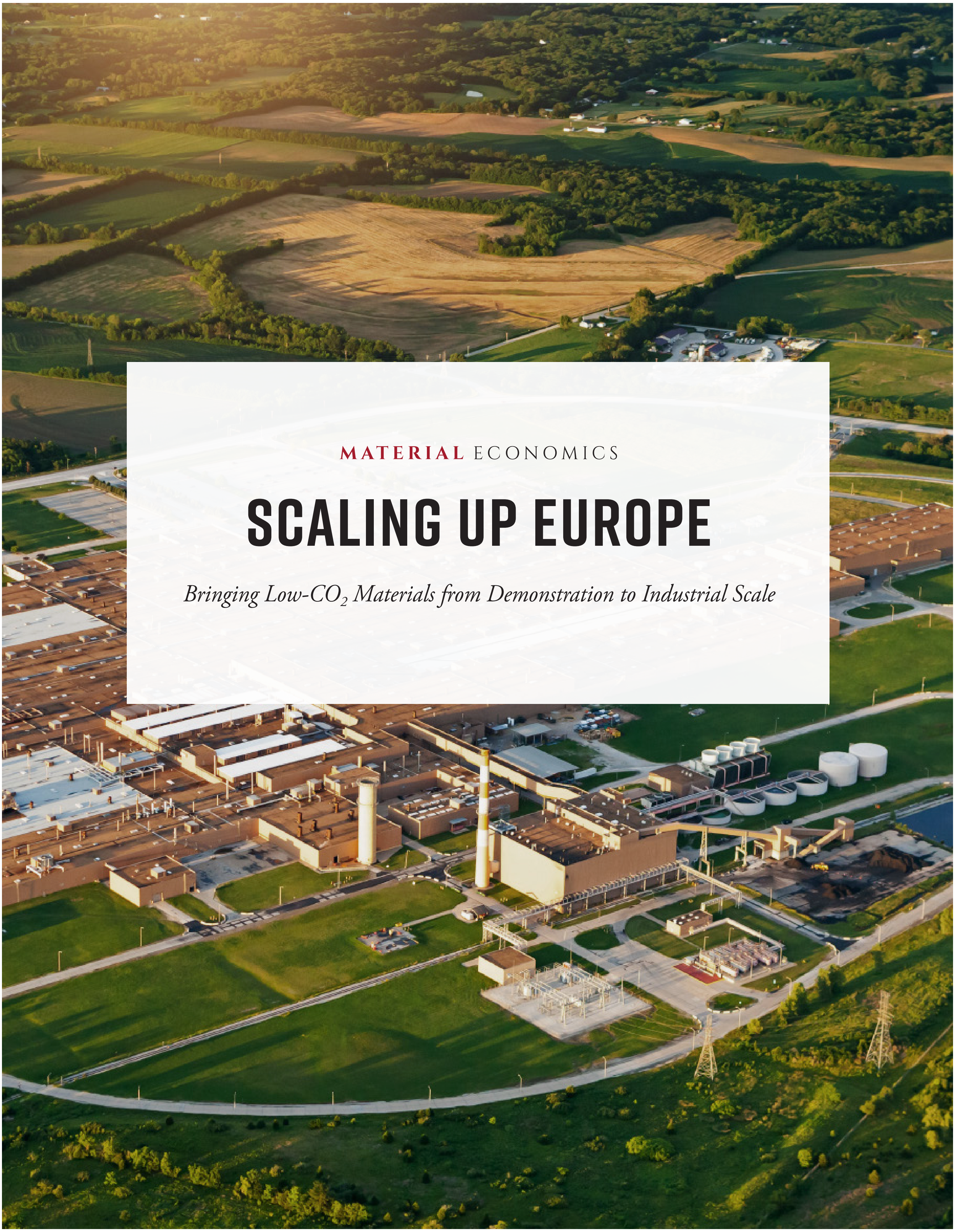


MATERIAL ECONOMICS

SCALING UP EUROPE

Bringing Low-CO_2 Materials from Demonstration to Industrial Scale

Commissioned by

Breakthrough Energy

MATERIAL ECONOMICS

SCALING UP EUROPE

Bringing Low-CO_2 Materials from Demonstration to Industrial Scale

Publication details

Please refer to this report as: Material Economics (2022). Scaling Up Europe.

PREFACE

Energy-intensive industries are a key piece of the puzzle as Europe seeks to transition to an economy with net zero greenhouse gases. Decarbonising industry is critical to EU climate targets and EU competitiveness. With Europe using more than 700 million tonnes of often-imported raw materials and energy inputs each year, industry is also central to an increasingly urgent debate about strategic autonomy.

Several "roadmaps" have already outlined what a net-zero industry could look like in 2050, showing the need for profound changes in the decades to come. This report shows that the future is already here. European companies are already moving from roadmap to action, with some 70 projects underway to commercialise and scale up new, breakthrough industrial production of steel, chemicals and cement/concrete. Key investment decisions will be made already in the next few years.

This report takes the pulse of that exciting development. We consulted with more than 30 companies and other organisations and found a real sense of opportunity – but also reasons for concern. There is a widening gap between industrial innovators' cleantech ambitions, and the policy and market conditions required to realise them at scale. If Europe is to harness this extraordinary potential, it needs not just targets and a vision towards 2050, but a concrete plan for the 2020s.

The analysis presented here can help define that plan. We describe the breakthrough projects being advanced by industrial cleantech pioneers, as well as the barriers they face in scaling up. Without proposing specific policies approaches, we then identify five core policy areas can be woven together for European companies to succeed in their ambitions to scale up. Our hope is to provide useful data and perspective to inform the ongoing revisions of EU and national policies.

This study was conducted by Material Economics, with support from Breakthrough Energy and in collaboration with the Mission Possible Partnership, the European University Institute Florence, Cleantech for Europe, and the International Energy Agency. We thank our partners and the more than 30 companies and organisations that shared their valuable insights. The findings of this report are those of the authors and do not necessarily reflect those of our partners or of the stakeholders consulted. Any remaining omissions or mistakes are of course the authors' own.

Per Klevnäs
Partner

Per-Anders Enkvist
Managing Partner

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Low-CO_2 materials – steel, cement, chemicals and more – are indispensable for EU climate targets. They also are a massive economic opportunity for European industries, which can tap into an emerging global market that could reach 100 USD billion by 2030. European companies now lead in this space, with more than 70 industrial projects with breakthrough clean technologies planned across the continent. Yet for all the promising entrepreneurial activity, policies and market conditions are not yet ready to seize this opportunity. The crucial step to industrial scale has yet to come, and final investment decisions are still pending. The EU and European countries urgently need to adopt a policy package and innovative financing mechanisms to put heavy industries on a path towards net zero – and, in the process, secure European industrial competitiveness for decades to come.

EUROPEAN ENERGY-INTENSIVE INDUSTRIES ARE MAKING BOLD MOVES

Something big is afoot in European energy-intensive industries. The normally slow-moving sectors of steel, chemicals and cement are now abuzz with innovation. More than 70 projects have been announced just in the last two or three years to bring new, clean technologies and business models online. They aim to produce steel with hydrogen instead of coal; use recycled plastics as feedstock to make chemicals; pioneer new types of concrete with less than half the climate impact of today's products; and capture carbon from industrial processes to be stored permanently underground or reused to make high-value products. Together, these breakthrough technologies could transform industrial production in the EU.

The impetus for all this innovation is the EU's commitment to a low-CO_2 future. Companies know their current trajectory collides with EU climate targets: CO_2 emissions from energy-intensive industries have been stuck at around 650 Mt CO_2 for many years. To achieve deep emission reductions, they need to change the fundamentals of production: make steel, chemicals and cement with different feedstock, invest in new core capital assets and novel business models, and mobilise massive amounts of clean energy. After years of development, the key technologies are largely known and increasingly ready to deploy. The challenge is to bring them to industrial scale in the real world.

European industry is rising to the challenge. The steel sector has its first major new entrants in several decades; more than a dozen start-ups are turning waste plastics into chemicals feedstock; companies want to launch entirely new concrete products; and technology companies are providing a wide range of novel solutions. Innovation is happening in all major EU regions, often through value chain collaborations between industrial companies and end-users. This could be a step-change for industry.

AN ECONOMIC OPPORTUNITY FOR EUROPE

Europe has every reason to support this effort to remake heavy industries. The steel, chemicals and cement sectors underpin value chains that together contribute as much as 14% of EU GDP and 7.4 million jobs. The current energy and geopolitical crisis only underlines the need to find ways to increase Europe's strategic autonomy in basic materials. The same technologies that cut CO_2 also enable increased use of indigenous resources: renewable electricity, green hydrogen, and circular use of steel and plastics in place of imported ores, coal, oil and gas.

European industry can also benefit from a fast-growing new market for low-CO_2 materials. Already, thousands of companies, cities and other actors globally have committed to sharply reduce their CO_2 footprint under initiatives such as the Science-Based Targets and the First Movers Coalition. As these companies decarbonise their supply chains, we estimate that by 2030, the market for low-CO_2 steel, chemicals (including plastics) and cement will reach 100 billion USD. These buyers will reward innovators and trailblazers. Europe is now ahead in this market and can seize this opportunity to secure its lead and set the standards.

Europe should thus work to rapidly scale up breakthrough technologies: get the first-generation, industrial-scale plants online by 2025, and fully redirect capital flows towards new low-CO_2 technologies by 2030. By mobilising 31-37 EUR billion of investment, Europe could ramp up production of 25 Mt steel, 2.5 Mt of high-value chemicals made from recycled plastics feedstock, 5 Mt of high-value chemicals produced with CCUS and 130 Mt of low-CO_2 concrete (equivalent to 20 Mt of cement) per year by 2030. To give a sense of the scale, in a single year, this would provide enough steel for 22 million cars, recycled plastics for ~15%

of plastics packaging in Europe, putting CCUS on 50% of the crackers in 8 clusters and enough concrete for 600 000 houses. The benefit would be massive, cutting 2030 emissions by 43 Mt CO_2 per year, creating 30 EUR billion worth of low-CO_2 materials, and positioning EU industry for global leadership.

EUROPE NEEDS TO ACT FAST TO CAPTURE THIS INDUSTRIAL OPPORTUNITY

Europe is not yet positioned to realise that potential, however. Stakeholders consulted for this study pointed to two concerns. First of all, the projects currently in the pipeline are not enough to reach the needed scale. Only in steel are there proposals for large-scale projects across the sector. Second, final investment decisions on many of the proposed projects are still pending. Stakeholders are awaiting confirmation that the business case can work and that the necessary finance, energy supply and infrastructure can be put in place. Time is short: key investment decisions are due within two or three years.

Without prompt action, Europe risks falling into old traps: leading in the early stages of technology development, but failing to follow through to scale. Stakeholders identified several challenges that need to be addressed. The current CO_2 prices are not effective in generating revenues for clean production, so companies risk being left without an answer when investors ask how they will pay for new low-CO_2 investments. Early movers need to manage the risk of untested new technologies, and overcome a powerful incentive to wait for others to take the first step. Producers and buyers alike need clear standards as well as lead markets pull to create the lead market on which new businesses can be built. Companies will need to obtain operating permits for new facilities faster than current systems can achieve, and secure access to the new energy supplies and infrastructure they need. Regulations need to be updated to ensure they do not keep innovations and new entrants out of the market.

In short, Europe must learn and act fast, or else it could lose this opportunity.

MAKING THE 2020S THE DECADE OF ACTION

The EU has a chance to solve these problems as part of the ongoing revamp of policy and regulations under the Green Deal and in response to new geopolitical and energy realities. If Europe wants to seize this opportunity, it needs to adopt a clear vision for transforming heavy industry, at scale, and then develop a comprehensive, coherent policy agenda to achieve it. Our analysis identifies five pillars of a successful industrial transformation:

1. Overcome the green cost premium and create lead markets. Especially for the first-of-a-kind projects, companies face a green cost premium of 100–150 EUR per tonne CO_2. While many see a clear route to competitiveness, the current lack of effective CO_2 prices for industry leaves a hole in the business case for clean industrial production. Proposed reforms to the EU Emissions Trading System, combined with carbon border adjustments, could address this in the long term, but likely not before the 2030s. An answer for the 2020s is therefore needed. Proposals under discussion include the free allocation of EU ETS allowances to non-emitters, subsidies such as carbon contracts for difference, and quotas for the use of recycled content in plastics. All told, we estimate a revenue gap in the range of 4–6 billion EUR per year by 2030. For comparison, annual support to biomass, wind and solar energy is 16–27 billion EUR each, while free allocation in the EU ETS is worth closer to 60 billion EUR per year.

2. Enable investment for innovation. European companies must invest 40–50 billion EUR in industrial production to 2030 to scale up breakthrough technologies. First movers create tremendous value through reference plants and experience on which further scaling and innovation can be built. Yet they are rarely rewarded for this, and instead face large, often undiversifiable risks in bringing new technology and business models to market. This creates a powerful incentive to wait until costs fall and risks are smaller. Public support can go a long way to bridge the financing gap, and both the EU and European countries are exploring mechanisms such as capex grants, loan guarantees to mobilise private finance, and blended finance derisking approaches to enable a more favourable capital structure.

3. Mobilise demand for green materials and chemicals. As noted, there is powerful latent demand for low-CO_2 products and value chains. Companies in automotive, packaging, construction and other sectors know that the additional cost even of fully decarbonised products can be minimal, often just 1–2% on the 2030 sales price, as the share of materials in the total production cost of a complex product is often small. Policy can support this nascent market. Stakeholders pointed to a range of potential options: 2030 production targets for green materials that help coordinate supply and demand; ambitious standards that define and differentiate green, breakthrough materials and can underpin a market premium; and public and private initiatives that drive demand for low-CO_2 materials, such as the limits for CO_2 content of construction materials now being introduced by some European countries.

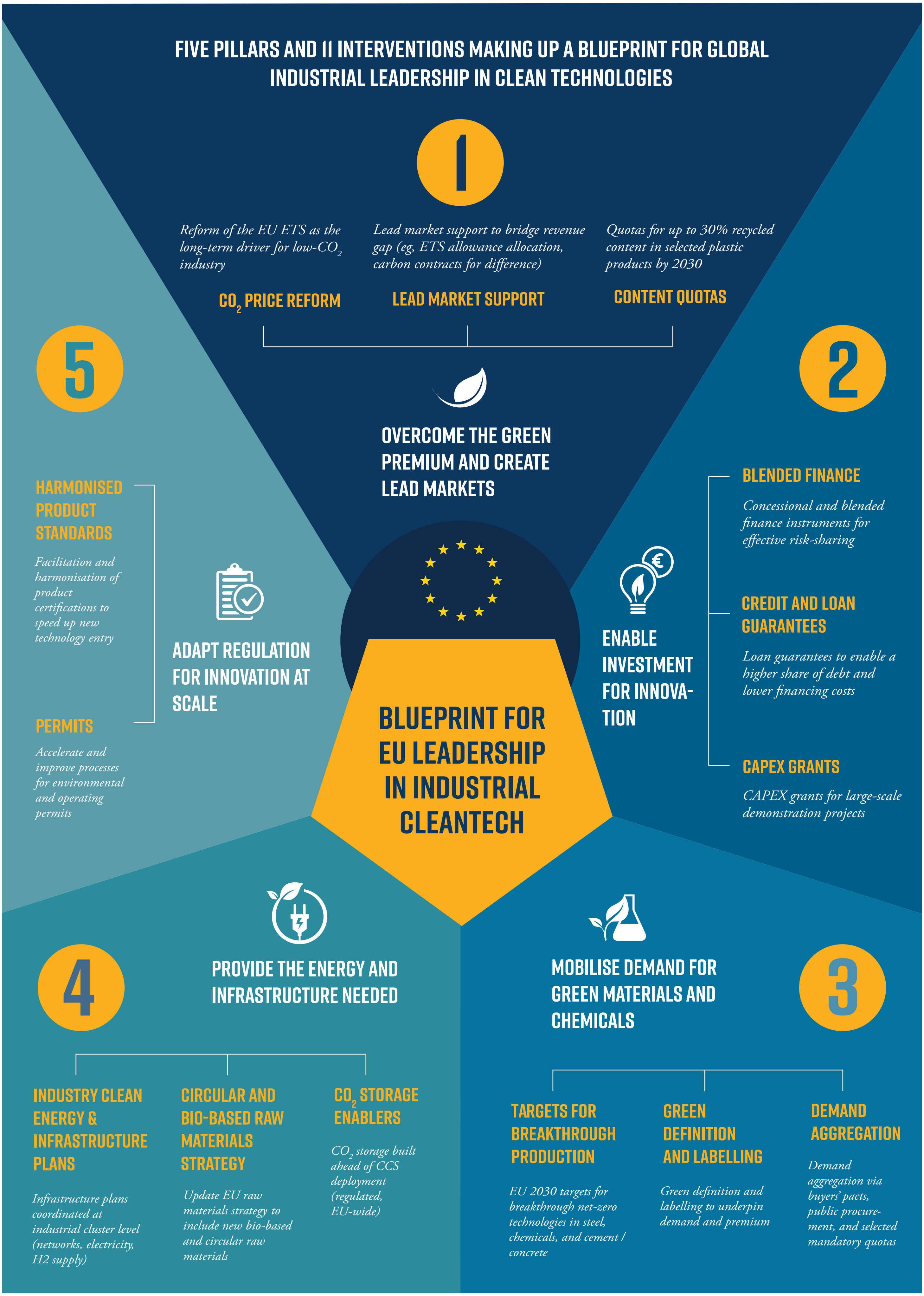
4. Provide the energy and infrastructure needed. Now more than ever, Europe clearly sees the value in mobilising its own energy and raw material resources. Industrial production is no exception. We estimate that scaling up industrial cleantech would require 90 TWh of additional low-CO_2 electricity, 20 TWh of low-CO_2 hydrogen, 10–15 Mt of storage capacity for industrial CO_2, and the effective recycling of another 10 Mt of plastic waste for use as feedstock in place of oil and gas. EU and national energy and infrastructure plans do not yet anticipate such large requirements. Europe needs climate and energy plans to serve the industrial clusters of the future, including prioritised access to clean hydrogen to reduce future reliance on imported gas by European steel and chemicals industries. It also needs a circular and bio-based raw materials strategy, to enable effective replacement of imported fossil energy and feedstock, as well as a CO_2 storage strategy that accounts for industrial needs.

5. Adapt regulations for innovation at scale. Post-war Europe saw the build-out of the current industrial base and infrastructure, creating many of today's industrial champions. But since the 1980s, Europe has lost its appetite and capacity for ambitious new industrial capacity and infrastructure, with national regulations tuned for slow change but unsuited to rapid transformation. To succeed, stakeholders say a new regime and social contract is needed: permitting processes that are streamlined and more predictable, new products permitted to enter the market rather than held back by legacy product standards, and new regulatory frameworks created to build the new infrastructure required – from CO_2 storage to hydrogen pipelines.

FAST-FORWARD TO THE FUTURE EUROPEAN INDUSTRY

The emergence of more than 70 breakthrough industrial projects in just a few years is truly inspiring. It provides line of sight to a competitive, low-CO_2, and much more autonomous future industry. There is every reason for optimism that a low-CO_2 transition will play to many European industrial strengths. European steel and chemicals companies have already gravitated towards high value-add niches over time, with innovation as the key antidote to other structural disadvantages, such as higher energy or feedstock prices. The same skillset will be key to the low-CO_2 transition. Where Europe has succeeded in the past – such as in mobile telephony, pharmaceuticals and automotive – it has combined tightly integrated innovation systems, leadership in setting standards, and clusters of initial domestic demand that can form the base for scaling to global markets.

If Europe can apply the same formula to its basic materials industries, it can unlock a major economic opportunity for the next few decades.



FIVE PILLARS AND 11 INTERVENTIONS MAKING UP A BLUEPRINT FOR GLOBAL INDUSTRIAL LEADERSHIP IN CLEAN TECHNOLOGIES
1
Reform of the EU ETS as the long-term driver for low-CO_2 industry
Lead market support to bridge revenue gap (eg, ETS allowance allocation, carbon contracts for difference)
Quotas for up to 30% recycled content in selected plastic products by 2030
CO_2 PRICE REFORM
LEAD MARKET SUPPORT
CONTENT QUOTAS
OVERCOME THE GREEN PREMIUM AND CREATE LEAD MARKETS
2
BLENDED FINANCE
Concessional and blended finance instruments for effective risk-sharing
CREDIT AND LOAN GUARANTEES
Loan guarantees to enable a higher share of debt and lower financing costs
CAPEX GRANTS
CAPEX grants for large-scale demonstration projects
ENABLE INVESTMENT FOR INNOVA-TION
5
HARMONISED PRODUCT STANDARDS
Facilitation and harmonisation of product certifications to speed up new technology entry
PERMITS
Accelerate and improve processes for environmental and operating permits
ADAPT REGULATION FOR INNOVATION AT SCALE
BLUEPRINT FOR EU LEADERSHIP IN INDUSTRIAL CLEANTECH
4
PROVIDE THE ENERGY AND INFRASTRUCTURE NEEDED
INDUSTRY CLEAN ENERGY & INFRASTRUCTURE PLANS
Infrastructure plans coordinated at industrial cluster level (networks, electricity, H2 supply)
CIRCULAR AND BIO-BASED RAW MATERIALS STRATEGY
Update EU raw materials strategy to include new bio-based and circular raw materials
CO_2 STORAGE ENABLERS
CO_2 storage built ahead of CCS deployment (regulated, EU-wide)
3
MOBILISE DEMAND FOR GREEN MATERIALS AND CHEMICALS
TARGETS FOR BREAKTHROUGH PRODUCTION
EU 2030 targets for breakthrough net-zero technologies in steel, chemicals, and cement / concrete
GREEN DEFINITION AND LABELLING
Green definition and labelling to underpin demand and premium
DEMAND AGGREGATION
Demand aggregation via buyers' pacts, public procure-ment, and selected mandatory quotas

1. THE IMPERATIVE AND OPPORTUNITY OF LOW-CARBON MATERIALS

SOMETHING BIG IS AFOOT IN EUROPE'S ENERGY-INTENSIVE INDUSTRIES.

Six years ago, SSAB, a Swedish steelmaker, announced a bold move: rather than reinvest in its existing coal-based production, it would launch an initiative jointly with mining company LKAB and electric utility Vattenfall to develop entirely new steelmaking technology based on hydrogen.[2] This proved to be a sign of things to come. Optimistic about the underlying technology and the future of green hydrogen, virtually all major EU steelmakers (ArcelorMittal, Liberty Steel, Salzgitter, Tata Steel, ThyssenKrupp, and Voestalpine) have launched similar initiatives, with 20 projects now underway across Europe that could transform the industry. The sector is also seeing its first new entrants in decades, including the start-up H2 Green Steel and LKAB. It is seeing new value chain collaborations – with utilities joining in the supply of hydrogen, and automotive companies investing in steel production or agreeing to long-term offtake of "green" steel. The Italian metals and mining technology company Tenova is starting to develop similar projects in China and beyond, while others already are looking to the next generation of hydrogen-based and electrified technology. Together, EU companies are leading the world in commercialising a crucial clean technology for a sector now responsible for 7% of global CO_2 emissions.[3]

"It is my belief that the next 1,000 unicorns – companies that have a market valuation over a billion dollars – won't be a search engine, won't be a media company, they'll be businesses developing green hydrogen, green agriculture, green steel and green cement"

LARRY FINK
CEO, BLACKROCK[1]

Profound shifts have also begun in the EU petrochemicals sector. More than 10 start-ups have launched 25 projects to develop and commercialise technology and supply chains that turns plastic waste into valuable feedstock for new chemicals production. Like the steelmakers, they want to create value through lower CO_2 emissions, a more circular economy, and reduced dependency on largely imported fossil fuels and feedstock. Large chemicals companies are joining forces with these start-ups, while also exploring other ways to reduce emissions. At its Terneuzen plant in the Netherlands, Dow plans to capture carbon and produce hydrogen fuel by 2026.[4] Dow and many other companies (BASF, Borealis, BP, Linde, Repsol, SABIC, Shell, Total Energies, and Versalis) are also mobilising to bring new electrified technology to market.

The cement sector is pursuing decarbonisation as well. The world's first industrial-scale carbon capture and storage (CCS) project at a cement production plant is set to open at Norcem's site in Brevik, Norway, in 2024.[5] Some 15 additional projects with similar ambitions have been proposed. Again, new, breakthrough technology is at the core. For example, new entrant technology company Calix has developed a novel kiln process that facilitates CO_2 capture.[6] Several others are finding new ways to produce valuable products from captured carbon. In addition, start-ups are working to develop new raw materials that can replace CO_2-intensive cement, such as a new concrete formulation by Ecocem that the Irish company says has one-sixteenth the carbon footprint of other cements.[7]

All in all, sectors that used to be seen as "hard to abate" are now racing ahead, with more than 70 projects underway. Timelines are fiercely ambitious, compressing what normally would be a 15- to 20-year innovation and investment cycle into just a decade. Together, they hold the keys to a reinvigorated future EU industrial base that is not only low-CO_2, but also more circular, less import-dependent and more competitive.

This study takes the pulse of this development and asks the critical question: what will it take to bring this promising initiative all the way to industrial scale – with all the benefits for climate, competitiveness, and strategic autonomy? In the chapters that follow, we examine what is at stake, what barriers stand in the way, and what EU policy-makers can do to support this breakthrough technology shift and secure Europe's leadership in low-CO_2 steel, chemicals and cement production.

1.1 AN EMERGING 100 BILLION USD MARKET FOR LOW-CARBON MATERIALS

Even as new low-CO_2 industrial materials are emerging, a growing market is eagerly awaiting them. Through initiatives such as the First Movers Coalition and the Science Based Targets Initiative, among others, thousands of businesses, cities, and others around the world have pledged to sharply reduce not just their own, direct carbon emissions, but also those in their supply chains.[8] For example, automakers covering 65% of global production have set such “Scope 3” emissions targets for net-zero supply chains.[9] They are joined by companies in appliances, renewable energy, construction, and packaged consumer goods, and more. Across sectors, a critical mass of low-CO_2 materials buyers is quickly emerging.

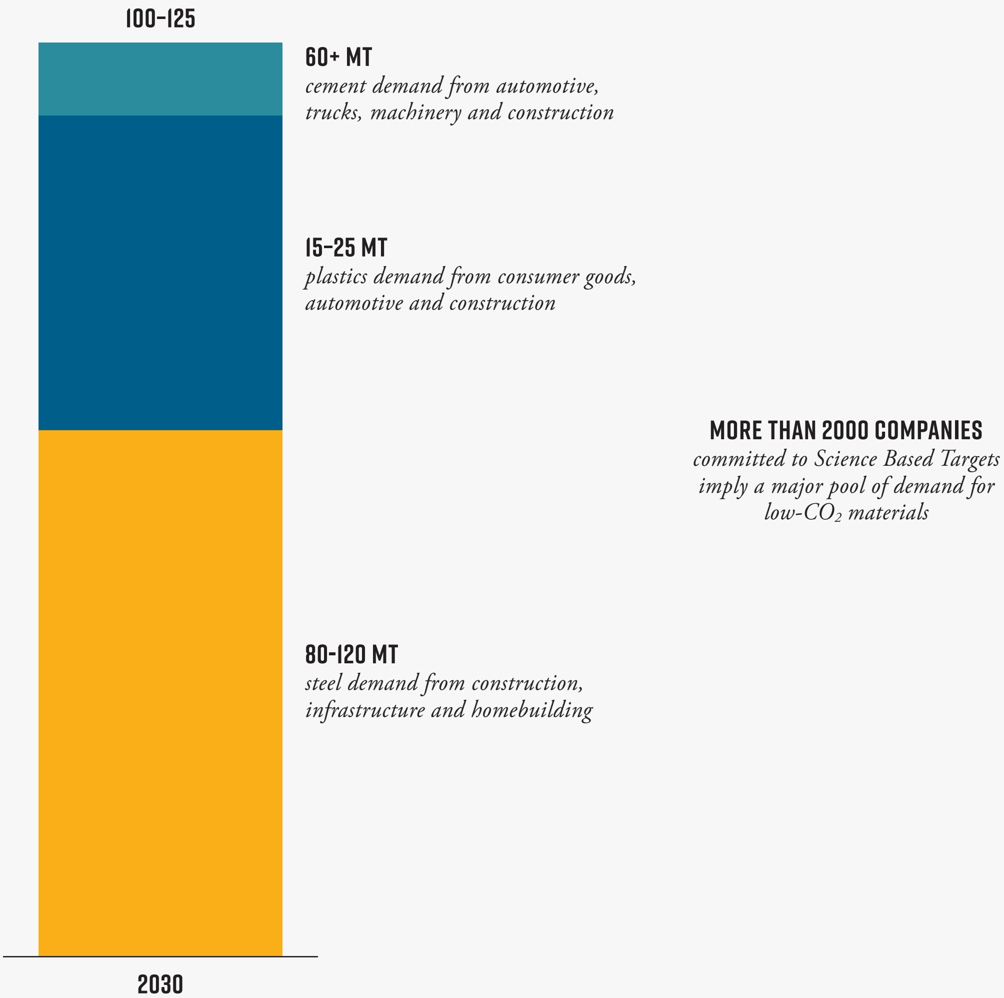
The resulting demand for low-CO_2 materials makes for a major business opportunity. Based on commitments made by more than 2,000 companies under the Science Based Targets alone, we estimate that by 2030, the global market for low-CO_2 steel, chemicals (including plastics) and cement will reach 100-125 billion USD (Exhibit 1). Demand spans multiple sectors: automotive, trucks and construction for steel; consumer goods, packaging and retail for chemicals/plastics; and cities and transport infrastructure authorities for cement. Europe leads, with half of the demand for some key categories. Adding it up, the demand for green materials is as large as Germany’s total production of these materials.[10]

As we discuss below, for now demand is growing much faster than supply. This creates an opportunity for innovators and trailblazers to benefit from early offerings in what looks set to be a decade of scarcity of green materials. It also makes it critical to put in place what is needed to bring new proposals for increased supply over the line.

Exhibit 1

AN EMERGING 100+ BILLION USD GLOBAL MARKET FOR LOW-CO_2 MATERIALS IS A MAJOR ECONOMIC OPPORTUNITY FOR EUROPE

GLOBAL 2030 MARKET FOR LOW-CO_2 MATERIALS
USD BILLION, 2030



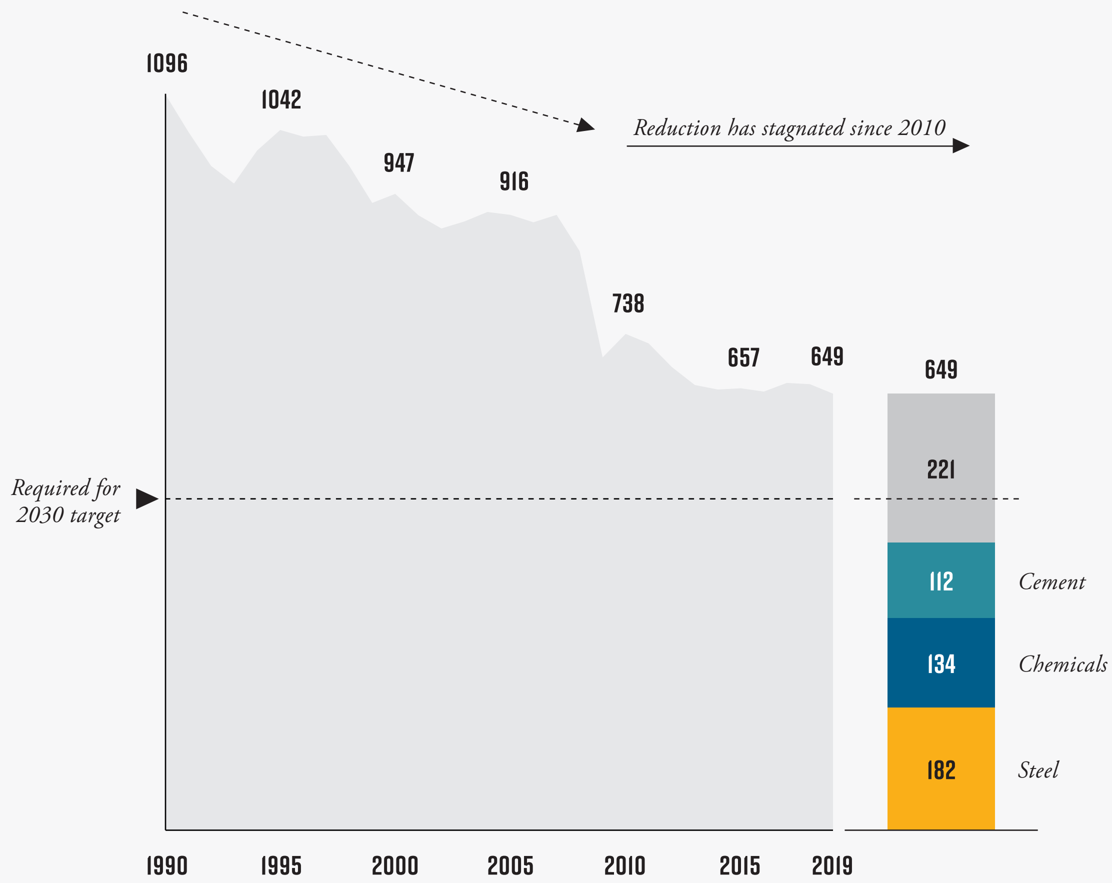
Notes: Estimates are based on the materials demand resulting from Science-Based Targets as of end of 2021.

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON REVENUE AND MATERIALS USE OF COMPANIES COMMITTED TO SCIENCE BASED TARGETS (SEE ENDNOTE).[11]

Exhibit 2

A STEP-CHANGE IS NEEDED: EMISSIONS REDUCTIONS FROM EU ENERGY-INTENSIVE INDUSTRIES HAVE STAGNATED

GREENHOUSE GAS EMISSIONS FROM EU ENERGY-INTENSIVE INDUSTRIES
MILLION TONNES OF CO_2E, EU27 AND UK, 1990-2019



SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON DATA FROM THE EU TRANSACTION LOG, SEE ENDNOTE.[12]

1.2 EU INDUSTRY FACES A CRITICAL DECADE

This business opportunity alone should be a major motivator for EU industries. But there are other compelling reasons to act as well: not only is it critical for climate targets, but also for Europe's future industrial competitiveness and strategic autonomy.

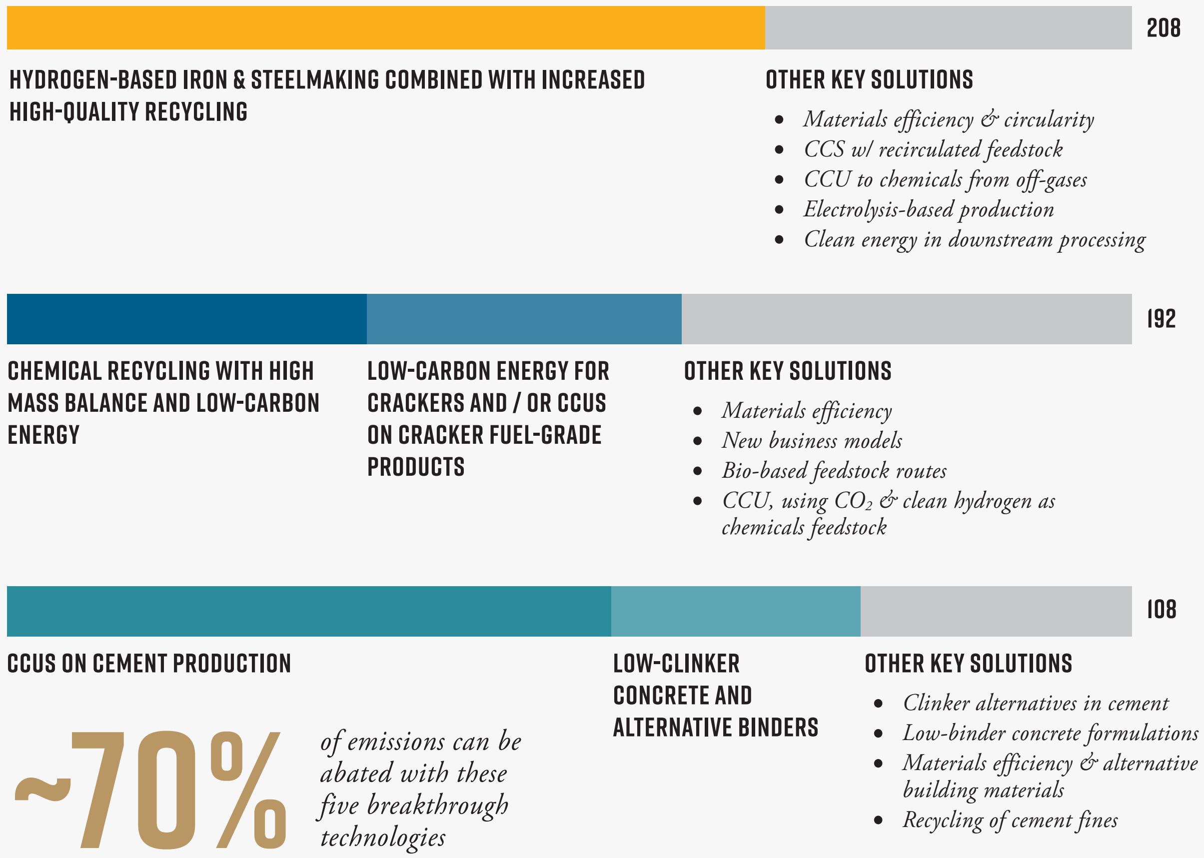
CLIMATE TARGETS REQUIRE RAPID SCALE-UP OF BREAKTHROUGH TECHNOLOGIES IN INDUSTRY

After significant reductions since 1990, CO_2 emissions from energy-intensive industries in the EU have hovered around 650 million tonnes (Mt) of CO_2 for much of the last decade (Exhibit 2). Much of the potential from energy efficiency and switching to lower-emitting fuels has already been realised. The deep emissions cuts needed to achieve net zero will instead require deploying entirely new, breakthrough technologies.

Exhibit 3

FIVE BREAKTHROUGH TECHNOLOGIES ARE KEY TO EU INDUSTRIAL TRANSFORMATION

EMISSIONS AND ABATEMENT IN 2050 NET-ZERO SCENARIOS FOR STEEL, CHEMICALS AND CEMENT
MT CO_2E PER YEAR



Note: The bars illustrate high-penetration scenarios for the selected breakthrough technologies; the contributions of other abatement measures may be larger than indicated by the grey fields. Chemical emissions in this scenario covers emissions from plastics production as well as from end-of-life treatment.

SOURCES: MATERIAL ECONOMICS SCENARIO ANALYSIS BASED ON MULTIPLE SOURCES AND PREVIOUS WORK; SEE MATERIAL ECONOMICS (2019).[14]

Several "roadmaps" have been published in the past few years showing how energy-intensive industry can get off this plateau and onto a path towards net-zero greenhouse gas emissions.[13] They show that two key things are needed. First, we need a step change in how efficiently we use and reuse materials that have already been produced – a truly circular economy. Second, we need a rapid deployment of breakthrough technologies for industrial production without greenhouse gas emissions.

The breakthrough technologies we focus on in this study are at the heart of this shift. Together they can deliver as much as 60–70% of the emission reductions needed for European steel, chemicals and cement industries to achieve net-zero emissions by mid-century (Exhibit 3). While many other approaches also will be needed, the insights from these case studies take the pulse on the cleantech shift in EU industry, shining a light on what it will take for Europe to keep its climate leadership position.

THE QUEST FOR FUTURE COMPETITIVENESS AND STRATEGIC AUTONOMY

The second imperative is to find new sources of industrial renewal and competitiveness – and to pivot to a more stable and diverse set of energy and raw materials inputs.

The energy-intensive industrial base is much more important to the EU economy than is commonly appreciated. Its direct share of GDP is only about 1%, but the broader impact is much larger, as basic materials and chemicals are the starting point of major value chains.[15] Overall, 14% of the EU's GDP is generated by sectors depending on steel, chemicals and cement to produce cars, electronics, buildings, pharmaceuticals, packaging, and more (Box 1). The strong sector links and joint innovation of these value chains are important sources of EU competitiveness far beyond the industrial materials themselves.

In recent years, however, Europe's energy-intensive industries have faced a tough set of factors. Steel and cement volumes are still below the levels before the 2008–2009 financial crisis, and in 2016, the EU became a net importer of steel for the first time.[16] This follows on structural concerns including global overcapacity, trade policies, and access to low-cost raw materials and energy sources.

More recently, energy prices have exploded, and their outlook is more uncertain than ever. For the first time since the oil crises of the 1970s, Europe has real reasons to be concerned about securing access to the energy that the current, fossil-fuel based industry requires.

In this situation, Europe's heavy industries need a new way to stand out and compete. Low-CO_2 production is a prime opportunity, as EU companies are already pioneers in the field. This is a chance to shape the industries of the future, playing to a traditional European strength: gravitating towards high-value-add niches over time, with innovation the key antidote to the structural disadvantages noted above.

The timing is particularly good, as nearly half of EU heavy industry's core assets – blast furnaces, steam crackers and cement kilns – require major investments to keep running beyond 2030. Instead of investing in legacy assets that risk being "stranded" as Europe decarbonises, companies can use the 2020s to jump-start their own low-CO_2 transitions. This means mobilising large investments to deploy breakthrough technologies, rebuild core capital assets, and adopt new inputs and novel business models – all within a few years. Massive amounts of clean energy will also be needed. It is an ambitious innovation agenda, but the payoff would be significant.

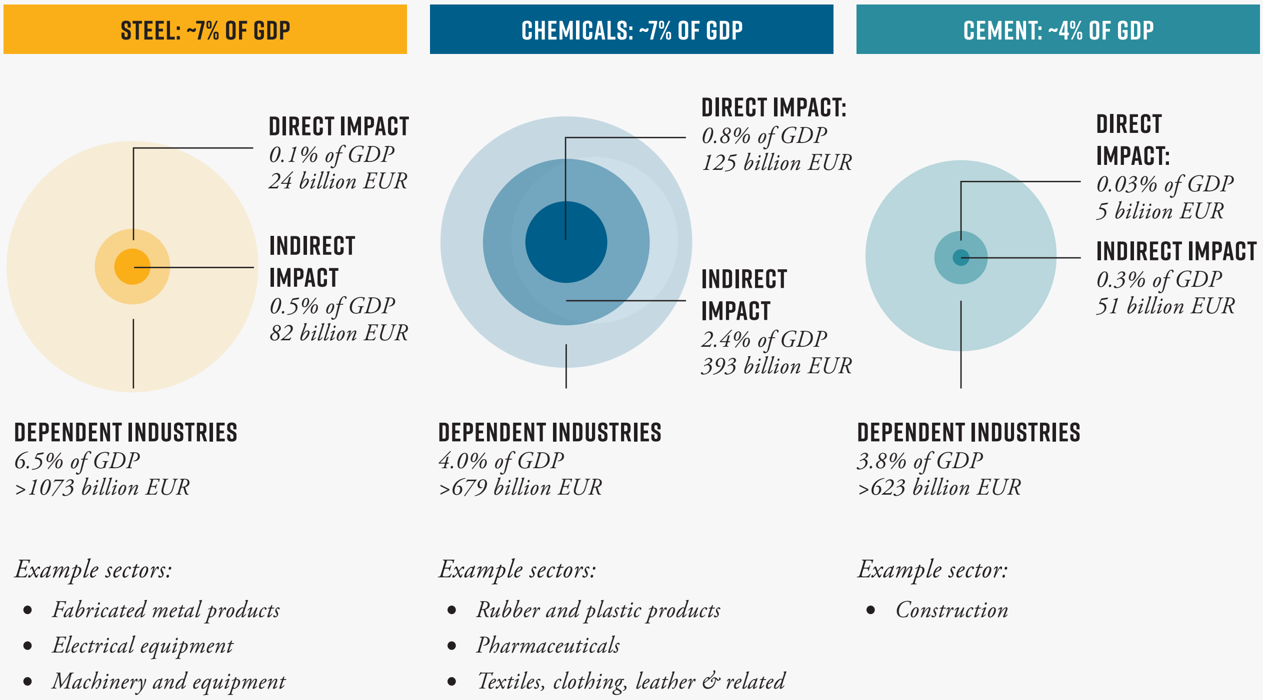
BOX 1: ENERGY-INTENSIVE INDUSTRIES PLAY CRITICAL ROLES IN THE EU ECONOMY

Steel, chemical and cement industries directly contribute 154 billion EUR, or 1%, of the EU's GDP, and as much as 680 billion EUR, or 4% when indirect contributions are also included.[17] This is roughly equivalent to the share of GDP from the information and communication sector, or from finance and insurance.[18] Similar direct and indirect impacts can be seen in the chemical and cement industries: they support just over 7.4 million jobs.[19] The chemical industry is the largest of the three, with a total gross value added of 518 billion EUR and 4.7 million jobs across the EU 27.[20]

Beyond their own contributions, these industries underpin a larger share of the EU economy as the starting point of major value chains such as construction, automotive, pharmaceuticals, and large parts of manufacturing. Around 14% of the EU's GDP is generated by sectors that depend on steel, chemicals and cement inputs, and domestic production contributes to close collaboration and innovation. Basic materials also form the basis of specialised industrial clusters, whose importance to the overall economy is particularly large. The European Observatory for Clusters and Industrial Change (EOCIC) estimates that such clusters host more than twice as many highly innovative firms and twice as many fast-growing start-ups as other locations.[21]

A strong domestic heavy industry is also a cornerstone of EU strategic autonomy. Today, the EU is effectively self-sufficient in the supply of steel, chemicals, and cement, exporting roughly as much of these materials as it imports.[22] However, although the EU was also largely self-sufficient on aluminium in the 1980s, today it imports 48% of the aluminium it uses, depending heavily on other countries, particularly China, for its supply.[23]

MATERIALS PRODUCTION UNDERPIN MAJOR EU VALUE CHAINS



Notes: The size of each bubble depends on the sector's respective share of the EU's total gross domestic product (GDP), based on gross value added (GVA) data. The GVA data used for steel and cement cover the EU 27 and the UK, while the GVA used for chemicals has been estimated based on EU 27 data and an extrapolation based on the GDP of the UK. The dependent industries included in the analysis are those for which at least 10% of their input value comes from either steel, chemicals, or cement, with the exception of the waste/sewage industry, which was excluded from the industries dependent on steel.

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES; SEE ENDNOTE.[24]

SCALING UP LOW-CO_2 MATERIALS PRODUCTION IN THE 2020S

The decisive scale-up of industrial cleantech still lies ahead. The first tonnes of low-carbon steel were produced at pilot scale only in 2020, and the world's first carbon-neutral chemicals and cement plants have yet to come online. The new industrial "unicorns" mentioned by Larry Fink have yet to emerge. That means Europe can still claim a leadership position and set the standards that will define this transition.

Where the EU has succeeded before, it has done so by fostering tightly integrated innovation systems and clusters, working in tandem with initial domestic demand and pools of capital and eventually scaling up to global markets while setting standards for new, emerging markets. This was the case for mobile telephony and the Global System for Mobile Communications (GSM) when it was first launched. It also underpinned European successes in pharmaceuticals. More recently, the EU achieved a remarkable turnaround of its position in global battery manufacturing. The EU is also still holding its own in the innovation pipeline for hydrogen production, with the majority of recent venture capital deals for hydrogen-related start-ups.[25] The core question now is what it will take to succeed similarly in energy-intensive industries.

14% of the EU's GDP is generated by sectors depending on steel, chemicals and cement to produce cars, electronics, buildings, pharmaceuticals, packaging, and more.

2. THE EMERGING EU LEADERSHIP IN INDUSTRIAL BREAKTHROUGH TECHNOLOGY

A deep dive into proposed breakthrough projects shows highly promising momentum and opportunity. However, success is far from assured. The scale of the initiatives in the pipeline is still too small, and without additional support, some proposals could fail to come to fruition. The first part of this section lays out the opportunity and quantifies the investments needed to scale up breakthrough industrial production by 2030. The second part lays out the key challenges, which are then addressed systematically in Section 3. The key take-away is that the EU must act fast to enable the transformation of its heavy industries.

European companies have launched more than 70 breakthrough projects for production of low-CO_2 steel, chemicals and cement.

2.1 AN OPPORTUNITY TO LEAD: 70 EARLY-STAGE BREAKTHROUGH PROJECTS AS THE NUCLEUS OF A FUTURE EU LOW-CO_2 INDUSTRY

At the end of 2021, there were more than 70 breakthrough projects under development across the EU in low-CO_2 steelmaking, chemicals and cement production (Exhibit 4). The pace of change is fast: new ones are being added every month, and more than half were announced in the last two years.

Together, these projects could make for a massive acceleration of low-CO_2 materials production. To give a sense of the scale proposed, in a single year, they would provide enough steel for 13 million cars, low-carbon plastic for one in six pieces of plastic packaging, and enough concrete for some 400,000 houses. They would also reduce emissions by about 30 Mt CO_2, similar to Finland's total greenhouse gas emissions in 2020.[26] All in all, they constitute a powerful push to go from demonstration to scale.

This push brings a new cast of characters on stage. Novel value chain collaborations are emerging, with consumer goods and automotive companies taking an active role in securing investments by their suppliers. Mining companies and utilities are joining industrial consortia, providing inputs such as ore or hydrogen to novel production systems. New entrants are emerging in the steel and concrete sectors, while more than a dozen start-ups are creating new technologies to turn plastics into feedstock for the chemicals industry. Meanwhile, a range of pure technology companies are targeting emerging value chains with solutions such as carbon capture, carbon utilisation, hydrogen production and more. This kind of entrepreneurship can reenergise European industry.

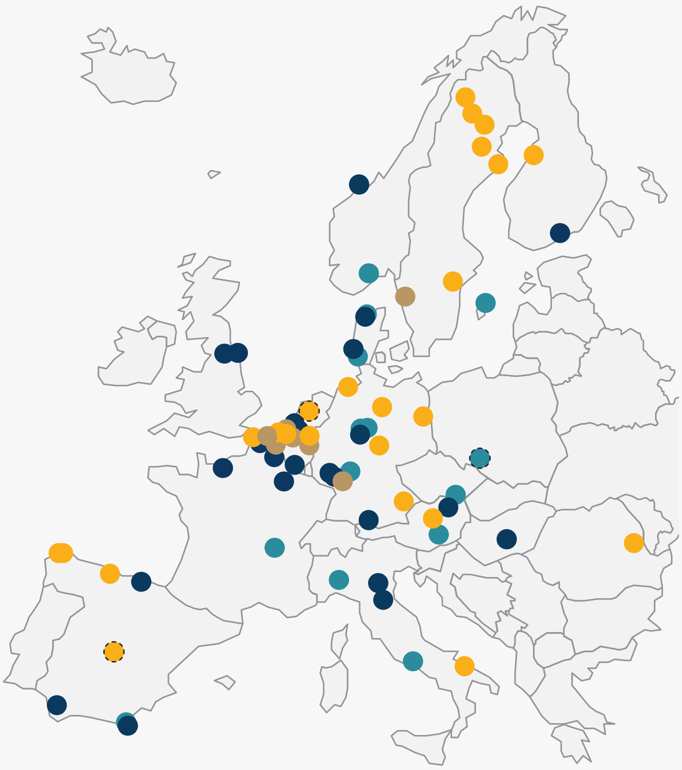
Capturing this opportunity could benefit actors all across the EU, and activity is already spread across Europe. There are proposals to develop hydrogen steelmaking in nine countries, and the same is true of cement with carbon capture (altogether, 14 countries have one or both types of projects). Initiatives to reduce emissions from petrochemical production are more concentrated in the major chemical clusters, notably in Belgium, the Netherlands and Germany, but advanced recycling projects can be found in numerous countries.

We provide additional detail on each case study below, with a more detailed introduction to the project pipeline for each technology in the Appendix.

Exhibit 4

EU COMPANIES AND INNOVATORS PLAN FOR MORE THAN 70 BREAKTHROUGH PROJECTS IN INDUSTRIAL CLEANTECH

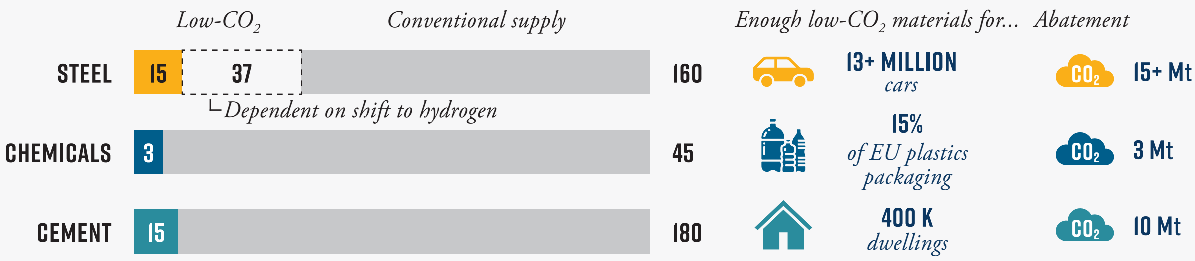
BREAKTHROUGH TECHNOLOGY PROJECTS ACROSS EU STEEL, CHEMICALS AND CEMENT



BREAKTHROUGH TECHNOLOGIES	# PROJECTS
Hydrogen-based steelmaking and scrap-based production	*21*
Chemicals production from recycled feedstock via pyrolysis	*26*
Alternative energy and carbon capture for petrochemical plants	*11*
Carbon capture on cement production	*15*

2030 ANNOUNCED LOW-CO_2 MATERIALS SUPPLY COMPARED TO TOTAL SUPPLY

MILLION TONNES PER YEAR



Notes: The map excludes other potentially important projects that are outside the scope of this report, such as chemical recycling via hydrothermal treatment, solvolysis, or gasification.

SOURCE: THE MAP AND NUMBER OF PROJECTS IS THE RESULT OF A SYNTHESIS OF PUBLIC ANNOUNCEMENTS AND COMPANY WEBSITES AS OF JANUARY 2022, WHILE THE MATERIALS SUPPLY ANALYSIS IS BASED ON PREVIOUS WORK BY MATERIAL ECONOMICS AND MULTIPLE SOURCES; SEE ENDNOTE.[27]

STEEL: HYDROGEN-AND SCRAP-BASED STEEL PRODUCTION

Just five years ago, the prospect of an EU steel sector based on clean electricity, hydrogen and recycled steel was considered far-fetched, with only one proposed project pioneered by SSAB, LKAB and the electric utility Vattenfall in Sweden. This has now completely changed. All major steel companies in the EU and several new entrants are now pursuing this route to lower CO_2 emissions.

The technology with the most current momentum is based on direct reduction using hydrogen (H-DRI). It combines two proven technologies – the electric arc furnace (EAF) and the direct reduction of iron (DRI) – with the breakthrough use of hydrogen. Although it builds on existing technology, it is a completely new way of producing iron and steel, replacing the current coal-based blast furnace process that is currently the basis of EU steelmaking. Deploying it thus requires a different set of core capital assets. The inputs would change as well: the process can incorporate large shares of recycled steel (50–80%, depending on the product), reducing the reliance on mostly imported iron ore and enabling a more circular economy.

Some 20 H-DRI projects have been proposed across the EU so far, planning for about 52 Mt in annual steel production (including from scrap; see Exhibit 5). Virtually all major EU steelmakers have major projects under development (ArcelorMittal, Liberty Steel, Salzgitter, Tata Steel, ThyssenKrupp, Voestalpine). This is substantial. Current ore-based steel production in the EU is some 100 Mt, so the projects correspond to more than half this volume.[28] Production capacity for some 10 Mt per year is planned to go online within the next five years. Several of those near-term projects are driven by new entrants, focused on regions (Scandinavia and the Iberian Peninsula) with promising prospects for near-term clean hydrogen supply at the volume and price required.

Behind this push is a tipping point of increased confidence in the technology, and in the prospects of low-cost, low-carbon hydrogen supplies. Momentum also is growing because companies are coming up to deadlines: either to reinvest in existing plants, risking future stranded assets, or to find alternative, long-term solutions.

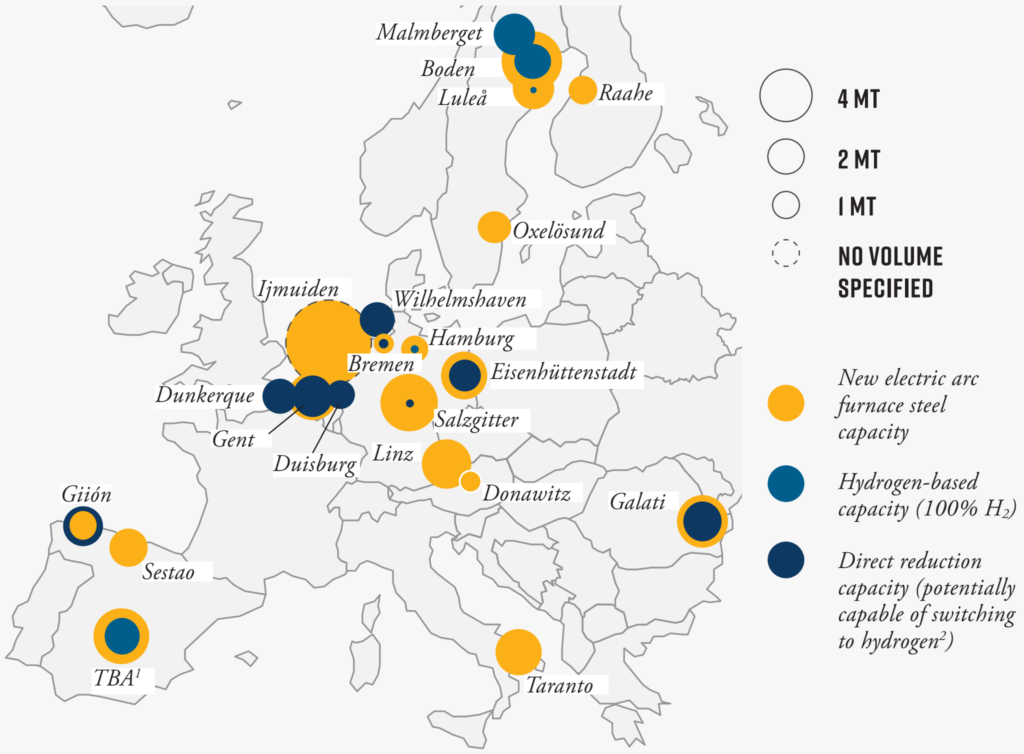
At the same time, innovation continues to flourish. Most hydrogen-based steelmaking projects so far have built on existing technology, with US-based Midrex Technologies and Italian Tenova as leading suppliers. Other companies are developing new approaches. For example, Finnish Metso Outotec is working on technology to use hydrogen directly on iron ore particles ("fines"), without the need to produce iron ore pellets. Primetals Technologies, part of Mitsubishi Heavy Industries, is trialling a similar approach in Austria, and Australian Calix is researching the same in the United Kingdom. More disruptive options also are getting closer to market. US-based Boston Metals aims to commercialise an iron production process based in electrolysis (skipping hydrogen altogether).

For all the promising momentum, there are many uncertainties left to unfold before hydrogen-based production can truly scale. As no one has yet produced any significant amounts of hydrogen-based steel, significant discovery and innovation still lies ahead, entailing risks for first movers. No final investment decision has been made for large-scale plants, though stakeholders indicated that several key decisions are expected in 2022 and 2023. Major capital expenditures and the mobilisation of new inputs (low-carbon hydrogen and electricity, in particular) will be needed to realise the plans.

A key question is how quickly these projects make the leap to breakthrough hydrogen-based production. Of the 52 Mt, only about 15 Mt will be 100% hydrogen-based from the start.[29] The remaining 37 Mt or so may initially be made with standard DRI with natural gas instead, hoping to switch to hydrogen over time. The unprecedented uncertainty about natural gas prices and supplies therefore creates a major issue to handle. There are some benefits even to an intermediate step: it avoids reinvestment in current "brown" assets and cuts emissions by about half.[30] On the other hand, gas-based DRI is nothing new; it already makes up some 10% of global steel production, and the emissions are still significant.[31] With natural gas markets going through profound change, the intermediate step to natural gas also looks like a less safe bet than it did before. The value of going rapidly to hydrogen has therefore increased. Doing so is less a matter of technology, and more one of ensuring availability. If EU steel companies can mobilise the hydrogen required, an increase in natural gas dependence can be avoided.

Exhibit 5

AS OF EARLY 2022, ~52 MILLION TONNES OF NEW HYDROGEN- AND SCRAP-BASED STEEL PRODUCTION HAD BEEN ANNOUNCED



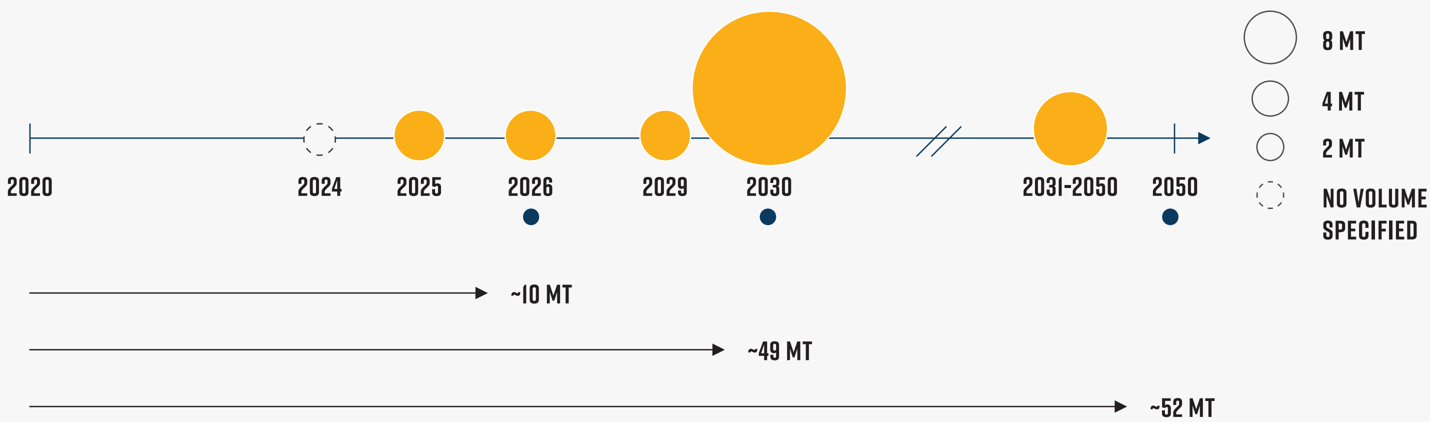
LOCATION	MAIN ACTOR
Malmberget	LKAB
Malmberget	HYBRIT
Boden	H2 green steel
Luleå	HYBRIT
Luleå	SSAB
Raahe	SSAB
Oxelösund	SSAB
Wilhelmshaven	Salzgitter
Hamburg	ArcelorMittal
Bremen	ArcelorMittal
Eisenhüttenstadt	ArcelorMittal
Gent	ArcelorMittal
Ijmuiden	TATA STEEL
Dunkerque	LIBERTY
Salzgitter	Salzgitter
Duisburg	thyssenkrupp
Linz	voestalpine
Donawitz	voestalpine
Galati	LIBERTY
Gijón	ArcelorMittal
Sestao	ArcelorMittal
TBA	H2 green steel
Taranto	ArcelorMittal

Notes: 52 Mt is total steelmaking capacity, including both H-DRI and scrap. Additional ~4 Mt EAF production not shown in map to be used in multiple locations for DRI production announced for Dunkerque (location not announced). [1] Location to be announced, multiple locations on the Iberian Peninsula are being considered.

SOURCES: COMPANY WEBSITES AND INTERVIEWS.

TIMELINE FOR ANNOUNCED NEW PRODUCTION CAPACITY

MT STEEL/YEAR



SOURCE: SEE ENDNOTE.[32]

CHEMICALS: CHEMICAL RECYCLING OF PLASTICS

Chemical recycling proposes a fundamental change to chemicals production: instead of using fossil fuels as feedstock, chemicals will be built from end-of-life plastics. For a continent that is poor in oil and gas resources, concerned about how to handle plastic waste, and actively seeking ways to reduce its import dependence, it is a bold proposal to rework and diversify raw materials supply. With geopolitical uncertainty at new heights, the imperative is stronger than ever. Long-term, chemical recycling offers one of few ways to create a future chemicals sector using much less fossil feedstock (alongside bio-based chemicals and chemicals produced from captured CO_2).

Chemical recycling also has the potential to cut some otherwise very hard-to-abate CO_2 emissions from the extraction and refining of oil, as well as from end-of-life plastics and chemicals. Today's effective recycling rate of plastics within Europe is low – according to new estimates by Material Economics, just 15% of European end-of-life plastics are turned into new, useful materials – much lower than the recycling rates typically cited.[33] Much higher rates of recycling therefore are needed to meet the EU's own climate and circular economy targets. Even if mechanical recycling is significantly increased, chemical recycling will be needed as well.[34]

There is a palette of potential chemical recycling solutions, but pyrolysis currently has the most momentum in the EU.[35] These processes target production of a plastic-derived oil that can be used instead of naphtha (today's dominant fossil-based feedstock) in petrochemicals plants. Eighteen plants are now either already running or stated to come online in the next few years, with joint capacity to process 1.2 Mt of plastic waste per year (Exhibit 6).

Chemical recycling is growing fast, but most plants are still pilot-scale, each at just 10,000–25,000 tonnes per year, an order of magnitude smaller than the feedstock of typical crackers. All the currently proposed plants combined would produce just 1% of EU high-value chemicals, and process less than 3% of total plastic waste volumes.[36] The landscape is dominated by new entrant technology companies that have secured long-term off-take agreements with petrochemicals producers and in some cases consumer goods companies seeking recycled material, principally for plastic packaging. Some incumbent producers are developing proprietary chemical recycling technologies as well.[37]

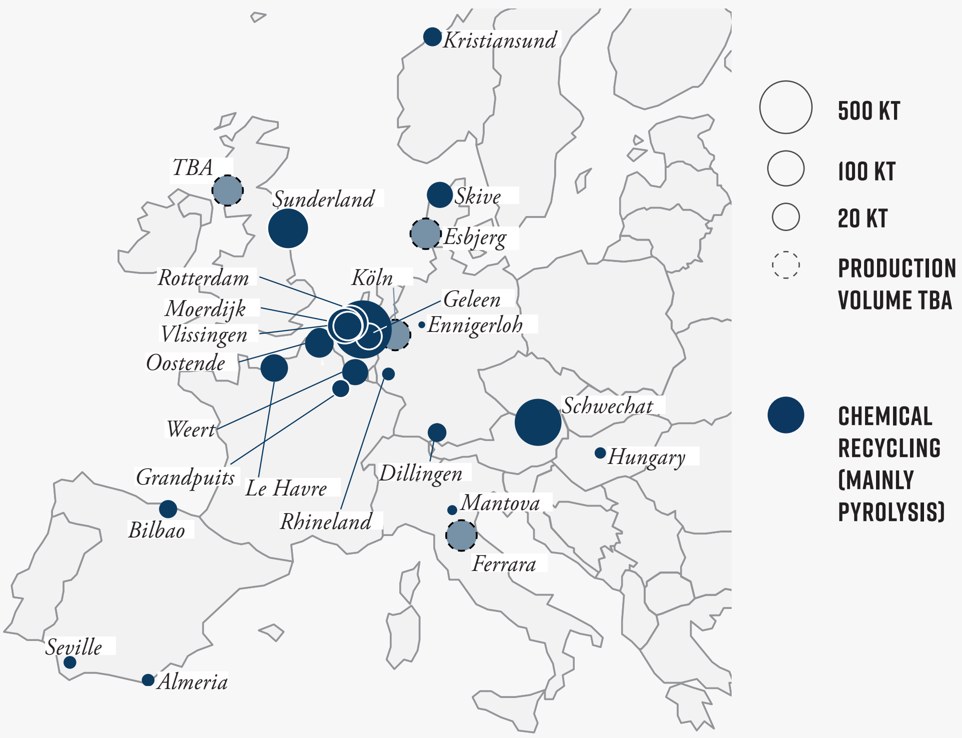
The next two or three years will be critical for this technology. Several companies consulted for this study are now considering when and how to push the button on much larger facilities in the range of 100,000–400,000 tonnes per year. This would enable them to capture economies of scale, create industrial-scale reference plants, and make a meaningful contribution to overall production. To achieve this, a step change will be needed, both in commitment to the technology, and in the capacity to concentrate highly dispersed waste plastics into large-scale, predictable flows of feedstock. Industry surveys indicate that capacity could grow to 3.4 Mt by 2030. That would represent a 70–85% increase over current mechanical recycling capacity.[38] However, our interviews suggest that, with the right conditions, a still greater increase is entirely possible.

The climate benefits of chemical recycling depend strongly on how it is implemented, however. We estimate that 24 Mt of plastics are currently burnt each year, creating 70 Mt CO_2 of emissions (a net 38 Mt increase after accounting for the fact that plastics displace some other fossil fuel use).[39] Yet if chemical recyclers use plastics that would otherwise be mechanically recycled, emissions could actually increase, as the chemical recycling process has substantial emissions of its own. Ultimately, the industry also needs to find ways to eliminate those emissions. It is technically feasible, but not yet part of current plans.

All in all, while chemical recycling is an indispensable long-term climate solution for net-zero chemicals, its near-term benefits depend on strict guardrails to ensure climate benefits. Stakeholders consulted for this study saw the lack of clarity on this topic as a major stumbling block to scaling the technology.

Exhibit 6

AS OF EARLY 2022, 1.1 MT OF CAPACITY OF CHEMICAL RECYCLING THROUGH PYROLYSIS HAD BEEN ANNOUNCED



LOCATION	MAIN ACTORS	LOCATION	MAIN ACTORS
Kristiansund	Quantafuel	Grandpuits	Plastic Energy, TotalEnergies
Skive	Quantafuel, BASF	Dillingen	Pryme, BASF
Esbjerg	Quantafuel	Schwechat	OMV, Borealis
Sunderland	Quantafuel	Mantova	S.R.S., eni versalis
Rotterdam	Pryme, Shell	Ferrara	lyondellbasell
Netherlands	Pryme, Shell	Bilbao	Petronor
Ennigerloh	Recenso, BASF	Seville	Plastic Energy
Moerdijk	BlueAlp, Shell	Almeria	Plastic Energy
Vlissingen	Neste	Köln	Plastic Energy, INEOS
Weert	fuenix, Dow	UK	Plastic Energy
Oostende	Renasci, Borealis	Hungary	BASF
Geleen	Plastic Energy, sabic	TBA	Quantafuel, BASF
Le Havre	Plastic Energy, ExxonMobil	TBA	Remondis, Quantafuel, BASF

SOURCE: SEE ENDNOTE.[40]

CHEMICALS: ALTERNATIVE ENERGY AND CCS FOR STEAM CRACKERS

Steam cracking is the core process in petrochemical production, converting principally oil-based feedstock (naphtha) into so-called high-value chemicals – themselves precursors to a range of other chemicals and products. The process also results in various by-products, which are used as fuel to meet the very high energy demands of the process. Reducing emissions from this process is challenging. The fuel-grade by-products are unavoidable. If burnt, they release CO_2. If they are not burnt, a different source of energy is needed to produce large amounts of heat at very high temperature – and a different use has to be found for the by-products.

EU industry is now pursuing two tracks towards deep cuts in these emissions.[41] One is carbon capture and storage (CCS): converting the by-products to hydrogen that can be burnt without releasing greenhouse gases, while capturing and burying the CO_2 that results when the hydrogen is produced. Such "reforming" of hydrocarbons to hydrogen is a mature technology, but it has not previously been used on cracker off-gases. To date, only one such project has been announced, out of the total 50 crackers in operation in the EU. It is at Dow's cracker complex in Terneuzen, in the Netherlands, with a 2026 target date for CCS to commence.

The second key technology in active development is steam cracking driven by electricity instead of fuels. This is still at a relatively early stage of development, driven by three separate pre-competitive collaborative research projects, with consortia building demonstration plants in Germany (BASF, Linde, SABIC), the Netherlands (Dow, Shell), and a third location yet to be announced (Borealis, BP, Total Energies, Repsol and Versalis). Stakeholders and companies diverge in their views on this technology. Some foresaw feasible commercial operation within five or six years. Others saw this as highly unlikely, with a post-2030 date for the technology to be scaled, mostly because it requires very large amounts of clean electricity. Recent volatility in electricity markets has highlighted the need to find ways to enable the first scaling without facing major cost increases or risks. Unlike hydrogen production, crackers need "always on" electricity to be fully electrified, so they are very exposed when electricity prices gyrate.

In summary, the chemicals sector stands where steel was perhaps three or four years ago: pioneer projects have been announced, but plans for a decisive shift to new technologies are still pending. The need to further improve those technologies is only one factor. Policy and markets have also yet to make a strong business case for the major investments required. With the right preconditions in place, we could see a major acceleration in scaling low-CO_2 technology.

This is a re-industrialisation agenda: building new factories and input supply chains at record pace while developing markets for low-CO_2 materials.

CEMENT: CARBON CAPTURE, UTILISATION AND STORAGE

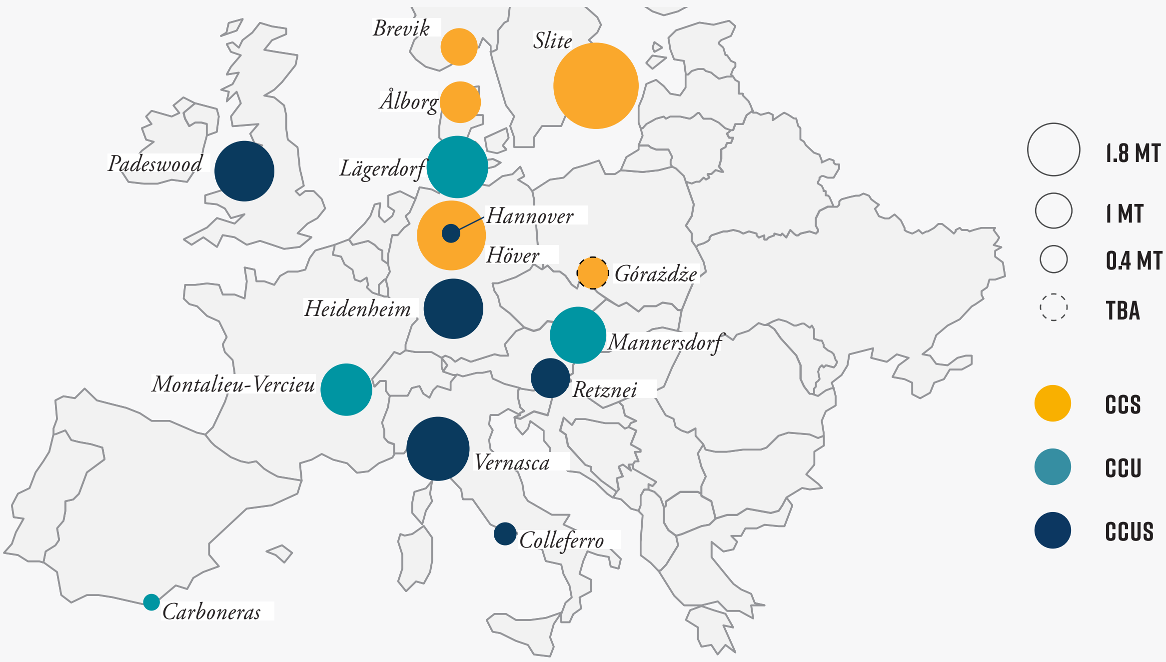
Cement presents a very particular climate conundrum. Conventional cement production starts with the need to heat limestone to very high temperatures. This converts some of the stone to CO_2 gas, and the resulting emissions make up as much as 60% of the EU cement sector's 119 Mt release of CO_2.[42] For conventional cement production, this CO_2 is unavoidable. Emissions can only be prevented by capturing the CO_2.

Carbon capture technology itself is ready to deploy, but plans to apply it to the EU cement industry have failed to materialise until now. Only one CCS plant is currently under construction in Europe – in Brevik, Norway. However, 12 other initiatives to capture a total of 10 Mt CO_2 from EU cement plants have been announced recently (Exhibit 7). This is a step-change in just two or three years, but nonetheless amounts to less than 9% of current emissions from the sector.[43] Of these initiatives, only four are focused solely on the permanent storage of CO_2 (CCS), while the rest include some degree of CO_2 "utilisation" – that is, using CO_2 to produce fuels, chemicals or other products. Stakeholders interviewed for this project indicated that continuing uncertainty about available CO_2 transport and storage infrastructure was a major reason for the renewed interest in CCU.

While all the elements of CCS (the capture, compression, transport and storage) are all known, two main innovation agendas still loom large. First, putting all component pieces together is a major undertaking, with much still to learn in creating efficient systems. Second, there is a very active innovation agenda to improve the capture technology that drives much of the cost. The technology used in Brevik (chemical absorption of CO_2) has been widely used for decades. It is the one regarded by stakeholders as sufficiently mature to use at scale now. However, many also thought that much cheaper options could be developed. So-called oxy-fuel technology (used widely in other industries but currently at the large prototype stage in the case of cement kilns) could bring down costs by as much as 40%. Even greater cost reductions could be possible with direct separation, currently being tested at pilot projects such as the Low Emissions Intensity Lime and Cement (LEILAC) pilot plant developed by Calix at the HeidelbergCement plant in Lixhe, Belgium.[45]

Exhibit 7

AS OF EARLY 2022, ~15 MT OF CEMENT PRODUCTION WITH CARBON CAPTURE (USE OR STORAGE) HAD BEEN ANNOUNCED



LOCATION	MAIN ACTORS	PROJECT
Brevik	NORCEM HeidelbergCement Group, HEIDELBERG CEMENT	*Norcem CCS*
Slite	CEMENTA HeidelbergCement Group, HEIDELBERG CEMENT	*Cementa CCS*
Ålborg	aalborgportland, cementirholding	*Aalborg CCS*
Lägerdorf	HOLCIM	*Westküste 100*
Padeswood	Hanson HeidelbergCement Group, HEIDELBERG CEMENT	*Padeswood CCS*
Hannover	Leilac, HEIDELBERG CEMENT	*LEILAC$_2$*
Höver	WESTKÜSTE 100, HOLCIM	*Höver CCS*
Górażdże	GÓRAŻDŻE HeidelbergCement Group, HEIDELBERG CEMENT	*ACCSESS*
Heidenheim	catch4climate	*Catch4Climate*
Mannersdorf	coolplanet, HOLCIM	*C$_2$PA*
Montalieu-Vercieu	VICAT	*Hynovi project*
Retznei	ecra, HOLCIM	*ECRA CCS*
Vernasca	Buzzi Unicem	*CLEANKER*
Colleferro	carbon clean, HOLCIM	*ECRA CCS*
Carboneras	ecra, HOLCIM	*ECCO$_2$-LH*

SOURCE: COMPANY WEBSITES AND PUBLIC ANNOUNCEMENTS, SEE ENDNOTE.[44]

CEMENT: LOW-CLINKER CONCRETE

The slow start to CCS makes it particularly important to explore alternative approaches to reducing emissions from cement production. Here, too, there is a flurry of early-stage activity across Europe. Research has long identified a wide range of opportunities either to change the type of cement to one that does not release as much CO_2, or to achieve formulations for concrete that require less cement. Building on this, past "roadmaps" for the cement sector have identified both approaches as major opportunities to reduce emissions. A handful of EU companies – primarily new entrants – now seek to bring these to market, aiming for rapid scaling.

One example is the Irish company Ecocem, which is developing ways to produce concrete with equivalent performance to standard offerings, but a much smaller share of ordinary clinker, the key binding agent of cement (which accounts for 95% of total emissions from cement production).[46] Other companies focus on using alternative binders such as natural pozzolans (volcanic ash), as developed by EMC; forms of calcined clays, as developed by Aalborg Portland Cement; or alternative processing of limestone, as developed by Fortera.[47] These approaches all have the potential to reduce standard clinker use and, therefore, emissions by up to 70%. According to their proponents, costs could be significantly lower than the use of CCS.

In some cases, additional work is needed to demonstrate the equivalent performance of these novel types of cement. However, even where technologies are already mature and proven, regulations can prevent them from scaling. Both cement and concrete are tightly regulated, and new offerings must go through lengthy approval processes – country by country – before they can enter the market.

To seize the low-CO_2 materials opportunity, Europe it needs to act fast and adopt an ambitious, highly integrated strategy to scale up breakthrough technologies.

2.2 RAISING AMBITION: A SCALE-UP SCENARIO FOR BREAKTHROUGH INDUSTRIAL PRODUCTION BY 2030

The dozens of breakthrough industrial projects being launched across Europe offer an exciting opportunity to revitalise a key economic sector and take the lead in a fast-growing market. If the EU wants to seize that opportunity, however, it needs to act fast and adopt an ambitious, highly integrated strategy to scale up those novel technologies. The first step is to define what it aims to achieve, as the EU has yet to formulate a vision for low-CO_2 materials. Looking at the existing project pipeline, climate targets and market opportunity, we have built an illustrative scale-up scenario where the EU deploys breakthrough technologies to produce 25 Mt of steel, 10 Mt of petrochemicals, and 20 Mt of cement (Exhibit 8). This would imply a huge acceleration of breakthrough initiatives to 2030.

To achieve this ambition, an innovation cycle that otherwise takes some 15 years will need to be compressed to 7–10 years, with some 30–35 billion EUR in investments. While substantial, this is only around 1% of the total energy system investments that EU countries will make during this period. As shown in Exhibit 3, the benefits would be massive: a 43 Mt CO_2 reduction in annual emissions by 2030, low-CO_2 materials worth 29 billion EUR and, most valuable of all, a new global leadership position for EU industry.

Scaling up to this level will require profound changes and extensive new investments in Europe's industrial heartland. This is, in effect, a reindustrialisation agenda: building new factories and input supply chains and, at the same time, developing markets for low-CO_2 materials. Three things need to happen:

First, there is a need to enable truly big, ambitious projects. So far that has only happened in the steel sector, where current plans cover about 5–10% of what is needed for a net-zero production system. To achieve climate targets, and to put the EU on the path towards leadership in low-CO_2 materials, equally large initiatives need to be encouraged and facilitated in other sectors.

Second, final investment decisions need to be brought over the line. In many of these projects, the companies still want to confirm that the business case is viable and that risks can be handled. Critical decisions are due already in 2022–2023 for production to launch by 2030. That means the policy, finance and market prerequisites to tip the scales need to be put into place as soon as possible, or else those projects could be postponed, scaled down, or even abandoned.

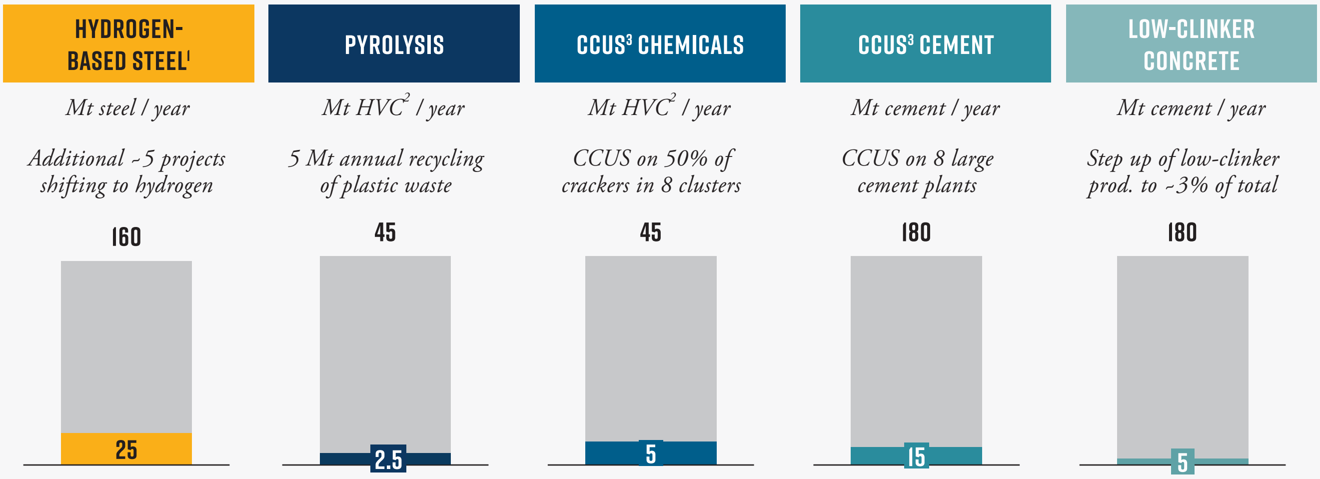
Third, there is a need to move fast, or else Europe could lose its early advantage. A flurry of activity on chemical recycling in the United States could well coalesce into the real hub of innovation, ahead of the EU. For hydrogen-based steelmaking, the EU has been the clear leader in ambition for the last five years, but due to implementation delays, it now seems likely that the first two or three hydrogen-based steelmaking plants in the world will be built in China instead. It is thus crucial to create the right conditions for EU technology pioneers to succeed at scale.

Exhibit 8

A VISION FOR SCALING UP FOR BREAKTHROUGH INDUSTRIAL CLEANTECH BY 2030

AMBITIOUS 2030 TARGETS FOR EU ENERGY-INTENSIVE INDUSTRIES

MT LOW CO_2 MATERIALS PRODUCTION 2030 VS. CURRENT PRODUCTION

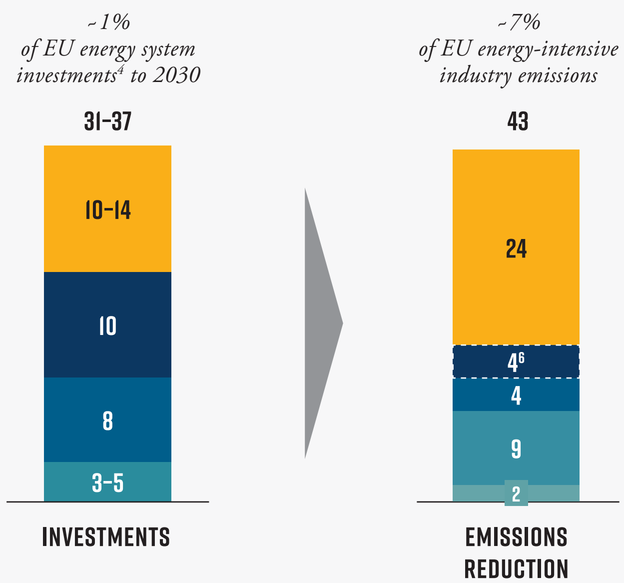


INVESTMENTS NEEDED

BILLION EUR

EMISSIONS REDUCTIONS[5]

MT CO_2 / YEAR, 2030



Notes: [1] Including 50% scrap. [2] High-value chemicals. [3] Carbon capture and use or storage. [4] For illustration, a decade of today's energy system investments of about 2% of the EU GDP annually would amount to roughly 2.5 trillion EUR. [5] Excluding emissions reduced by scrap share in steel (the scrap would otherwise be exported and used elsewhere). [6] End-of-life emissions from avoided incineration.

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES, SEE ENDNOTES.[48]

3. GOING FROM DEMONSTRATION TO SCALE

Across the five case study areas, interviews and analysis for this study indicate a common set of prerequisites that must be put in place (Exhibit 9). In short, they involve managing the first mover and technology risks of first-of-a-kind plants; building the business case for costlier production; orchestrating the energy and input supply chains and infrastructure required by new industrial production systems, and adapting regulations and market arrangements to fit a new industrial logic.

Exhibit 9

FOUR KEY BARRIERS HOLD BACK THE CURRENT CLEANTECH PROJECT PIPELINE IN STEEL, CHEMICALS, AND CEMENT

BUSINESS CASE AND A GREEN PREMIUM FOR EARLY MOVERS

HIGHER COSTS

Early breakthrough projects face 20–100+% higher costs, corresponding to CO_2 abatement costs of up to 100–300+ EUR / t CO_2

IMMATURE GREEN MARKETS

Market premiums for greener materials are emerging but fragmented, providing insufficient market pull to motivate investments

INCREASED VOLATILITY

New input markets and policy create additional volatility for breakthrough projects

FIRST-MOVER AND TECHNOLOGY RISK BLOCK VIABLE FINANCING

CAPITAL NEEDS

Scaling breakthrough production require 2–3x increases in investments stretching company balance sheets

RISK

Early projects face irreducible technology and performance risk that cannot be diversified

INCENTIVE TO WAIT

Cleantech first movers face investment costs and a powerful incentive to delay

LACK OF CLEAN ENERGY AND UNDERDEVELOPED SUPPLY CHAINS

POWER AND HYDROGEN SUPPLY

Breakthrough production requires unprecedented build-out of clean energy and inputs to key industrial clusters

CIRCULAR MATERIALS

Mobilising new inputs requires a step-change in new circular value chains for materials

INFRASTRUCTURE

New electricity grid and CO_2 transport and hydrogen infrastructure are needed specifically for industrial clusters

REGULATION AND MARKETS UNFIT FOR RE-INDUSTRIALISATION

PERMITS

Scale-up is held back by costly and unpredictable processes for permits

GREEN STANDARDS

Lack of clarity on what will count as 'green' in emerging lead markets

PRODUCT REGULATION

Existing standards failing to accommodate novel products such as green concrete or recycled plastics

3.1 BUILDING A STRONG BUSINESS CASE FOR EARLY MOVERS

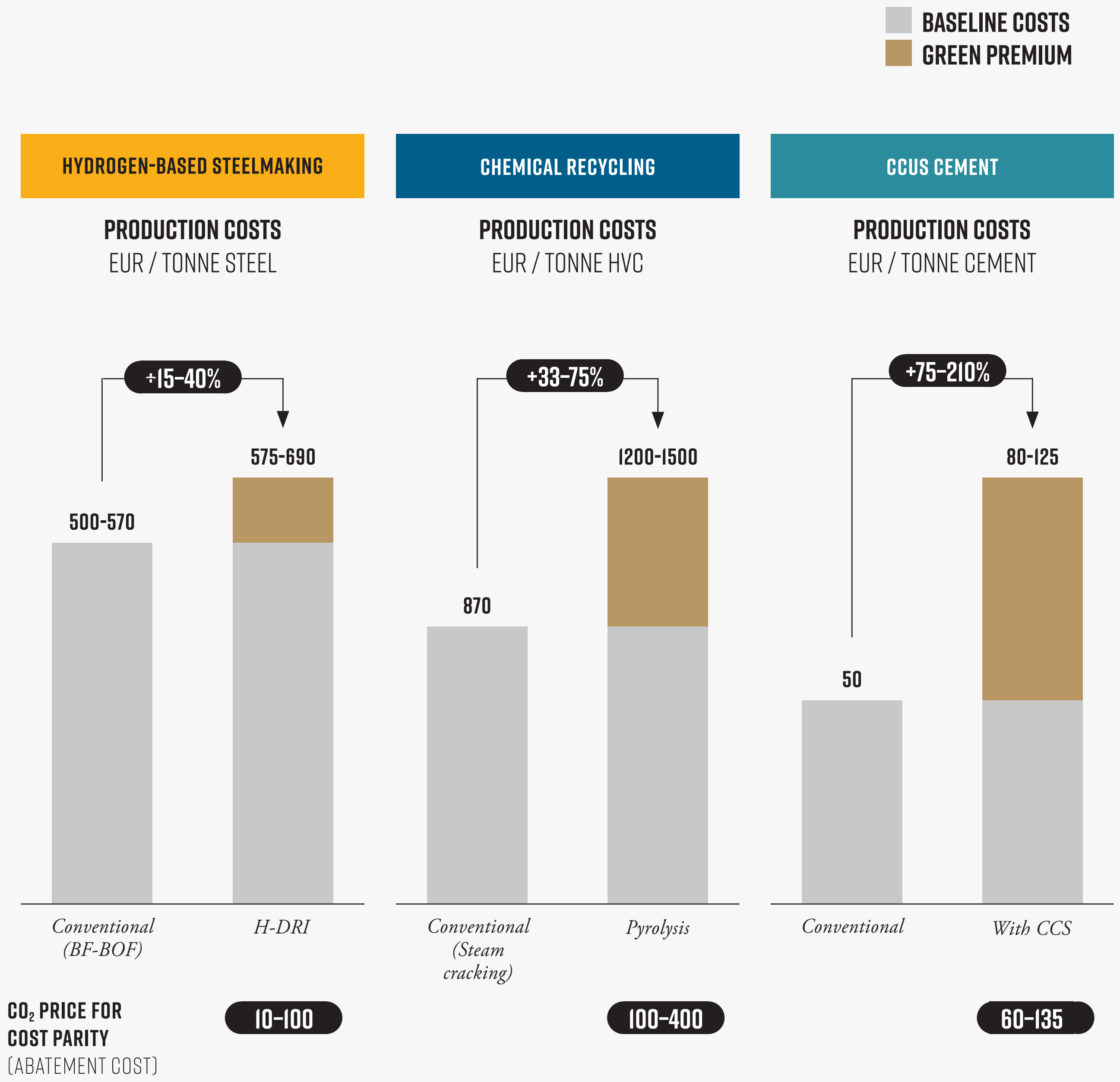
The costs of production with novel, low-CO_2 technologies are often significantly higher than for incumbent, high-carbon production. Higher costs must be balanced by higher revenue for the business case to work. This is the most fundamental prerequisite for a scaling of breakthrough projects.

Using proprietary data from companies as well as published studies, we made a detailed analysis of the costs of breakthrough low-CO_2 production. It is clear that the first plants, at least, will have significantly higher costs than existing plants (Exhibit 10). For hydrogen-based steel, the costs could be 20–40% higher than for coal-based steel production. Chemicals production employing waste plastics and/or CCS and electric cracking face an even higher cost difference, rising to 50% or more. For cement, adding CCS can more than double production costs. These are indicative numbers only: costs vary across projects depending on what companies are charged for plastic waste, how cheap local renewable energy is, or how close sites are to suitable CO_2 storage, for instance.[49]

Companies consulted for this study were careful to point out that none of this means that these technologies are "uncompetitive". On the contrary, in a decarbonising economy, they are the solutions that will win. Some noted that even at today's carbon prices, their proposed investments could make perfect financial sense – if the flaws in the current carbon pricing regime did not prevent it. However, as discussed in the next section, the mechanisms introduced to avoid "carbon leakage" (EU companies losing business to other regions that do not regulate CO_2) have the side effect of also preventing CO_2 prices from supporting breakthrough technologies.

Exhibit 10

LOW CO_2 TECHNOLOGIES HAVE HIGH GREEN PREMIUMS RANGING ABOVE EXPECTED CO_2 PRICES

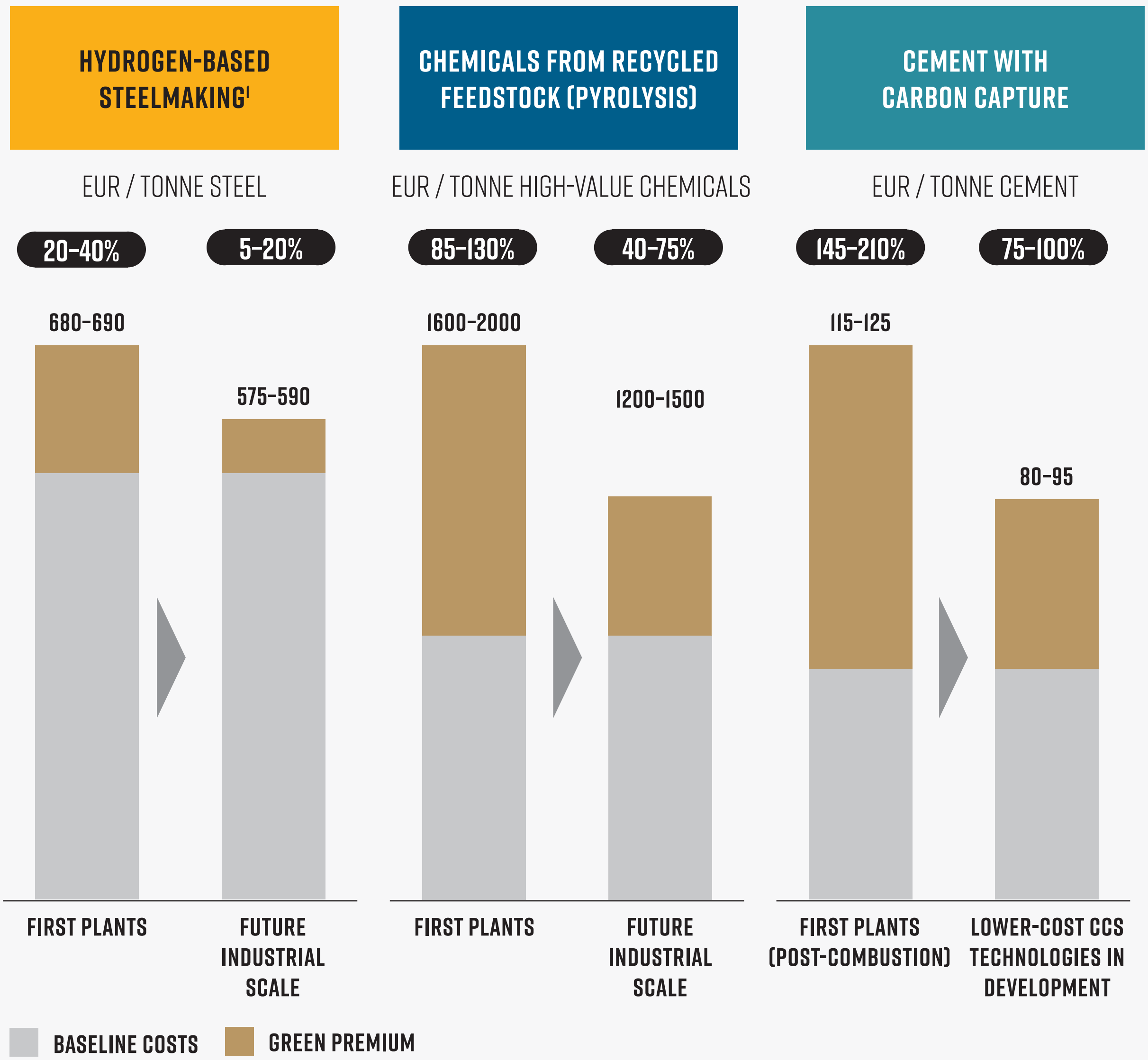


Notes: Steel costs based on coking coal prices of 70–150 EUR / t and calculated assuming 50% use of scrap (not contributing to abatement). Chemicals abatement depends on reduction of avoided end-of-life emissions from plastics (up to 3 tCO_2 / t plastics), as well as on the payment model for plastic waste and allocation of emissions reductions along the value chain. Values shown are for large-scale plants rather than near-term small-scale trials. Cement costs represented based on range from oxyfuel CCS to post-combustion technology for large-scale applications. CCS transport and storage costs assumed at 30–50 EUR / tCO_2. Numbers are rounded. Costs are average of first-generation plants and industrial-scale plants where applicable.

SOURCES: MATERIAL ECONOMICS INDUSTRY MODEL, BASED ON PUBLISHED DATA AND CONSULTATION WITH COMPANIES

Exhibit 11

GREEN PREMIUMS EXPECTED TO FALL SIGNIFICANTLY OVER TIME



Notes: Steel plant assumes 50:50% scrap and new metal. Chemical recycling illustrated including reduction of end-of-life emissions from avoided incineration of plastics. Cement initial projects based on established post-combustion carbon capture technology; future on lower-cost but currently not demonstrated other options (oxyfuel, indirect heating and capture). CCS transport and storage costs assumed at 30-50 EUR / tCO_2. Numbers are rounded. Costs are average of first-generation plants and industrial scale plants in favourable locations.

ENABLING THE LEARNING CURVE TOWARDS LOWER FUTURE COSTS

Some of the companies consulted – and especially some of the new entrants – see credible routes to much lower future costs (Exhibit 11). For carbon capture, utilisation and storage (CCUS) in the cement industry, the key is novel capture technology and benefiting from economies of scale in CO_2 storage. For steel, maturing technology, large-scale production, and falling renewable energy and hydrogen costs are the key drivers (with further opportunities if the processes to use iron ore fines are successful). For chemicals, a key will be improving process efficiencies, scaled-up production, and much more efficient supply chains for sorted plastic waste. These cost reductions will not happen automatically, but depend on an effective innovation cycle that includes deployment at scale that enables learning-by-doing. Those who do this also will develop the know-how and intellectual property for future, competitive production. Getting innovation started with the first generation of plants at scale is therefore critical.

3.2 SECURING FINANCE FOR FIRST-MOVER PROJECTS

Investments to scale early-stage technology are not like ordinary industrial investments. Early innovators face additional risks, higher costs, and more uncertain revenue. Europe therefore must find a way to overcome companies' powerful incentive to wait for others to move first, and for costs to fall. For an early mover, several considerations arise:

First, industrial production at scale involves major commitments of capital. Investments are in the range of 1.1–1.5 billion EUR for a 1.25 Mt H-DRI plant, and 800 million EUR for 400,000-tonne pyrolysis plant (Exhibit 12) – in many cases, "bet the company" investment levels. At the same time, these investments can be major opportunities to increase productivity, such as removing bottlenecks and increasing throughput, or achieving higher utilisation or increased returns to scale.

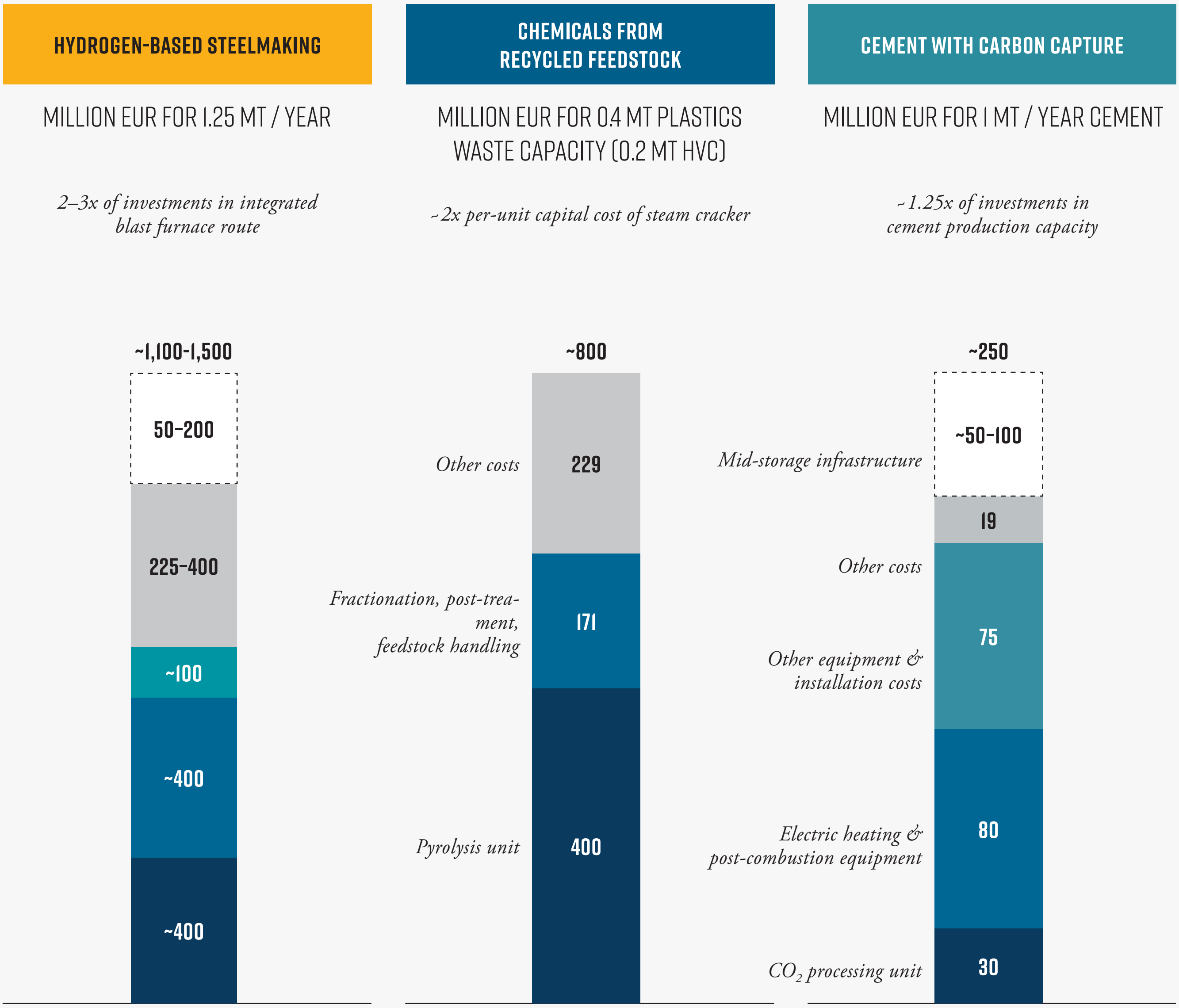
Second, investment requirements for early plants will be higher than for those coming after. One reason is that key drivers of capital expenditure are on sharply falling cost trajectories – such as the cost of renewable energy and electrolyser systems for hydrogen production. Another is that it will be possible to build larger plants once technology has been proven (smaller scale means that fixed costs are distributed over fewer tonnes of output, so costs per unit are higher throughout the plant lifetime). Adding this up, the first movers can see much higher investment needs. For steel, for instance, investment needs for second-generation plants could be 25% lower per unit of output than for the first, smaller-scale units – or even 40% lower after factoring in declines in electrolyser costs and other key inputs.[50]

Third, early projects face an "innovation premium": risks and costs that arise precisely because they are breaking new ground. Stakeholders noted several ways this can affect project economics. One is through longer periods of trial and error to adjust configurations and reinvest in new solutions (as seen in several early chemical recycling efforts, for example). It can also manifest in the difficulty of predicting future cost, as new solutions do not benefit from experience, or from guarantees from suppliers (e.g., for process efficiency in steelmaking), mature markets for inputs (e.g., a steady supply of waste plastics) or, sometimes, the availability of insurance products. Finally, longer ramp-up periods to full capacity can mean longer periods without revenue.

All this means that the financing equation for breakthrough investment is much harder to balance. When left to private capital markets, the innovation premium translates to higher financing costs: less low-cost debt finance, and more high-cost equity or higher-interest loans. Some of the projects have managed to find private-sector solutions to these challenges. For example, some greenfield projects have been put in place with significant shares of private rather than bank capital, and with various creative ways to limit downside risks (notably, long-term off-take agreements for products). However, for large-scale deployment, other ways to mitigate financing risks are also needed.

Exhibit 12

BREAKTHROUGH TECHNOLOGIES REQUIRE THE BUILDING OF NEW, CAPITAL-INTENSIVE PRODUCTION CAPACITY



Notes: Steel example is based on the H-DRI investments. With 50% scrap, this means investments for the H-DRI share of 2.5 Mt steel. Investment compared with reinvestment in blast furnace, basic oxygen furnace, sinter plant and coke plant. Chemicals example based on pyrolysis; costs not representative for other potential technologies (e.g., hydrothermal treatment, gasification). Investments in cement CCUS based on post-combustion (amine) carbon capture. Interim storage costs are highly situation-specific and variable, with some projects avoiding them altogether and others facing costs of up to a reported 100 EUR/t. Other costs include a range of factors such as project management and development, facilities for raw materials handling and waste disposal, allowance for ramp-up and longer construction times, etc. Numbers might not sum up due to rounding. Investments are based on an average early plant.

SOURCES: MATERIAL ECONOMICS INDUSTRY MODEL, USING DATA FROM PUBLISHED SOURCES AND COMPANY INFORMATION.

3.3 MOBILISING DEMAND FOR GREEN MATERIALS

The increasing commitments to CO_2-free supply chains mean that several materials markets and value chains are starting to experiment with "green premiums", so that low-CO_2 products fetch a higher price. This is a nascent phenomenon, and public information is scarce and in flux. Surveying a range of industries, we see that limited volumes of recycled plastics have started to trade at prices 50–100% above benchmark levels for standard virgin plastics. An emerging supply of bioplastics and bio-based textiles similarly can fetch a higher price. "Green" steel also has been contracted at a market premium of 10–25% from future breakthrough projects, and best-in-class, existing producers of recycled steel can get about 5% extra. Small premiums are also starting to be negotiated for a range of other commodities, such as a few percentage points for aluminium at less than 4–5 tCO_2 per tonne, or some contracts with a 20–30% markup for lithium with substantially lower CO_2 emissions.

Companies can push this much further, as more and more markets start to differentiate between high- and low-CO_2 products. Some companies orchestrate long-term off-take agreements with customers, notably in the automotive and consumer goods sectors. For example, steel companies such as Salzgitter, SSAB and H2 Green Steel recently have contracts for significant volumes, with some referencing premiums of 20–25%.[51] Likewise, the announcement in early 2022 by Eastman of a new chemical/molecular recycling plant in France was accompanied by letters of intent for multi-year supply agreements from several leading consumer brands.[52]

Taking this further will require major market developments. Industrial ecosystems are highly complex, so existing steel or chemicals producers often have hundreds of separate products, reaching thousands of different customers.[53] Likewise, any given region is typically served by two or three cement plants, and any one factory has hundreds of ultimate end-users. While companies must convert whole factories to low-CO_2 production, they typically only access a green premium from a subset of customers who are able and willing to pay more.

Improved transparency also can help. To access a premium, industry innovators also need more clarity on what counts as "green" low-CO_2 materials and feedstocks (such as hydrogen). Separating greenwashing from genuine emissions reductions is a minimum. Beyond this, breakthrough projects would be especially helped by definitions and benchmarks that reward the deep emissions cuts that only novel, and riskier technology makes possible. Buyers of materials in automotive, construction, packaging, and other sectors noted that it can be very hard to evaluate the green credentials of materials. Solid definitions, carbon accounting and certification systems, and labelling are required for the market to develop to its full potential.

Exhibit 13

GREEN MATERIALS ARE STARTING TO COMMAND A PREMIUM, BUT VOLUMES ARE SMALL

% PREMIUM PAID OVER CONVENTIONALLY PRODUCED MATERIALS

STEEL

10–25%	**~5%**
Future H-DRI breakthrough projects	*Best-in-class recycled steel production*

PLASTICS

50–100%	**~50%**
Chemically recycled plastics	*Bio-based plastics / textiles*

OTHER

2–5%	**20–30%**
Lower-CO_2 aluminium	*Low-CO_2 lithium*

SOURCES: MATERIAL ECONOMICS ANALYSES OF PUBLIC STATEMENTS AND INTERVIEWS WITH VALUE CHAIN PARTICIPANTS.

3.4 LINING UP NEW SUPPLY CHAINS AND INFRASTRUCTURE

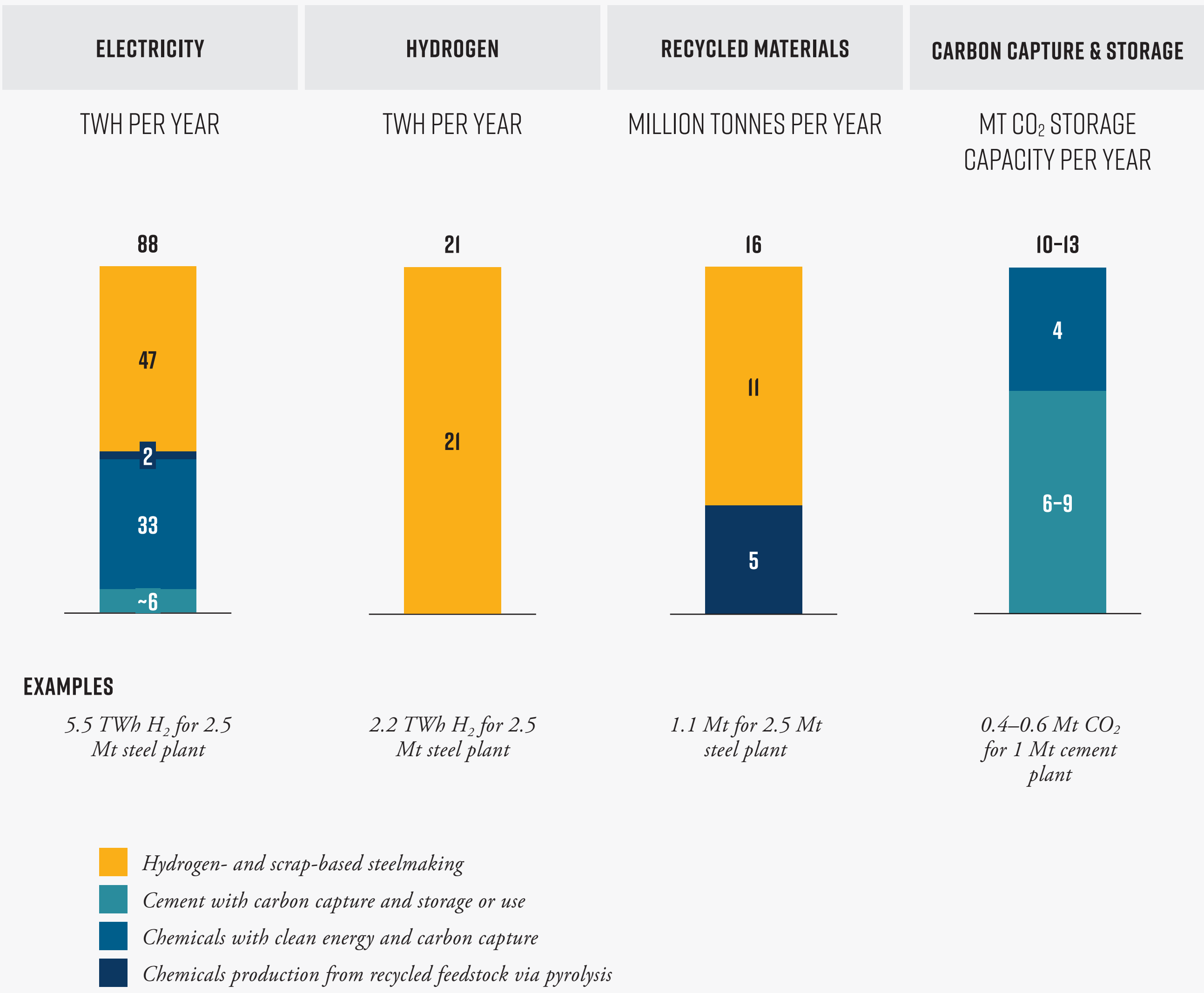
Existing industrial production relies on massive feedstock and energy flows. The EU petrochemicals, steel and cement industries together use more than 680 million tonnes of their key inputs of iron ore, coking coal, naphtha and limestone – some 1.5 tonnes of inputs per European. In addition, they burn large amounts of fossil fuels for heat and steam[54]. Arrayed behind this is a huge infrastructure of mines, ports and pipelines. Europe's industrial clusters have co-evolved with a gigantic supply system.

The switch to breakthrough production upends this logic by pivoting to entirely new inputs. This could be very good for the EU, enabling a major shift from imported commodities and towards domestic resources, with more value capture for the European economy. It also offers a key way to reduce European dependence on imports from unreliable sources. Indeed, the agenda of breakthrough industrial production is integral to a broader push to diversify and secure Europe's supply of energy and raw materials.

However, this also means that entirely new supply chains and infrastructure must be built out – and at record pace. Instead of coal, oil and gas, low-CO_2 materials production requires large amounts of renewable electricity, clean hydrogen, steel scrap, waste plastics, biomass, and other inputs. We estimate that by 2030, 88 TWh of low-CO_2 electricity per year would be needed – roughly the electricity generation of Belgium – in part to power the production of 21 TWh of hydrogen (Exhibit 14).[55] For cement and chemicals, some 10–13 Mt of CO_2 storage would be needed, corresponding to a quarter of 25% of currently planned storage capacity in Europe.[56]

Exhibit 14

SCALING UP BREAKTHROUGH TECHNOLOGIES TO 2030 WILL REQUIRE LARGE AMOUNTS OF CLEAN ENERGY, FEEDSTOCK, AND NEW INFRASTRUCTURE



Notes: Based on 25 Mt H-DRI-based (with 50% scrap) steel, 2.5 Mt HVC chemically recycled via pyrolysis, 5 Mt HVC produced with CCUS, 15 Mt CCUS cement and 5 Mt low-clinker cement. Numbers are for additional capacity needed, e.g. need for breakthrough technology vs. current use. Steel analysis is based on 50% scrap use hydrogen-based iron & steelmaking via electric arc furnace route. Electricity estimates include power needed for hydrogen production via electrolysis.

SOURCES: MATERIAL ECONOMICS INDUSTRY MODEL

Entirely new supply chains and infrastructure must be built out – and at record pace

These input and infrastructure needs are also highly concentrated and need to serve large point sources of demand. For example, even if 50% recycled steel is used, a plant producing 2.5 million tonnes of steel from hydrogen needs some 5.5 TWh of electricity – the yearly output of some 100–500 new wind turbines, depending on size and location, or roughly Denmark's cumulative offshore capacity to date.[57] For another comparison, supplying 30% of the feedstock for a 700 kt cracker in each of the eight major petrochemical clusters in the EU would require around 5 Mt of sorted plastics waste[58] – equivalent to a quarter of all the plastic packaging waste generated in the EU each year, or the total plastic waste from some 23 million EU households.[59]

Another priority is to scale up circular value chains for materials. The new steel plants using DRI inputs can also use much more steel scrap, even as the amount of steel available for recycling is growing.[60] For the chemicals sector, the next step is enormously ambitious: to repurpose plastic waste to a major feedstock source, via a major revamp of how plastics are handled at end-of-life (Exhibit 15).

BOX 2: THE NEED FOR MORE CIRCULAR MATERIALS: LESS THAN A QUARTER OF EU PLASTICS ARE SEPARATED AND SENT FOR RECYCLING

For plastics, a more circular economy is a major opportunity to turn a major source of waste and CO_2 emissions into a valuable feedstock. There is no shortage of end-of-life plastics in the EU: we estimate that some 45 million tonnes are generated each year. This means that the recycling rate for plastics (measured as recycled plastics produced in Europe over total end-of-life plastics) is only around 12% in the EU today – or 15% if plastics exported for recycling are included. The carbon content of end-of-life flows is more than 120 Mt CO_2, more than the total annual emissions of the EU cement sector; the emissions from plastics that are burnt, some 70 Mt CO_2; and the net emissions (accounting for the fact that using plastics as fuel replaces some other fossil fuel use), just under 40 Mt CO_2.

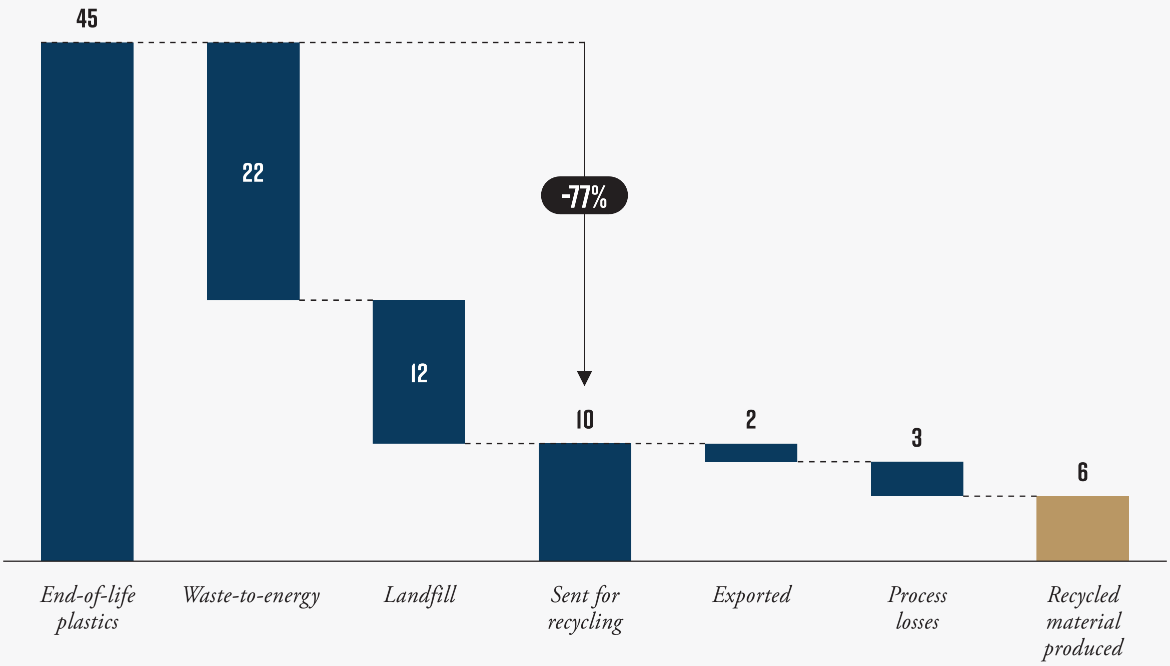
While there is no shortage of plastics that could be used for feedstock, mobilising them as industrial inputs will require major changes. The stakeholders consulted for this project noted that the EU still landfills or burns most of its plastic waste, but it can be very difficult for a recycler or chemicals producer to secure enough plastic waste for use as a large-scale feedstock. It is still harder to do so in predictable and long-term contracts.

Enabling chemical recycling will therefore require a step-change in the efficiency and scale of EU waste management. Plastics are broadly dispersed throughout the economy, so sorting and cleaning them to the point where they can be used as feedstock for large-scale chemicals plants is a major challenge. Today's systems are local and highly fragmented, often operating at the municipality level, and there is little international trade in plastics as a raw material within the EU. Several stakeholders said the most promising route forward is to extract plastics from residual waste, something already starting to happen in the Netherlands, Sweden and Norway. This also would have the largest guaranteed climate benefit, as this plastic otherwise is very likely to be burnt.

Exhibit 15

TREATMENT OF END-OF-LIFE PLASTICS IN EUROPE, 2020

MILLION TONNES OF PLASTICS PER YEAR, EU27+UK/NO/CH



Notes: Based on 25 Mt H-DRI-based (with 50% scrap) steel, 2.5 Mt HVC chemically recycled via pyrolysis, 5 Mt HVC produced with CCUS, 15 Mt CCUS cement and 5 Mt low-clinker cement. Numbers are for additional capacity needed, e.g. need for breakthrough technology vs. current use. Steel analysis is based on 50% scrap use hydrogen-based iron & steelmaking via electric arc furnace route. Electricity estimates include power needed for hydrogen production via electrolysis.

SOURCE: MATERIAL ECONOMICS INDUSTRY MODEL

Finally, new infrastructure is required both to make new inputs available, and to enable CCS. Electricity is a major issue, as electrified crackers or hydrogen production for steel require large amounts of electricity at industrial clusters that previously have used relatively little. For example, a medium-sized chemical cluster planning for a transition based on electrification or hydrogen, CCS, and chemical recycling would need around 1,000 MW of additional electric power generation – a major demand on any regional electrical distribution grid in the EU.

Infrastructure is also crucial to scaling up CCS. Demand for CO_2 storage already exceeds supply, and the storage infrastructure launched to date (e.g., Northern Lights in Norway, Porthos in the Netherlands, C_4 in Denmark, and the Humber and Teesside storage plans in the UK) is oversubscribed (Exhibit 16). Government ownership or direct subsidies have made a big difference in getting the first projects on track. Looking ahead, stakeholders said a more stable regulatory regime will be needed. Among other things, this needs to handle the "natural monopoly" characteristics of pipeline networks and enable early construction of overcapacity ahead of CCS projects coming online.

Hydrogen networks provide another case in point. In some countries, such as Germany, regulatory regimes are now being put in place, adjusting incentives (returns) to attract investments in riskier projects.[61] However, many EU countries have yet to define a framework of regulation and incentives for the construction of hydrogen pipelines and storage facilities.

A final consideration is that breakthrough investments require rapid scale-up of several equipment supply chains. For hydrogen-based steel production, as much as 7.5 GW of electrolysers would be needed if for the full pipeline of current proposed projects is to be realised.[62] The current total manufacturing capacity (for all sectors) is around 2–3 GW per year.[63] Steel producers also need access to ore that has been processed so that it is suitable for use in the new direct-reduction facilities. For chemical recycling to reach large scale, up to 8 million tonnes of additional plastics waste would need to be sorted per year, requiring a near-doubling of currently installed sorting equipment. As noted above, CCS also requires "downstream" investments to be viable – in a nascent transport and storage sector.

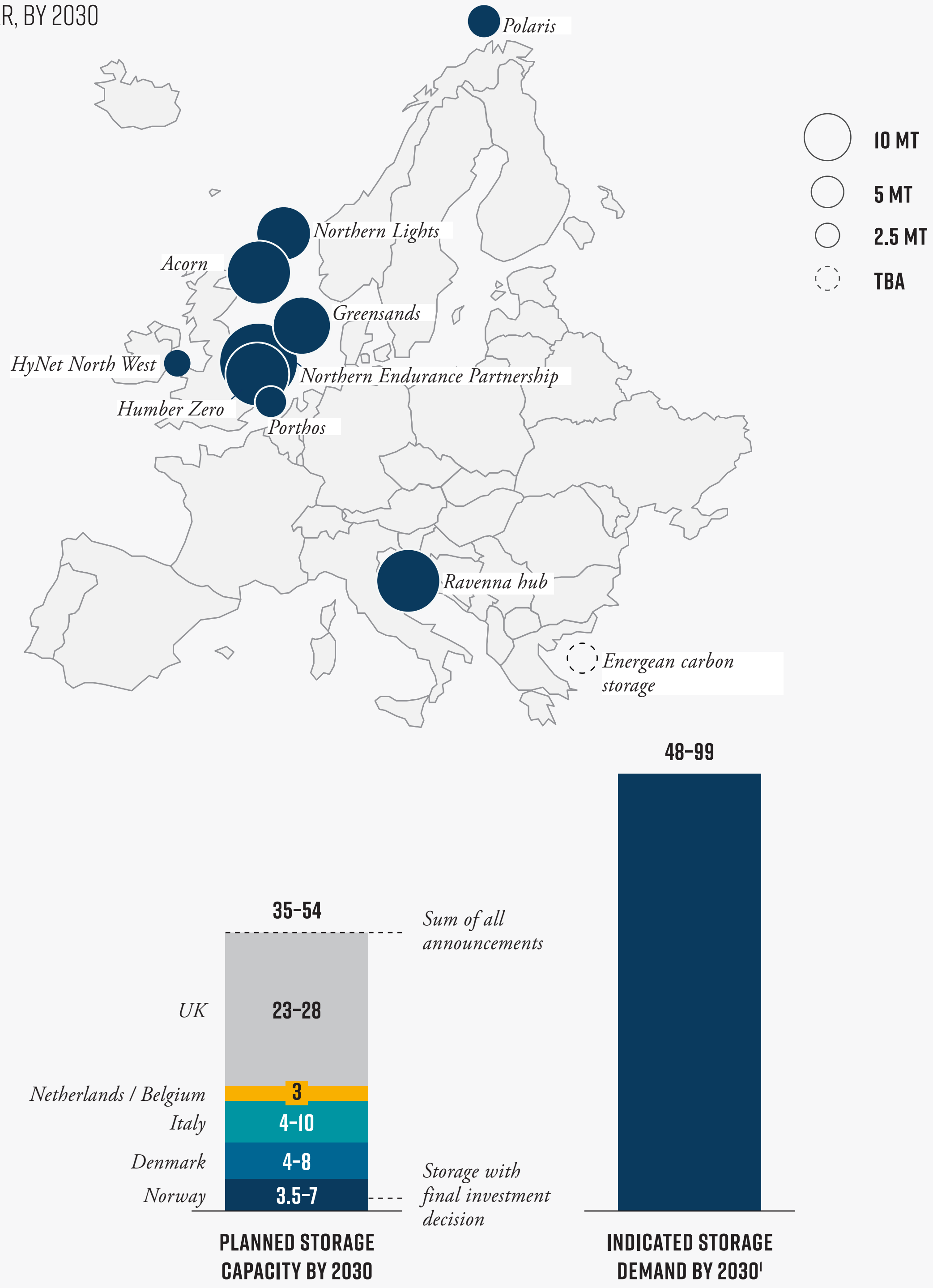
The need to invest thus cascades far beyond just the core industrial sectors. And crucially, the system needs to synchronise to avoid bottlenecks. For this to happen, all value chain actors need to know how likely it is that Europe will deliver on its current pipeline of projects. Until this is clearer, there is a real risk of shortages or bottlenecks in various parts of the respective value chains.

Exhibit 16

PLANNED CO_2 STORAGE CAPACITY BY 2030 IS INSUFFICIENT TO COVER DEMAND

PLANNED CO_2 STORAGE CAPACITY

MT CO_2 / YEAR, BY 2030



Note: [1] Based on clients in discussion with Northern Lights (representing 48 Mt CO_2/year) and storage demand of projects associated with the planned storage projects (capture projects related to storage sites Polaris, Greensands, HyNet North West, Humber Zero, Acorn and Ravenna hub).

SOURCES: MATERIAL ECONOMICS ANALYSIS, BASED ON GLOBAL CCS INSTITUTE, 2021, AND COMPANY WEBSITES.

3.5 ALIGNING MARKETS AND REGULATIONS FOR REINDUSTRIALISATION

EU climate ambitions are far-reaching, and the materials transition requires no less than a reindustrialisation of Europe. However, in many parts of Europe, it has been decades since large-scale industrial plants were last built. The new generation of industrial pioneers therefore encounter regulatory systems unprepared for the rapid decisions required for large-scale industrial build-out. This can stop or delay industrial initiatives, jeopardise the infrastructure and energy they require, or even prevent market entry altogether.

Today, stakeholders interviewed for this study unanimously agreed, permitting processes can significantly hinder the rapid deployment of breakthrough technologies. Those processes exist for good reasons: to address a range of societal concerns, notably about the safety and environmental impact of new activities. However, in most EU Member States, operating and environmental permitting processes have been honed for small, incremental changes to existing infrastructure – not for ambitious new projects. This means that obtaining approvals can take a long time and be costly and unpredictable. Some were blunt: company boards cannot approve the investment decisions required in the next two or three years without much more confidence that permitting roadblocks stop new production in its tracks some years down the line.

In some cases, product regulations and standards need to be updated before low-CO_2 materials can be used at all. A prime example is low-clinker concrete, which is either not allowed, or accepted only up to a certain percentage under current EU and national standards. Even the testing protocols for performance assessments need to be updated to work with novel concrete formulations. Similarly, many countries do not yet recognise chemical recycling as a form of recycling, which is makes it difficult to create demand for chemically recycled plastics.

Again, regulations of this sort were put in place for good reason, but unless adapted they risk becoming a hindrance to entirely valid innovation. The need to seek approval country by country prevents the rapid scaling of demand for new solutions – a recurring theme in Europe's capacity to scale cleantech solutions.

Without prompt action, Europe risks falling into old traps: leading in the early stages of technology development, but failing to follow through to scale.

4. A BLUEPRINT FOR TRANSFORMING EU INDUSTRY

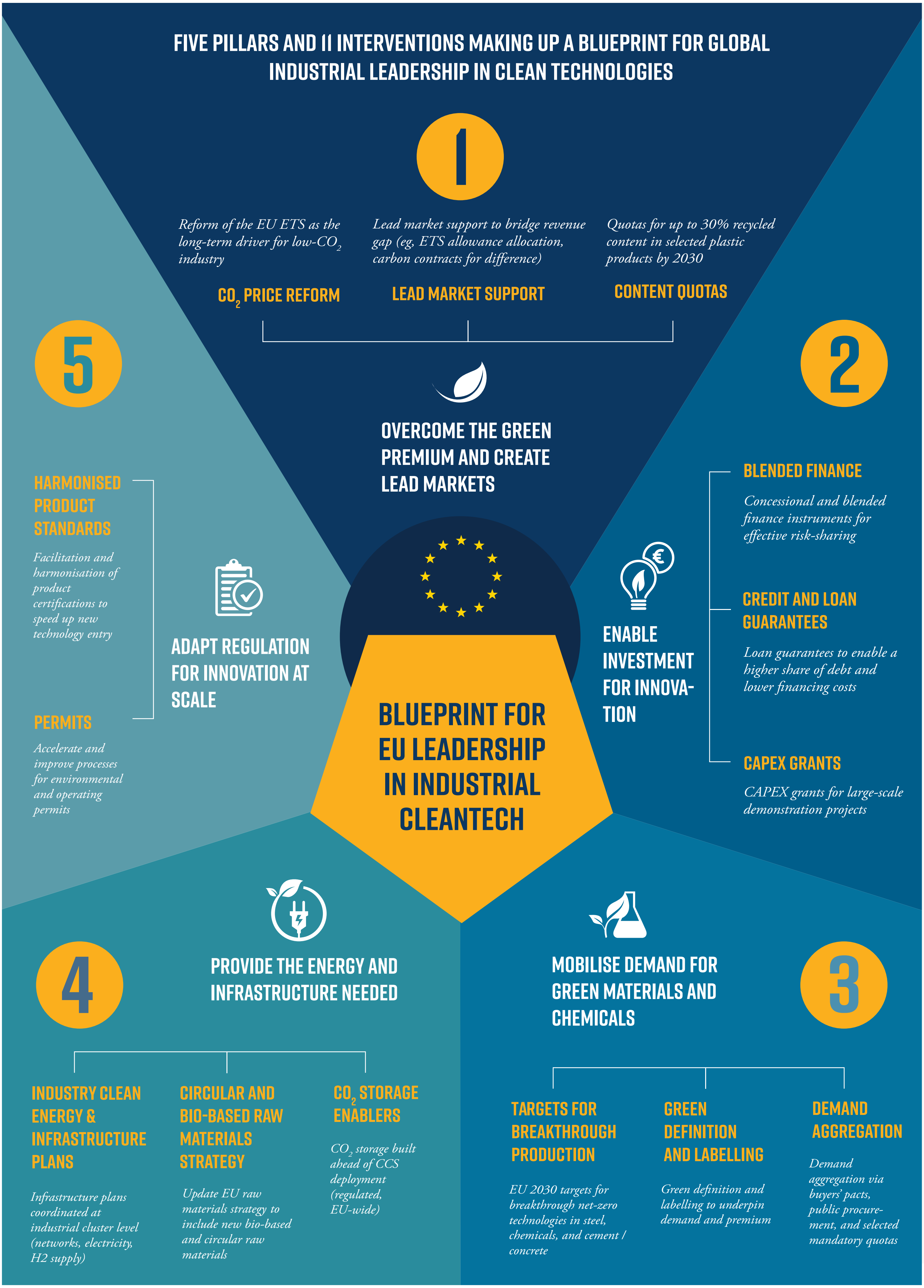
The EU has a crucial decade ahead to capitalise on its emerging front-runner position in industrial cleantech. This section lays out an agenda for action, starting right away, to systematically put in place the prerequisites for large-scale industrial transformation.

We offer no individual policy recommendations, but identify the issues to solve and the approaches now under discussion as the EU and European countries consider policy revisions under "Fit for 55" and other initiatives.

Europe needs to adopt a clear vision for transforming industry, at scale, and then develop a comprehensive, coherent policy agenda to achieve it.

Such a breakthrough industry policy package is ambitious and broad ranging, yet would be surprisingly affordable: For the scale-up ambition sketched in the previous section, the direct investment support needed would total less than 10 billion EUR to 2030. Ongoing support to offset additional production costs would be 4–6 billion EUR per year by 2030. For comparison, free allocation in the EU ETS will be worth some 400 billion EUR in 2022–2030,[64] and the EU budget will spend more than 500 billion EUR on the European Green Deal.[65] For end-users, meanwhile, the price impact would be tiny – less than 1–2% for cars, buildings, packaged consumer goods or pharmaceuticals, even if end-users were to pay for 100% low-CO_2 materials.[66] In investment terms, the amounts required are on the order of 1% of the total amount expected to be invested in the energy system in the next decade.

Exhibit 17 shows five areas of action for the EU and European countries to consider as they seek to catalyse a transformation of their heavy industries, each addressing a challenge identified in Section 3. The first priority is to make the business case work. The second is to enable investment through direct financial support and climate policy. Third, the EU needs to mobilise demand for green materials and chemicals. Fourth, Europe must put in place the infrastructure, energy supply, and raw materials value chains on which the new industry will depend. Fifth, and crucially, EU and Member State permitting processes and regulations need to be revamped to enable the rapid deployment and scaling up of breakthrough technologies.



FIVE PILLARS AND 11 INTERVENTIONS MAKING UP A BLUEPRINT FOR GLOBAL INDUSTRIAL LEADERSHIP IN CLEAN TECHNOLOGIES
1
Reform of the EU ETS as the long-term driver for low-CO_2 industry
CO_2 PRICE REFORM
Lead market support to bridge revenue gap (eg, ETS allowance allocation, carbon contracts for difference)
LEAD MARKET SUPPORT
Quotas for up to 30% recycled content in selected plastic products by 2030
CONTENT QUOTAS
OVERCOME THE GREEN PREMIUM AND CREATE LEAD MARKETS
2
ENABLE INVESTMENT FOR INNOVA-TION
BLENDED FINANCE
Concessional and blended finance instruments for effective risk-sharing
CREDIT AND LOAN GUARANTEES
Loan guarantees to enable a higher share of debt and lower financing costs
CAPEX GRANTS
CAPEX grants for large-scale demonstration projects
BLUEPRINT FOR EU LEADERSHIP IN INDUSTRIAL CLEANTECH
3
MOBILISE DEMAND FOR GREEN MATERIALS AND CHEMICALS
TARGETS FOR BREAKTHROUGH PRODUCTION
EU 2030 targets for breakthrough net-zero technologies in steel, chemicals, and cement / concrete
GREEN DEFINITION AND LABELLING
Green definition and labelling to underpin demand and premium
DEMAND AGGREGATION
Demand aggregation via buyers' pacts, public procure-ment, and selected mandatory quotas
4
PROVIDE THE ENERGY AND INFRASTRUCTURE NEEDED
INDUSTRY CLEAN ENERGY & INFRASTRUCTURE PLANS
Infrastructure plans coordinated at industrial cluster level (networks, electricity, H2 supply)
CIRCULAR AND BIO-BASED RAW MATERIALS STRATEGY
Update EU raw materials strategy to include new bio-based and circular raw materials
CO_2 STORAGE ENABLERS
CO_2 storage built ahead of CCS deployment (regulated, EU-wide)
5
ADAPT REGULATION FOR INNOVATION AT SCALE
HARMONISED PRODUCT STANDARDS
Facilitation and harmonisation of product certifications to speed up new technology entry
PERMITS
Accelerate and improve processes for environmental and operating permits

4.1 OVERCOMING THE GREEN PREMIUM THROUGH CARBON PRICING AND EFFECTIVE LEAD MARKETS

Long-term effective carbon pricing	Lead market support for the 2020s
Increased revenue for breakthrough industrial production by enabling pass-through of CO_2 prices to market prices for materials without causing carbon leakage	Ahead of effective carbon pricing, create lead markets via time-limited direct support mechanisms for breakthrough industrial production, without distorting intra-EU competition
Solutions under discussion: Cross-border carbon border adjustment mechanism and sectoral agreements providing effective carbon leakage protection in place of free allowance allocation, while safeguarding EU exports Phase-out of free allocation to enable pass-through of CO_2 prices to product prices	**Solutions under discussion:** Free allocation of EU ETS allowances to non- / very low-CO_2 production EU and /or national carbon contracts for difference support schemes, providing stable revenue at levels offsetting the green premium For plastics, quotas for 30% recycled content in packaging and other product categories by 2030, supporting emerging market premium for recycled plastics

The EU's heavy industries will adopt breakthrough technologies at scale only if there is a business case for doing so. That requires overcoming the green cost premium for emerging low-CO_2 steel, chemicals and cement production. The long-term solution chosen by EU policy-makers is carbon pricing – but reforms are needed to keep high-CO_2 imports (or EU-made materials) from undercutting the new, cleaner alternatives, and they will take time to have effect. Additional measures therefore would be needed to enable near-term investment decisions by first movers, supporting lead markets for low-CO_2 materials.

LONG-TERM EFFECTIVE CARBON PRICES

In principle, the revenue gap for breakthrough technologies could be closed by a carbon price such as that established by the EU's Emissions Trading System (ETS). Most stakeholders consulted for this work see this as the most likely, long-term solution. However, two issues must then be solved.

First, prices must be high enough. To be cost-competitive, the first wave of breakthrough projects in industry would need prices of 150 or even 200 EUR/tCO_2, significantly higher even than recent record prices of 90 EUR. Some stakeholders interviewed for this report questioned whether carbon prices will rise to those levels, as that could deal a major blow to the competitiveness of EU companies. Some suggested that high prices would cause policy-makers to intervene to keep prices lower, just as they added a Market Stability Reserve to raise prices when prices were thought to be too low.

Second, CO_2 prices would need to be fully passed through to market prices for steel, cement, or chemicals. These higher prices in turn would provide low-CO_2 producers with the additional revenues they need to offset higher costs. However, due to global competition and EU measures to help European producers, carbon pricing in the EU does not currently work like that for industry. Low-emitting producers do not see the revenue they need (Box 3 illustrates the problem).

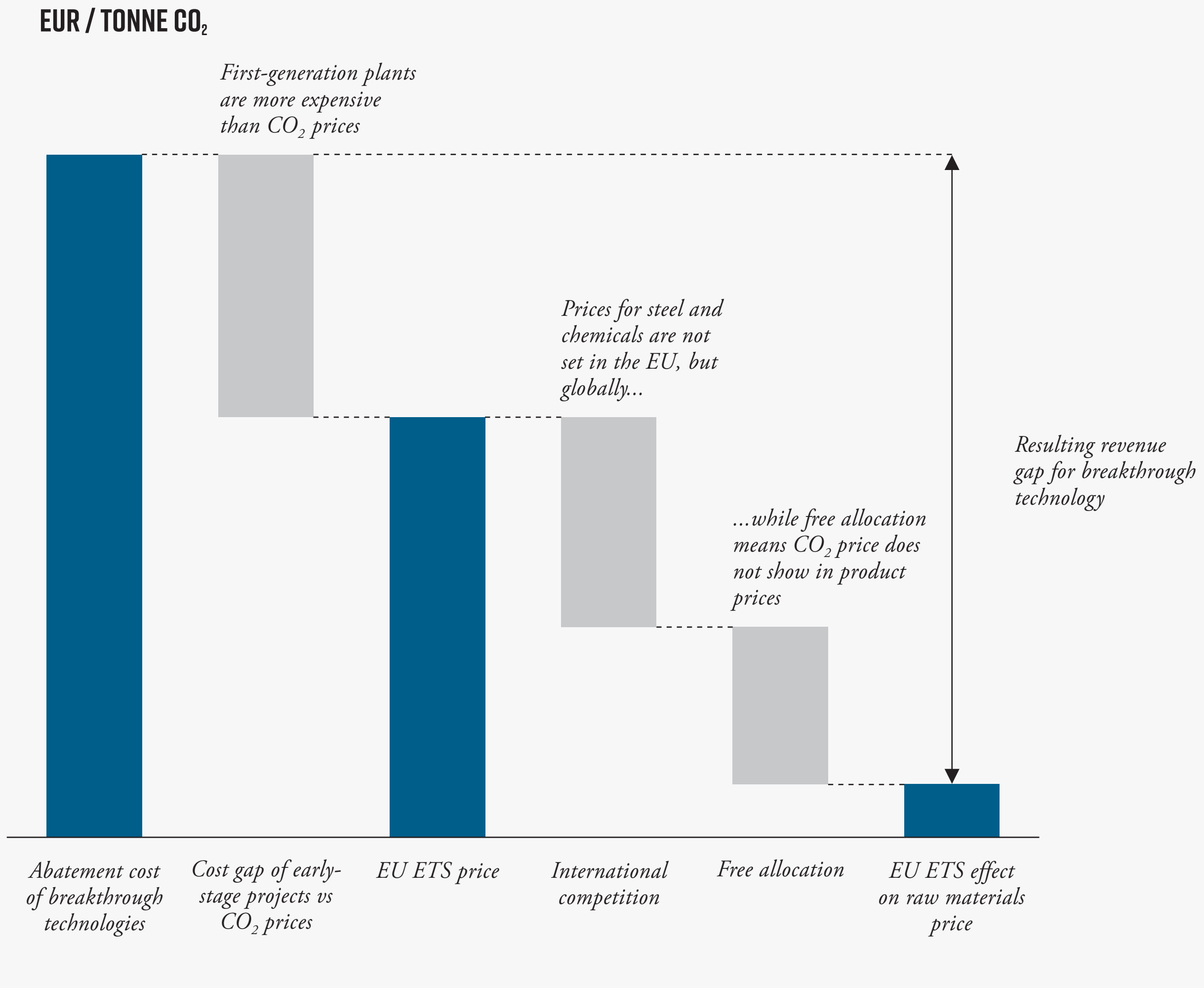
BOX 3: THE EU ETS CURRENTLY DOES LITTLE TO IMPROVE THE BUSINESS CASE FOR LOW-CO_2 INDUSTRIAL PRODUCTION

If all producers faced the same CO_2 costs, market prices for steel, chemicals or cement would increase to cover those costs (much like they cover the cost of inputs such as iron ore, coking coal, oil or gas). That is already how EU electricity markets generally work. When the CO_2 price under the EU ETS increases, so does the cost of coal- and gas-fuelled generation – and of electricity itself. As a result, low-carbon electricity producers earn relatively higher revenues. For industry, however, this mechanism is not in play, for three main reasons:

• **Unlike for electricity,** prices of steel and chemicals are set globally, not within the EU. CO_2 costs that apply only to EU producers would not necessarily raise prices and increase low-CO_2 producers' profits, as imports would remain less expensive.

• **The free allocation of ETS allowances** blunts the price signal. Free allocation is motivated by the need to prevent unfair competition from companies outside the EU. However, it also means that companies face only a portion of the full CO_2 price. For cement, for example, the net carbon cost is about 15% of the CO_2 price. Moreover, only a fraction of the CO_2 price is passed onto the prices for steel, chemicals or cement – so low-CO_2 producers do not get much extra revenue.

• **Finally,** current allocation rules can actively discourage the conversion of existing sites. Companies that receive free allowances risk losing them if they switch to a production method that is not covered by the ETS, so their revenue could drop, not increase.



Resolving these issues requires a way to handle the difference in CO_2 prices faced by EU and non-EU producers. This discussion is long-standing but now has new life, including some proposals for more ambitious policy in other parts of the world, international sectoral agreements, and/or a carbon border adjustment mechanism (CBAM). These could reduce the problem with differences in CO_2 prices on both sides of the EU border and, potentially, eliminate the need for free allocation.

However, many consulted for this study believe that is likelier to happen after 2030, too late to help companies now seeking to adopt breakthrough technologies. For instance, the current CBAM design foresees a full phase-out of free allocation only by the mid-2030s. The proposal also excludes many products altogether, such as polymers and chemicals, and there are many questions to resolve about how the mechanism can be effective all through the relevant value chains.

LEAD MARKET SUPPORT FOR THE 2020S

Given the likely delay before effective carbon pricing is in place, there is now a lot of attention on additional, near-term measures. These focus on direct support mechanisms for low-CO_2 producers. Several initiatives are already underway to address the green premium, with early signs of support for a new industrial agenda.

Analysis for this report indicates that additional support of 3–6 billon EUR per year by 2030 would be enough to enable the scale-up scenario introduced in Section 2.2. For comparison, 2020 support for biomass energy across the EU was around 14 billion EUR, and for wind and solar, around 19–27 billion EUR. ETS free allowances, meanwhile, correspond to about 56 billion EUR at a price of 80 EUR/tCO_2.[67]

There are different ways to design such a support mechanism, but stakeholders highlighted several key elements:

- **Support breakthrough innovation,** not just incremental emissions reductions or marginal increases in proven technologies;

- **Provide enough support** for the first wave of breakthrough industrial production;

- **Provide support equitably** to different breakthrough technologies and across EU regions to avoid distorting competition;

- **Ensure stable revenues** to reduce the additional volatility faced by breakthrough production;

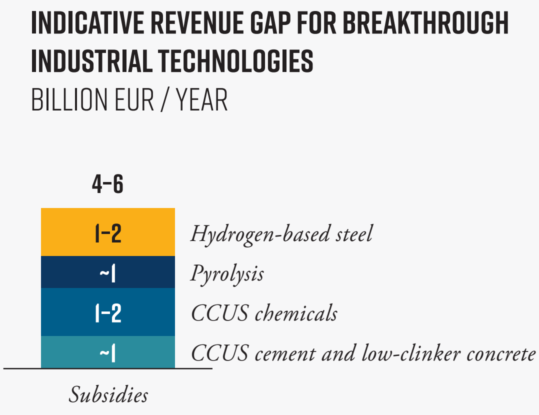
- **Ensure long-term credibility,** including co-existence with future effective CO_2 prices;

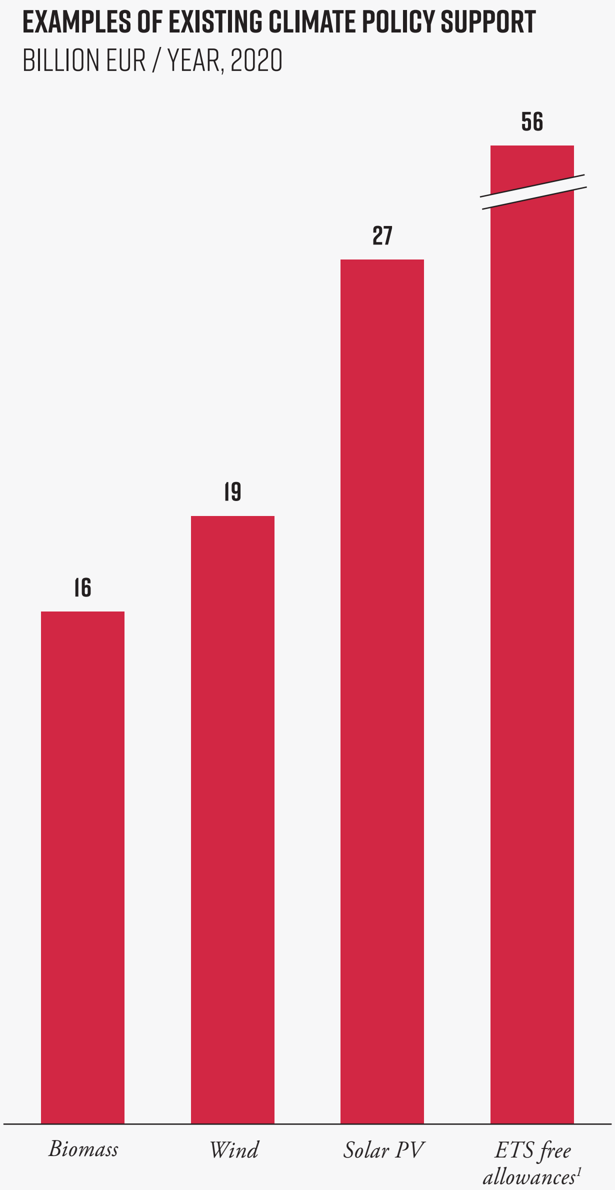
- **Secure funding** to limit the risk of discontinuation.

Proponents also emphasise that any such mechanism would be time-limited, covering the period of first scale-up while effective CO_2 prices remain elusive. In the long term, CO_2 prices would bridge the cost gap.

Exhibit 18

ADDITIONAL REVENUE OF 4–6 BILLION EUR PER YEAR IS NEEDED BY 2030 IN A SCALE-UP AMBITION FOR INDUSTRIAL BREAKTHROUGH TECHNOLOGY





Notes: [1] Based on 700 million free allowances in the EU ETS and the current carbon price of approximately 80 EUR / t CO_2

SOURCES: MATERIAL ECONOMICS ANALYSIS BASED ON MULTIPLE SOURCES; SEE ENDNOTE.[68]

FREE ALLOCATION OF EU ETS ALLOWANCES ALSO TO LOW-CO_2 PRODUCERS

The European Commission's proposal for a revised EU ETS Directive mentions the possibility of allocating free allowances to low-CO_2 or non-emitting producers. Allocation is linked to production volumes via benchmarks, so this would provide a direct output subsidy once producers sell their allowances. The idea here is to use a pre-existing system and funding source to bridge the revenue gap created by current CO_2 prices.

Much remains to clarify for this to work. For example, free allowances at benchmark levels would not fully close the cost gap for many breakthrough technologies, as the CO_2 price is unlikely to rise to the level needed and allocation benchmarks are set lower than industry averages. Some have suggested addressing this via some form of "scaling mechanism" that gives innovative low-CO_2 projects a bigger allocation.[69]

There are political issues to address as well. Giving allowances to innovators would reduce the number available for leakage protection for incumbent industry.[70] Some stakeholders consulted thought that the notion of deliberately providing allowances to companies that do not "need them" would go against the grain of what free allocation is for. Others questioned whether the current system of uniform "benchmarks" can continue to operate at all as some factories decarbonise and others do not, and the spread in carbon intensity thus increases.

DIRECT SUPPORT VIA 'CARBON CONTRACTS FOR DIFFERENCE'

There also are various proposals for direct support schemes for low-CO_2 industrial production. The most prominent is to introduce "carbon contracts for difference" (CCDs), inspired by the use of this type of output subsidy in the electricity sector. Under these proposals, eligible industrial production would receive a subsidy payment per unit of production. The payment would be designed as a "contract for difference", varying the subsidy level so that total revenues (market price + subsidy) were kept constant, providing financial stability to make financing easier.

As part of a proposed revision of the EU ETS, the European Commission envisions expanding the scope of the Innovation Fund to include support via CCDs.[71] However, the current budget for the fund – a total of 10 billion EUR available to 2030 – means it is too small on its own to support more than a few industrial projects. The first call for projects, with a 1 billion EUR budget, received 311 applications seeking 21.7 billion EUR.[72] The proposed EU ETS revision would also significantly increase the fund's size.

Several Member States are exploring complementary direct support schemes of their own. The Netherlands already operates a version via its SDE++ scheme, although this currently is limited to CCS for industry. In early 2022, Germany announced it was preparing a version of CCDs as part of a forthcoming "Easter package". France also has made clear its intention to create such a scheme. Various Member States are looking to provide subsidies for green hydrogen production as well, which could be an indirect way to support some of the breakthrough industrial technologies. The State Aid Guidance proposed by the Commission in late 2021 appears to give Member States more leeway to support such industrial decarbonisation initiatives.

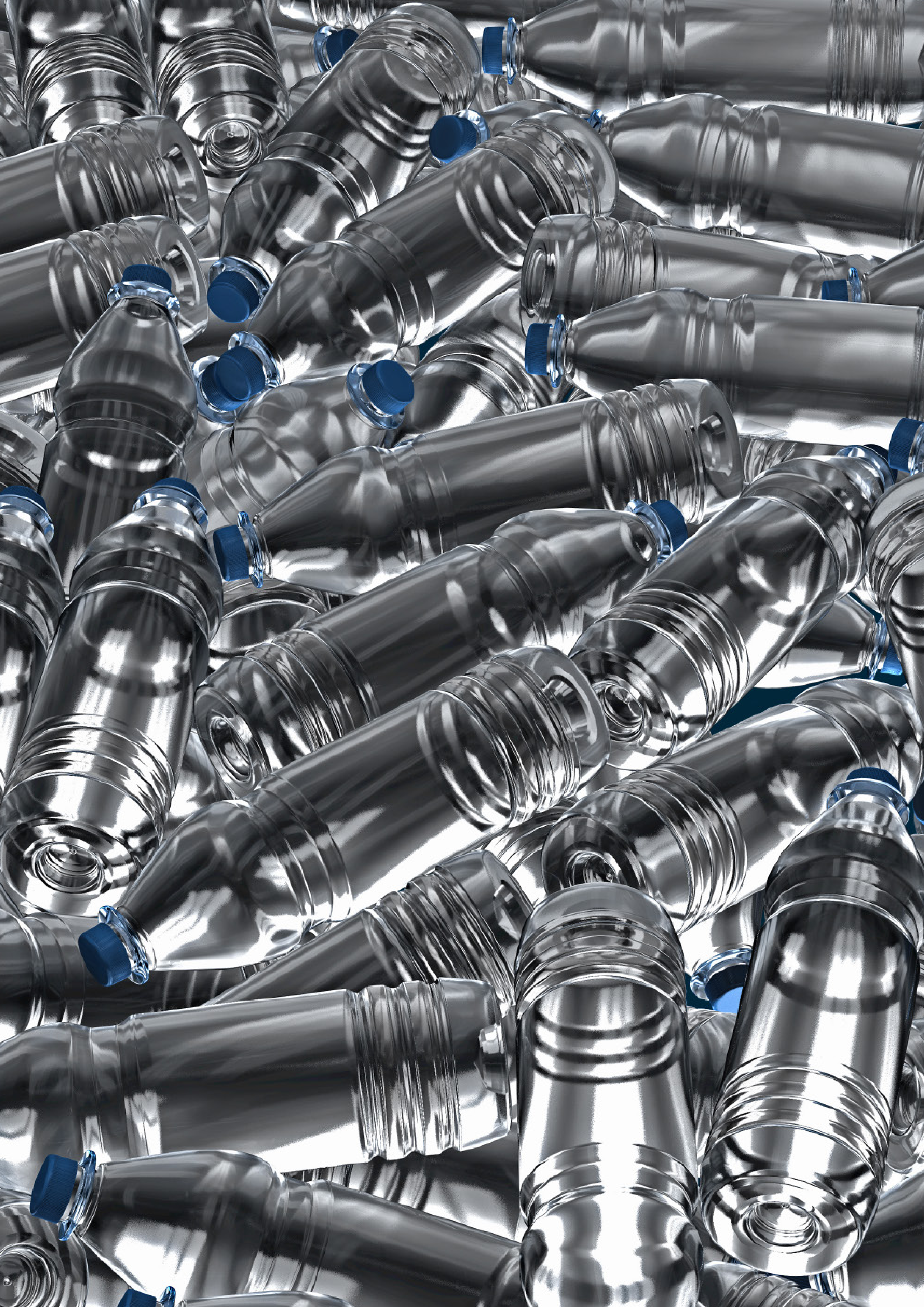
These mechanisms could be very effective in addressing the green cost premium head-on. However, as with any new policy mechanism there also are potential pitfalls. The most obvious is that unlike free allowance allocation or a CCD scheme under the Innovation Fund, national schemes could skew the competition among similar projects in different Member States. If they only support specific technologies, they could also disadvantage valuable, but perhaps lesser-known solutions. There also is no comprehensive proposal on the table yet describing how key aspects of the scheme would work, such as how subsidy levels could be set and what reference prices to use for the "difference" element.

QUOTAS FOR UP TO 30% RECYCLED CONTENT IN SELECTED PLASTIC PRODUCTS BY 2030

An alternative to subsidising production is to put in place standards or quotas that create a market premium. This approach has precedents in EU climate policy, having been used for renewable electricity (portfolio standards and green certificate schemes) and for energy efficiency (white certificates).

It would be complex to use this approach for most industrial production. The output of a single steel mill or chemicals factory may be used in hundreds of different products, making it difficult to set a targeted quota that can help transform production. For cement, meanwhile, the high geographical concentration of the market makes quotas difficult, as it could directly interfere with competition between just a few factories. However, industry bodies have noted that input quotas could work well with certain plastic products.

The closest analogue is the recycled content requirements for plastic bottles introduced by the Single-Use Plastics Directive. They have helped create a 40–60% market premium for recycled PET plastic that is now driving investment in new food-grade recycling capacity. The EU plastics industry has called for a broadening of this requirement through revision of the Packaging and Packaging Waste Directive, to introduce a mandatory recycled content requirement for all plastics packaging of up to 30% by 2030 – provided other enabling conditions also are put in place.[73] The scope could in principle be expanded further: for example, the European Commission communication on sustainable carbon cycles mooted the idea that 20% of the carbon input to EU plastics and chemicals products be from non-fossil origin by 2030.[74]



4.2 ENABLING INVESTMENT FOR INNOVATION

Direct Investment support	Credit and loan guarantees	Concessional and blended finance
Speed up transition by overcoming the first-mover disadvantages of higher cost and incentive to delay.	Enable lower risk and cheaper capital structure for industrial scale-up investment by reducing undiversifiable technology and market risk.	Expand the pool of available capital via strategic use of public lending to mitigate risks and crowd in private capital.
Solutions under discussion:	**Solutions under discussion:**	**Solutions under discussion:**
Scaled up direct investment support for industrial low-CO_2 projects, targeting a total of €5-9 billion EUR for steel, chemicals, and cement to 2030.	State-backed credit guarantees for capital investment via national agencies and InvestEU.	Blended finance facilities for new industrial breakthrough scale-up via InvestEU and existing institutions such as EIB.

Getting the overall business case in place will always be the foundation for any investment decision in new technology. But beyond this, there are several other steps EU policy-makers and financial institutions can take to mobilise the capital needed and to reduce the cost of financing. Three in particular would be very valuable for the first wave of breakthrough scale-up projects in industry: direct capital expenditure (capex) grants, credit and loan guarantees, and blended finance.

CAPEX GRANTS TO REDUCE THE FIRST-MOVER DISADVANTAGE

As discussed above, early investments in breakthrough technologies face an "innovation premium" in securing finance for first-of-a-kind projects: lack of scale benefits, higher early equipment costs, immature supply chains, ongoing reinvestment needs in immature technology configurations, and higher project development costs in the absence of existing reference plants.

Direct capex grants are one instrument used to mitigate some of this risk and thus help encourage early investment.[75] A key objective is to reduce the need for high-cost equity capital. Across technologies, we estimate that this could reduce total costs by 10–20%, by enabling a higher debt-to-equity ratio.[76]

The EU Innovation Fund operates in this space, also providing support for investment in large-scale plants. The first round of large-scale projects, in 2021, included two industrial projects, in chemicals and steel – but as noted the application round was very oversubscribed. National-level programmes are emerging as well, but more ad-hoc, in some cases via an individual memorandum of understanding between a company and the government. Some stakeholders said they would welcome more predictable, open and structured programmes of capex support, in compliance with the revised State Aid guidance.

The level of capex support needed would vary. More incremental technology options might face very little risk, while the bigger leaps could see as much as a 20–30% investment "penalty" for early movers. For illustration, defraying 20–30% of total capital expenditure would require 5–9 billion EUR until 2030 in the scale-up scenario. If the Innovation Fund is expanded as envisioned, it could potentially mobilise this kind of capex support for industry.

CREDIT AND LOAN GUARANTEES TO REDUCE UNDIVERSIFIABLE RISK

Many of the risks faced by first movers are "undiversifiable": there are no market mechanisms to hedge, reduce or spread them. Instead, risk must be confronted by investors head-on. The flip side of this risk is the social value of learning-by-doing: by taking these risks, companies help drive the learning curve down for all future investments, accelerating the transition to low-CO_2 industry. This means there is a case in principle for society to take a share of the risk, reflecting the broader social value that innovators create.


09.7

Credit guarantees offer a concrete mechanism for this, and they are already used to enable private finance in several other contexts. For example, export credit agencies use them in support of national exporters competing for overseas sales. During the COVID crisis, governments provided loan guarantees to hard-hit businesses such as airlines – ensuring continued access to private finance that otherwise would have dried up. In both cases, the mechanism works not by injecting public funds, but by enabling private credit. The public agency's role is to take on some of the risk that loans are not paid back.

These types of mechanism are starting to be pioneered also for low-CO_2 industrial investment. The InvestEU Fund is designed to provide 26 billion EUR of guarantees, including for green recovery. At country level, Sweden recently launched a programme that provides government guarantees against 80% of the total amount borrowed for eligible industrial breakthrough projects.[77] Investors consulted for this study thought expanded guarantee programmes could provide a very powerful way to boost industrial innovation.

CONCESSIONAL AND BLENDED FINANCE TO CROWD IN PRIVATE CAPITAL

As an alternative to providing investment grants and guarantees, public financial institutions can provide finance directly, and on terms not available from the private market. When it works well, such concessional finance can help "crowd in" additional private finance that otherwise would not have happened (though there is always some risk of "crowding out" – replacing rather than complementing private finance).

The EU-Catalyst Partnership offers a model for how this can be done via blended finance.[78] It will provide investment support of up to 50% to commercially critical clean technologies (clean hydrogen, sustainable aviation fuels, direct air capture, and long-duration energy storage), targeting a 20% grant share overall. It blends private and philanthropic funds raised through Breakthrough Energy Catalyst (a private investment vehicle) in the form of grants, equity investment and offtake agreements with public EU funds available via Horizon Europe and the Innovation Fund in the form of grants, loan guarantees and quasi-equity. Investments are managed through the InvestEU Green Transition Facility, aiming to leverage 3 EUR of private funding for every 1 EUR of public funds committed. A similar model could be used for industrial clean technologies.

SUPPORT FOR CLEANTECH SCALE-UP FINANCE TO FEED THE INNOVATION PIPELINE

Although this study focuses on projects that are now ready to scale, there is an important link between scale-up and early-stage cleantech investment. There are encouraging signs of EU leadership in early-stage cleantech investment, which has grown 7.5 times over the last decade.[79] According to the Cleantech Group, Europe has an outsize share of early-stage cleantech entrepreneurs in several areas. In industry, however, the pipeline is still relatively small.

Investors consulted for this study noted that where the EU falls behind in is the scale-up stage, with a lack of access to growth equity, fragmented national markets that inhibit benefits of scale, and a lack of exit routes to equity markets. Promising early-stage innovation therefore frequently leaks to the US or other places at the critical growth stage. This, in turn, creates a major barrier for new entrants, including in industrial sectors.

To turn industrial breakthrough scale-up into economic opportunity, the EU needs to boost the capacity of its financial system. Where this has worked best – such as in the push to re-establish the EU as a major player in the market for batteries – it has been done through a highly coordinated push including aggregate targets, technology roadmaps, robust demand signals, direct public investment support, and public-private partnerships. Similar initiatives could help unclog scale-up financing for industrial cleantech.[80]

BOX 4: THREE KEY THEMES TO UNLOCK FINANCE

Enabling finance for breakthrough technologies must be done through several different mechanisms. The direct capex support, credit guarantee, and concessional finance approuaches can all help. However, finance on its own is not enough. To be effective, financing support must be mobilised in the context of an overall positive business case and other enabling conditions. The overall policy package to scale breakthrough technology in industry therefore needs to address all three main barriers to viable financing: i) mobilising an attractive capital structure, ii) adjusting the risk/return profile, and iii) guarding against adverse scenarios and systemic risks that risk undermining the financial case.

CAPITAL STRUCTURE

OVERCOME EQUITY-TYPE RISKS FOR LARGE CAPEX PROJECTS

- *Large investment needs vs balance sheets given high capex intensity and large new assets*
- *Technology and performane risk absent reference plants and lack of warranties from suppliers*
- *First-mover disadvantage, via falling technology costs, ramp-up risk, higher reinvestment need, smaller-scale plants*

ENABLE DEBT FINANCING
via equity-like capital, credit and loan guarantees, direct capex grants

RISK/RETURN PROFILE

ADVERSE RISK/RETURN PROFILE WITH HIGH COSTS AND VOLATILE REVENUES

- *Green premiums: 40–100% for first-generation plants, exceeding expected CO_2 price signal*
- *Unclear green definitions and market orchestration to enable into future market demand for green products*
- *Return votality with loss of 'natural hedge' and uncertainty about future market premiums*

SUPPORT AND STABILISE
revenue and orchestrate private market demand

WIDER SYSTEMIC RISKS

RISKS THAT KEY INPUTS AND REGULATIONS ARE UNAVAILABLE

- *New and large point-source demands for energy and inputs (H_2, electricity, etc.)*
- *New infrastructure requirements such as CO_2 transport & storage and build-out of electricity or H_2 networks*
- *Project development risk especially via lengthy permit processes*
- *Markets access risk through product regulations and green definitions*

CREATE CERTAINTY
for permits, inputs, infrastructure, and market access

4.3 MOBILISE DEMAND FOR GREEN MATERIALS AND CHEMICALS

Targets for green industrial production	Demand mobilisation	Green definitions and labelling
Coordinate value chain, infrastructure, investment, and policy through targets for breakthrough industrial production by 2030	Tap into public and private demand to create a green market premium and underpin investment in breakthrough industrial production	Differentiate breakthrough / very low-CO_2 industrial production and create transparency required for support schemes, investment decisions, and market demand
Solutions under discussion:	**Solutions under discussion:**	**Solutions under discussion:**
EU 2030 targets for very low-CO_2 production steel, cement and concrete, and chemicals from breakthrough technologies	A First Movers' Coalition Europe to orchestrate emerging private-sector demand for very low-CO_2 materials Public procurement of very low-CO_2 materials CO_2 standards on materials used in construction, automotive, and packaging value chains	Standardised EU definitions of green steel, chemicals, plastics, and cement/concrete, accommodating emerging technologies that enable 75-90% reductions on current practice CO_2 labelling requirements for key product categories including packaging, construction, and automotive

As discussed in Section 1, there is significant momentum globally to decarbonise supply chains, with the market projected to grow to 100 billion USD by 2030. Within Europe, as noted in Section 3.3, green premiums for a range of recycled and for low-CO_2 materials are already emerging in some supply chains. This nascent market can provide a powerful boost to investors in breakthrough industrial production. Policy can play an important role in enabling this market: by coordinating expectations, orchestrating mechanisms that mobilise demand, and establishing green definitions and market transparency.

2030 TARGETS FOR BREAKTHROUGH PRODUCTION OF GREEN MATERIALS AND CHEMICALS

Transforming industrial production requires enormous coordination to mobilise research and development, investments, new business creation and market entry, novel policy instruments, energy and raw materials inputs, infrastructure build-out, permits for new industrial facilities, and demand for new low-CO_2 materials. Ensuring these multiple factors move in lockstep will be a major challenge for the EU materials transition.

In this situation, targets for breakthrough industrial production could be effective, creating a common reference point for the pace of change and size of the future market. Explicitly articulating an expected future volume of low-CO_2 steel, chemicals, and cement would be especially valuable now, when so many final investment decisions are pending.

EU climate, energy and industrial policies have frequently used such targets. A prime example is the "20-20-20 targets" for emissions reductions, renewable energy deployment, and energy efficiency improvement set in 2007. Softer, non-binding targets have also been used. For example, the EU Hydrogen Strategy set a target for 6 GW of electrolyser capacity by 2024, increasing to at least 40 GW by 2030.[81] Likewise, as noted above, the European Battery Alliance was driven by an early 2016 agreed target for EU manufacturing capacity and performance.[82] Even non-binding targets can set common expectations and follow-up mechanisms, encouraging investment.

ORCHESTRATE PRIVATE AND PUBLIC DEMAND FOR LOW-CO_2 MATERIALS

A FIRST MOVERS COALITION EUROPE TO HARNESS EMERGING PRIVATE-SECTOR DEMAND FOR VERY LOW-CO_2 MATERIALS

The EU can help coordinate demand by fostering initiatives that pledge the future use of breakthrough industrial products. One option proposed by some stakeholders was to build on the First Movers Coalition.[83] Launched last year at COP26 in Glasgow, the coalition provides a platform for companies to make purchasing commitments that create early market demand for emerging low-CO_2 technologies. The goal is explicitly to provide more market certainty for companies investing in breakthrough technologies. In the steel sector, coalition members are pledging that at least 10% of the steel they purchase each year (by volume) by 2030 will be "near-zero emissions".[84]

The idea would be to establish a similar First Movers Coalition for Europe, linking key end-use sectors – construction, automotive, industrial machinery, packaging and more –with the emerging pipeline of low-CO_2 materials producers. This has been done before in the EU, but only on a smaller scale: For example, the Circular Plastics Alliance, launched with the 2018 EU Plastics Strategy, mobilised commitments to use 10 Mt of recycled plastics by 2030.

PUBLIC PROCUREMENT OF VERY LOW-CO_2 MATERIALS

Demand for very low-CO_2 products can also be created through public procurement. Public authorities spend about 1.8 trillion EUR every year – some 14% of EU GDP.[85] The 2014 Public Procurement Directive allows for environmental criteria,[86] and some proposed standards are harmonised via the 2008 Green Public Procurement Directive.[87] Several EU countries and cities have trialled various procurement approaches, such as the carbon "shadow prices" used in the Netherlands,[88] setting outright standards for recycled content of materials used at the city level,[89] or gradually tightening CO_2 limits for transportation infrastructure (for both new projects and maintenance).[90]

Stakeholders differed in their views on whether public procurement would be effective in practice. For public procurement to make a significant difference in creating lead markets for breakthrough production, more ambitious standards would be required in major economies and at the EU level. For example, materials with very low CO_2 impact could be explicitly mandated or favoured. This approach has not yet been used at the EU level, but some stakeholders suggested it could add to the demand signal for the investments now in the pipeline.

GREEN DEFINITIONS AND LABELLING OF VERY LOW-CO_2 MATERIALS

Another key element of mobilising demand that stakeholders highlighted is to provide clear guidance for buyers, so they can choose truly low-CO_2 materials with confidence. Agreeing on what qualifies as "green" is also crucial for demand aggregation efforts, procurement standards and support mechanisms.

STANDARDISED EU DEFINITIONS OF 'GREEN' MATERIALS AND CHEMICALS

An analysis of the pipeline of breakthrough projects makes clear that it will be possible to achieve deep reductions in the CO_2 footprint of major materials already by 2030, with the leaders cutting emissions by as much as 75–90% along the full steel, chemicals and cement value chains. Thus, steel produced using hydrogen could emit 0.3–0.4 tCO_2 per tonne steel (with some targeting 0.1 tCO_2 or less); high-value chemicals could be made from 100% non-fossil feedstock (using a "mass balance" approach); and novel concrete and cement types could cut emissions to 0.2 tCO_2/t via high capture rates for CO_2 or low-binder formulations in combination with alternative binders.

This provides a starting point for discussing how to define "green" materials and chemicals. However, this study has not developed proposals for the exact definitions to be used. The choices made are likely to be contentious, as they will qualify or exclude individual projects from support schemes and lead markets. Any definition must therefore balance the need to encourage a larger number of low-CO_2 production initiatives with the value of prioritising the most disruptive and transformative initiatives.

CO_2 LABELLING FOR KEY PRODUCT CATEGORIES INCLUDING PACKAGING, CONSTRUCTION AND AUTOMOTIVE

Demand for lower-CO_2 products can also be bolstered by transparent communication of CO_2 performance via labelling and certification. The EU already has frameworks for the labelling of a range of products, from the energy performance of appliances or buildings, to the CO_2 emissions intensity and fuel economy of cars. However, there is no single framework for CO_2 footprint. Instead, there are multiple competing national frameworks for Environmental Product Declarations and a range of other national certification schemes.

The 2020 Circular Economy Action Plan foresaw an extended product policy framework that also standardises ways to substantiate environmental claims, including CO_2 footprints. Like standard-setting, this will also raise complex debates. Still, a common basis for comparison would enable the most ambitious low-CO_2 producers to stand out, while providing crucial information for buyers in nascent markets for green materials. Several existing regulatory frameworks could be used for implementation, such as widening the remit of the Energy Performance of Buildings Directive or changing the Construction Products Regulation.[91]

4.4 PROVIDE THE ENERGY AND RAW MATERIALS FOR A RENEWED EU INDUSTRIAL BASE

Green electricity and hydrogen supply	A Circular and bio-based raw materials strategy for the EU	CO_2 storage and transport infrastructure
Mobilise the low-CO_2 electricity and hydrogen inputs needed for a scale-up 2030	Tap into public and private demand to create a green market premium and underpin investment in breakthrough industrial production	Make available the ~15 Mt storage capacity required for industrial carbon dioxide by 2030
Solutions under discussion: Co-ordinated clean energy infrastructure plans for EU industrial clusters incorporated in National Energy and Climate Plans with EU-level follow-up process to capture cross-border requirements For hydrogen specifically, national hydrogen strategies incorporating industrial demand	**Solutions under discussion:** An EU Circular and Bio-based raw materials strategy for increased separate collection and reduced contamination of steel, plastics, and other raw materials	**Solutions under discussion:** Industrial CO_2 storage strategy with aggregate targets, coordinated build-out ahead of demand, incorporating aggregate targets, plans for specific industrial clusters, and regulatory certainty about liability and future cost of storage

Scaling of breakthrough industrial technologies and business models entails a fundamental shift from the use of oil, gas and coal, and towards electricity, hydrogen, recycled metal and plastics, biogenic feedstock, and captured CO_2. It will take concerted effort to rapidly build out these new supply chains and the associated infrastructure.

CLEAN ENERGY AND INFRASTRUCTURE PLANS FOR INDUSTRY

The transformation of EU industrial base depends on the use of very large quantities of clean electricity and hydrogen. They need to serve very large point sources of demand, in many cases in existing industrial clusters that previously have used entirely different energy sources. This requires a step-change on current plans and procedures.

Future industrial needs are often left out of current plans for energy infrastructure. Thus, the current crop of National Energy and Climate Plans (which summarise Member State plans for infrastructure build-out and funding under the EU Energy Union Governance Regulation) set out plans for the whole of the 2020s, but mostly overlook the new infrastructure and energy needed if current proposed industrial breakthrough projects are to become reality. Stakeholders across several Member States noted a similar gap in national energy planning processes, such as plans for national transmission grids to accommodate future industrial needs.

Given the long lead times to build out energy infrastructure, the roughly 90 TWh of clean electricity and 20 TWh of hydrogen required for an ambitious industrial scale-up scenario would require very rapid action. One approach would be to start through plans for the different industrial clusters, and then coordinate at both the national level and internationally via EU mechanisms such as Important Projects of Common European Interest (IPCEIs) and Regional Just Transition Plans.

Likewise, many breakthrough projects in steel and chemicals depend on a rapid scale-up of clean hydrogen supplies. As noted in Section 3, lack of access to hydrogen is a major reason that many steel projects consider an interim phase of using natural gas instead. Given recent efforts to reduce reliance on imported gas, and concerns about continuing high natural gas prices, the need to make hydrogen available is more urgent than ever. The needs of industry therefore need to be accounted for and prioritised in the emerging national hydrogen strategies and the overall framework, including updated State Aid regulations, revisions of the Renewable Energy Directive, hydrogen IPCEIs,[92] and the implementation of financial support mechanisms at the Member State level.

It is also crucial for industry to have clarity on which forms of hydrogen qualify as low-CO_2. This could be done through the proposed lifecycle carbon intensity definitions in the revision of the Renewable Energy Directive.

AN EU CIRCULAR AND BIO-BASED RAW MATERIALS STRATEGY

The EU has several initiatives to secure raw materials access for EU industry, starting with the 2008 Raw Materials Initiative,[93] and followed by initiatives such as the European innovation partnership (EIP) on raw materials.[94] Breakthrough industrial production will require a major update to priorities, reflecting the new inputs needed to scale novel production processes.

• **For end-of-life steel,** there is a need for a plan to safeguard the quality and availability of future steel scrap. In the coming decades, end-of-life steel supply will grow to some 80% of EU production, expanding the opportunity for scrap-based production. Keeping the EU steel stock free from contamination by copper is therefore a climate and industrial priority, but one which currently receives little attention. Revisions to the End-of-Life Vehicles Directive, with support for technology development, could be important steps.

• **For end-of-life plastics,** there is a need to build a much more robust supply chain: today's supply options are often not an investable basis for large-scale production. As shown in Exhibit 15, plastics collection across the EU is now fragmented and incomplete, so only about 10 Mt of the nearly 45 Mt of plastics that reach end-of-life each year are made available for recycling within the EU. If plastics are to be used as feedstock in place of oil and gas, regulations and waste management systems need to anticipate large-scale recycling facilities that source end-of-life plastics from a wide geographic area. Trade in secondary plastics then needs to be made much simpler than it is today. The attempts since 2008 to implement "End of Waste" criteria under the Waste Framework Directive have now largely stalled for plastics, but the need very much remains.

• **For biomass,** stakeholders noted the disparity between energy uses of biomass and ones that use biomass as feedstock for chemicals and for materials production. Today's subsidies, tariffs and mandates almost universally steer towards bioenergy applications, putting feedstock uses at a disadvantage in competition for a scarce resource.[95] In addition, there is a need for rules to guide what counts as "sustainable". The closest precedents are the rules of the Renewable Energy Directive and the definitions in the Taxonomy, but these apply only to the fulfilment of EU energy targets and to investments – and are contentious. Addressing these issues will be complex and no doubt controversial, as even seemingly similar biomass categories can encompass enormous variation in environmental impact. However, policy-makers cannot shy away from the topic: lack of clarity otherwise risks holding back investment in novel industrial production routes.

• **For CO_2,** the current proposal is to credit utilisation of CO_2 emissions that are "permanently chemically bound in a product so that they do not enter the atmosphere under normal use",[96] but it is still undefined which use cases will or will not qualify. The lack of clarity creates significant risk for investors in CCU projects, so there is a need to clarify as soon as possible.

CO_2 STORAGE BUILD-OUT AND REGULATION

The CO_2 transport and storage infrastructure now emerging in Europe is the result of pioneering initiatives in a few Member States. The Norwegian government provided 1.7 billion EUR for the Northern Lights project (covering both capture, transport, and storage costs).[97] Likewise, the Dutch government has put in place long-term subsidies for CO_2 storage from industry while providing 2.1 billion EUR in support for the Porthos CO_2 storage initiative.[98]

To truly scale up, some companies suggested a coordinated European approach would be more effective, setting targets and building CO_2 storage at the same time as supporting demand, to avoid the "chicken and egg" problem for investments in CCS. They also noted a need to make the concentrated and limited EU CO_2 storage sites available to a broad range of projects across different countries. The recent inclusion of CO_2 storage infrastructure in the Trans-European Networks for Energy (TEN-E) regulation[99] opened the door for pooled EU-level funding via the Connecting Europe Facility and increased coordination. However, further coordination will be needed to bring forward the full volumes needed by 2030.

Regulation of this emerging infrastructure will also be key to create the confidence for investment. With strong natural monopoly elements, finding a stable regulatory regime for the availability, liability, pricing, and counterparty status of storage will be critical.

4.5 ADAPT REGULATIONS AND STANDARDS FOR INNOVATION AT SCALE

Permits for industrial facilities and for infrastructure	Regulatory frameworks to support new entrants
Reduce lead times and increase predictability in obtaining environmental and operating permits required for new industrial capacity	Remove barriers to entry for innovative products with significant CO_2 benefits by reforming product standards and certification
Solutions under discussion: National task forces to remove permit bottlenecks to investment in energy supply, infrastructure, and industrial capacity	**Solutions under discussion:** EU-harmonised approach to fast-track approval of new entrant products including novel cement, concrete, and recycled plastic categories Clear carbon accounting, mass balance, and recycling framework for production based on carbon capture and utilisation and chemical recycling

Much of existing EU industry is many decades old, and investment has long been more about maintaining and consolidating an existing industrial base than about building a new one. Scaling breakthrough technologies will change this. New infrastructure and new factories will need to be built at pace. Likewise, novel products need to be certified and introduced to markets, new supply chains set up, and new business models enabled.

PERMITS FOR INDUSTRIAL FACILITIES AND FOR INFRASTRUCTURE

The need for permits is among the most acute and tangible barriers facing companies seeking to scale new industrial production. To capture a new reindustrialisation opportunity, and to rebuild infrastructure and energy systems so they are fit for low-carbon energy, many EU countries will need to update their permitting processes to eliminate unnecessary delays. Both operating and environmental permit processes need to be shortened and made more predictable – without jeopardising the underlying social and environmental objectives.

The changes needed will differ across jurisdictions. Many stakeholders saw room for bottom-up reform – for example, to increase administrative capacity to handle applications, eliminate redundancy when multiple authorities handling the same issue, pre-approval of some novel technology configurations, increased efficiency in applying previous rulings, etc. But many also thought more far-reaching, top-down reform would be needed: working backwards from aggregate targets, deployment in the latter half of this decade, in some cases entirely new procedures may be needed to enable timely permitting of large-scale facilities that are of critical importance to meeting national climate targets.

HARMONISED PRODUCT STANDARDS TO ENABLE AN EU-WIDE MARKET FOR SCALE-UP

The EU needs to consider how to achieve fast-track approval of innovative, low-CO_2 products. To avoid holding back new products, there is a need to harmonise regulatory approval, for example for novel plastics and cement/concrete products, and to minimise the need to obtain separate approval in every country when bringing novel products to market. Examples include novel concrete types (EN 206) and rules for the use of recycled plastics for food-contact applications – again, without jeopardising the safety and other concerns that the norms were created to safeguard.

There also is a need to rapidly clarify the eligibility status of different plastic recycling approaches towards EU recycling targets. This includes an accepted standard for agreeing on standard ”mass balance” approaches, whereby a share of recycled feedstock is allocated to a subset of the products from a given chemicals factory.

5. CONCLUSION: AIMING FOR EU LEADERSHIP IN GREEN MATERIALS

The emergence of more than 70 breakthrough industrial projects in just a few years is truly inspiring. It provides line of sight to a competitive, low-CO_2, and much more autonomous future industry. There is every reason for optimism that a low-CO_2 transition will play to many European industrial strengths. European steel and chemicals companies have already gravitated towards high value-add niches over time, with innovation as the key antidote to other structural disadvantages, such as higher energy or feedstock prices. The same skillset will be key to the low-CO_2 transition. Where Europe has succeeded in the past – such as in mobile telephony, pharmaceuticals and automotive – it has combined tightly integrated innovation systems, leadership in setting standards, and clusters of initial domestic demand that can form the base for scaling to global markets.

If Europe can apply the same formula to its basic materials industries, it can unlock a major economic opportunity for the next few decades. There is much work to be done to design an integrated approach – and no time to lose.

ENDNOTES

[1] Clifford, C. 2021. “Blackrock CEO Larry Fink: The next 1,000 Billion-Dollar Start-Ups Will Be in Climate Tech.” CNBC. October 25, 2021. https://www.cnbc.com/2021/10/25/blackrock-ceo-larry-fink-next-1000-unicorns-will-be-in-climate-tech.html.

[2] SSAB’s website package on “fossil-free steel”: https://www.ssab.com/fossil-free-steel and announcements of the launch of the low-CO2 steel initiative in April 2016: https://www.ssab.com/News/2016/04/SSAB-LKAB-and-Vattenfall-launch-initiative-for-a-carbondioxidefree-steel-industry and a joint venture in June 2017: https://www.ssab.com/News/2017/06/SSAB-LKAB-and-Vattenfall-form-joint-venture-company-for-fossilfree-steel.

[3] IEA. 2020. “Iron and Steel Technology Roadmap.” Technology report for Energy Technology Perspectives. Paris: International Energy Agency. https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[4] The Terneuzen plan is “multi-generational”; by 2030, the plan is to scale up carbon capture and replace gas turbines with electric drivers; by 2050, the implementation of “e-cracking” technology would allow the plant to reduce its emissions by 95% relative to conventional processes. See the Terneuzen case study on Dow’s website: https://corporate.dow.com/en-us/seek-together/carbon-neutrality-case-study.html.

[5] The plant is expected to capture and permanently store 400,000 tonnes of CO2 per year. See press release from Norcem’s parent company, HeidelbergCement: https://www.heidelbergcement.com/en/pr-15-12-2020 and updated project information: https://blog.heidelbergcement.com/en/brevik-css-start-milestone-project.

[6] Calix, founded in 2005 in Australia, is applying its technology in several sectors. Its LEILAC (Low Emissions Intensity Lime And Cement) project, supported by EU Horizon 2020 research and innovation funds, is piloting and demonstrating the technology at HeidelbergCement plants in Lixhe, Belgium, and Hannover, Germany. See https://www.calix.global/industries/cement/ and https://www.project-leilac.eu.

[7] See https://www.ecocem.ie/benefits/enviromental/.

[8] Major global initiatives to raise climate ambition include, among others: the Science Based Targets: https://sciencebasedtargets.org/companies-taking-action; the Climate Ambition Alliance: Net Zero 2050: https://climateinitiativesplatform.org/index.php/Climate_Ambition_Alliance:_Net_Zero_2050; the Climate Action 100+: https://www.climateaction100.org; the Race to Zero Campaign: https://unfccc.int/climate-action/race-to-zero-campaign and the First Movers Coalition: https://www.weforum.org/first-movers-coalition.

[9] Ambitions and targets vary among companies, but public announcements support the overall consensus that the major players of the automotive industry have set net-zero goals. The percentage is based on vehicle sales data as well as average steel content per vehicle and global steel production from the World Steel Association (2021). Cavini, N. 2021. “Global Auto Market 2020. Volkswagen Group Leads the Market While Hyundai-Kia Holds Successfully.” Focus2Move (blog). February 25, 2021. https://www.focus2move.com/worl-group-car-ranking/. World Steel Association. 2021. “Global Crude Steel Output Decreases by 0.9% in 2020.” Press Releases. January 26, 2021. http://www.worldsteel.org/media-centre/press-releases/2021/Global-crude-steel-output-decreases-by-0.9--in-2020.html. See also the World Steel Association’s “Steel in Automotive” web page: World Steel Association. 2021. “Steel in Automotive.” 2021. https://www.worldsteel.org/steel-by-topic/steel-markets/automotive.html.

[10] Authors’ calculations based on: World Steel Association. 2021. “World Steel in Figures 2021.” Brussels. https://worldsteel.org/publications/bookshop/world-steel-in-figures-2021/. Germany Trade & Invest. 2018. “The Plastics Industry in Germany.” https://www.gtai.de/resource/blob/64132/90bb4f93ab4a2780476d37d1c0a678c1/industry-overview-plastics-industry-in-germany-en-data.pdf. Perilli, D. 2020. “Update on Germany.” Global Cement, August 12, 2020. https://www.globalcement.com/news/item/11214-update-on-germany.

[11] This analysis was performed to gauge the current momentum of demand for low-CO2 materials in 2030. It is based on company commitments (as of 2 November 2021) to the Science Based Targets, a leading and particularly stringent framework for greenhouse gas emission reductions. When companies commit to the SBTs, they commit to a two-year deadline to set targets and meet the associated requirements in line with their desired ambition level. While ambition levels vary, the existing target portfolio is successively shifting towards higher ambitions as more and more of the already committed companies are setting new targets aligned with the recently introduced Net-Zero Standard. The portfolio is also growing as the number of new commitments has approximately doubled every year. In response to these developments, our snapshot momentum analysis is based on a simplified middle ground, assuming no additional commitments but that all current commitments and targets will result in net-zero targets and that these will be met to a 20–30% degree on average by 2030. It is further assumed that, in meeting those targets, companies will demand a similar share of their input materials as low-CO2 materials. Input materials are in turn estimated on a sector-by-sector basis using benchmarks and extrapolation by company revenue, while double counting was avoided as well as possible by focusing on end uses. See the SBT web pages for companies taking action: https://sciencebasedtargets.org/companies-taking-action and the Net-Zero Standard: https://sciencebasedtargets.org/net-zero.

[12] See the European Environment Agency’s database of national greenhouse gas inventories: https://www.eea.europa.eu/ds_resolveuid/45b73e8a0ced4df4b40e364c497717ee.

[13] Below are some well-known reports, although the list could be made much longer. Material Economics. 2019. “Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry.” Stockholm. https://materialeconomics.com/publications/industrial-transformation-2050. Witecka, W.K. et al. 2021. “Breakthrough Strategies for Climate-Neutral Industry in Europe : Policy and Technology Pathways for Raising EU Climate Ambition ; Study.” Berlin: Agora Energiewende. http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-77513. Mission Possible Partnership. 2021. “Net-Zero Steel: Sector Transition Strategy.” https://missionpossiblepartnership.org/wp-content/uploads/2021/10/MPP-Steel-Transition-Strategy-Oct-2021.pdf. IEA. 2021. “Net Zero by 2050: A Roadmap for the Global Energy Sector.” Paris: International Energy Agency. https://www.iea.org/reports/net-zero-by-2050. McKinsey & Company. 2020. “Net-Zero Europe - Decarbonization Pathways and Socioeconomic Implications.” December 3, 2020. https://www.mckinsey.com/business-functions/sustainability/our-insights/how-the-european-union-could-achieve-net-zero-emissions-at-net-zero-cost.

[14] Material Economics scenario analysis based on multiple sources and previous work. See: Material Economics. 2019. “Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry.” Stockholm. https://materialeconomics.com/publications/industrial-transformation-2050.

[15] Material Economics analysis based on multiple sources: Oxford Economics. 2019. “The Impact of the European Steel Industry on the EU Economy.” Oxford, UK. https://www.oxfordeconomics.com/publication/download/316776. EUROFER. 2020. “European Steel in Figures 2020.” Brussels: European Steel Association. https://www.eurofer.eu/publications/archive/european-steel-in-figures-2020/. European Commission, and I. Directorate-General for Internal Market Entrepreneurship and SMEs. 2018. “Competitiveness of the European Cement and Lime Sectors : Final Report.” Publications Office. doi:10.2873/300170. Cefic. 2021. “2022 Facts and Figures of the European Chemical Industry.” Cefic.Org. June 12, 2021. https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/. See also Eurostat data: National Accounts Aggregates by Industry

(up to NACE A*64): https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_a64&lang=en. Symmetric Input-Output Table at Basic Prices (Product by Product): http://appsso.eurostat.ec.europa.eu/nui/show.do?wai=true&dataset=naio_10_cp1700. Annual Detailed Enterprise Statistics for Industry (NACE Rev. 2, B-E): https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sbs_na_ind_r2&lang=en. Annual Detailed Enterprise Statistics for Construction (NACE Rev. 2, F): https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sbs_na_con_r2&lang=en. Share of Housing Costs in Disposable Household Income, by Type of Household and Income Group - EU-SILC Survey: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_mded01&lang=en.

[16] World Steel Association. 2010. "Steel Statistical Yearbook 2010." Steel industry statistics. http://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook-.html. World Steel Association. 2011. "Steel Statistical Yearbook 2011." Steel industry statistics. Brussels, Belgium. https://www.worldsteel.org/en/dam/jcr:c12843e8-49c3-40f1-92f1-9665dc3f7a35/Steel%2520statistical%2520yearbook%25202011.pdf. World Steel Association. 2020. "Steel Statistical Yearbook 2020." Steel industry statistics. Brussels, Belgium. https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html. EUROFER. 2020. "European Steel in Figures 2020." Brussels: European Steel Association. https://www.eurofer.eu/publications/archive/european-steel-in-figures-2020/. Also see Eurostat data for EU Trade since 1988 by HS2-4-6 and CN8 (DS-045409): http://epp.eurostat.ec.europa.eu/newxtweb/setupdimselection.do.

[17] Material Economics analysis based on multiple sources: EUROFER. 2020. "European Steel in Figures 2020." Brussels: European Steel Association. https://www.eurofer.eu/publications/archive/european-steel-in-figures-2020/. Cefic. 2021. "2022 Facts and Figures of the European Chemical Industry." Cefic.Org. June 12, 2021. https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/. Oxford Economics. 2019. "The Impact of the European Steel Industry on the EU Economy." Oxford, UK. https://www.oxfordeconomics.com/publication/download/316776. European Commission, and I. Directorate-General for Internal Market Entrepreneurship and SMEs. 2018. "Competitiveness of the European Cement and Lime Sectors : Final Report." Publications Office. doi:10.2873/300170. Also see graphic from the European Cement Association (CEMBUREAU): https://cembureau.eu/media/jrlhowdo/figures_05.png.

[18] Eurostat. 2020. "Output of Economic Activities in the EU Member States." October 28, 2020. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20201028-1.

[19] Material Economics analysis based on multiple sources: EUROFER. 2020. "European Steel in Figures 2020." Brussels: European Steel Association. https://www.eurofer.eu/publications/archive/european-steel-in-figures-2020/. Cefic. 2021. "2022 Facts and Figures of the European Chemical Industry." Cefic.Org. June 12, 2021. https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/. Also see the European Commission's web page on the chemicals sector: https://ec.europa.eu/growth/sectors/chemicals_en.

[20] See the European Commission's web page on the chemicals sector: https://ec.europa.eu/growth/sectors/chemicals_en.

[21] European Commission, Executive Agency for Small and Medium sized Enterprises., I. Merkelbach, and H. Hollanders. 2020. European Panorama of Clusters and Industrial Change: Performance of Strong Clusters across 51 Sectors and the Role of Firm Size in Driving Specialisation : 2020 Edition. LU: Publications Office. https://data.europa.eu/doi/10.2826/451726.

[22] See Eurostat data on EU Trade since 1988 by HS2-4-6 and CN8 (DS-045409): http://epp.eurostat.ec.europa.eu/newxtweb/setupdimselection.do. Products included:

• Products of the chemical or allied industries, excluding pharmaceuticals – CODES 28, 29, 31–38

• Cement, incl. cement clinkers, whether or not coloured – CODE 2523

• Iron and steel, excluding primary materials; iron and non-alloy steel in ingots or other primary forms; semi-finished products of iron or non-alloy steel – CODES 7208–7229

[23] See European Aluminium's web page on EU import dependency: https://www.european-aluminium.eu/data/economic-data/eu-aluminium-imports-dependency/.

[24] Material Economics analysis based on multiple sources: Oxford Economics. 2019. "The Impact of the European Steel Industry on the EU Economy." Oxford, UK. https://www.oxfordeconomics.com/publication/download/316776. EUROFER. 2020. "European Steel in Figures 2020." Brussels: European Steel Association. https://www.eurofer.eu/publications/archive/european-steel-in-figures-2020/. European Commission, and I. Directorate-General for Internal Market Entrepreneurship and SMEs. 2018. "Competitiveness of the European Cement and Lime Sectors : Final Report." Publications Office. doi:10.2873/300170. Cefic. 2021. "2022 Facts and Figures of the European Chemical Industry." Cefic.Org. June 12, 2021. https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/. See also Eurostat data on: National Accounts Aggregates by Industry (up to NACE A*64): https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nama_10_a64&lang=en. Symmetric Input-Output Table at Basic Prices (Product by Product): http://appsso.eurostat.ec.europa.eu/nui/show.do?wai=true&dataset=naio_10_cp1700. Annual Detailed Enterprise Statistics for Industry (NACE Rev. 2, B-E): https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sbs_na_ind_r2&lang=en. Annual Detailed Enterprise Statistics for Construction (NACE Rev. 2, F): https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sbs_na_con_r2&lang=en. Share of Housing Costs in Disposable Household Income, by Type of Household and Income Group - EU-SILC Survey: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_mded01&lang=en.

[25] IEA. 2021. "Global Hydrogen Review 2021." Paris: International Energy Agency. https://www.iea.org/reports/global-hydrogen-review-2021.

[26] Finland's greenhouse gas emissions in 2020, including international aviation, amounted to 31.35 Mt CO_2e, per official EU data. See https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.

[27] Material Economics analysis based on multiple sources. The number of dwellings is based on the EU average floor area per dwelling times the typical cement consumption per floor area, divided by the announced volume of low-CO2 cement. The abatement figure for cement is based only on CCUS and does not include the abatement from low-clinker cements. The displayed number of cars is conservatively calculated from the steel production that is certain to be H-DRI based from the start (may be larger if/once the remaining DRI plants run on renewable hydrogen), divided by the average steel content per car. The abatement from steel does not include savings from scrap use as it is currently used in other regions through exports. It could be higher if the 37 Mt are shifted to hydrogen. The plastic emissions reduction includes end-of-life emissions. See the European Commission's EU Buildings Database: https://ec.europa.eu/energy/eu-buildings-database_en, as well as: Agora Energiewende. 2021. "Breakthrough Strategies for Climate-Neutral Industry in Europe : Policy and Technology Pathways for Raising EU Climate Ambition ; Study." Berlin: Agora Energiewende. http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-77513. Material Economics. 2019. "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry." Stockholm. https://materialeconomics.com/publications/industrial-transformation-2050.

[28] Material Economics analysis assuming constant steel production 2050 around ~160 Mt (saturating steel stock), with constant share of purely scrap

based production around 65 Mt, which yields 95 Mt to be transitioned from BF-BOF to breakthrough technologies to be decarbonised. 52 Mt is thus more than half of these 95 Mt. Analysis based on: EUROFER. 2020. "European Steel in Figures 2020." Brussels: European Steel Association. https://www.eurofer.eu/publications/archive/european-steel-in-figures-2020/.

[29] ~15 Mt H-DRI based steel includes 1 Mt by ArcelorMittal in Hamburg, 5 Mt by SSAB/HYBRIT/LKAB, 5 Mt by H2GS in Boden and 2.5-5 Mt by H2GS in the Iberian Peninsula.

[30] Based on a benchmark of 1.9 tonne CO2 per tonne steel for the BF-BOF route and a range of 0.9–1.5 tonnes CO2 per tonne steel for the DRI route. The DRI range depends on the fuel used for pelletisation, the local carbon footprint of electricity used in EAFs as well as variations in the impact of downstream processing. For more information, see the Annex to this report. Rechberger, K. et al. 2020. "Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking." Steel Research International 91 (May). doi:10.1002/srin.202000110.

[31] World Steel Association. 2021. "World Steel in Figures 2021." Brussels. https://worldsteel.org/publications/bookshop/world-steel-in-figures-2021/.

[32] Material Economics analysis based on information available on company websites and public announcements. The estimated 52 Mt are based on the following assumed EAF capacities by 2030: H2 Green Steel, 5 Mt, Boden; SSAB, 2.2 Mt, Luleå (assumed split of announced 3.5 Mt based on current production capacitites in Luleå and Raahe); SSAB, 1.3 Mt, Raahe; SSAB, 1.5 Mt, Oxelösund; ArcelorMittal, 1 Mt, Hamburg; ArcelorMittal, 0.5 Mt, Bremen (assumed split of the announced combined capacity of 3.5 Mt at the industrial-scale plant in Eisenhüttenstadt and pilot-scale plant in Bremen); ArcelorMittal, 3 Mt, Eisenhüttenstadt; ArcelorMittal, 3.2 Mt, Gent (assuming the total capacity to remain constant at 5.5 Mt and blast furnace B to operate in parallel with the new EAFs); Tata Steel, 7.5 Mt, Ijmuiden (assuming the total capacity to remain constant at 7.5 Mt); Liberty Steel / SHS Group, 4 Mt, Ascoval / Ostrava (based on (H)-DRI capacity in Dunkerque); Salzgitter, 5.2 Mt, Salzgitter (assuming the total capacity to remain constant at 5.2 Mt); Voestalpine, 4 Mt, Linz (based on a BOF capacity of 6 Mt and an announcement that two-thirds of BF-BOF will be converted by 2030); Voestalpine, 0.8 Mt, Donawitz (based on a BOF capacity of 6 Mt and an announcement that half of BF-BOF will be converted by 2030); Liberty Steel, 4 Mt, Galati; ArcelorMittal, 1.1 Mt, Gijón; ArcelorMittal, 1.6 Mt, Sestao (existing EAF capacity); ArcelorMittal, 2.5 Mt, Taranto; H2 Green Steel, 3.75 Mt, Iberian Peninsula.

[33] Material Economics. 2022 (forthcoming). "Europe's Missing Plastics: Taking Stock of EU Plastics Circularity." Stockholm. https://materialeconomics.com/publications.

[34] Material Economics. 2019. "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry." Stockholm. https://materialeconomics.com/publications/industrial-transformation-2050.

[35] There are a range of different pyrolysis and similar advanced chemical recycling processes being developed, with different types of reactors, with and without the use of catalysts, with different tolerance for moisture etc., resulting in different yields and output compositions. The cost and other estimates in this study focuses on pyrolysis.

[36] The currently proposed plants have an aggregated capacity to convert 1.2 Mt of plastic waste, corresponding to almost 0.6 Mt chemically recycled high-value chemicals (HVC) assuming an average plastics-to-HVC conversion rate of 46%. This is approximately 1% of the 45.5 Mt HVC production in the EU + UK. (Agora, 2021). Agora Energiewende. 2021. "Breakthrough Strategies for Climate-Neutral Industry in Europe : Policy and Technology Pathways for Raising EU Climate Ambition ; Study." Berlin: Agora Energiewende. http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-77513.

[37] For example, OMVs ReOil technology. OMV. 2019. "Circular Economy." In OMV Sustainability Report 2019. Vienna. https://omv.online-report.eu/en/sustainability-report/2019/focus-areas/innovation/circular-economy.html. OMV. 2020. "ReOil: 200,000 Kg of Plastic Waste Recycled with OMV's Circular Economy Pilot Project." June 5, 2020. https://www.omv.com/en/news/reoil-200-000-kg-of-plastic-waste-recycled-with-omv-s-circular-economy-pilot-project-.

[38] Steilemann, M. 2021. "European Plastics Manufacturers Plan 7.2 Billion Euros of Investment in Chemical Recycling." Plastics Europe, May 26, 2021. https://plasticseurope.org/european-plastics-manufacturers-plan-7-2-billion-euros-of-investment-in-chemical-recycling-2/.

[39] Material Economics. 2022 (forthcoming). "Europe's Missing Plastics: Taking Stock of EU Plastics Circularity." Stockholm. https://materialeconomics.com/publications.

[40] Material Economics summary based on information available on company websites and public announcements. Capacities shown are plastic recycling capacities (input) unless otherwise specified. Capacities announced as pyrolysis oil or similar (output) have been converted assuming a 70% yield as an average of multiple sources including Larrain et al. (2020), Riedewald et al. (2021), Thunman et al. (2019) and Neelis et al. (2005). The total 1.2 Mt plastic waste capacity by 2030 is based on the following plants: Quantafuel, 10 kt, Kristiansund; Quantafuel, 20 kt, Skive; Quantafuel, 100 kt, Sunderland; Quantafuel, TBA; Teeside; Pryme, 60 kt, Rotterdam; Recenso, 1 kt, Ennigerloh; Bluealp, 30 kt, Moerdijk; Ravago, 55 kt, Vlissingen; Fuenix Ecogy Group, 20 kt, Weert; Renasci, 20 kt (converted), Oostende; Plastic Energy, 20 kt, Geleen; Plastic Energy, 25 kt, Le Havre; Plastic Energy, 15 kt, Grandpuits; Pyrum, 20, Dilingen; OMV, 200 kt, Schwechat; Servizi di Ricerche e Sviluppo, 6 kt, Mantova; LyondellBasell, <1 kt, Ferrara; Petronor, 10 kt, Bilbao; Plastic Energy, 5 kt, Seville; Plastic Energy, 5 kt, Almeria; Pryme, 350 kt (converted), location TBA; Quantafuel, capacity TBA, location TBA; Plastic Energy, capacity TBA, location TBA; Plastic Energy, capacity TBA, location likely in the UK; New Energy, 8 kt, location TBA; Remondis, capacity TBA, location TBA. Larrain, M. et al. 2020. "Economic Performance of Pyrolysis of Mixed Plastic Waste: Open-Loop versus Closed-Loop Recycling." Journal of Cleaner Production 270 (October): 122442. doi:10.1016/j.jclepro.2020.122442. Riedewald, F. et al. 2021. "Economic Assessment of a 40,000 t/y Mixed Plastic Waste Pyrolysis Plant Using Direct Heat Treatment with Molten Metal: A Case Study of a Plant Located in Belgium." Waste Management 120 (February): 698–707. doi:10.1016/j.wasman.2020.10.039. Thunman, H. et al. 2019. "Circular Use of Plastics-Transformation of Existing Petrochemical Clusters into Thermochemical Recycling Plants with 100% Plastics Recovery." Sustainable Materials and Technologies 22 (December): e00124. doi:10.1016/j.susmat.2019.e00124. Neelis, M. L. et al. 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.

41 Roadmaps for the chemicals sector have identified several other options (Material Economics, 2019). Byproducts can be upgraded and turned into products instead. Likewise, fossil feedstock can be replaced to some degree by bio-based feedstock that releases no fossil CO2. In the long run, the cracker process itself can be bypassed to some degree, by using other routes to make the basic chemicals needed. To date, however, these solutions are not part of active development by the EU chemicals industry. The main exception are several projects to produce methanol, a major chemical, from biomass and from captured CO_2. Material Economics. 2019. "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry." Stockholm. https://materialeconomics.com/publications/industrial-transformation-2050.

[42] Material Economics analysis based on clinker production emissions from EU ETS data and emissions split from WBCSD Cement Sustainability Initiative. WBCSD Cement Sustainability Initiative. 2016. "Getting the Numbers Right (GNR) Project, Emission Report 2016." http://www.wbcsdcement.org/GNR-2016/index.html.

[43] Based on the EU cement sector emissions and the aggregated cement CCS capacity to be realised by 2030 according to public announcements and company websites.

44 Material Economics summary based on information available on company websites and public announcements. Capacities shown are in tonnes CO_2 per year by 2030 or earlier. Some capacities have been calculated based on cement production data assuming 0.8 tonne CO_2 per tonne cement. The total

~10 Mt carbon capture capacity is based on the following projects: Norcem, 0.4 Mt (50% of the plant's emissions), Brevik; Cementa, 1.8 Mt , Slite; Aalborg Portland, 0.45 Mt, Ålborg; Holcim, 1 Mt (assuming that the full carbon capture potential is utilized), Lägerdorf; Hanson, 0.8 Mt, Padeswood; Leilac, 0.1 Mt, Hannover; Westküste100 and Holcim, 1.3 Mt, Höver; Górażdże, capacity TBA, Górażdże; Catch4Climate, 0.8 Mt (calculated), Heidenheim; Coolplanet with Holcim and Hereon, 0.7 Mt, Mannersdorf; Vicat, 0.7 Mt (calculated), Montalieu-Vercieu; ECRA and Holcim, 0.4 Mt (calculated), Retznei; Buzzi Unicem, 0.9 Mt (calculated assuming carbon capture applies to all plant emissions with the targeted capture efficiency of 90%), Vernasca; Carbon Clean and Holcim, 0.14 Mt (calculated), Colleferro; ECRA and Holcim, 0.07 Mt (may be later scaled up to 0.7 Mt), Carboneras.

[45] Costs for electrified Leilac carbon capture is similar to the costs for oxy-fuel CCS, but Leilac carbon capture with alternative fuel could be some 20% cheaper than oxy-fuel CCS, given that the alternative fuel is very cheap.

[46] The approach includes a combination of further compacting, adding fillers and plasticisers, reducing water content, and replacing standard clinker with other binder materials. Clinker accounts for 95% of the emissions from ordinary cement production. See: WBCSD Cement Sustainability Initiative. 2016. "Getting the Numbers Right (GNR) Project, Emission Report 2016." http://www.wbcsdcement.org/GNR-2016/index.html.

[47] Gilliam, R., and K. Krugh. 2021. "Fortera: Low-CO2 Cement Inspired by Nature," September 27, 2021. https://www.globalcement.com/magazine/articles/1230-fortera-low-co2-cement-inspired-by-nature.

[48] McDowell, A. 2019. "Big Ambitions and Investments for Net-Zero Emissions." European Investment Bank, April 4, 2019. https://www.eib.org/en/stories/energy-transformation.

[49] Some 30% of current EU cement production takes place at plants that emit less than 500,000 tonnes of CO2 emissions per year, so the cost per tonne is higher. A third of production occurs more than 300 km from any major port that could take CO2 for offshore storage, making transport and storage much more expensive. See Annex to this report for more information.

[50] Material Economics analysis based on multiple sources including the key ones listed below. For more information, see the Annex to this report. Bhaskar, A. et al. 2021. "Decarbonizing Primary Steel Production : Techno- Economic Assessment of a Hydrogen Based Green Steel Production Plant in Norway," September. doi:10.5281/zenodo.5526695. Pei, M. et al. 2020. "Toward a Fossil Free Future with HYBRIT: Development of Iron and Steelmaking Technology in Sweden and Finland." Metals 10 (7): 972. doi:10.3390/met10070972. Agora Energiewende. 2021. "Breakthrough Strategies for Climate-Neutral Industry in Europe : Policy and Technology Pathways for Raising EU Climate Ambition ; Study." Berlin: Agora Energiewende. http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-77513.

[51] See Salzgitter's "green steel" website; SSAB's "fossil-free steel" website: https://www.ssab.com/fossil-free-steel; and H2 Green Steel announcement: https://www.affarsvarlden.se/intervju/afv-avslojar-h2-green-steel-har-salt-for-over-20-miljarder.

[52] See the Eastman website: https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Our-investment-in-France.aspx.

[53] Energy Transitions Commission, and Material Economics. 2021. "Steeling Demand: Mobilising Buyers to Bring Net-Zero Steel to Market before 2030." Prepared for the Net-Zero Steel Initiative, part of the Mission Possible Partnership. https://materialeconomics.com/publications/steeling-demand.

[54] Material Economics analysis based on annual production of steel, plastics and cement as well as inputs needed per production of each tonne of these materials. Based on annual EU production (2019 or latest available number) of 157 Mt steel using 234 Mt iron ore (both lump ore and sinter/pellets) and 133 Mt coking coal (both coal to make coke and coal as reducing agent), 40 Mt HVC plastics using 62 Mt Naphtha and 182 Mt cement using 252 Mt limestone. Multiple sources, including: EUROFER. 2020. "European Steel in Figures 2020." Brussels: European Steel Association. https://www.eurofer.eu/publications/archive/european-steel-in-figures-2020/. Agora Energiewende. 2021. "Breakthrough Strategies for Climate-Neutral Industry in Europe : Policy and Technology Pathways for Raising EU Climate Ambition ; Study." Berlin: Agora Energiewende. http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-77513. See also "Key Facts & Figures" web page from CEMBUREAU: https://cembureau.eu/cement-101/key-facts-figures/.

[55] Gross electricity generation data from BP (2021). bp. 2021. "Statistical Review of World Energy 2021." https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf.

[56] Material Economics has identified 35–54 Mt CO2 of planned carbon-capture storage capacity by 2030 based on information from the Global CCS Institute (2021) and by summarising announcements from Polaris, Northern Lights, Acorn, Greensands, Northern Endurance Partnership, Humber Zero, Porthos, HyNet, North West and Ravenna Hub. Global CCS Institute. 2021. "Global Status of CCS 2021: CCS Accelerating to Net Zero." Melbourne, Australia: Global Carbon Capture and Storage Institute. https://www.globalccsinstitute.com/resources/global-status-report/.

[57] Material Economics analysis based on the European context with data from Wind Europe (2021). The number of turbines required depends heavily on size and location. Offshore turbines tend to be larger than onshore turbines, which allows them to generate more power as well as capture energy at lower wind speeds. In addition, they typically operate under better and more consistent wind conditions and can therefore generate power closer to their rated capacity throughout the year. If 5.5 TWh of electricity per year were to be generated from new offshore wind power ordered today, around 110 to 170 turbines would be needed, depending on the achieved capacity factor (the European range is approximately 35-55%) and assuming an average capacity of 10.4 MW per offshore turbine (according to the latest order data). Similarly, if 5.5 TWh of electricity were to be generated from onshore wind turbines, around 430 to 500 turbines would be needed, based on capacity factors in the range 30-35% and assuming an average capacity of 4.2 MW per onshore turbine (according to the latest order data). See: Wind Europe. 2021. "Wind Energy in Europe: 2020 Statistics and the Outlook for 2021-2025." Brussels. https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2020-statistics-and-the-outlook-for-2021-2025/.

[58] Assuming 1 Mt of total HVC capacity, and 46% plastics-waste-to-HVC conversion rate. According to Deloitte (2021), there are 8 main petrochemical clusters in the EU. Deloitte et al. 2021. "IC2050 Project Report: Shining a Light on the EU27 Chemical Sector's Journey toward Climate Neutrality." https://news.cefic.org/storage/5200/iC2050-Project-report-'Shining-a-light-on-the-EU27-chemical-sector%E2%80%99s-journey'-October-2021.pdf.

[59] Plastic waste per household is calculated as the total volume of EU27 end-of-life plastics, based on our Circular Economy Model (2018), divided by the number of households in the EU27 region. See: Material Economics. 2018. "The Circular Economy - A Powerful Force for Climate Mitigation." Stockholm. https://materialeconomics.com/publications/the-circular-economy. Also see Eurostat household data: https://ec.europa.eu/eurostat/databrowser/view/lfst_hhnhwhtc/default/table?lang=en.

[60] Material Economics. 2018. "The Circular Economy - A Powerful Force for Climate Mitigation." Stockholm. https://materialeconomics.com/publications/the-circular-economy.

[61] Verordnung der Bundesregierung. 2021. "Verordnung Über Die Kosten Und Entgelte Für Den Zugang Zu Wasserstoffnetzen Und Zur Änderung Der Anreizregulierungsverordnung." https://www.bmwi.de/Redaktion/DE/Downloads/V/verordnung-ueber-kosten-und-entgelte-fuer-zugang-zu-wasserstoffnetzen-und-aenderung-anreizregulierungsverordnung.pdf?__blob=publicationFile&v=6.

[62] Material Economics analysis, assuming 4,000 hours per year, 70% power-to-hydrogen energy efficiency.

[63] Our assumption is based on the findings of the Energy Sector Management Assistance Program (ESMAP, 2020). ESMAP estimated that the electrolyser manufacturing capacity in 2020 was 300 MW and 2,100 MW for PEM and alkaline electrolysers, respectively, and that they would pass 1,500 MW and 3,000 MW in 2025. However, this would not only need to cover the needs of the steel industry. For comparison, the IEA (2021) claims that the global installed electrolyser capacity would need to reach 180 GW by 2030 to meet the current pledges of governments around the world, or as much as 850

GW in their net-zero scenario. See IEA. 2021. "Global Hydrogen Review 2021." Paris: International Energy Agency. https://www.iea.org/reports/global-hydrogen-review-2021. Energy Sector Management Assistance Program. 2020. Green Hydrogen in Developing Countries. World Bank, Washington, DC. doi:10.1596/34398.

[64] Approximately 4.5 billion allowances will be allocated during the years 2022–2030. The value depends on the average allowance price – the 400 billion value applies even if there is no further increase from today's (record) levels of around 90 EUR/tCO_2.

[65] Leyen, U. von der. 2021. "Statement by the President on Delivering the European Green." European Commission – Press Room. July 14, 2021. https://ec.europa.eu/commission/presscorner/detail/en/STATEMENT_21_3701.

[66] Material Economics. 2019. "Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry." Stockholm. https://materialeconomics.com/publications/industrial-transformation-2050.

[67] EU carbon prices fluctuate, but they exceeded 80 EUR for much of December 2021–February 2022.

[68] European Commission et al. 2021. "Study on Energy Subsidies and Other Government Interventions in the European Union: Final Report." Luxembourg: Publications Office of the European Union. doi:10.2833/513628; Elkerbout, M. 2022. "Can ETS Free Allocation Be Used as Innovation Aid to Transform Industry?" Policy Brief. Brussels: Centre for European Policy Studies. https://www.ceps.eu/ceps-publications/can-ets-free-allocation-be-used-as-innovation-aid-to-transform-industry/.

[69] Elkerbout, M. 2022. "Can ETS Free Allocation Be Used as Innovation Aid to Transform Industry?" Policy Brief. Brussels: Centre for European Policy Studies. https://www.ceps.eu/ceps-publications/can-ets-free-allocation-be-used-as-innovation-aid-to-transform-industry/.

[70] Moreover, if low-CO2 installations are included among the top 10% of sites on which benchmarks are based, allocations to existing plants could be reduced drastically – further undermining carbon leakage protection.

[71] European Commission. 2021. "Proposal for a Directive of the European Parliament and of the Council Amending Directive 2003/87/EC Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union, Decision (EU) 2015/1814 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading Scheme and Regulation (EU) 2015/757." COM(2021) 551 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0551.

[72] Of the 311 proposals, 204 involved energy-intensive industries. See DG CLIMA. 2020. "First Innovation Fund Call for Large-Scale Projects: 311 Applications for the EUR 1 Billion EU Funding for Clean Tech Projects." Directorate-General for Climate Action News. November 5, 2020. https://ec.europa.eu/clima/news-your-voice/news/first-innovation-fund-call-large-scale-projects-311-applications-eur-1-billion-eu-funding-clean-tech-2020-11-05_en.

[73] See https://plasticseurope.org/knowledge-hub/plastics-europes-position-on-recycled-content-for-plastics-packaging-under-the-review-of-the-directive-94-62-ec-on-packaging-and-packaging-waste-ppwd/.

[74] European Commission. 2021. "Sustainable Carbon Cycles: Communication from the Commission to the European Parliament and the Council." COM(2021)800. Brussels. https://ec.europa.eu/transparency/documents-register/detail?ref=COM(2021)800&lang=en.

[75] An alternative would be to provide sufficient ongoing revenue, so investors are persuaded to cover the additional upfront cost. However, this risks being inefficient. The financing equation of untried technologies is already stretched, and additional marginal (typically, equity) capital can get expensive. Ongoing payments are therefore often less effective at overcoming barriers specific to early entry.

[76] The range is based on a comparison of two different debt/equity ratios and a small range for the cost of debt: case 1– debt 70%, equity 30%, cost of debt 4–5% and cost of equity 20%; case 2 – debt 40%, equity 60%, cost of debt 4% and cost of equity 15%.

[77] See https://www.riksgalden.se/fi/our-operations/guarantee-and-lending/credit-guarantees-for-green-investments/.

[78] European Commission. 2021. "Questions and Answers: EU-Catalyst Partnership." Press Corner. November 2, 2021. https://ec.europa.eu/commission/presscorner/detail/en/QANDA_21_5647.

[79] Cleantech Group. 2021. "Cleantech for Europe: Seizing the EU's Man on the Moon Moment." https://www.cleantechforeurope.com/report-download.

[80] A concrete initiative for this was announced in February 2022, via the European Scale-Up Initiative. The European Investment Fund/European Investment Bank will manage a multi-investor "fund of funds" aiming specifically to support promising new companies in the scale-up phase EIF. 2022. "EIB Group Supports the Pan-European Scale-up Initiative to Promote Tech Champions." European Investment Fund News. February 9, 2022. https://www.eif.org/what_we_do/equity/news/2022/eib-supports-the-pan-european-scale-up-initiative-to-promote-tech-champions.htm.

[81] European Commission. 2020. "A Hydrogen Strategy for a Climate-Neutral Europe: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions." COM(2021)301 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301.

[82] European Commission. 2016. "Become Competitive in the Global Battery Sector to Drive E-mobility Forward." SET Plan Action No. 7 Declaration of Intent. SET Plan Secretariat. https://setis.ec.europa.eu/system/files/2021-05/action7_declaration_of_intent_0.pdf.

[83] See https://www.weforum.org/first-movers-coalition.

[84] See the FMC factsheet on steel: https://www3.weforum.org/docs/WEF_Steel_2021.pdf.

[85] See the European Commission's Green Public Procurement website: https://ec.europa.eu/environment/gpp/what_en.htm.

[86] The Directive was last updated in January 2022. See European Parliament, and Council of the European Union. 2022. Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on Public Procurement and Repealing Directive 2004/18/EC (Text with EEA Relevance) Text with EEA Relevance. http://data.europa.eu/eli/dir/2014/24/2022-01-01/eng.

[87] European Commission. 2008. "Public Procurement for a Better Environment: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions." COM(2008) 400 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52008DC0400.

[88] OECD. 2016. "Country Case: Green Public Procurement in the Netherlands." Public Procurement Toolbox. Paris: Organisation for Economic Co-operation and Development. https://www.oecd.org/governance/procurement/toolbox/search/green-public-procurement-netherlands.pdf.

[89] For example, the city of Zurich requires the use of recycled aggregates in publicly funded construction. See Land, P. 2019. "The Swiss Example: Using Recycled Concrete." July 1, 2019. https://global-recycling.info/archives/2956.

[90] For example, the Swedish Transport Administration is gradually raising standards for suppliers in investment and maintenance projects, with the goal of making infrastructure climate-neutral by 2045. See https://www.trafikverket.se/for-dig-i-branschen/miljo---for-dig-i-branschen/energi-och-klimat/klimatkrav/ (in Swedish). See also this peer-reviewed study: Karlsson, I., J. Rootzén, and F. Johnsson. 2020. "Reaching Net-Zero Carbon Emissions in Construction Supply Chains – Analysis of a Swedish Road Construction Project." Renewable and Sustainable Energy Reviews 120 (March): 109651.

doi:10.1016/j.rser.2019.109651.

[91] See https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en and https://ec.europa.eu/growth/sectors/construction/construction-products-regulation-cpr_en.

[92] See https://ec.europa.eu/growth/industry/strategy/hydrogen/ipceis-hydrogen_en.

[93] European Commission. 2008. "The Raw Materials Initiative: Meeting Our Critical Needs for Growth and Jobs in Europe: Communication from the Commission to the European Parliament and the Council." COM(2008) 699 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A52008DC0699.

[94] See https://ec.europa.eu/growth/sectors/raw-materials/eip_en.

[95] Material Economics. 2021. "EU Biomass Use in a Net-Zero Economy – A Course Correction for EU Biomass." Stockholm. https://materialeconomics.com/latest-updates/eu-biomass-use.

[96] European Commission. 2021. "Proposal for a Directive of the European Parliament and of the Council Amending Directive 2003/87/EC Establishing a System for Greenhouse Gas Emission Allowance Trading within the Union, Decision (EU) 2015/1814 Concerning the Establishment and Operation of a Market Stability Reserve for the Union Greenhouse Gas Emission Trading Scheme and Regulation (EU) 2015/757." COM(2021) 551 final. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0551.

[97] See Q&A on the Norwegian government website: https://www.regjeringen.no/en/topics/energy/landingssider/ny-side/sporsmal-og-svar-om-langskip-prosjektet/id2863902/.

[98] Porthos. 2021. "Dutch Government Supports Porthos Customers with SDE++ Subsidy Reservation." Press Release (blog). June 9, 2021. https://www.porthosco2.nl/en/dutch-government-supports-porthos-customers-with-sde-subsidy-reservation/.

[99] Council of the European Union. 2021. "Outcome of Proceedings: Proposal for a Regulation of the European Parliament and of the Council on Guidelines for Trans-European Energy Infrastructure and Repealing Regulation (EU) No 347/2013." 9732/21. Brussels. https://www.consilium.europa.eu/media/50423/st09732-en21.pdf.

SCALING UP EUROPE

Bringing Low-CO_2 Materials from Demonstration to Industrial Scale

Low-CO_2 materials – steel, cement, chemicals and more – are indispensable for EU climate targets. They also are a massive economic opportunity. European companies now lead in this space, with more than 70 industrial projects with breakthrough clean technologies planned across the continent.

However, the crucial step to industrial scale has yet to come, with final investment decisions still pending. This study examines how the EU and European countries can act to put its energy-intensive industries on a path towards net zero – and, in the process, secure European industrial competitiveness for decades to come.

Disclaimer: The analysis and conclusions of this report are those of Material Economics. Material Economics is solely responsible for the contents of this report and the views are those of the authors

Please refer to this report as: Material Economics, 2022. "Scaling up Europe – Bringing Low-CO_2 Materials from Demonstration to Industrial Scale."

Available at: materialeconomics.com/publications/scaling-up-europe.

MATERIAL ECONOMICS

Material Economics Sverige AB www.materialeconomics.com info@materialeconomics.com