting template - Example 160214. <http://www.eurofer.org/Sustainable%20Steel/CO2%20Standard.fhtml>.

Vogl, V., Åhman, M. and Nilsson, L. J. (2018). Assessment of hydrogen

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.

Doug Zuliani, Vittorio Scipolo and Carsten Born (2009). Opportunities to reduce costs and lower GHG emissions in EAF and BOF steelmaking. *Stahl und Eisen*, 129.

Xiaoling Li, Wenqiang Sun, Liang Zhao and Jiuju Cai (2017). Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes. *Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes*, 19 May. <https://doi.org/10.1080/08827508.2017.1324440>.

And expert interviews.

¹⁰ Several roadmaps have analysed scenarios for deeper emission cuts in the EU steel sector. Eurofer (2013) predicts that approximately 15% of emissions can be reduced economically by 2050 relative to baseline, and that 57% is the 'maximum theoretical abatement with CCS'. To reach further emission reduction, 'hypothetic breakthrough technologies in combination with CCUS' would be required in the Eurofer roadmap. In the EU long-term strategy by the European Commission (2018), emission cuts reach up to 97% reductions in the scenarios and are between 80-90% in most scenarios in the PRIMES and FORECAST model. In the IEA ETP by the International Energy Agency (2017), there is no EU scenario, but a global steel scenario. In the IEA's 'World 2°C Scenario' 60% of emissions are cut by 2050 relative baseline while the 'World Beyond 2°C Scenario' reach 85% emission cuts.

The European Steel Association (EUROFER) (2013). A Steel Roadmap for a Low Carbon Europe 2050. Steel Industry.

European Commission (2018). A European Long-Term Strategic Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy.

International Energy Agency (2017b). World Energy Outlook 2017. www.iea.org.

¹¹ Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

¹² See chapter 5 in Material Economics (2018),

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

¹³ See chapter 6 in Material Economics (2018).

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

¹⁴ Material Economic analysis based on Pauliuk et al. (2013) and Eurofer (2018).

Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

¹⁵ Losses are based on an 85% effective recovery rate based on Pauliuk (2013) and World Steel Association (2009). All steel scrap exported is assumed to be used and consequently recycled.

Stefan Pauliuk, Tao Wang and Daniel B. Müller (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.

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

¹⁶ In 2017, 94 Mt steel scrap was consumed in the EU while net export was 17 Mt based on Eurofer (2018). Based on an 85% effective recovery rate, according to Pauliuk (2013) and World Steel Association (2009), this means that the total amount of steel falling out of use equals 131 Mt. The value of steel scrap falling out of use has been calculated by using the price of €259 per tonne steel scrap based on Fishedick (2014) and The London Metal Exchange (2019). Steel scrap as share of iron input to EU steelmaking is based on the 94 Mt steel consumption, while total production of steel was 169 Mt based on Eurofer (2018). Adjusting for the non-iron content and losses in remelting, the share of iron input was approximately 50%.

EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

Fishedick, M., Marzinkowski, J., Winzer, P. and Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, 84. 563–80. DOI:10.1016/j.jclepro.2014.05.063.

The London Metal Exchange (2019). LME Steel Scrap. London Metal Exchange: LME Steel Scrap, 27 February. <https://www.lme.com/Metals/Ferrous/Steel-Scrap#tabIndex=2>. Price.

¹⁷ Steel scrap falling out of use in 2050 is based on Material Economics modelling that it based on Pauliuk et al (2013). A stock-based model with four product categories (construction, transportation, products and machinery) where each product category has its own maximum life length and the steel falls out of the steel stock when it reaches the end of its useful life. Steel scrap falling out of use in 2050 is 175 Mt excluding losses. Assuming the same share of production between BF-BOF (61%) and EAF (39%) as today, this would result in a scrap need of 95 Mt in 2050 under a production level of 181 Mt, resulting in a net export of 80 Mt steel scrap.

Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

¹⁸ Material Economics stock modelling based on Pauliuk et al. (2013). Assuming different lifetimes for four product groups: Transport 20 years, construction 70 years, machinery 25 years and products 15 years. Actual scrap levels depend on the level of circularity applied from today until 2050 - higher production levels between today and 2050 will mean that more scrap falls out of use in 2050.

Stefan Pauliuk, Tao Wang and Daniel B. Müller (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.

¹⁹ This would mirror the transition undertaken in the United States, where 67% of steel is produced through scrap-based EAFs - although the US imports more of the steel it uses than does the EU, which is not necessarily desirable for the EU.

World Steel Association (2018b). Steel Statistical Yearbook 2018. https://www.worldsteel.org/en/dam/jcr:e5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf. Steel industry statistics.

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EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

²⁰ The EU produced 95 Mt of flat products and 59 Mt of long products in 2017 according to Eurofer (2018).

EUROFER (2018). European Steel in Figures 2018. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

²¹ 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.

Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²² Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²³ Material Economics analysis based on multiple sources and expert interviews, including:

The Boston Consulting Group (2013). Steel's Contribution to a Low-Carbon Europe 2050. Scientific report.

Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

Tata Steel (2017). Hisarna: Game Changer In The Steel Industry. https://www.tatasteeleurope.com/static_files/Downloads/Corporate/About%20us/hisarna%20factsheet.pdf. Steel Industry

Fischedick, M., Marzinkowski, J., Winzer, P. and Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, 84. 563–80. DOI:10.1016/j.jclepro.2014.05.063.

Jan van der Stel (2013). Development of the ULCOS-Blast Furnace: Working toward technology demonstration. https://ieaghg.org/docs/General_Docs/Iron%20and%20Steel%20%20Secured%20presentations/1050%20Jan%20van%20der%20Stel.pdf.

Hybrit (2017). Hybrit - Towards Fossil-Free Steel. Info on Steel Industry.

Tanaka, H. (2013). Potential for CO₂ emissions reduction in MIDREX direct reduction process. https://ieaghg.org/docs/General_Docs/Iron%20and%20Steel%20%20Secured%20presentations/2_1400%20Hidetoshi%20Tanaka.pdf.

²⁴ Material Economics (2018). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²⁵ Biomass can be used to make a partial substitute for coke. Unfortunately, biomass cannot entirely replace coke. Pre-processed biomass, for example in the form of charcoal, can offset up to 57% of the CO₂ emissions on-site. However, the best option may be making charcoal by slow pyrolysis, as the resulting charcoal is similar to conventional coal. Some plants in Brazil have completely replaced coke with charcoal, but only in small blast furnaces. European blast furnaces are bigger, so the fuel needs to meet more stringent requirements, and charcoal on its own is not enough.

²⁶ Global DRI production in 2017 was 87.1 Mt based on MIDREX (2018) and global steel production was 1,690 Mt according to World Steel (2018b).

MIDREX (2018). World Direct Reduction Statistics 2017. MIDREX. https://www.midrex.com/assets/user/news/MidrexStatsBook2017.5_24_18.pdf. Scientific

World Steel Association (2018b). Steel Statistical Yearbook 2018. https://www.worldsteel.org/en/dam/jcr:c5a8eda5-4b46-4892-856b-00908b5ab492/SSY_2018.pdf. Steel industry statistics.

²⁷ Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

²⁸ It is possible that future steel production will be done using electrolysis instead of hydrogen. Both use electricity as the main input to produce the steel. In this report, we have focused on Hydrogen Direct Reduction (H-DR), because it has a higher technological readiness level than electrolysis. At present, reduction by electrolysis is at a more experimental and research stage. With further development, electrolysis could yet prove to be the future for the steel sector. However, the electricity demand of this technology should be roughly similar to that of H-DR, so an electrolysis-driven future would not substantially change our conclusions.

²⁹ If this is achieved, two small sources of emissions would remain from H-DR. First, there would be some very minor emissions from the electrodes during the process of making hydrogen by electrolysis. These amount to just 2-5 kg of CO₂ per tonne of steel. However, these emissions can be eliminated by using biological carbon instead of fossil carbon. Second, there are some emissions from the lime used in the steel production process, amounting to 20 kg of CO₂ per tonne of steel. Lime production would need to be decarbonised in a similar way to cement (see chapter 4).

³⁰ J. P. Birat, D. Maizières-lès-Metz and UNIDO (United Nations Industrial Development Organization) (2010). Global Technology Roadmap for CCS in Industry. UNIDO and ArcelorMittal. <https://hub.globalccsinstitute.com/sites/default/files/publications/15671/global-technology-roadmap-ccs-industry-steel-sectoral-report.pdf>. Steel sectoral report.

³¹ The European Steel Association (EUROFER) (2013). A Steel Roadmap for a Low Carbon Europe 2050. Steel Industry.

³² DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

³³ Hydrogen Council (2017). Hydrogen scaling up - A sustainable pathway for the global energy transition. November. http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-Scaling-up_Hydrogen-Council_2017.compressed.pdf

³⁴ DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

³⁵ Plastics packaging represent 40% of demand (see Plastics Europe, 2018), and has a mean lifetime in the economy of 0.5 years (see Geyer et al., 2017).

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

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/sciadv.1700782.

³⁶ Material Economics analysis based on multiple sources, including data provided by industry experts.

Harry Croezen and Marisa Korteland (2010). Technological Developments in Europe A Long-Term View of CO2 Efficient Manufacturing in the European Region.

Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

World Steel Association (2018a). Fact Sheet Steel And Raw Materials. https://www.worldsteel.org/en/dam/jcr:16ad9bcd-dbf5-449f-b42c-b220952767bf/fact_raw%2520materials_2018.pdf. Information.

Fischedick, M., Marzinkowski, J., Winzer, P. and Weigel, M. (2014). Techno-economic evaluation of innovative steel production technologies. *Journal of Cleaner Production*, 84, 563–80. DOI:10.1016/j.jclepro.2014.05.063.

Vogl, V., Åhman, M. and Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production*, 203, 736–45. DOI:10.1016/j.jclepro.2018.08.279.

³⁷ The appendix gives a more systematic account of the cost modelling for circular economy levers.

³⁸ Electricity need has been calculated based on future production volumes and electricity use of different steps in the production routes. Future steel production volumes have been modelled by Material Economics and varies in each pathway depending on the level of circularity and material efficiency in major value chains as well as the focus of different production routes, for example if the focus is electrification using Hydrogen Direct Reduction or CCS using Smelting Reduction with CCS.

Electricity use for Primary Production process include electricity needed for processes to produce primary steel from the BF-BOF route, the Hydrogen Direct Reduction (H-DR) route, and the Smelting reduction with CCS route. This excludes electricity used to produce hydrogen in the H-DR route.

Electricity use for Electric Arc Furnace processes is based on an electricity consumption of 0.45 MWh/t steel based on conversations with industry experts. Electricity use of the EAF route has been compared with multiple sources and range from 0.40 to 0.54 MWh/t steel based on Xiaoling (2017), Hybrit (2017), and Steelonthenet (2018).

Electricity use for hydrogen production is around 2.8 MWh/t steel in the Hydrogen Direct Reduction route. It is based on a hydrogen consumption of 61 kg hydrogen per tonne steel which includes 20% losses on top of the 51 kg hydrogen needed per tonne steel (which excludes losses) as stated in Vogl. (2018). In the New Processes and Circularity pathways all hydrogen is produced using electrolysis which require 45 MWh/t hydrogen according to Philibert (2017) The electricity need per tonne hydrogen using electrolysis also corresponds to data given by other sources including Vogl (2018) and DECHEMA (2017). In the Carbon Capture pathway, 50% of the hydrogen is produced using electrolysis while the remaining 50% is produced using Steam Methane Reforming with CCS.

Electricity use for downstream processes include electricity need for continuous casting and hot rolling which is about 0.10 MWh/t steel today according to Milford (2012). Included downstream processes are also assumed to be fully electrified by 2050 in order to reach net-zero emissions. Current fuel use for downstream processes are 0.36 MWh/t steel (excluding electricity use) based on Milford et al (2012) and this is assumed to linearly decrease to zero by 2050 as processes are electrified.

Rachel L Milford, Stefan Pauliuk, Julian M Allwood and Daniel B Müller (2012). Supporting Information: The last blast furnace? 37.

Steelonthenet (2018). Electric Arc Furnace Steelmaking Costs 2018. March. <https://www.steelonthenet.com/cost-eaf.html>. Costs for electric arc steelmaking.

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Hybrit (2017). Hybrit - Towards Fossil-Free Steel. Info on Steel Industry.

EUROFER (2019). Eurofer Reporting template - Example 160214. <http://www.eurofer.org/Sustainable%20Steel/CO2%20Standard.fhtml>.

ArcelorMittal (2015). Worldwide Resource Efficient Steel Production. VITO: Vision on technology, . 60.

Xiaoling Li, Wenqiang Sun, Liang Zhao and Jiuju Cai (2017). Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes. *Material Metabolism and Environmental Emissions of BF-BOF and EAF Steel Production Routes*, 19 May. <https://doi.org/10.1080/08827508.2017.1324440>.

Åhman, M., Olsson, O., Vogl, V., Nyqvist, B., Maltais, A., Nilsson, L. J., Hallding, K., Skåneberg, K. and Nilsson, M. (2018). Hydrogen Steelmaking for a Low-Carbon Economy : A Joint LU-SEI Working Paper for the HYBRIT Project. Miljö- och energisystem, LTH, Lunds universitet. <http://lup.lub.lu.se/record/e8289959-1fa9-48e0-87d6-e3f79cb93aac>.

Vogl, V., Åhman, M. and Nilsson, L. J. (2018). Assessment of hydrogen

Philibert, C. (2017). Producing ammonia and fertilizers: new opportunities from renewables. International Energy Agency, . 6.

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³⁹ Hybrit (2017). Hybrit - Towards Fossil-Free Steel. Info on Steel Industry.

CHAPTER 3 - *Plastics*

¹ Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

² Szeteiová, K. (2010). AUTOMOTIVE MATERIALS PLASTICS IN AUTOMOTIVE MARKETS TODAY. Institute of Production Technologies, Machine Technologies and Materials, Faculty of Material Science and Technology in Trnava, Slovak University of Technology Bratislava, . 7.

³ Al-Sherrawi, M. H., Edaan, I. M., Al-Rumaithi, A., Sotnik, S. and Lyashenko, V. (2018). FEATURES OF PLASTICS IN MODERN CONSTRUCTION USE. International Journal of Civil Engineering and Technology, 9(4). 11.

⁴ Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

⁵ Net exports calculated as difference between production and EU plastics converter demand as reported in Plastics Europe (2018).

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

⁶ Volumes of primary plastics production, demand, and use segments from Plastics Europe (2018). End-of-life volumes are based on latest available official numbers for end-of-life treatment of collected plastics (Plastics Europe, 2018). These numbers, however, only covers the collected end of life plastics. An analysis of the stock-build up of plastics looking at the use segments and mean lifetime of plastics in the economy (based on Geyer et al., 2017, and Plastics Europe, 2018) suggests that the actual end of life volumes of plastics is almost 50% higher than the official numbers. The fate of the non-collected plastics waste is uncertain, but some ends up as mixed waste in municipal waste streams, some is lost in the environment, etc. Of the collected plastics waste, 7.4 Mt of plastics was sent to recycling in 2016. Official numbers of actual volumes of plastics produced through mechanical recycling are however not available. According to Deloitte and Plastics Recyclers Europe (2015), the recycling yield for different plastics resins is in the range of 70-80%. Moreover, the quality losses in mechanical recycling means that recycled plastics often is used for lower-quality applications, meaning that the actual replacement rate of primary plastics with recycled plastics is lower still. Our analysis suggests that the actual volumes of plastics produced through mechanical recycling was around 3.6 Mt in 2015. The total volume of incinerated plastics waste is estimated to be 20-30 million tonnes including plastics waste collected for incineration, residues from mechanical recycling processes, and plastics waste incinerated in municipal waste streams. The extra-EU exports of plastics waste was 2.5 Mt in 2017 (Eurostat, 2019). This number has however declined to 1.9 Mt in 2018 following China's drastic cut-back on plastics waste imports (Brooks et al., 2018).

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment. http://www.plasticsrecyclers.eu/sites/default/files/BIO_Deloitte_PRE_Plastics%20Recycling%20Impact_Assessment_Final%20Report.pdf.

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/sciadv.1700782.

Eurostat (2019). EU Trade since 1988 by HS2-HS4 [DS-016894].

Brooks, A. L., Wang, S. and Jambeck, J. R. (2018). The Chinese import ban and its impact on global plastic waste trade. Science Advances, 4(6). eaat0131. DOI:10.1126/sciadv.aat0131.

⁷ Analysis based on segments of plastics use (Plastics Europe, 2018) and mean lifetime of plastics per market sector (Geyer et al., 2017).

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

Roland Geyer, Jenna R. Jambeck and Kara Lavender Law (2017). Supplementary material for: Production, use, and fate of all plastics ever made. Science Advances, 3. DOI:10.1126/sciadv.1700782.

⁸ Neelis, M. L., Patel, M., Gielen, D. J. and Blok, K. (2005). Modelling CO2 emissions from non-energy use with the non-energy use emission accounting tables (NEAT) model. Resources, Conservation and Recycling, 2005(45). 226–50. <https://dspace.library.uu.nl/bitstream/handle/1874/20683/NW&SE-2005-74.pdf?sequence=1>.

⁹ IPCC Intergovernmental panel on climate change, Riitta Pipatti, Chhemendra Sharma, Masato Yamada, Virginia Carla Sena Ciani, et al. (2006). Chapter 2 Waste generation, composition and management data. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006(Volume 5: Waste). https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_2_Ch2_Waste_Data.pdf.

¹⁰ Net extra-EU exports of plastics have been fluctuating between 9 Mt and 13 Mt between 2007 and 2017. We assume a stable continued export of 10 million tonnes per year until 2050. Exports calculated as difference between EU28 + N/CH production and converter demand based on Plastics Europe (2006, 2007, 2009, 2010, 2011, 2012, 2013, 2015a, 2015b, 2016, 2017, 2018).

Plastics Europe (2006). The Compelling Facts About Plastics 2006.

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Plastics Europe (2015a). Plastics – the Facts 2015.

Plastics Europe (2016). Plastics – the Facts 2016.

Plastics Europe (2017). Plastics – the Facts 2017.

Plastics Europe (2018). Plastics – the Facts 2018.

¹¹ Material Economics (2018b). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

¹² While the world market for chemicals has grown by 230% percent, the EU's share has declined over the last two decades, from 33% in 1996 to 15% in 2016. Demand is increasing rapidly in China, India and other emerging economies, but slowly in Europe and North America, which are EU's main sales markets. Moreover, plastics is a global commodity market and production is highly energy-intensive. Europe's high energy costs has impact on competitiveness, compared to Middle East and North America who enjoys domestic access to low-cost oil and gas feedstock. According to Cefic, ethylene production is three times costlier in Europe compared to the US or Middle East.

CEFIC (2018). Landscape of the European Chemical Industry 2018. <http://www.chemlandscape.cefic.org/wp-content/uploads/combined/fullDoc.pdf>.

¹³ Calculated as a weighted average of the emission factors of the most common plastics types (PE, PP, PVC, PET, PS, PUR) based on the Ecoprofiles published by Plastics Europe (2019), and market share of different polymers (Plastics Europe, 2018).

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

Deloitte and Plastics Recyclers Europe (2015). Increased EU Plastics Recycling Targets: Environmental, Economic and Social Impact Assessment. http://www.plasticsrecyclers.eu/sites/default/files/BIO_Deloitte_PRE_Plastics%20Recycling%20Impact_Assessment_Final%20Report.pdf.

Plastics Europe (2019). Eco-profiles. <https://www.plasticseurope.org/en/resources/eco-profiles>.

¹⁴ The GHG emissions factor from incineration of plastics is calculated at 2 697 kg CO₂e/t of plastic waste, based on IPCC (2006), using the formula: kg CO₂ = kg waste for incineration * oxidation factor of carbon in incinerator (0.98) * conversion factor of C to CO₂ (3.67) * Σ(waste fraction (in %) * dry matter content * carbon content (g/g dry weight)). The dry matter content of plastic waste is equal to 1. The carbon content of plastic waste is 0.75 (Gg C/Gg dry weight waste). Moreover, the end-of-life emissions vary between different plastics types. The emissions are higher for incineration of e.g. polystyrene (PS) and PE (around 3 kg/kg plastics) and lower for e.g. PP and PUR (around 2.5 kg/kg plastics). For the purpose of this work, 2.7 kg CO₂/kg plastics have been used for all incinerated end of life plastics.

IPCC Intergovernmental panel on climate change, Riiitta Pipatti, Chhemendra Sharma, Masato Yamada, Virginia Carla Sena Cianci, et al. (2006). Chapter 2 Waste generation, composition and management data. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, 2006 (Volume 5: Waste). https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_2_Ch2_Waste_Data.pdf.

¹⁵ European Parliament (2018). Circular economy: MEPs back plans to boost recycling and cut landfilling | News | European Parliament. 27 February. <http://www.europarl.europa.eu/news/en/press-room/20180227IPR98710/circular-economy-meps-back-plans-to-boost-recycling-and-cut-landfilling>.

¹⁶ Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

¹⁷ This study examines the CO₂ emissions from both the production of plastics and their end-of-life handling. Both sources must be abated if the industry is to achieve net-zero emissions. The extraction of oil and gas, the processing of polymers into finished plastics products as well as the use phase of plastics are not included in the scope of this analysis. The outlined process in the exhibit shows the production of plastics from naphtha from crude oil, which is the most common feedstock in the EU today. Production of plastics from e.g. ethane instead uses natural gas as input.

OECD (2018). Improving Markets for Recycled Plastics: Trends, Prospects and Policy Responses. OECD Publishing, Paris. <http://dx.doi.org/10.1787/9789264301016-en>.

Ghanta, M., Fahey, D. and Subramaniam, B. (2014). Environmental impacts of ethylene production from diverse feedstocks and energy sources. Applied Petrochemical Research, 4(2). 167–79. DOI:10.1007/s13203-013-0029-7.

Plastics Europe (2018). Plastics - the Facts 2018. www.plasticseurope.org.

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Masnadi, M. S., El-Houjeiri, H. M., Schunack, D., Li, Y., Englander, J. G., et al. (2018). Global carbon intensity of crude oil production. Science, 361(6405). 851–53. DOI:10.1126/science.aar6859.

¹⁸ CEFIC (2013). European Chemistry for Growth: Unlocking a Competitive, Low Carbon and Energy Efficient Future. <http://www.cefic.org/Industry-support/>.

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

Energy Transitions Commission (ETC) (2018). Mission Possible - Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sector by Mid-Century. <http://www.energy-transitions.org/mission-possible>.

¹⁹ There are few comprehensive assessments of this topic. The ones available tend to ask what would happen if all plastics had to be replaced, and this happening in the current high-carbon energy and transportation system. Unsurprisingly, this leads to emissions increases, not least from increased transportation emissions. In assessing substitution potential for this study, the approach is instead to ask what marginal replacement could take place, and what the CO₂ impact would be in a future, low-carbon economy. This results in significant net savings of resources, not least biomass. As discussed later in this chapter, producing plastics from the biomass routes investigated in this work require 1.9-3.5 tonnes of bio resource for every tonne product. Fibre-based products often also require a larger amounts of material than do plastics solutions, but have a much less punishing ratio.

Franklin Associates, A Division of Eastern Research Group (ERG) (2014). Impact of plastics packaging on life cycle energy consumption & greenhouse gas emissions in the United States and Canada - Substitution analysis. 19.

Franklin Associates, A Division of Eastern Research Group (ERG) (2018). Life Cycle Impacts of Plastic Packaging Compared To Substitutes in the United States and Canada - Theoretical Substitution Analysis. 172.

Trucost, The American Chemistry Council (ACC) and Rick Lord (2016). Plastics and Sustainability: A Valuation of Environmental Benefits, Costs and Opportunities for Continuous Improvement. www.trucost.com.

Material Economics (2018b). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²⁰ Materials substitution plays only a marginal role in current plastics and CO₂ strategies. However, the EU parliament's ban on single-use plastics products arguably is one such example, where equivalent products will need to be produced from other materials instead, such as fibre- and wood-based alternatives or metals.

²¹ A detailed bottom-up analysis of the properties required in 35 packaging segments suggests that one quarter of plastics used in packaging could be replaced by fibre-based materials without significant compromise (Material Economics, 2018a). This substitution comes in two main forms: in applications that do not utilise the properties where plastics is uniquely suitable, such as transparency and barrier properties, and in applications where the plastics use can be reduced to a thin barrier while fibre comprises the bulk of the packaging material.

Material Economics (2018a). Sustainable Packaging - The Role of Materials Substitution. <http://materialeconomics.com/publications/publication/sustainable-packaging>.

²² Material Economics (2018b). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²³ This assessment is based on Material Economics modelling of polymer types and their mapping to plastics use and end-of-life flows, combined with data on recycling yields, plastics ageing, and effective substitution rates for different applications.

²⁴ This low recycling rate may be surprising. Official statistics often quote rates of 30% or more (e.g., European Parliament, 2018), and higher still for individual segments (Eurostat, 2018). A detailed account of the lower actual recycling rate is found in Material Economics (2018). In brief, there are three sources of difference (see also sources in Endnote 6): 1) statistics only refer to waste identified as plastics, whereas consumption data and average lifetimes of plastics products make clear that the total volume of end-of-life plastics is larger than what gets separately classified as such in waste statistics; 2) the official recycling rates refer to material sent for recycling, but the yield of recycling processes is substantially lower; and 3) recycled plastics typically are not equivalent to new plastics in quality, which leads less than one-to-one replacement.

Eurostat (2018). Packaging waste statistics - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics.

Buhl, J. (2014). Revisiting Rebound Effects from Material Resource Use. Indications for Germany Considering Social Heterogeneity. *Resources*, 3(1). 106–22. DOI:10.3390/resources3010106.

Zink, T. and Geyer, R. (2017). Circular Economy Rebound. *Journal of Industrial Ecology*, 21(3). 593–602. DOI:10.1111/jiec.12545.

²⁵ For a detailed assessment, see Material Economics (2018b), which provides a detailed assessment of plastic types, end-uses, end-of-life streams, and options to increase the quality and quantity of plastics recycling.

Material Economics (2018b). The Circular Economy - A Powerful Force for Climate Mitigation. www.materialeconomics.com.

²⁶ 40% of EU plastics demand is used in packaging applications, which almost exclusively can be categorised into single use. Other single-use plastics products include plastics plates, cups and cutlery, straws, cotton swabs, etc.

EU Environment (2019). European Parliament votes for single-use plastics ban. Environment - European Commission, 8 January. https://ec.europa.eu/environment/efe/content/european-parliament-votes-single-use-plastics-ban_en. Text.

²⁷ 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>.

²⁸ The demand for recycled and primary plastics in 2015 was 53 Mt. The demand in a 2050 baseline scenario is estimated to be 62 Mt of plastics. Achieving a 30% replacement of virgin plastics by mechanical recycling would require collection rates as high as 75% for the largest suitable end-of-life streams (around 20-30% today); improved sorting of plastics waste so yield losses in sorting and processing are reduced; an increased number of use-cycles to 5 or more for major applications (1-2 today); and an effective replacement of new plastics by recycled ones of 0.8. These all entail a step change from today's practices. The fact that overall replacement rate is not higher than 30% is primarily because many plastics are not technically recyclable through mechanical means; that there are several flows individually low volumes of speciality plastics; that recycled plastics have a limited number of cycles before they are worn out; and that contamination and mixing make it impossible to substitute 1:1 for new plastics in all applications.

²⁹ CEFIC (2013). European Chemistry for Growth: Unlocking a Competitive, Low Carbon and Energy Efficient Future. <http://cefic.org/Industry-support/>.

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

³⁰ Based on specific CO₂-emissions for fuel use in steam crackers, and the representative yields for different feedstocks in steam crackers in Neelis et al (2005) and stakeholder

interviews carried out for this project.

Neelis, M. L., Patel, M., Gielen, D. J. and Blok, K. (2005). Modelling CO₂ emissions from non-energy use with the non-energy use emission accounting tables (NEAT) model. *Resources, Conservation and Recycling*, 2005(45). 226–50. <https://dspace.library.uu.nl/bitstream/handle/1874/20683/NW&SE-2005-74.pdf?sequence=1>.

³¹ Stefan Pauliuk, Tao Wang and Daniel B. Müller (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. resource management, capacity planning, and climate change mitigation within the steel sector. During their use phase, steel-containing products provide service to people, and the size of the in-use stock of steel can serve as an indicator of the total service level. We apply dynamic material flow analysis to estimate in-use stocks of steel in about 200 countries and identify patterns of how stocks evolve over time. Three different models of the steel cycle are applied and a full uncertainty analysis is conducted to obtain reliable stock estimates for the period 1700–2008. Per capita in-use stocks in countries with a long industrial history, e.g., the U.S, the UK, or Germany, are between 11 and 16 tons, and stock accumulation is slowing down or has come to a halt. Stocks in countries that industrialized rather recently, such as South Korea or Portugal, are between 6 and 10 tons per capita and grow fast. In several countries, per capita in-use stocks of steel have saturated or are close to saturation. We identify the range of saturation to be 13±2 tons for the total per capita stock, which includes 10±2 tons for construction, 1.3±0.5 tons for machinery, 1.5±0.7 tons for transportation, and 0.6±0.2 tons for appliances and containers. The time series for the stocks and the saturation levels can be used to estimate future steel production and scrap supply.”- DOI:”10.1016/j.resconrec.2012.11.008”, ”ISSN”:”0921-3449”, ”title-short”:”Steel all over the world”, ”journalAbbreviation”:”Resources, Conservation and Recycling”, ”language”:”English”, ”author”:[{”literal”:”Stefan Pauliuk”},{”literal”:”Tao Wang”},{”literal”:”Daniel B. Müller”}], ”issued”:[{”date-parts”:[[”2013”]]}], ”schema”:”https://github.com/citation-style-language/schema/raw/master/csl-citation.json”}

³² Miljö- och energidepartementet (2018). Det går om vi vill. SOU 2018: Betänkande från Utredningen om hållbara plastmaterial (M 2017:06).

³³ Miljö- och energidepartementet (2018). Det går om vi vill. SOU 2018: Betänkande från Utredningen om hållbara plastmaterial (M 2017:06).

Smet, M. D. and De-Smet, M: A circular economy for plastics. 244.

³⁴ In the modelling for this study, the further processing of cracker by-products is represented through the production of methanol from methane and other by-products, which are subsequently transformed into olefins via the methanol-to-olefins route. In actual chemical production settings, there may be more efficient routes available.

³⁵ DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

³⁶ In the pyrolysis route, the plastics waste is processed into naphtha-like pyrolysis-oil through pyrolysis, which is used to produce HVC’s through steam cracking. As a transitional solution, this could be done with conventional steam crackers, but in order to reach deep emission reductions and high yields, an electrified steam cracker would reduce the fuel gas emissions associated with steam cracking. The fuel gas consists dominantly of methane, which can be further processed into methanol and olefins through MTO to increase the yield. These steps result in a total yield of 0.9 kg plastics per kg plastics waste, and CO₂ emissions of 0.3 kg per kg of plastics produced.

In the gasification route, plastics waste is gasified into sweet syngas, with addition of hydrogen, followed by methanol synthesis and subsequently production of plastics through MTO (methanol-to-olefins). This route results in a total yield of 0.9 kg plastics per kg of plastics waste, and CO₂ emissions of 0.15 kg CO₂ per kg plastic waste, assuming low-CO₂ production of hydrogen.

The routes described in this chapter should be seen as representative. Different routes are better suited to different types of plastics waste, so there is not likely one single answer that is suitable for all chemical recycling. Gasification is the more ‘heavy-duty’ route, with higher energy requirements primarily stemming from the production of hydrogen, whereas pyrolysis is arguably a milder treatment, suitable for purer streams. Gasification on the other hand can be an option for more problematic plastics waste streams.

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

³⁷ This poor mass balance arises because of the chemical nature of bio-feedstock. In contrast to fossil feedstocks like naphtha, biomass such as cellulose consists of 40% or more oxygen, whereas most polymers contain very little. Much of the mass therefore is lost. The oxygen-carbon ratio varies between different sources of biomass: it is higher in sugars, starches and cellulose, and lower (more naphtha-like) in lignin and fats. This means some optimisation is possible.

³⁸ In the anaerobic digestion route, biomass is processed into biogas and the sulfur is removed. Methanol is produced through catalytic methanation with the addition of hydrogen, in this representation produced through solid-oxide electrolysis. Gasification of biomass produces methanol directly, and depending on the gasification temperature, also produces aromatics. Combining these two routes, 2.7 tonnes of biomass is needed per tonne of HVCs, compared with to around 1.5–1.8 tonnes of feedstock for cracking of naphtha or ethane. Biomass is assumed to contain 30% moisture and have an energy value of 18.5 MJ/kg based on Ericsson (2017). There are also other routes of producing plastics from biomass, such as fermentation of biomass into bioethanol which is further processed into bioethylene, which are not represented in this report.

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

Ericsson, K. and Lunds universitet (2017). Biogenic Carbon Dioxide as Feedstock for Production of Chemicals and Fuels: A Techno-Economic Assessment with a European Perspective. Miljö- och energisystem, LTH, Lunds universitet, Lund.

Keith, D. W., Holmes, G., St. Angelo, D. and Heidel, K. (2018). A Process for Capturing CO₂ from the Atmosphere. *Joule*, 2(8). 1573–94. DOI:10.1016/j.joule.2018.05.006.

Research Institutes of Sweden (RISE) (2017.). Plaståtervinning - Utbyten via olika konverteringsvägar.

Sokoli, H. U. (2016). Chemical Solvolysis as an Approach to Recycle Fibre Reinforced Thermoset Polymer Composites and Close the End-of the Life Cycle. DOI:10.5278/vbn.phd.engsci.00171.

Thunman, H. (n.d.). GoBiGas demonstration – a vital step for a large-scale transition from fossil fuels to advanced biofuels and electrofuels. 130.

Thunman, H., Seemann, M., Berdugo Vilches, T., Maric, J., Pallares, D., et al. (2018). Advanced biofuel production via gasification - lessons learned from 200 man-years of research activity with Chalmers’ research gasifier and the GoBiGas demonstration plant. *Energy Science & Engineering*, 6(1). 6–34. DOI:10.1002/ese3.188.

³⁹ Weikl, M. C. and Schmidt, G. (n.d.). CARBON CAPTURE IN CRACKING FURNACES. 11.

⁴⁰ Pemal, M. and Confederation of European Waste-to-Energy Plants (CEWEP) (2016). Waste-to-Energy in Europe in 2016. 1.

⁴¹ Endnote: One tonne of olefins produced via methanol-to-olefins requires 2.28 of methanol. Producing methanol from CO₂ and hydrogen requires 11 MWh/t methanol, and the methanol-to-olefins (MTO) process another 1.4 MWh/t olefins.

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

⁴² In this regard, this study differs from the approach taken in the European Commission's A Clean Planet for All, where there are substantial 'negative emissions' from the capture of CO₂ for the production of plastic products. This would require both close to 100% recycling, so that every plastic product made is returned to make new plastics, as well as close to 100% mass balance in the recycling process. The analysis carried out for this study suggests these are not viable assumptions.

⁴³ The main exception to this principle is water electrolysis, where all studies agree on a significant reduction in capital cost in scenarios where the technology is deployed at scale. This study uses an assumption of 450 USD / kW in 2050, which is in the middle of a range of literature estimates.

CHAPTER 3 - *Ammonia*

¹ 90% used for fertilizers: Average need for ammonia per tonne fertilizer in the European fertilizer composition is 1.27 tonne NH₃ per average tonne fertilizer. Total demand in the EU-28 was 12 Mt N.

International Fertilizer Association (IFA) (2016). Ammonia production and trade statistics.

² Smil, V. (2001). Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production. MIT, Cambridge, Mass. London.

³ International Fertilizer Association (IFA) (2016). Ammonia production and trade statistics.

⁴ Fertilizers Europe. EU fertilizer market, key graphs. http://www.fertilizerseurope.com/fileadmin/user_upload/publications/statistics_publications/Stat_website.pdf.

⁵ Fertilizers Europe (2018). Industry Facts and Figures 2018.

⁶ Christian Egenhofer, Dr Lorna Schrefler, Vasileios Rizos, Federico Infelise, Dr Giacomo Luchetta, Dr Felice Simonelli, Wijnand Stoefs, Jacopo Timini and Lorenzo Colantoni (2014). For the procurement of studies and other supporting services on commission impact assessments and evaluation. Centre for European Policy Studies, . 37.

⁷ Hydrogen Europe (2017). Hydrogen in Industry | Hydrogen. <https://hydrogeneurope.eu/hydrogen-industry>.

⁸ Asa, Y. I. (2018). Fertilizer Industry Handbook 2018. 97.

⁹ Christian Egenhofer, Dr Lorna Schrefler, Vasileios Rizos, Federico Infelise, Dr Giacomo Luchetta, Dr Felice Simonelli, Wijnand Stoefs, Jacopo Timini and Lorenzo Colantoni (2014). For the procurement of studies and other supporting services on commission impact assessments and evaluation. Centre for European Policy Studies, . 37.

¹⁰ EEA (2018). Agricultural land: nitrogen balance. European Environment Agency. <https://www.eea.europa.eu/airs/2018/natural-capital/agricultural-land-nitrogen-balance>. Briefing.

¹¹ Eurostat (2015). Agri-environmental indicator - mineral fertiliser consumption - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_mineral_fertiliser_consumption.

¹² EEA (2018). Agricultural land: nitrogen balance. European Environment Agency. <https://www.eea.europa.eu/airs/2018/natural-capital/agricultural-land-nitrogen-balance>. Briefing.

¹³ Steffen, W., Richardson, K., Rockstrom, J., Cornell, S. E., Fetzer, I., et al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science, 347(6223). 1259855–1259855. DOI:10.1126/science.1259855.

¹⁴ Baligar, V. C., Fageria, N. K. and He, Z. L. (2001). NUTRIENT USE EFFICIENCY IN PLANTS. Communications in Soil Science and Plant Analysis, 32(7–8). 921–50. DOI:10.1081/CSS-100104098.

EEA (2018). Agricultural land: nitrogen balance. European Environment Agency. <https://www.eea.europa.eu/airs/2018/natural-capital/agricultural-land-nitrogen-balance>. Briefing.

¹⁵ Eurostat (2019). Population on 1st January by age, sex and type of projection (proj_15npms).

⁶ An intriguing possibility is that ammonia would find new uses in a low-CO₂ economy. If ammonia production can be rendered CO₂-free, then ammonia itself is free of carbon, and could be used not just as an input to fertiliser, but as a fuel. The main use would be in transportation, and in particular long-distance shipping, where it could be an alternative to biofuels, or to synthetic fuels made from CO₂. In this study, we have not speculated on this entirely new potential demand source, but the solutions for low-CO₂ production would be the same as those described here.

¹⁷ EU emission factor used for the calculations is 350 g CO₂/kWh

DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.

¹⁸ Brown, T. (2016). Ammonia production causes 1% of total global GHG emissions. AMMONIA INDUSTRY, 26 April. <https://ammoniaindustry.com/ammonia-production-causes-1-percent-of-total-global-ghg-emissions/>.

- ¹⁹ Zakkour, P. and Cook, G. (2010). CCS Roadmap for Industry: High-purity CO₂ sources Sectoral Assessment – Final Report. DOI:10.13140/rg.2.1.3717.8722.
- ²⁰ ICIS (2010). Urea Production and Manufacturing Process. Icis. <https://www.icis.com/explore/resources/news/2007/11/07/9076560/urea-production-and-manufacturing-process>.
- ²¹ Another option would be to change diets. As noted above, the amount of fertiliser required varies significantly between different foodstuffs, with meat among the most demanding. Changes to diets happen continuously, and no doubt food intake in 2050 will look different from today. However, this study has deliberately focussed on solutions that do not involve any perceived ‘sacrifice’ on the part of consumers, and as a conservative assumption it therefore does not make any of the pathways to net-zero emissions dependent on behavioural change.
- ²² Eurostat (2015). Agri-environmental indicator - mineral fertiliser consumption - Statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_mineral_fertiliser_consumption.
- ²³ Assuming 3 tonne food per hectare using 64 kg of fertilisers (wheat as approximation of yield per ha)
- Baligar, V. C., Fageria, N. K. and He, Z. L. (2001). NUTRIENT USE EFFICIENCY IN PLANTS. Communications in Soil Science and Plant Analysis, 32(7–8). 921–50. DOI:10.1081/CSS-100104098.
- ²⁴ Stenmarck, Å., Jensen, C., Quedsted, T., Moates, G., Buksti, M., et al. (2016). Estimates of European Food Waste Levels. <http://edepot.wur.nl/378674>.
- ²⁵ European Commission (2016). EU actions against food waste. Food Safety - European Commission, 17 October. https://ec.europa.eu/food/safety/food_waste/eu_actions_en. Text.
- ²⁶ Stenmarck, Å., Jensen, C., Quedsted, T., Moates, G., Buksti, M., et al. (2016). Estimates of European Food Waste Levels. <http://edepot.wur.nl/378674>.
- ²⁷ Lammel, J. and Brentrup, F. (2017). Input from Yara to the public consultation on Ireland’s first national mitigation plan. 26.
- ²⁸ EU Nitrogen Expert Panel (2015). Nitrogen Use Efficiency (NUE) - an indicator for the utilization of nitrogen in agriculture and food systems. <http://www.eunep.com/wp-content/uploads/2017/03/Report-NUE-Indicator-Nitrogen-Expert-Panel-18-12-2015.pdf>.
- ²⁹ DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.
- 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/Ellen-MacArthurFoundation_Growth-Within_July15.pdf.
- IEAGHG (2017). IEAGHG technical report 2017 - 03. https://ieaghg.org/exco_docs/2017-03.pdf.
- ³⁰ IEAGHG (2017). IEAGHG technical report 2017 - 03. https://ieaghg.org/exco_docs/2017-03.pdf.
- ³¹ The estimated cost is 55-80% higher than the two main routes included in the pathways based on a biomass price of 40 Euro/MWh and CAPEX included for both the SMR+Haber-Bosch unit and a gasification plant for biomass.
- ³² IEAGHG (2017). IEAGHG technical report 2017 - 03. https://ieaghg.org/exco_docs/2017-03.pdf.
- ³³ See Steel chapter for more discussion of hydrogen production routes.
- ³⁴ DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V., Alexis Michael Bazzanella and Florian Ausfelder (2017). Low carbon energy and feedstock for the European chemical industry. 168.
- ³⁵ Global CCS Institute (2010). 3.1 High-purity CO₂ sources | Global CCS Institute. https://hub.globalccsinstitute.com/publications/carbon-capture-and-storage-industrial-applications-technology-synthesis-report/31-high#c03_tbl_001.
- ³⁶ Estimates this at 1.6 MJ/Nm³ H₂ produced. Other options include switching low-temperature CO₂ separation and membrane technology applied on the tail gases from the pressure swing adsorption (PSA) process. This technology decreases natural gas consumption slightly and can increase production of H₂. A third option is to switch to a H₂ rich fuel instead of natural gas as supplementary fuel for the SMR burners. Capturing just the process CO₂ then gives a possible capture rate of ~64%. A final option is methane pyrolysis, which is under development but less mature than other capture technologies.
- IEAGHG (2017). IEAGHG technical report 2017 - 03. https://ieaghg.org/exco_docs/2017-03.pdf.
- ³⁷ In contrast, energy for compression is required for many more hours per year, so is assumed to come at a higher price of €60 per MWh.

CHAPTER 4

¹ Calculated based on a production volume of 167 Mt cementitious product per year based on WBCSD (2016) for EU 2015, an EU population of 508 million in 2015 according to Eurostat (2015), and an average cement content of 10-15% in concrete, based on binder intensity data in Favier et al. (2018).

WBCSD Cement Sustainability Initiative (2016). *Getting the Numbers Right (GNR) Project, Emission Report 2016*. <http://www.wbcsdcement.org/GNR-2016/index.html>.

Eurostat (2015). First population estimates: EU population up to 508.2 million at 1 January 2015. <https://ec.europa.eu/eurostat/documents/2995521/6903510/3-10072015-AP-EN.pdf/d2bfb01f-6ac5-4775-8a7e-7b104c1146d0>.

Euroslag (2016a). Euroslag Statistics 2016. <https://www.euroslag.com/wp-content/uploads/2019/01/Statistics-2016.pdf>.

Favier, A., De Wolf, C., Scrivener, K. L. and Habert, G. (2018). A sustainable future for the European Cement and concrete industry. https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf.

² Steel use in the construction sector is based on Eurofer (2018) and includes 100% of 'Construction', and about 50% of 'Tubes' and 10% of 'Metalware'.

EUROFER (2018). *European Steel in Figures 2018*. European Steel Association (EUROFER). <http://www.eurofer.org/News%26Events/PublicationsLinksList/201806-SteelFigures.pdf>.

³ This is the total production volume of cementitious products in the EU28 according to WBCSD (2016). It includes grey and white cementitious products.

WBCSD Cement Sustainability Initiative (2016). *Getting the Numbers Right (GNR) Project, Emission Report 2016*. <http://www.wbcsdcement.org/GNR-2016/index.html>.

⁴ Direct added value of the cement industry is based on 'gross value added to the economy' for the cement sector based on CEMBUREAU (2017).

CEMBUREAU (2017). Key facts & figures. <https://cembureau.eu/cement-101/key-facts-figures/>.

⁵ There are around 200 cement kilns in the EU28 according to the EEA PRTR database by the European Environment Agency (2016). If including grinding plants, this number would rise to about 343 according to Cemnet (2017).

Cemnet (2017). The Global Cement Report - Online Database of Cement Plants. *CemNet.com the home of International Cement Review*. <https://www.cemnet.com/global-cement-report/>. Cement statistics.

The European Environment Agency (EEA) (2016). E-PRTR. *European Pollutant Release and Transfer Register*. <https://prtr.eea.europa.eu/#/facilitylevels>. European pollutant database.

⁶ The capital cost of a new cement plant is €196 million based on IEAGHG (2013). The study was done by the European Cement Research Academy.

IEAGHG (2013). *Deployment of CCS in the Cement Industry*. IEAGHG. https://ieaghg.org/docs/General_Docs/Reports/2013-19.pdf.

⁷ CEMBUREAU (2013). *The Role of Cement in the 2050 Low Carbon Economy*. <http://lowcarboneyconomy.cembureau.eu/>.

⁸ The values for the concrete industry are based on CEMBUREAU (2017) and have been calculated by subtracting the value of the cement industry from the combined cement and concrete industry since no data was given for only the concrete industry.

CEMBUREAU (2017). Key facts & figures. <https://cembureau.eu/cement-101/key-facts-figures/>.

⁹ The total production volume of 167 Mt cementitious product per year is based on WBCSD (2016) for EU 2015 while the split between different uses are based on Favier et al (2018).

WBCSD Cement Sustainability Initiative (2016). *Getting the Numbers Right (GNR) Project, Emission Report 2016*. <http://www.wbcsdcement.org/GNR-2016/index.html>.

Favier, A., De Wolf, C., Scrivener, K. L. and Habert, G. (2018). A sustainable future for the European Cement and concrete industry. https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf.

¹⁰ WBCSD Cement Sustainability Initiative (2016). *Getting the Numbers Right (GNR) Project, Emission Report 2016*. <http://www.wbcsdcement.org/GNR-2016/index.html>.

¹¹ Material Economics analysis based on multiple sources, including:

WBCSD Cement Sustainability Initiative (2016). *Getting the Numbers Right (GNR) Project, Emission Report 2016*. <http://www.wbcsdcement.org/GNR-2016/index.html>.

Favier, A., De Wolf, C., Scrivener, K. L. and Habert, G. (2018). A sustainable future for the European Cement and concrete industry. https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf.

Betonginitiativet and Fossilfritt Sverige (2018). Färdplan för klimatneutralkonkurrenskraft: Betongbranschen.

¹² Current production is based on WBCSD (2016). Emissions include direct and indirect emissions from cement production. Direct emission factor of cement has been calculated by using the direct emission factor and clinker-to-cement ratio from WBCSD (2016). Indirect emissions have been calculated by using electricity usage of cement based on

WBCSD (2016) and an average EU electricity CO₂ emission factor of 0.35 tCO₂/MWh based on the International Energy Agency (2017).

Future production is based on cement demand model that expects underlying cement demand to increase 10% from today until 2050, as described in Material Economics (2018). Emission factor of cement in a baseline scenario is expected to decrease because of continuing energy efficiency improvements in the cement industry as well as decarbonized power sector eliminating indirect emissions.

WBCSD Cement Sustainability Initiative (2016). *Getting the Numbers Right (GNR) Project, Emission Report 2016*. <http://www.wbcsdcement.org/GNR-2016/index.html>.

International Energy Agency (2017b). World Energy Outlook 2017. www.iea.org.

Material Economics (2018). *The Circular Economy - A Powerful Force for Climate Mitigation*.

¹³ CEMBUREAU (2013). *The Role of Cement in the 2050 Low Carbon Economy*. <http://lowcarboneyconomy.cembureau.eu/>.

European Commission (2011). *COMMISSION STAFF WORKING PAPER Impact Assessment*. Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Energy Roadmap 2050. https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf.

¹⁴ Data is for all non-metallic minerals.

European Commission (2011). *COMMISSION STAFF WORKING PAPER Impact Assessment*. Accompanying the document COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Energy Roadmap 2050. https://ec.europa.eu/energy/sites/ener/files/documents/sec_2011_1565_part2.pdf.

¹⁵ International Energy Agency (2017a). Energy Technology Perspectives 2017. www.iea.org/etp2017.

¹⁶ Material Economics (2018). *The Circular Economy - A Powerful Force for Climate Mitigation*.

Favier, A., De Wolf, C., Scrivener, K. L. and Habert, G. (2018). A sustainable future for the European Cement and concrete industry. https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf.

Shanks, W., Dunant, C. F., Drewniok, M. P., Lupton, R. C., Serrenho, A. and Allwood, J. M. (2019). How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling*, 141. 441–54. DOI:10.1016/j.resconrec.2018.11.002.

John, V. M., Damineli, B. L., Quattrone, M. and Pileggi, R. G. (2018). Fillers in cementitious materials — Experience, recent advances and future potential. *Cement and Concrete Research*, 114. 65–78. DOI:10.1016/j.cemconres.2017.09.013.

Scrivener, K. L., John, V. M. and Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry. *Cement and Concrete Research*, . DOI:10.1016/j.cemconres.2018.03.015.

¹⁷ Material Economic analysis based on Material Economics (2018), Favier et al. (2018), Scrivener, John et al. (2018), Shanks et al. (2019), and WBCSD (2016).

Material Economics (2018). *The Circular Economy - A Powerful Force for Climate Mitigation*.

Favier, A., De Wolf, C., Scrivener, K. L. and Habert, G. (2018). A sustainable future for the European Cement and concrete industry. https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf.

Scrivener, K. L., John, V. M. and Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO₂ cement-based materials industry. *Cement and Concrete Research*, . DOI:10.1016/j.cemconres.2018.03.015.

Shanks, W., Dunant, C. F., Drewniok, M. P., Lupton, R. C., Serrenho, A. and Allwood, J. M. (2019). How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling*, 141. 441–54. DOI:10.1016/j.resconrec.2018.11.002.

WBCSD Cement Sustainability Initiative (2016). *Getting the Numbers Right (GNR) Project, Emission Report 2016*. <http://www.wbcsdcement.org/GNR-2016/index.html>.

¹⁸ The relevant standard is norm EN 206-1 and the national annexes to this. Most of the concrete used in the EU is subject to a minimum standard of 300 kg cement for commonly used exposure classes. See Müller (2012).

Müller, C. (2012). Use of cement in concrete according to European standard EN 206-1. *HBRC Journal*, 8(1). 1–7. DOI:10.1016/j.hbrj.2012.08.001.

¹⁹ Favier, A., De Wolf, C., Scrivener, K. L. and Habert, G. (2018). A sustainable future for the European Cement and concrete industry. https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf.

²⁰ Favier, A., De Wolf, C., Scrivener, K. L. and Habert, G. (2018). A sustainable future for the European Cement and concrete industry. https://europeanclimate.org/wp-content/uploads/2018/10/AB_SP_Decarbonisation_report.pdf.

- ²¹ Damineli, B. L., Kemeid, F. M., Aguiar, P. S. and John, V. M. (2010). Measuring the eco-efficiency of cement use. *Cement and Concrete Composites*, 32(8). 555–62. DOI:10.1016/j.cemconcomp.2010.07.009.
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INDUSTRIAL TRANSFORMATION 2050

Pathways to Net-Zero Emissions from EU Heavy Industry



There is intense debate about how to close the gap between current climate policy and the aim of the Paris Agreement to achieve close to net-zero emissions by mid-century. Heavy industry holds a central place in these discussions. The materials and chemicals it produces are essential inputs to major value chains: transportation, infrastructure, construction, consumer goods, agriculture, and more. Yet their production also releases large amounts of CO₂ emissions: more than 500 Mt per year, or 14% of the EU total.

Policymakers and companies thus have a major task ahead. There is an urgent need to clarify what it would take to reconcile a prosperous industrial base with net zero emissions, and how to get there in the 30 remaining years to 2050.

This study seeks to support these discussions. It characterises how net zero emissions can be achieved by 2050 from the largest sources of 'hard to abate' emissions: steel, plastics, ammonia, and cement. The approach starts from a broad mapping of options to eliminate fossil CO₂-emissions from production, including many emerging innovations in production processes. Equally important, it integrates these with the potential for a more circular economy: making better use of the materials already produced, and so reducing the need for new production. Given the uncertainties, the study explores several different 2050 end points as well as the pathways there, in each case quantifying the cost to consumers and companies, and the requirements in terms of innovation, investment, inputs, and infrastructure.

MATERIAL ECONOMICS