Breakthrough Strategies for Climate-Neutral Industry in Europe

Policy and Technology Pathways for Raising EU Climate Ambition

STUDY

Agora Energiewende

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Breakthrough Strategies for Climate-Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition

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Preface

Dear reader,

The basic materials industries are a cornerstone of Europe's economic prosperity, increasing gross value added and providing around 2 million high-quality jobs. But they are also a major source of greenhouse gas emissions. Despite efficiency improvements, emissions from these industries were mostly constant for several years prior to the Covid-19 crisis and today account for 20 per cent of the EU's total greenhouse gas emissions.

A central question is therefore: How can the basic material industries in the EU become climate-neutral by 2050 while maintaining a strong position in a highly competitive global market? And how can these industries help the EU reach the higher 2030 climate target – a reduction of greenhouse gas emissions of at least 55 per cent relative to 1990 levels?

In the EU policy debate on the European Green Deal, many suppose that the basic materials industries can do little to achieve deep cuts in emissions by 2030. Beyond improvements to the efficiency of existing technologies, they assume that no further innovations will be feasible within that period. This study takes a different view. It shows that a more ambitious approach involving the early implementation of key low-carbon technologies and a Clean Industry Package is not just possible, but in fact necessary to safeguard global competitiveness.

We hope you enjoy reading this study.

Dr. Patrick Graichen,
Executive Director, Agora Energiewende

Prof. Dr. Manfred Fischedick
President, Wuppertal Institute

Key conclusions at a glance:

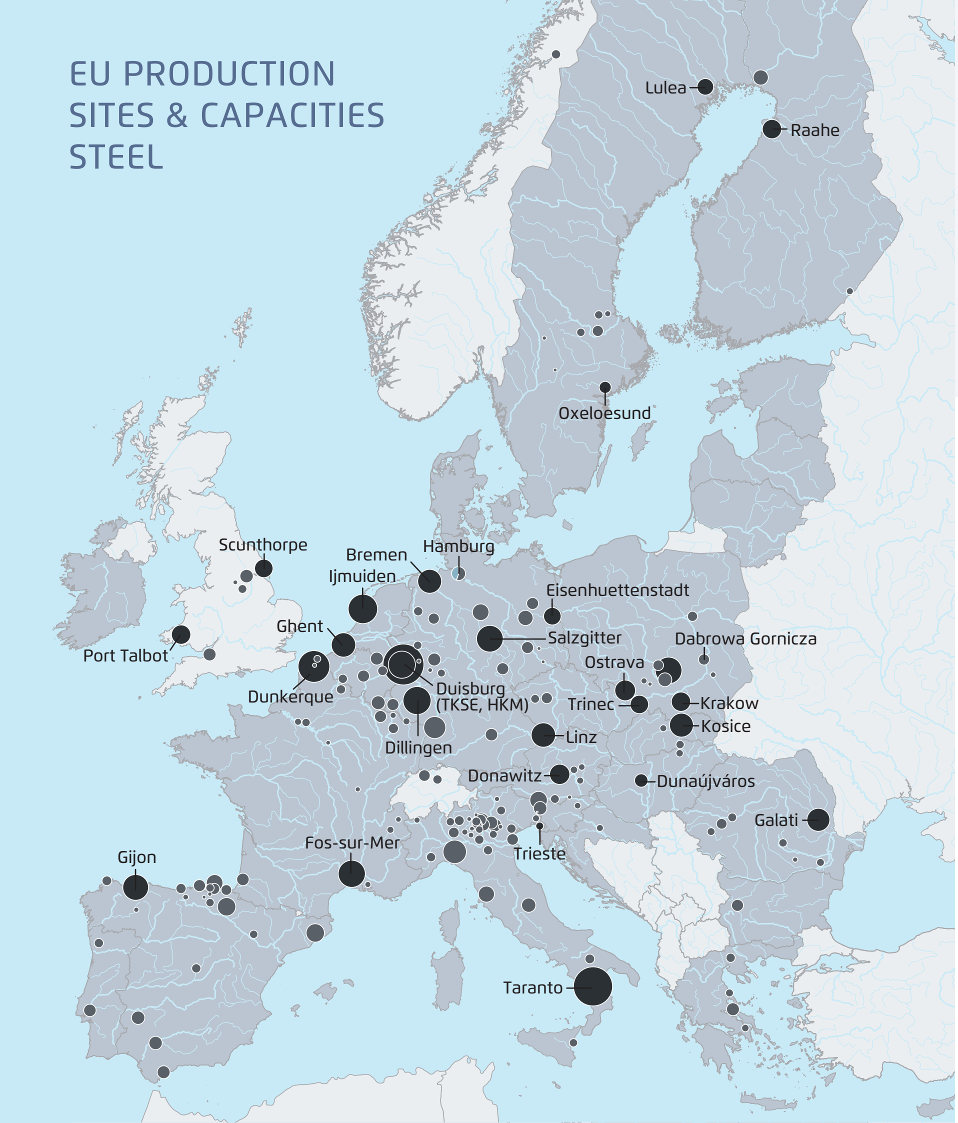
1. **Given the new paradigm of achieving climate neutrality by 2050, current climate and industry policies will lead to investment leakage or risk stranded industrial assets.** Industrial companies understand: The EU objective of climate neutrality by 2050 has clear implications for industrial reinvestment in the 2020s. Carbon-intensive technologies have lifetimes of up to 70 years. Reinvestments into long-lived assets will not be made unless there is an investment framework to deploy climate-neutral technologies.

2. **With a new policy framework, the basic materials industries can support the increased EU 2030 climate target of at least -55 per cent. Key low-carbon technologies are available and can be deployed well before 2030.** The CO_2 abatement potential of key low-carbon technologies in the steel, chemicals, and cement sectors alone amounts to 145 Mt of CO_2 by 2030, exceeding the required emission reductions from industry under the EU ETS. Their deployment will represent a breakthrough in Europe's industrial sector and ensure it a leading global role.

3. **By 2030, 30 to 50 per cent of existing assets in cement, steel, and chemicals will require major reinvestment. New policies are needed now to create a business case for breakthrough technologies.** Key low-carbon technologies are available, but their abatement costs are still in the range of 100 to 170 €/t of CO_2. The EU should adopt policy instruments to cover the gap between these abatement costs and the EU ETS price as soon as possible.

4. **Europe needs a Clean Industry Package in 2021 to kick-start breakthrough investments and protect existing assets.** By refining existing carbon leakage protection instruments it will be possible to protect existing plants until they can be replaced. At the same time, decisive support for investments in breakthrough technologies is needed. This should come in the form of carbon contracts-for-difference, planning and financing for clean-energy installations and infrastructure, and standards to create markets for climate-neutral and circular products.

EU PRODUCTION SITES & CAPACITIES STEEL



Direct CO_2 emissions from the steel industry in the EU27 (+UK) in 2017
188 $MtCO_2$ (+12.6 $MtCO_2$ in the UK)

Steel production in the EU27 (+UK) in 2017
161 Mt of crude steel
(+7.5 Mt of crude steel in the UK)

Steel demand in 2017 (EU28)
159 Mt of finished steel

LEGEND

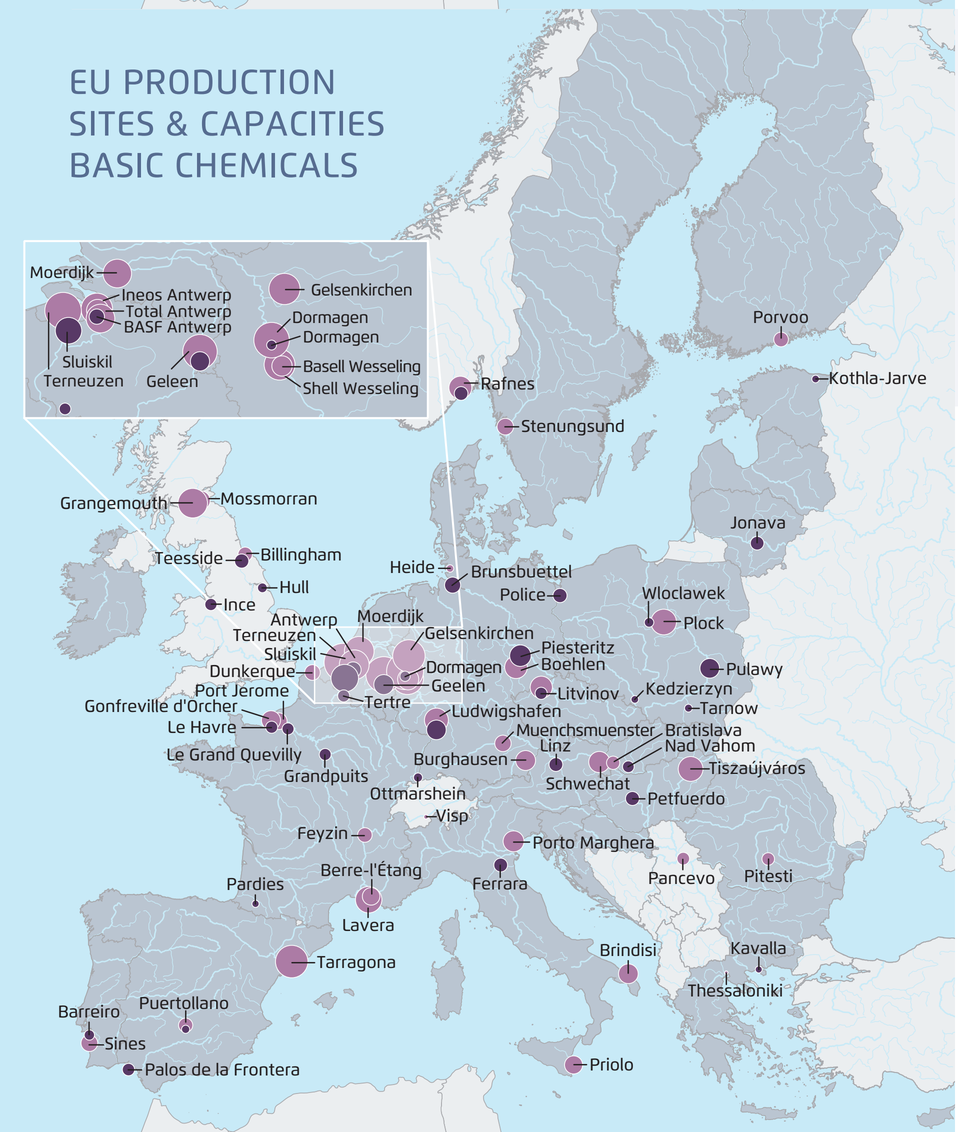
Production capacity crude steel

- Integrated blast furnace route (BF-BOF)
- Direct reduction with natural gas (DRI)
- Electric arc furnace with steel scrap (EAF)

- 1,000 kt/a
- 2,000 kt/a
- 3,000 kt/a
- 4,000 kt/a

Wuppertal Institute, 2020

EU PRODUCTION SITES & CAPACITIES BASIC CHEMICALS



Direct CO_2 emissions from the chemical industry in the EU27 (+UK) in 2017
129 $MtCO_2$ (+11 $MtCO_2$ in the UK)

Chemical production in the EU27 (+UK) in 2017
40.2 Mt of HVC (high value chemicals)
(+5.3 Mt of HVC in the UK)

Chemical demand in 2017 (EU28)
40.7 Mt of HVC

LEGEND

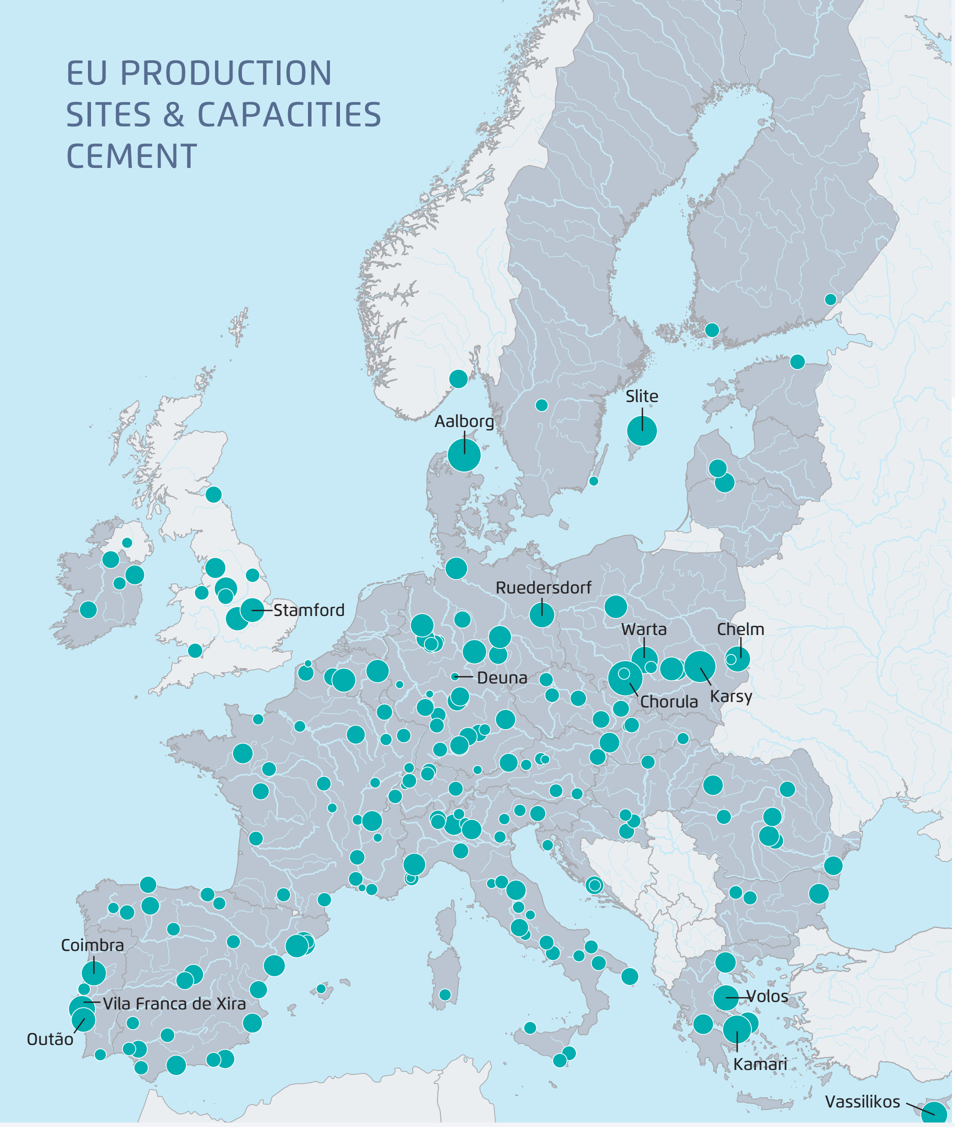
Production capacity basic chemicals

- Ammonia (kt/a)
- Steam crackers (kt HVC/a)

- 1,000 kt/a
- 2,000 kt/a
- 3,000 kt/a

Wuppertal Institute, 2020

EU PRODUCTION SITES & CAPACITIES CEMENT



Direct CO_2 emissions from the cement industry in the EU27 (+UK) in 2017
112 $MtCO_2$ (+6 $MtCO_2$ in the UK)

Cement production in the EU27 (+UK) in 2017
159 Mt of cement (+8.6 Mt of cement in the UK)

Cement demand in 2017 (EU28)
168 Mt of cement

LEGEND

Production capacity cement

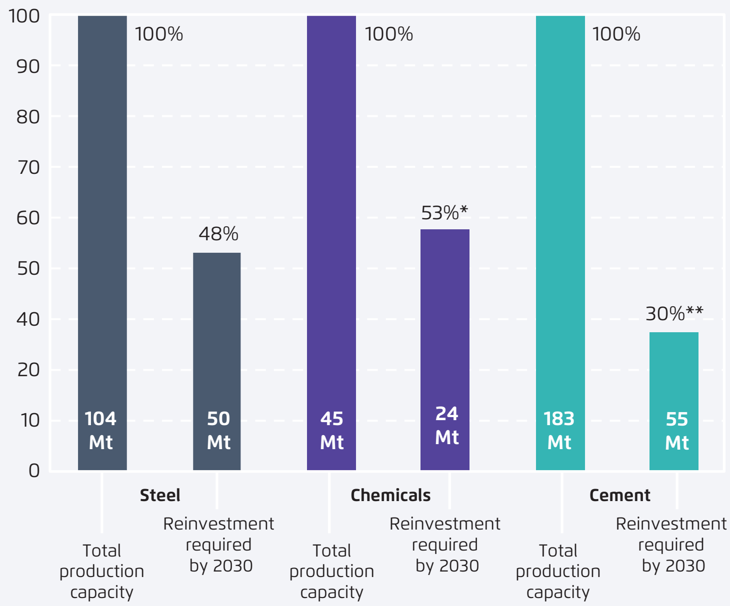
Cement clinker (kt/a)

- 1,000 kt/a
- 2,000 kt/a
- 3,000 kt/a
- 4,000 kt/a

Wuppertal Institute, 2020

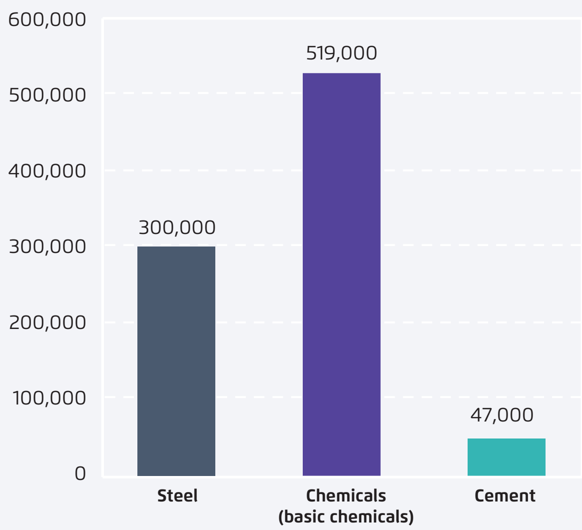
REINVESTMENT NEEDS BY 2030 AND DIRECT EMPLOYMENT IN CEMENT, STEEL AND BASIC CHEMICALS IN THE EU

REINVESTMENT REQUIREMENTS FOR PRIMARY PRODUCTION CAPACITY IN EU27 BY 2030



Source: Wuppertal Institute, 2020

PEOPLE DIRECTLY EMPLOYED BY THE SECTORS IN 2017



Source: Eurostat, 2020

Agora Energiewende/Wuppertal Institute, 2020

* Steam crackers are normally maintained and modernised continuously so that they do not have to be replaced all at once. Nevertheless, the graph provides a rough estimate of the reinvestment needs for existing facilities.
** Cement data represent numbers for Germany only. We estimate that the reinvestment requirements for the EU27 are in a similar range.

Content

Executive Summary

1 Introduction

Under the European Green Deal and the 2030 Climate Target Plan, the European Commission has recommended that the EU reduce its greenhouse gas emissions by at least -55 per cent by 2030 (relative to 1990 levels) and achieve climate neutrality by 2050.[1] European industry has a vital role to play in delivering this target. Direct industrial emissions accounted for 719 $MtCO_{2eq}$ in 2017, equivalent to approximately 20 per cent of annual net greenhouse gas emissions in the EU27 (Eurostat, n.d.).[2]

By 2030, EU industry will therefore need to reduce greenhouse gas (GHG) emissions in the range of 22 to 25 per cent compared with 2015 levels. To achieve climate neutrality by 2050, the EU will need to reduce its combined industrial emissions by approximately 95 per cent and offset residual emissions with carbon sinks.

So far, discussions have focused mostly on measures for meeting 2030 objectives. Based on the European Commission's Impact Assessment that accompanied the 2030 Climate Target Plan Communication[3] for industry, the targets represent a reduction of between 168 and 188 $MtCO_{2eq}$, i.e. 25 to 28 per cent of emissions in 2018.[4] According to the European Commission, this can be achieved using best available technologies referenced in the Impact Assessment.[5]

We believe that a more sustainable approach is to define the path for industrial transformation based on the 2050 climate neutrality target. Hence, in this study we identify strategies and investments that meet the increased 2030 target and achieve climate neutrality by 2050. To those ends, we recommend the rapid introduction of key low-carbon breakthrough technologies that takes advantage of the EU's industrial modernisation needs over the coming decade. During this period, some 48 per cent of the EU's production capacities in the steel industry, 53 per cent of its capacities in the chemical industry, and 30 per cent of its capacities in cement production will need replacing or refurbishing. Reinvestment[6] in traditional production processes, even if the best available technologies are used, is not an option so long as those processes are not easily convertible to zero-carbon or carbon-negative operation.

Though the necessary breakthrough technologies exist, their deployment will require appropriate policies. In this regard, the EU is at a crossroads: either institute breakthrough technologies aligned with the European Green Deal and a sustainable recovery from the Covid-19 economic crisis, or face a high risk of accelerated deindustrialisation, job losses, stranded assets, and carbon leakage.

This paper presents concrete strategies and pathways that capitalise on opportunities for breakthrough development in European industry. We opt for a dual approach that deploys breakthrough technologies for industrial capacities in need of

1 This summary of the full study was published in November 2020 prior to the EU Council decision in December 2020 to adopt an EU 2030 climate target of -55 per cent GHG emissions reduction.

2 The figure excludes emissions from energy sectors such as upstream power and heat production, refining, and solid fuel production.

3 In the following this will be simply referred to as the Impact Assessment.

4 Since industrial GHG emissions have grown in recent years, the gap is larger for 2018 than for 2015.

5 See Impact Assessment, 2020.

6 Reinvestment refers to investments that are required to maintain production capacities when existing production capacities reach the end of their lifetime.

reinvestment while allowing industrial assets with traditional processes to continue operation until they are scheduled for replacement.

The goal of this study is to define a Clean Industry Package at the EU and member-state levels that mobilizes investments that are compatible with meeting an EU 2030 climate target of at least -55 per cent while laying the groundwork for long-term climate neutrality and economic prosperity.

2 Where do the EU basic materials industries currently stand?

2.1 The role of industry in the economy

Basic materials industries are a cornerstone of the EU's economy and prosperity. In addition to making a major contribution to GDP, they directly provide over 1.8 million high-quality jobs.[7] As the starting point of Europe's industrial value chains, they provide basic materials such as steel, chemicals, and cement that are essential to every-day life today and the climate-neutral infrastructure of the future. These industries are also the fundament of several millions of indirect manufacturing jobs and the foundation of regional industrial clusters that often extend beyond the borders of individual member states. Naturally, the EU wants to preserve the competitiveness and strategic role of these sectors while reducing their GHG footprint. This means preventing market share loss and carbon leakage and maintaining the integrity of European value chains to ensure resilience against future crises. To do both, the EU needs a technology transition that puts its basic materials industries on a steady and sustainable path to climate neutrality. A transformation based on smart policies and key low-carbon technologies will ensure long-term economic prosperity, jobs, and income, and it will position the EU as a leader in technologies, markets, and standards that align with the new climate-neutrality paradigm.

2.2 Opportunities and challenges for industry to achieve higher climate ambition in 2030 and climate neutrality in 2050

The EU has set itself the goal of achieving climate neutrality by 2050. This means that all sectors, including the so-called "hard-to-abate" industries such as steel, chemicals, and cement, will have to become virtually climate-neutral within the coming three decades. In addition, the European Commission recommended in its 2030 Climate Target Plan Communication from September 2020 to increase the EU's greenhouse gas reduction targets from -40 per cent to at least -55 per cent by 2030 (relative to 1990 levels). On 7 October 2020 the EU parliament even voted in favour of increasing this greenhouse gas reduction target for 2030 to -60 per cent. A final decision on the EU 2030 climate target has not been taken yet, but is expected in December 2020.

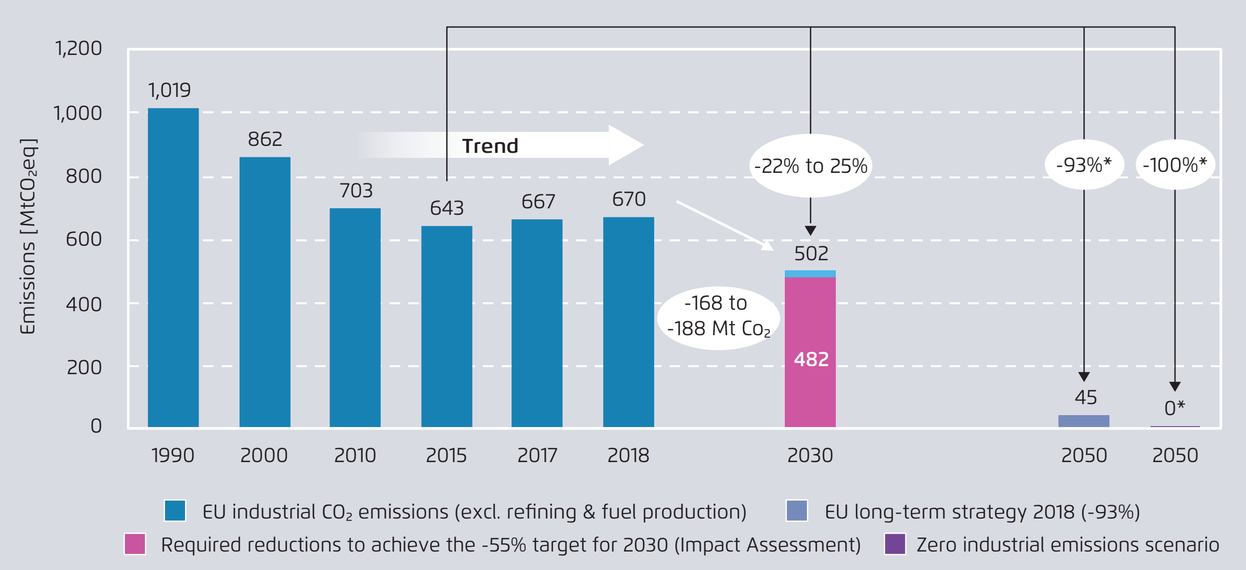
An EU climate target of at least -55 per cent would require heightened emission reduction efforts for the industrial sector. Despite reductions during the 1990–2010 period through energy efficiency measures, industrial greenhouse gas emissions have stayed mostly constant since then (see figure ES.1). In 2015, emissions began to rise along with economic growth. Though energy efficiency continues to be important, it alone will not suffice for a -22 to 25 per cent reduction by 2030, as indicated in the European Commission's Impact Assessment. Moreover, there is a risk that pressure or incentives to invest in efficiency measures for GHG-intensive assets with long lifetimes offers only a marginal GHG abatement benefit while increasing capital allocation and operational lifetimes. The result would be that short-term mitigation conflicts with the long-term climate neutrality objective.

This is why the introduction of key low-carbon technologies is needed for industrial plants when they are scheduled for replacement or refurbishment.

7 The employment numbers for 2017 are based on Eurostat 2020.

CO_2 emitted by the EU27 industrial sector from 1990 to 2018 and proposed sector targets for 2030 and 2050

Figure ES.1



Agora Energiewende, 2021, based on data from Eurostat, 2017, European Commission, 2020b & EEA, 2021

Note: Data are for CO_2 emissions only. They exclude non-CO_2 emissions from industry, from refining, solid fuel production for energy and non-energy uses.

* To achieve climate neutrality, residual emissions will have to be offset by negative emissions technologies, many of which could be developed in the industrial sector such as BECCS. By capturing and using CO_2 from other non-industry sectors, industry can provide net-negative emissions.

These technologies can make up for the stagnating emission reductions of the last decade and initiate a steady path to climate neutrality.

Currently, the EU's basic materials industries are preoccupied with the immediate economic effects of the Covid-19 pandemic. Due to lockdowns and significantly decreased economic activity in virtually all EU member states, it is clear that the demand for basic materials such as steel, cement and some chemical products will be significantly lower in 2020 than in previous years. For instance, the steel industry in Europe was particularly affected by decreased demand from key sectors such as car manufacturing and machinery production and cement companies faced a decline in construction activity. It is uncertain when and if demand will return to pre-crisis levels. The difficult economic environment has already started to force some companies to make temporary plant closures permanent, as with ArcelorMittal's Krakow plant in Poland. The risk is that productive capacities will be eliminated and that the crisis will accelerate the relocation of industrial capacities to other countries. And because most other countries have more GHG-intensive production methods than Europe, this will lead to carbon leakage.

At the same time, the crisis has also created opportunities. For instance, the unprecedented amount of public funding for economic recovery such as the *Next Generation EU Facility* and the national rescue funds can be used to give public investment support for the industrial transformation. *Next Generation EU* provides members states 750 billion € to be spent during the 2021–2025 period; 30 per cent must be spent on climate-related measures. This funding is in addition to the general EU budget (the *Multi-annual Financial Framework* or MFF) and the new *EU Innovation Fund*.[8] The question now is how these funds can be best allocated to maximise long-term benefits as well as short-term economic recovery. As a principle, it is important that the funds are used to accelerate the energy transition across all sectors. This means that investment support should target innovative solutions that are compatible with climate neutrality and readily available for deployment. Moreover, they must offer sustained greenhouse gas abatement and other economic benefits.

From the perspective of the industrial transformation, it is important to create an adequate regulatory framework for investment in key low-carbon technologies. With the effective use of *Next Generation EU* funding, the EU and its member states could kickstart a green industrial revolution in energy-intensive sectors. Besides compensating for the immediate economic impacts of the Covid-19 crisis, the development and commercialisation of key low-carbon technologies during the coming decade would put European companies at the forefront of growing domestic and international markets for clean basic materials, production technologies, and climate-neutral consumer products.

Climate neutrality is emerging as the new paradigm not only in the EU but also at the international level. China, the largest emitter of greenhouse gases and producer of energy-intensive basic materials, has announced a plan for carbon neutrality by 2060. Japan, the world's third largest economy, and the Republic of Korea, another heavyweight in energy-intensive industries, have also announced net-zero targets for 2050. Moreover, the designated US president Joe Biden has pledged that his administration will make achieving climate neutrality by 2050 a top priority.

8 https://ec.europa.eu/info/live-work-travel-eu/health/coronavirus-response/recovery-plan-europe/pillars-next-generation-eu_en

Such pledges are not limited to countries. In September 2020, ArcelorMittal, the world's largest steel producer, announced its commitment to company-wide carbon neutrality by 2050. Thyssenkrupp Steel Europe, the EU's second-largest producer after ArcelorMittal, has vowed to make itself climate-neutral by mid-century. LafargeHolcim and HeidelbergCement, the world's number one and two cement producers by volume, have announced targets of carbon neutrality by 2050 backed by the science-based target initiative.

Because industrial assets have long lifetimes – 40 years on average – the investments in new production capacities need to be assessed based on their compatibility with respective climate or carbon neutrality targets. Therefore, the transition to a climate-neutral industry in China and other major industrial economies will need to start well before 2030. In fact, it would not be surprising to see the first signs of this paradigm shift to carbon neutrality in China's 14th Five Year Plan (2021–2025). These announcements do not only open the door for international cooperation on the transition to climate neutral industry; they also herald the creation of large future markets for climate-neutral basic materials and key low-carbon technologies. The EU must not miss the opportunity to position itself as a global leader in this unprecedented transformation. The key low-carbon technologies to achieve climate neutrality are either already available or nearly market-ready – with many of them being developed in and by EU companies.

2.3 A portfolio of climate-neutral technological solutions in the offing

Technological solutions that could be harnessed to make energy-intensive basic materials industries almost entirely climate-neutral are already known. Some solutions, such as the production of green hydrogen from renewable energies, are nearly market-ready and are set to be scaled up during the coming years. Other examples of key low-carbon technologies include: the direct reduction of iron

Overview of possible key technologies for nearly carbon-neutral basic materials industries — Figure ES.2

Steel	Key technology	Earliest possible market readiness
	Direct reduction with hydrogen and smelting in the electric arc furnace	before 2025 (initially with natural gas)
	Alcaline iron electrolysis	2040 – 2045
	HIsarna® process in combination with CO_2 capture and storage	2030 – 2035
	CO_2 capture and utilisation of waste gases from integrated blast furnaces	2025 – 2030
Chemicals	**Key technology**	**Earliest possible market readiness**
	Heat and steam generation from power-to-heat	From 2020
	CO_2 capture at combined heat and power plants	2030 – 2035
	Green hydrogen from renewable energies	2020 – 2030
	Methanol-to-olefin/-aromatics route	2025 – 2030
	Chemical recycling	2025 – 2030
	Electric steam crackers	2030 – 2040
Cement	**Key technology**	**Earliest possible market readiness**
	CO_2 capture with the oxyfuel process (CCS)	2025 – 2030
	CO_2 capture in combination with electrification of the high temperature heat at the calciner	2025 – 2030
	Alternative binders	2020 – 2030 (depending on product)

Agora Energiewende/Wuppertal Institute, 2020

ore with natural gas or hydrogen in the steel industry (instead of conventional reduction in coal-fired blast furnaces); the chemical recycling of plastics (instead of their production from virgin fossil fuels and the incineration of the resulting waste plastics); and carbon capture and storage (CCS) for cement emissions. Figure ES.2 describes 13 key technologies that can significantly reduce greenhouse gas emissions in the steel, chemical, and cement industries. Other promising key low-carbon technologies such as smart crushing for cement recycling, recarbonation, circular economy and material efficiency measures also have much potential for reducing industrial greenhouse gas emissions.

At present, the key low-carbon technologies are still significantly more expensive than conventional manufacturing processes. Furthermore, the additional costs cannot be passed on to customers because of fierce international competition. To stimulate investment in these breakthrough innovations now, the government needs to create concrete policy proposals signalling to industry actors that it will actively support the transformation.

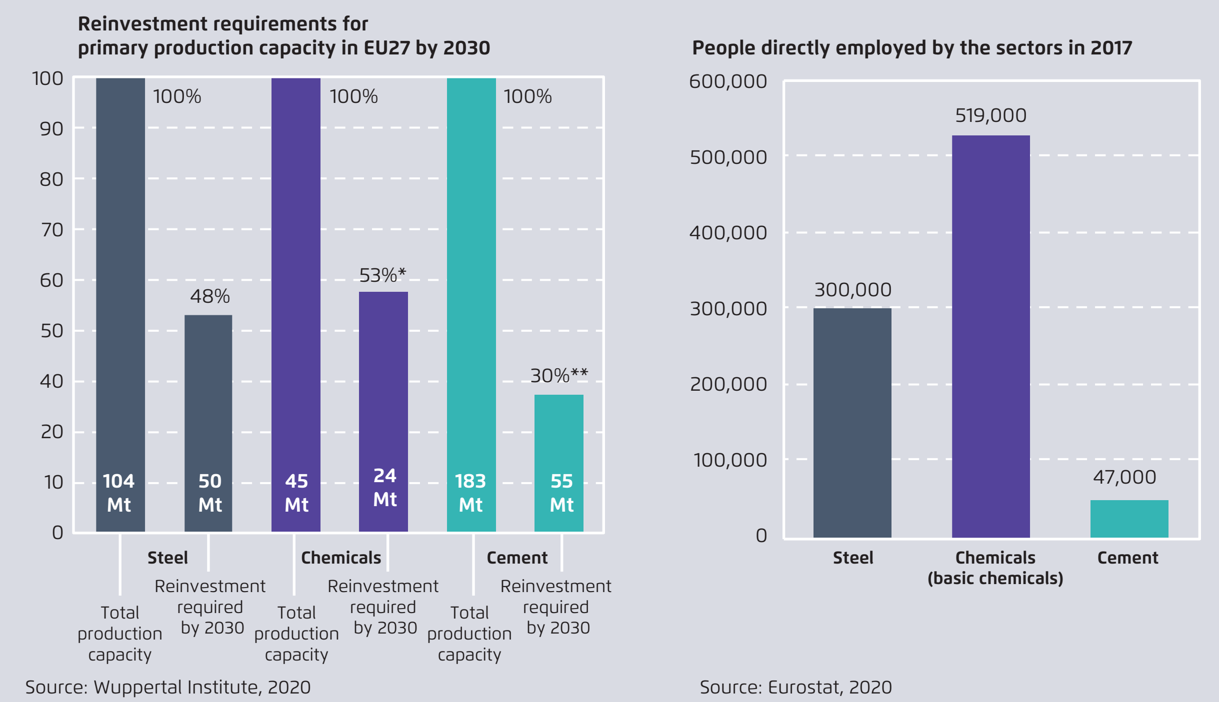
2.4 European industry at the crossroads

Because of the long lifetime of productive assets, the European basic materials industries stand at the crossroads: between now and 2030, roughly half of the EU's primary steel manufacturing and steam cracker facilities and an estimated 30 per cent of its cement production plants will reach the end of their lifetimes.

Since the lifetimes of these industrial assets range from 20 to 70 years (see figure ES.4), the reinvestment and location choices that companies in the steel, chemical, and cement sectors make during the next decade will create long-lasting path dependencies. Against the background of the 2050 climate neutrality target, this means that from now on all major investment must be focused on technologies that can operate with zero- or net-negative carbon emissions, if stranded assets (i.e. the premature shutdown of well-functioning plants) and high economic losses are to be avoided.

A special case is the relining of blast furnaces in the steel industry. While new and integrated steelworks have a technical lifetime of 50 years, blast furnaces – which make up the core operation of steel plants – must be relined every 20 years or so. A relining in 2025 can extend a plant's operational lifetime to 2045 and in theory is still compatible with the EU's 2050 climate-neutrality target. But relining conventional blast furnaces runs the risk of making them stranded assets, representing a lost opportunity for building a steady path to climate neutrality. Under the more ambitious EU 2030 climate target of at least -55 per cent, the European Commission's Impact Assessment projected that the share of coal will represent no more than 2 per cent of the EU's 2030 power mix. By 2035, conventional blast furnaces would be some of the last coal-based, high-emitting assets in the entire EU economy. In such an environment, continued operation until 2045 would be questionable. Such an asset would face increasing carbon prices, stricter environmental regulations,

Reinvestment needs by 2030 and direct employment in cement, steel and basic chemicals in the EU — Figure ES.3

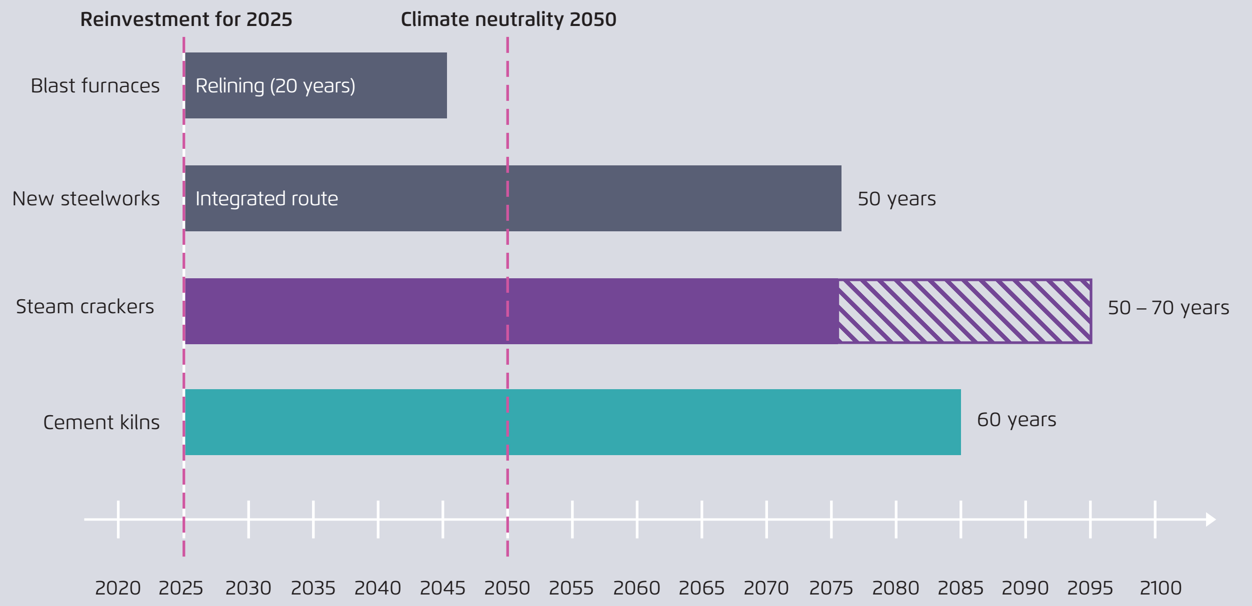


Agora Energiewende/Wuppertal Institute, 2020

* Steam crackers are normally maintained and modernised continuously so that they do not have to be replaced all at once. Nevertheless, the graph provides a rough estimate of the reinvestment needs for existing facilities.
** Cement data represent numbers for Germany only. We estimate that the reinvestment requirements for the EU27 are in a similar range.

Technical lifetime of selected primary production plants in the steel, chemical, and cement sectors scheduled to receive reinvestment in 2025

Figure ES.4



Agora Energiewende / Wuppertal Institute, 2020

pressure from NGOs, and declining demand for its high-carbon products both domestically and abroad. Moreover, the transition to a climate-neutral industry is about more than replacing individual assets. It is also about transforming the logic of existing industrial clusters and the related energy infrastructure, a process that requires much time and planning. At the same time, it is important to transform the skills and capacities of the industrial workforce, the service providers, and the equipment industry.

However, this reality is not yet widely understood. For example, in its Impact Assessment, the European Commission largely focused on the deployment of conventional best available technologies to achieve the required industrial emission reductions under the EU ETS for an increased EU 2030 climate target of at least -55 per cent. While this may, in theory, be a sound strategy to achieve the CO_2 abatement requirements of 2030, given the long lifetimes of industrial assets and the 2050 climate neutrality target, this would not be a sustainable strategy beyond 2030 for major reinvestments in the basic materials industries. Moreover, the use of technologies that do not allow zero-carbon or carbon-negative operation (or that cannot be easily converted to provide such operation) would also represent a lost opportunity in preparing for the broader transition to climate neutrality. Any rationally acting company and financial investor in Europe will foresee the long-term risks of stranded assets and will be reluctant to make reinvestments in CO_2-intensive assets in the 2020s. Besides, the promise of future conventional plant conversions to use clean hydrogen[9] or carbon capture and storage may prove elusive, especially for reinvestments in regions where access to clean hydrogen or the transport of CO_2 to sites for carbon capture are unlikely to be developed.

9 "Clean hydrogen" includes both "green hydrogen" (produced from water electrolysis with renewable electricity) and "blue hydrogen" (produced from fossil fuels with carbon capture and storage) as well as "turquoise hydrogen" (from methane pyrolysis with storage of the resulting carbon black).

Whether a particular investment or technology does or does not provide a solid foundation for the steady path to climate neutrality depends of course on the sector, process, and site. Ultimately, it will be up to industry and financial investors to decide on the best course of action. But state aid guidelines and policy instruments should be optimized to ensure effective investment incentives. The regulatory framework should promote technologies that have demonstrated their compatibility with climate neutrality by 2050, are readily available for deployment, and offer sustained greenhouse gas abatement and other economic benefits. At the same time, there must be clear policy guidance at the EU level that both limits the risk of high-carbon technology lock-in and reduces the possibility of future state aid for "bailing out" GHG-intensive investments that are clearly incompatible with the climate neutrality goal.[10]

In the absence of a sound Clean Industry Package to steer a steady path to climate neutrality by 2050, the EU basic materials industries remain in limbo. Right now, there is no viable business case for investments in key low-carbon technologies. At the same time, investing in conventional assets that are marginally more efficient from the perspective of greenhouse gas emissions but create a certain level of carbon lock-in and therefore risk being stranded under increasingly stringent greenhouse gas abatement targets and carbon prices is not a viable option, either. As a result, many companies may decide not to invest in the EU and move their production to other parts of the world with less climate ambition.

If the uncertainty continues, it is very likely that Europe will lose productive capacity, resulting in reduced GDP, the destruction of industrial networks and integrated value chains, the loss of jobs, carbon leakage, and increased global greenhouse gas emissions.

Based on this analysis, there are two possible pathways for the future of individual assets and industrial sectors. Depending on the specific situation of each installation and member state, different pathways may and will occur, of course. However, the objective of an adequate regulatory framework under an EU Clean Industry Package must be to optimize the outcome from an economic, social, and environmental perspective. Figure ES.5 illustrates two scenarios:

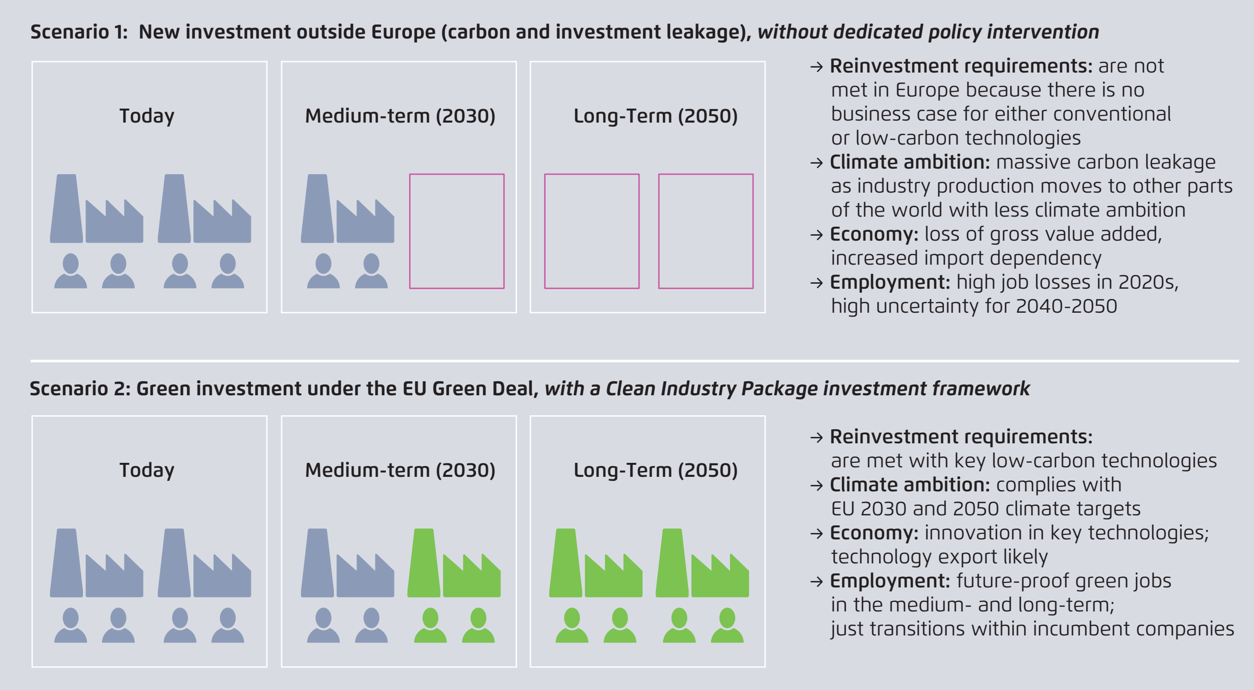
- → **Scenario 1:** New investment outside Europe (carbon and investment leakage), *without dedicated policy intervention*
- → **Scenario 2:** Green investment under the EU Green Deal, *with a Clean Industry Package investment framework*

Which pathway the basic materials industries will take will be determined by the investment choices in the 2020s which will have a major impact on innovation, climate ambition, the economy, and hundred thousands of jobs in the EU's steel, chemical, and cement sectors (see figure ES.5). These choices, in turn, will be shaped by regulatory conditions. While it is clear that scenario 2 is the most desirable option, the situation today of the EU basic materials industries is closer to scenario 1. Rational companies will foresee the long-term risks for reinvestment in conventional CO_2-intensive technologies, but because they do not have a credible business case for investment in key low-carbon technologies, they may decide not to reinvest in Europe at all. The result would be a creeping decline of the basic materials industries in Europe. What is worse, the stark economic consequences of the Covid-19 pandemic have already put immense pressure on basic materials companies in virtually all EU member states, making them more reluctant to make unsafe bets in Europe.

For all that, scenario 2 is still within reach, but requires an adequate investment framework for key

10 One possible way to do this is via the establishment of climate-neutral technology standards under, say, the Industrial Emissions Directive, and which would apply to major investments with lifetimes beyond 2030 (see Section 5.2).

Two scenarios for new investment in the 2020s and their implications for climate change, the economy, and employment in the EU — Figure ES.5



Agora Energiewende, 2020

low-carbon technologies. As the next section demonstrates, meeting the urgent reinvestment requirements with a swift deployment of key low-carbon technologies in the 2020s will allow EU industry to meet an increased EU 2030 climate target of at least -55 per cent. In contrast to reinvestment in conventional best available technologies, this will put the EU's industry on a steady path to climate neutrality.

3 Breakthrough technology pathways for climate-neutral industry

3.1 How much do EU ETS industries need to contribute to higher EU climate ambition 2030?

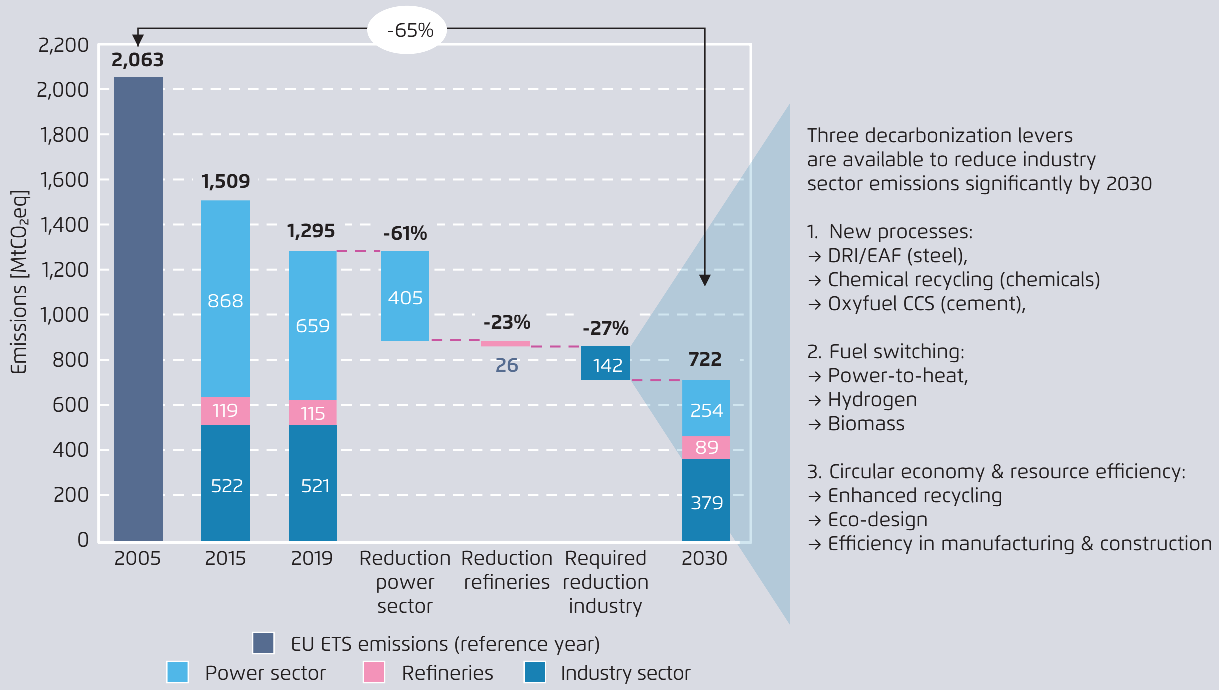
To meet the increased EU 2030 climate target, significant emissions reductions have to be delivered by the energy-intensive basic materials industries under the EU Emissions Trading Scheme (EU ETS).[11] Based on the European Commission's "MIX" scenario in the Impact Assessment, a -55 per cent economy-wide climate target for the EU by 2030, we have assumed a 65 per cent reduction of the greenhouse gas emissions cap for the EU ETS relative to that in 2005 (see figure ES.6).

This would represent an ambitious reduction target for current EU ETS sectors and would require gradually reducing the emissions cap from 1,295 $MtCO_{2eq}$ in 2019 to 722 $MtCO_{2eq}$ in 2030. Following the Impact Assessment, we assume that by 2030 the power sector will have reduced its emissions by 71 per cent and that refineries will

11 The significant greenhouse gas emission reduction potential in non-ETS industry sectors was not included in this study.

Expected emissions reductions from EU ETS industry for the EU's 2030 -55% climate target, along with decarbonisation levers to deliver those reductions

Figure ES.6



Agora Energiewende, 2020, based on data from European Commission, EEA, and Eurostat.

Note: Emissions that relate to industrial processes such a coking plants and power plants for industrial use are accounted for in the industry sector and not in the transformation sector. ETS emissions in 2005 are notional base-year emissions with respect to the 2030 target, i.e. they account for the change in the ETS scope and size of the EU since 2005.

have lowered their emissions by 25 per cent (both relative to 2015 levels).

This latter assumption is derived from the required emission reductions of the transport sector (approximately 20 per cent relative to 2015 levels) and from the assumed *partial* adoption of more efficient technologies to limit EU ETS compliance costs[12]. For industry sectors covered by the EU ETS, this would mean a need to reduce emissions by 27 per cent relative to 2015 levels, or a total of **142 $MtCO_{2eq}$** relative to 2019 levels.

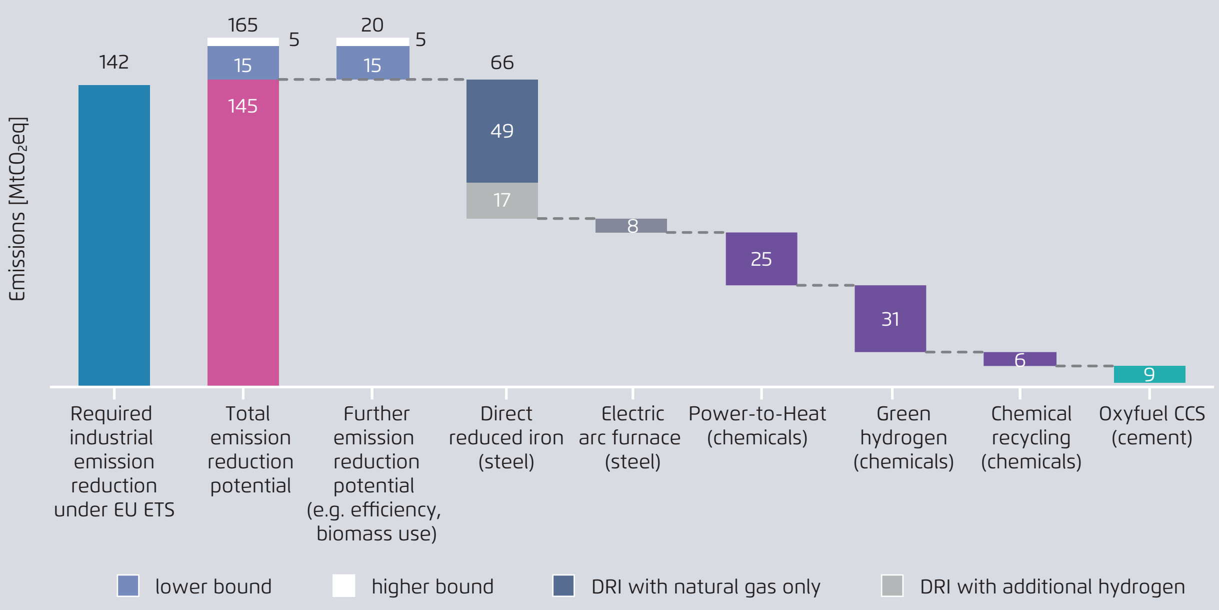
3.2 GHG abatement needs can be met with key low-carbon technologies

The strategic deployment of key low-carbon technologies in the basic materials industries has great potential to significantly reduce CO_2 emissions by 2030 and prepare the path to climate neutrality. Indeed, the required CO_2 reductions for industry under the EU ETS, for an EU 2030 climate target of at least -55 per cent, can be achieved by a decisive deployment of key low-carbon technologies in the steel, chemical and cement sectors *alone*. Overall, the abatement potential of these three sectors amounts to **145 $MtCO_2$** and thus exceeds the required emissions reductions of *all* industry sectors under the EU ETS (see figure ES.7). Further significant emission reduction potential exists through cross-cutting strategies such as biomass use, energy

12 See pages 178 and 213 of the Impact Assessment.

CO_2 abatement potential of selected key low-carbon technologies in the steel, chemical, and cement sectors by 2030

Figure ES.7



Agora Energiewende / Wuppertal Institute, 2020

efficiency, and circular economy measures in other industry sectors of the EU ETS.

By contrast, the Impact Assessment greatly relies on a switch to conventional best available technologies to meet GHG abatement requirements for 2030. The problem is that these technologies are not always compatible with the climate-neutral objectives for 2050. We have thus devised a scenario that focusses on climate neutrality as defined by the European Green Deal to spur innovation and green investment and secure future-proof industrial jobs and economic resilience.

For this vision to become reality, industrial companies will require a framework for investing in key-low carbon technologies, an infrastructure for clean hydrogen and CCS, and a sufficient and stable supply of green electricity (see sections 4 and 5). Our estimates are not based on a modelled scenario, but, rather, illustrate the CO_2 abatement potential of certain key low-carbon technologies if deployed in the industrial sector based on their effective or projected technological availability by 2030. Greenhouse gas abatement potential was calculated based on the 2017 asset base and production levels.

In the scenarios below, we apply only technologies that would be available with high confidence for large-scale deployment by 2030. Accordingly, we ignore a host of supply-side key low-carbon innovations that could nonetheless further contribute to the transition to climate neutral industry beyond 2030. Furthermore, our estimates do not include demand-side measures to increase recycling rates and quality or to improve material efficiency in final products. Hence, our estimates are somewhat conservative in what they assume about total mitigation potentials by 2030 and for the path to climate neutrality by 2050.

3.2.1 Key low-carbon technologies in steelmaking

In line with the EU Green Deal's overarching vision of innovation, future-proof investments, and increased climate ambition, we assume that there will be no new investment in conventional coal-based blast furnace technology. Instead, the 48 per cent of primary steel capacity that requires relining or reinvestment before 2030 will be replaced with key low-carbon technologies that are already available and that are compatible with the climate neutrality target. Based on these criteria, we selected the production of direct reduced iron as a technology for primary steelmaking and the electric arc furnace for secondary steelmaking.

Direct Reduced Iron (DRI) for primary steel production: DRI with clean hydrogen is the only key low-carbon technology close to market readiness that can significantly reduce emissions in primary steelmaking – by up to -97 per cent relative to the blast furnace route. Moreover, the technology is sufficiently mature, so that it can be deployed in the 2020s to meet reinvestment requirements in the EU steel industry. It can be initially fuelled by natural gas, which will reduce emissions by approx. -66 per cent compared with the conventional blast furnace route (1.8 t of CO_2/ t of crude steel). The residual emissions can be largely eliminated by substituting natural gas with increasing shares of clean hydrogen. With its capability and flexibility, DRI can serve as an anchor for increasing investment in the production and transport of hydrogen and so contribute to the creation of clean hydrogen-based industrial clusters.

We therefore assume that 90 per cent of the conventional blast furnaces that reach the end of their lifetime before 2030 will be replaced by DRI reactors. Until enough clean hydrogen is available, DRI plants will operate with natural gas. For the envisaged production of 41 Mt DRI steel with natural gas, the CO_2 abatement potential is **49 $MtCO_2$** (see figure ES.7, DRI with natural gas only). Later, increasing amounts of clean hydrogen can replace fossil gas in the DRI plants without major retrofits. For 2030 we assume that, on average, DRI plants will run on 65 per cent green hydrogen and 35 per cent fossil natural gas, for an emissions reduction of -89 per cent relative to the blast furnace route. Compared with natural gas DRI, this produces an additional CO_2 abatement of **17 $MtCO_2$** by 2030 (see figure ES.7, DRI with additional hydrogen). The required amount of green hydrogen (ca. 50 TWh) in the steel industry is equivalent to 15 per cent of the planned green hydrogen production (333 TWh) within the EU by 2030, as described in the *EU Hydrogen Strategy*. To date, steel companies in Sweden (1x), Germany (3x), Romania (1x), and Italy (1x) either have planned or operate DRI pilot and demonstration plants or have announced concrete plans to produce DRI steel on a commercial scale before 2030.

Electric arc furnaces for secondary steel production: Another low-carbon transformation strategy in the steel sector in line with climate neutrality is to increase the share of secondary steel, replacing primary steelmaking with coal-based blast furnaces. Studies have shown that the share of secondary steel production in the EU could rise from ca. 40 per cent today to between 60 and 70 per cent by 2050[13]. We conservatively assume that 10 per cent of the primary steel production capacity that requires reinvestment before 2030 will be converted to electric arc furnaces, equivalent to an increased production of 4.6 Mt of secondary steel in 2030. The specific emission reduction per ton of crude steel is 1.68 t of CO_2 (-93 per cent), which translates into emission reductions of **8 $MtCO_2$** for 2030. The Swedish steel company SSAB has already announced plans to replace approx. 1.5 Mt of conventional steelmaking capacity in Oxeloesund with electric arc furnaces by 2025.

3.2.2 Key low-carbon technologies in the chemical sector

In the chemicals industry the key low-carbon technologies that are already available or can become available

13 Material Economics. (2019). *Industrial Transformation 2050.*

on a commercial scale in the 2020s are power-to-heat, clean hydrogen, and chemical recycling. These technologies can contribute to a significant reduction of greenhouse gas emissions before 2030.

Power-to-heat (PtH): In light of the accelerated EU coal phase-out under the increased 2030 climate target of at least -55 per cent and the efficiency gains over clean hydrogen, PtH technologies are particularly attractive from environmental and economic perspective. In the -55 per cent scenarios of the European Commission's Impact Assessment, coal accounted for a mere 2 per cent of the European power mix in 2030. As a result, electricity generation will have to be based on a significant expansion of renewable sources. Specific greenhouse gas emissions per kWh of electricity will be comparably low, offering a convenient opportunity to substitute the use of fossil fuels for heat production.

Based on country-specific data for low- and medium-temperature heat in the chemicals sector (i.e. steam demand of up to 500°C), we assume that a total demand of 342 TWh_{th} can be supplied by an evolving mix of technologies. Today, heat demand in the chemicals sector is supplied by a combination of combined heat and power plants (CHP) as well as natural gas-fired boilers with a greenhouse gas intensity of 223 g of CO_2/kWh_{th}. Starting from this baseline, we assume a gradual evolution with increasing shares of PtH.

For lower temperatures, we assume the use of high-temperature heat pumps, corresponding to about 10 per cent of total heat demand. Another 40 per cent of total heat demand can be supplied by electrode boilers. The remaining 50 per cent of heat in 2030 will continue to be supplied with natural gas-fired boilers and conventional CHP plants, as is largely the case today. When assessing the greenhouse gas abatement potential for these technologies, we make the simplified assumption that both PtH technologies operate at 8,000 full-load hours.

To determine the GHG abatement potential for 2030, it is necessary to estimate the specific greenhouse gas intensity of the future electricity mix. For this purpose, we relied on the modelling results of an accelerated coal phase-out scenario that is compatible with the -55 per cent target of the Impact Assessment (Agora Energiewende 2020, forthcoming). Based on this modelling we assume an average grid emission factor of 76 g CO_2/kWh for the EU27 power mix. We also factored in the specific average grid emission factors for Germany (113 g CO_2/kWh), Poland (154 g CO_2/kWh), the Czech Republic (119 g CO_2/kWh), and Spain (46 g CO_2/kWh). CO_2 emissions can be reduced by **25 $MtCO_2$** compared with when supplying steam demand from natural gas-fired boilers with a greenhouse gas intensity of 223 g of CO_2/kWh_{th}. The additional electricity required for this strategy will amount to 148 TWh, with 11 TWh for heat pumps (with a coefficient of performance of 3) and 137 TWh for electrode boilers with 100 per cent conversion efficiency.

Considering the flexibility of PtH, this analysis is somewhat simplistic but its estimates of the greenhouse gas abatement potential are conservative. In reality, PtH would operate mainly in times when renewable electricity is cheap and abundant. The specific greenhouse gas intensity of electricity during those times is lower than on average, generating an even higher reduction in greenhouse gas emissions. Moreover, PtH will cease when renewable power generation is scarce and the greenhouse gas intensity of grid electricity is high, because industries will rely on conventional heat sources from CHP and natural-gas boilers. Thanks to this flexibility, PtH in the chemical industry can efficiently use renewable electricity when it is abundant and compensate for its lack when wind and solar generation is low. To make effective use of this solution and its benefits for the power sector and the economy, it will be necessary to establish market mechanisms that align with cost efficiency and minimise GHG emissions.

Hydrogen use in the chemical industry: By 2030, the EU chemicals industry will be among the largest users of clean hydrogen (AFRY 2021, forthcoming). The European Commission's *Hydrogen Strategy for a Climate-Neutral Europe* envisages by 2030 a total production of 333 TWh of renewable electricity-based green hydrogen within the EU borders, another 333 TWh of imports from countries such as Ukraine and Morocco, and a significant amount of blue hydrogen. We estimate that the chemical industry will use around 115 TWh of green hydrogen in the production of ammonia (91 per cent) and methanol (9 per cent). Producing 115 TWh of green hydrogen via electrolysis can reduce **31 MtCO_2** relative to conventional hydrogen production based on the steam-methane reforming of natural gas with specific emissions of 9t CO_2/t of H_2.

Chemical recycling: The recycling of plastic waste with chemical methods is an important opportunity for material substitution because chemically recycled plastic waste can serve as a substitute for petroleum-based naphtha. By replacing this fossil source, it closes the carbon cycle and avoids greenhouse gas emissions. While the technology has not yet been implemented on a commercial scale, we assume that this will be possible over the coming years, provided that the appropriate policy incentives are introduced. We assume that by 2030 five per cent of chemical raw materials for the production of two million tons of *high-value chemicals* (HVC) can be supplied by feedstock generated from the chemical recycling of plastic waste. This will replace an equivalent volume of petroleum-based naphtha in plastic production and avoid the CO_2-intensive incineration of plastic wastes. Conventional petroleum-based plastics production and the subsequent incineration of plastic waste generates about 4.5 t of CO_2 per t of HVC. Chemical recycling by the pyrolysis of plastic waste and the use of pyrolysis oil in conventional steam crackers will enable GHG emission reductions of 3.1 t of CO_2/t of HVC, or 69 per cent relative to the status quo. In 2030, this will amount to a CO_2 abatement potential of **6 MtCO_2**.

The commercial proof of concept indicates that the share of chemical recycling can be increased after 2030. Moreover, the greenhouse gas reduction potential can be further increased through technological optimisation such as the electrification of steam crackers and the gasification of the heavy fuel oil fractions coupled with methanol-to-olefin technology. The emission reduction potential of this fully *integrated chemical recycling route* amounts to 93 per cent (4.2 of CO_2/t of HVC) relative to conventional processes.

3.2.3 Key low-carbon technologies in the cement sector

An array of measures to reduce emissions along the value chain is available for the cement sector. Demand-side measures such as efficient design can reduce the amount of concrete needed, lowering demand for cement. The total amount of cement per unit of concrete, in turn, can be lowered by the more efficient application and packing of granules. Furthermore, the clinker content of cement can be reduced by substituting a portion of the clinker with other binders, such as so-called limestone and calcinated clay substitutes ("LC3" solutions).

Another promising approach is based on the principle of material circularity: concrete from demolition is crushed and the aggregates are separated and then either re-used as cement substitute directly (unhydrated cement) or brought back to cement plants for recarbonation and recycled to be used to produce new recycled clinker.

But even with recycling, the industry will still need to produce new cement clinker in the future. Roughly one-third of the emissions from clinker production (energy-related emissions) can be avoided in the future through the use of biomass or the electrification of kiln heating. The remaining two-thirds of process-related emissions, however, will require carbon capture technologies if the cement sector is to achieve climate neutrality and possibly even negative emissions.

Oxyfuel CCS: Oxyfuel CCS can play a key role in delivering significant emission reductions. CCS infrastructure in coastal areas could be developed by 2030 for cement as well as for the production of blue hydrogen. We assume that by 2030 eleven cement plants that are close to the Atlantic Ocean or navigable rivers could be connected to long-term CO_2 storage sites that are being developed in the Netherlands and Norway. This will require an infrastructure to transport CO_2 via pipelines or ships. Compared with the conventional production of cement with specific emissions of 0.61 t of CO_2/ t of cement, Oxyfuel CCS can capture and store 90 per cent of CO_2 emissions. By 2030, this technology can cut emissions by a total of **9 MtCO$_2$**. Bio-energy coupled with CCS, known as BECCS, can achieve even better results. For instance, a 25 per cent share of biomass in the fuel mix coupled with Oxyfuel CCS can make a cement plant climate neutral; higher shares of biomass have the potential to produce negative emissions.

Further reduction levers:
Significant reduction potentials also exist in EU ETS industry sectors outside steel, chemicals, and cement. Moreover, a number of additional options such as energy efficiency, biomass use, and circular economy measures can be used across all the sectors. The Impact Assessment of the European Commission has shown that by solely relying on an ambitious deployment of best available conventional technologies, the industry sectors under the EU ETS could reduce emissions by **144 MtCO$_2$** by 2030. Though our scenario rules out most conventional best available technologies in steel, chemicals, and cement because of CO_2-intensive lock-in, cross-cutting technologies such as pumps, drive systems, compressors, and ventilators can still do much to lower emissions generally.

Power-to-heat applications in EU ETS industries other than chemicals, biomass, and further circular economy measures also have great potential. We conservatively estimate a combined CO_2 reduction potential of **at least 15 to 20 MtCO$_2$** by 2030, or about 10 to 14 per cent of the best available conventional technology potential in the Impact Assessment. We have not quantified here the potentials of circular economy and material efficiency measures because our focus was on the development of supply-side breakthrough technologies. Nevertheless, the potentials in these areas point to the many technical levers that EU ETS-compliant industry sectors have at their disposal for reaching a -65 per cent ETS cap in 2030.

To realise this breakthrough scenario and embark on the path to climate neutrality, the EU's industry will require a comprehensive framework for investment in key low-carbon technologies that must be created as soon as possible.

Industry-wide transformation at scale depends on the fulfilment of certain basic conditions along the entire industrial value chain. This is one reason why the EU doesn't need a magic bullet policy to unlock industrial transformation; it needs a Clean Industry Package. In this chapter we explain the importance of introducing such a package as soon as possible.

4 A Clean Industry Package to kickstart industrial transformation

4.1 Insufficient policy action will lead to deindustrialisation and carbon leakage

Due to the upcoming modernisation requirements and the long lead times for the licensing and construction of new plants (typically 5 years or more), companies in the basic materials industries will soon have to decide which reinvestment to make in Europe. The current regulatory framework does not create a business case for investment in conventional CO_2-intensive technologies, which are likely to lead to stranded assets; nor does it create a business case for investments in key low-carbon technologies, which are significantly more expensive than conventional CO_2-intensive technologies.

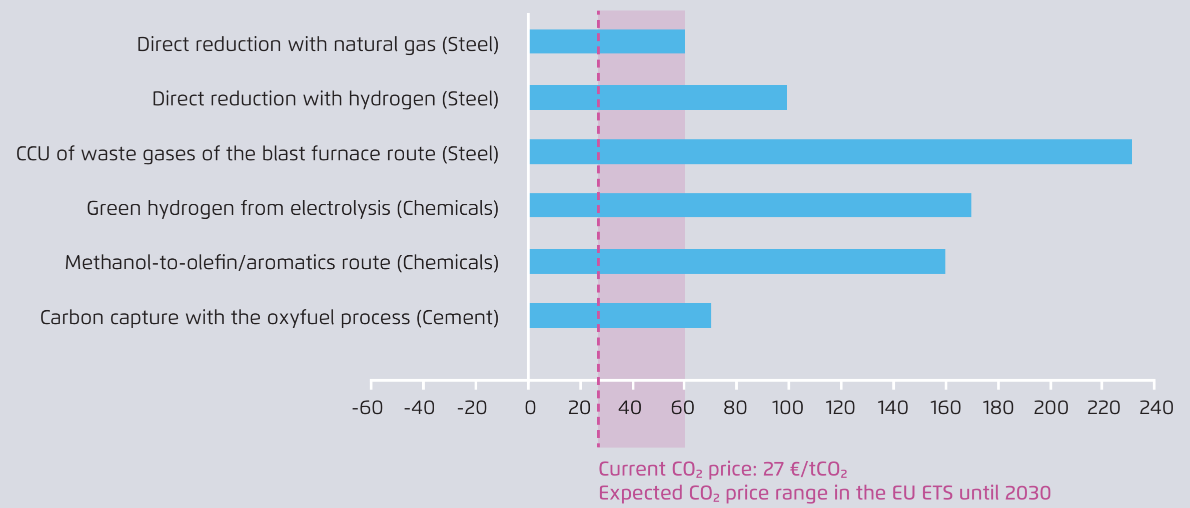
The regulatory limbo demands a breakthrough strategy with a more ambitious vision than that offered by the European Commission's Impact Assessment, which neglects the large CO_2 reduction potentials of truly transformative low-carbon technologies. While the Impact Assessment shows that industries governed by the EU ETS can achieve the EU's 2030 climate target of -55 per cent by adopting the best available conventional technologies, this is not a sustainable strategy for climate neutrality in the steel, chemicals, and cement sectors given the inevitability of carbon lock-in and stranded assets.

However, the EU is ready to begin investing in a portfolio of key low-carbon technologies during the next 5 years. Key low-carbon technologies such as direct reduced iron in the steel sector; green hydrogen, power-to-heat, and chemical recycling in the chemicals sector; and carbon capture and storage technologies in the cement sector can be deployed well before 2030. Provided an appropriate regulatory framework and necessary infrastructure are in place, the introduction of key-low carbon technologies for needed reinvestment alone will ensure that EU ETS industries can meet the 2030 reduction target.

4.2 Carbon pricing and border carbon adjustments alone will not be sufficient

The costs of key low-carbon technologies are significantly higher than today's conventional technologies. Even under optimistic assumptions (lower bounds for 2030), the estimated CO_2-abatement costs of key low-carbon technologies are well above he carbon price range of 45-60€/t of CO_2 that the Impact Assessment projects for the EU-ETS through 2030, as shown in the European Commission's 2030 Climate Target Plan (see ES.8).

Estimated CO_2 abatement costs of selected key low-carbon technologies versus today's conventional reference process for 2030 — Figure ES.8



Agora Energiewende/Wuppertal Institute, 2020

Note: CO_2 abatement costs depend very much on assumptions about electricity costs. For the calculation of these values, electricity costs of 60 euros per MWh were usually assumed. The estimates here are based on Agora Energiewende/Wuppertal Institut, 2019 and represent the lower bound of CO_2 abatement costs in 2030. Higher CO_2 abatement costs are to be expected before 2030 than after 2030 because the technologies must still undergo learning curves for cost reductions.

In fact, the CO_2 abatement costs of these technologies are likely to be even higher before 2030. First-of-a-kind plants still face certain unique project risks, because of the learning curve for new technologies and the need for proof of concept on a commercial scale. This means that even assuming the EU can overcome the many obstacles to swiftly implementing a well-functioning border carbon adjustment mechanism in the 2020s, the expected CO_2 prices are not sufficient to create a viable business case for investment in key low-carbon technologies. The combination of higher carbon prices and border carbon adjustments alone will not create a sufficient investment framework for these key technologies.

4.3 Only a coordinated set of policies across the value chain will enable the necessary investments

To incentivize investment in key low-carbon technologies in the basic materials industry certain basic conditions along the entire industrial value chain need to be met.

- → **Upstream:** The industrial sector needs reliable access to clean energy (renewable electricity and clean hydrogen) and raw materials at competitive prices along with the required infrastructure, such as power grids, hydrogen production and transport, CO_2 transport, and CCS. Pan-European solutions will be required to develop, plan, and finance the necessary infrastructure.
- → **Midstream**: The industrial sector needs the right economic and financial conditions to develop, implement, and operate investments in key low-carbon technologies. Moreover, policies are needed to address the risks of carbon leakage in a sustained manner.
- → **Downstream:** The industrial sector needs demand and scalable markets for decarbonised and circular products, markets that have internalised the higher costs of decarbonised products, and incentives to integrate the circular economy and resource efficiency along the value chain.

If these basic conditions along the value chain are not fulfilled, the industrial sector will not invest in key low-carbon technologies. A cement producer will not invest in the installation of carbon capture technologies unless the government has committed to CO_2 infrastructure (upstream). And even if the cement plant can be connected to a CCS infrastructure, the company will not invest in key low-carbon technologies unless there are mechanisms to cover the significant additional costs of low-carbon cement at the stage of production (midstream) and at the final sale of the product (downstream).

The new European Commission has started to propose policies that, if properly implemented, will address some – though not all – of the industrial sector's specific needs. These policies include the *Hydrogen Strategy*, the *Sustainable Products Policy Initiative*, and the *Circular Economy Strategy*. However, in some key areas such as industrial infrastructure planning for key industrial clusters, implementing instruments to support the high operating costs of low-carbon technologies, or creating new markets for ultra-low carbon products, the European Commission has yet to make concrete proposals. Accordingly, key gaps still need filling.

Our proposed Clean Industry Package for Europe aims at comprehensively and adequately addressing the basic conditions along the entire industrial value chain. It consists of policies that *both* preserve the business case for existing industry assets until they reach the end of their lifetimes *and* create a framework for new investments compatible with the 2050 climate-neutrality target.

Figure ES.9 provides an overview of the 11 policies. The next section describes them in more detail.

5 The Clean Industry Package: 11 policy instruments for the entire value chain

5.1 Upstream policies

1) Support instruments to create a business case for clean hydrogen

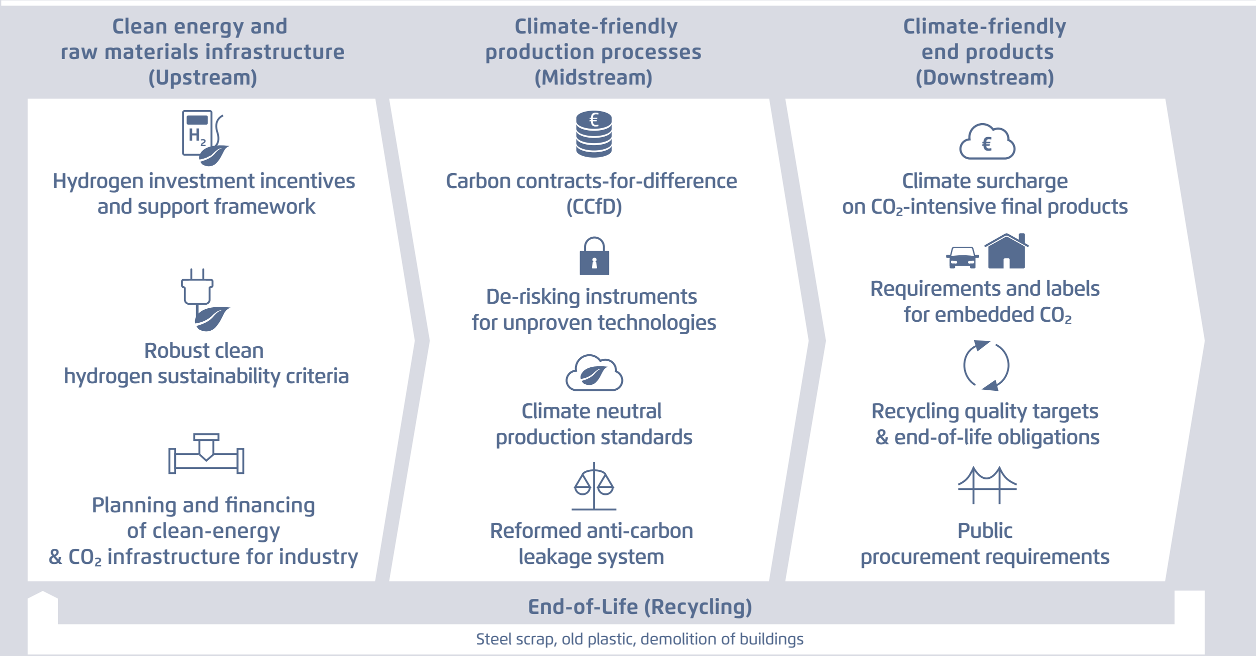
To mobilize the required investment in clean hydrogen production and infrastructure, a reliable business case for the production and transport of clean hydrogen must first be established. There are three main options for instruments to establish the required incentives:

→ **A feed-in premium for hydrogen** can close the price gap between the production of clean hydrogen and conventional hydrogen (produced from the steam reforming of natural gas). Such feed in premiums may also be awarded through *hydrogen contracts-for-difference* and possibly be auctioned. They might also be appropriate for supporting early stage investments in greening existing hydrogen production, i.e., the switching from GHG-intensive fuels to clean sources for industrial processes that already use hydrogen. This will encourage the creation of supply for other green hydrogen applications as well.

→ **carbon contracts-for-difference (CCfD)** for the production, transport, and use of clean hydrogen. The additional costs of clean hydrogen can also be covered by financing its use in industrial production applications. This would channel clean hydrogen directly to no-regret-use sectors such as steel (e.g. direct reduction with hydrogen) and chemicals (e.g. low-carbon ammonia).

→ **A clean hydrogen quota** can be applied on sellers of maritime and aviation fuels. In this way, the private sector absorbs the cost of blending a share of renewable fuels in the end product

Policy needs in the value chain — Figure ES.9



Agora Energiewende, 2020

(e.g. airplane tickets). This option may not be appropriate for general industry because the higher cost of hydrogen blending would make it difficult to compete with foreign competitors that do not use renewable hydrogen.

2) A robust sustainability framework for clean hydrogen production and use

To develop clean hydrogen that does not contribute to increasing emissions along the industrial value chain (scope 3 emissions), the EU will need to develop rules that classify hydrogen as "clean" and thus eligible for state aid. These rules could be part of a revised Renewable Energy Directive. Specifically, rules are needed to govern guarantees of origin for clean hydrogen and the "additionality" of renewable or decarbonised energy for clean hydrogen production; to ensure that clean hydrogen is allocated to the most appropriate "no-regret" options (e.g. steel, chemicals, maritime, and aviation); and to govern the safety of hydrogen production, transport, and use.

3) Planning, financing, and regulatory steps to enable clean energy and a CO_2 storage infrastructure

Current infrastructure planning varies greatly from member state to member state. For the development of a pan-European hydrogen, electricity, and CCS infrastructure, future *National Energy and Climate Plans* (NECP) must explicitly include the planning and financing of strategic industrial infrastructure. The plans could then serve as a reference point for other planning and EU financing instruments such as the *Trans-European Networks for Energy regulation* ("TEN-E"), *Regional Just Transition Plans*, *Projects of Common Interests*, and state-aid approval requests.

5.2 Midstream policies

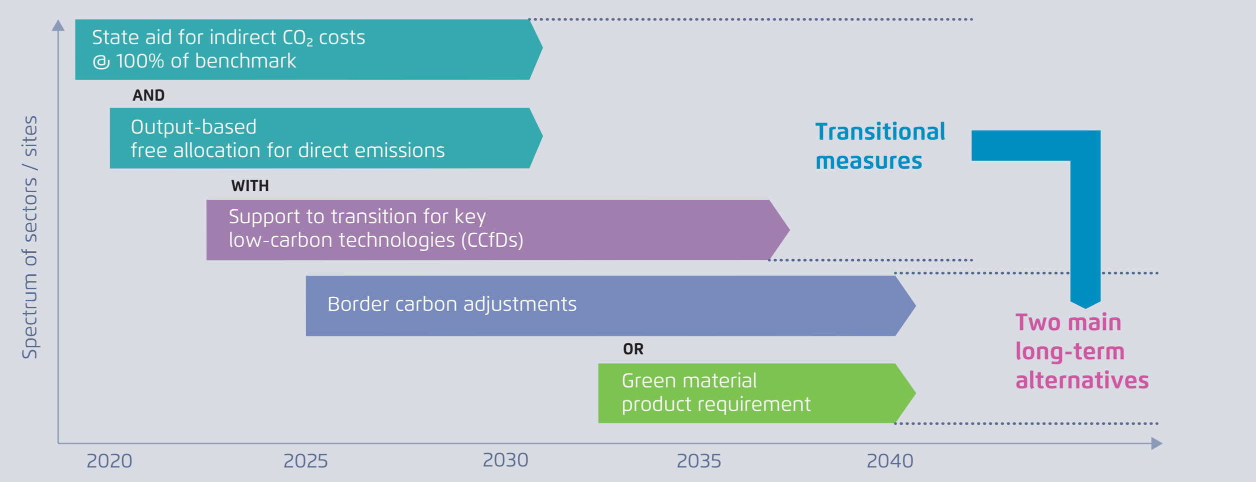
4) An EU policy framework for carbon contracts-for-difference (CCfDs)

By covering the price difference between conventional and key low-carbon technologies, CCfDs can provide a credible business case for investments that are compatible with climate neutrality. Payments to these projects would be calculated based on the difference between the EU ETS carbon price and a pre-agreed strike price (that is, the breakeven carbon price to make this investment viable). Accordingly, CCfDs are critical for covering the cost gap that arises from the expected CO_2 abatement costs of key low-carbon technologies, which in the 2020s will be higher than the projected EU ETS carbon prices. In the medium term, CCfDs could also complement a border carbon adjustment regime to guarantee investors a sufficiently high CO_2 price above the carbon price defined by the border carbon adjustment.

5) De-risking instruments for capital expenditure in first-of-a-kind, large-scale investments

CCfDs can be supplemented by financing instruments that address the capital investment risk that results from large-scale deployment of new, unproven, and often highly capital-intensive technologies. Funds such as the *EU Innovation Fund and InvestEU* already exist for this purpose. They are relatively small, however. The *EU Innovation Fund* must support all sectors of the entire energy system and the size of *InvestEU* was dramatically lowered during the EU's recent recovery and budget negotiations.
To boost these instruments, the EU must devise additional funding mechanisms. Potential options are an EU-wide climate surcharge on products with large amounts of basic materials that are sold in the EU market or the extraction of new revenues from ETS auctions.

Short-, medium-, and long-term policy tools for carbon leakage protection — Figure ES.10



Agora Energiewende, 2020

6) Set standards for production processes compatible with climate neutrality

The EU needs standards that dissuade new investment in industrial plants and technologies that are incompatible with achieving climate neutrality by 2050. Appropriate standards can prevent the introduction of more CO_2-intensive conventional technologies and "half-way solutions" that reduce emissions in the short run but lock in technologies with relatively high emissions. They can also clarify eligibility for state aid, identify specific criteria for the use of policy instruments such as CCfDs, and facilitate the creation of lead markets for climate-neutral materials (e.g. through green public procurement).

7) A reformed anti-carbon leakage system, robust to higher carbon prices

Under existing policies, the EU ETS Directive provides two main measures for tackling the risk of "carbon leakage," i.e. when production, jobs, and emissions move to countries with less climate ambition. The first is the free allocation of emissions allowances to sectors at risk of carbon leakage, which include energy-intensive basic materials industries. The second is the possibility of state-aid payments to compensate for higher electricity prices. But these solutions need to be revised in light of projected increases in carbon prices and decreases in free allowances. In the short run, free allocation must be continued at the full technology benchmark but adjusted based on true output ("output-based allocation"). Moreover, state-aid guidelines should be reformed to enable maximum aid levels for electro-intensive industries once the carbon price rises above 30€/t of CO_2 (full power-price compensation). Border carbon adjustments or carbon product requirements must be prepared carefully and gradually implemented for relevant sectors (see figure ES.10). Depending on the specific design of certain policies further reforms may be needed.

5.3 Downstream policies

8) A climate surcharge on material-intensive final products

Some of the policies at the upstream and midstream levels such as carbon contracts-for-difference require a refinancing option to cover additional funds. One option would be a climate surcharge on certain final products containing large amounts of basic materials (cars, plastic bottles, houses). The climate surcharge would be applied to the final product (e.g. car) regardless of its origin (EU, non-EU) or the production process (conventional steel, low-carbon steel) and would thus be compatible with WTO rules. The additional cost increases in the final product are small (e.g. <1–2 per cent of final product price).

9) Requirements to improve recycled material quality and material efficiency in manufacturing and construction

One of the biggest barriers to boosting the circular economy for basic materials such as steel, non-ferrous metals, and plastics is the degraded quality of secondary scrap and plastic. This limits the share of recycled materials that can be used to replace new virgin materials and a share of energy-intensive primary production processes. One option to incentivise the improvement of material quality would be the introduction of stronger incentives for material conservation and minimum recycled content requirements. A second option would be an EU ban, tax and label products with low recyclability or poor material efficiency. This would ensure that products such as vehicles, machines, and buildings are designed with longevity and ease of disassembly in mind. A third option would be the adoption of minimum requirements for end-of-life dismantling, sorting, and tracing; and of tighter regulations for buildings and construction waste and for vehicle shredding.

10) Climate-neutral product labelling and eco-design requirements for embedded carbon in final products

Product labelling and eco-design requirements are a prerequisite for the creation of lead markets for low-carbon basic materials. One option is to create an EU-wide low-CO_2 product label for basic materials to allow end customers to distinguish between green and conventional products. For example, a "climate-neutrality compatibility label" for low-carbon steel could be used by car manufacturers and other leading private-sector purchasers who wish to advertise their green credentials. Another option are specific design requirements for final products via minimum requirements for embedded carbon in final products. This can help tackle the overestimation of material requirements in construction and inefficient manufacturing processes.

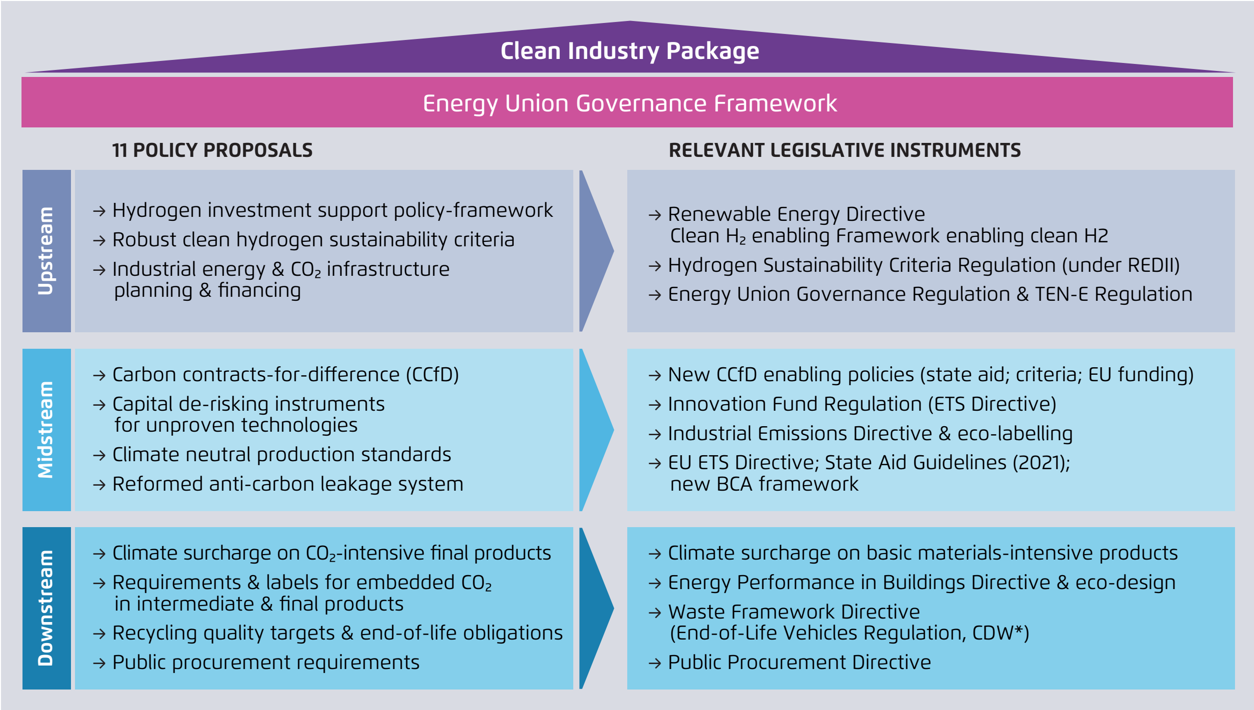
11) Green public procurement requirements for basic materials

EU public procurement legislation from 2014 already permits – but does not require – environmental criteria to be used in public procurement for the domestic market. One potential reform option is to set declining maximum CO_2 limits on specific materials that are eligible for use in public projects. A second option is to introduce mandatory life-cycle CO_2 performance criteria for assessing projects that are based on harmonised European methodology.

Figure ES.11 summarises the eleven policy recommendations and maps them onto existing EU-level legislative instruments. The figure shows that, apart from legislation for carbon contracts-for-difference and border carbon adjustment legislation, nearly all the proposed instruments can be attained with reforms to existing legislative tools.

The continuation of existing policies is not an option if EU industry is to be part of an EU Green Deal that spurs innovation and green investment while securing future-proof industrial jobs in a resilient economy. Moreover, border carbon adjustments alone will not suffice, because CO_2 prices for EU ETS are not expected to be high enough to make key low-carbon

Policies and legislative instruments to implement the Clean Industry Package — Figure ES.11



Agora Energiewende, 2020

Note: CDW stands for Construction and Demolition Waste period.

technologies economically viable. With a good deal of industrial capacity slated for replacement or refurbishment in the 2020s, European industry needs policymakers to make a strong commitment to preserving industrial production in Europe, despite higher climate ambition for 2030. This entails maintaining a business case for existing conventional assets until they reach the end of their lifetimes (see instrument 7 on carbon leakage) as well as the introduction of a framework for investment in key low-carbon technologies. The protection of existing assets will ensure that companies have the financial vitality to handle transformational challenges, while the investment framework will need to create instruments (such as carbon contracts-for-difference) as well as new product standards and markets that can support the higher operating costs of key low-carbon technologies. Together, these measures will be crucial for kick-starting industrial transformation under the EU Green Deal. In tandem with other elements of the Clean Industry Package, they will help to spur necessary investment during the coming investment cycle and beyond.

Part A: Introduction

1 The role of the basic materials industries in Europe

The basic materials industries[1] play an important role in Europe's economy. Basic materials are the foundation of essential value chains in manufacturing and construction. In 2017, the basic materials industries generated approximately 176 billion euros in value added (Eurostat, n.d.), which is about 10 per cent of total value added by the EU manufacturing industry. They directly employ approximately 1.8 million people across the EU27 (Eurostat, n.d.). However, as the starting point for multiple integrated supply chains they are also the basis for several millions of indirect jobs across diverse value chains. This data is summarised by sector in Table A.1.

The relevance of the basic materials industries to Europe's economy can also be expressed in other dimensions. Basic materials are the foundation of regional industrial clusters that provide employment in non-metropolitan regions of many EU member states and therefore support local manufacturing economies. In many of these places, the workforce consists mainly of well-trained specialists and engineers with high-incomes that support the local economy.

Basic materials will also be required in a climate-neutral future. While strategies such as a circular economy, increased resource efficiency, and new biobased materials are an important part of the solution, basic materials such as steel, aluminium, chemicals, and cement will remain essential to manufacturing and construction for the foreseeable future. In order to strengthen resilience against future

1 Table A.1 provides an overview of Europe's manufacturing industries. This study focuses only on the key sectors of the basic materials industries: steel, chemical and cement sectors. Their process- and energy-related emissions account for the largest share of greenhouse gases released by the basic materials industries. Our recommendations in this report for transforming these sectors apply to the others as well.

Direct employees and Gross Value Added (GVA) in the basic materials industries in the EU27 in 2017 — Table A.1

Sector	Employees	GVA in billions of euros
Iron and steel (NACE C24.1)	300,000	23.7
Non-ferrous metals and casting of metals (NACE C24.4 and C24.5)	402,000	27.9
Basic chemicals (NACE C20.1)	519,000	80.4
Cement (NACE C23.5.1)	47,000	5.1
Lime and plaster (NACE C23.5.2)*	16,200	1.6
Glass and ceramic (NACE C23.1 and C23.3.1)	333,000	17.8
Pulp and paper (NACE C17.1)*	166,000	19.3
Basic materials industries specified in this study	**1,783,000**	**175.7**
Industry total (manufacturing industry) (NACE C)	**26,900,000**	**1,830**

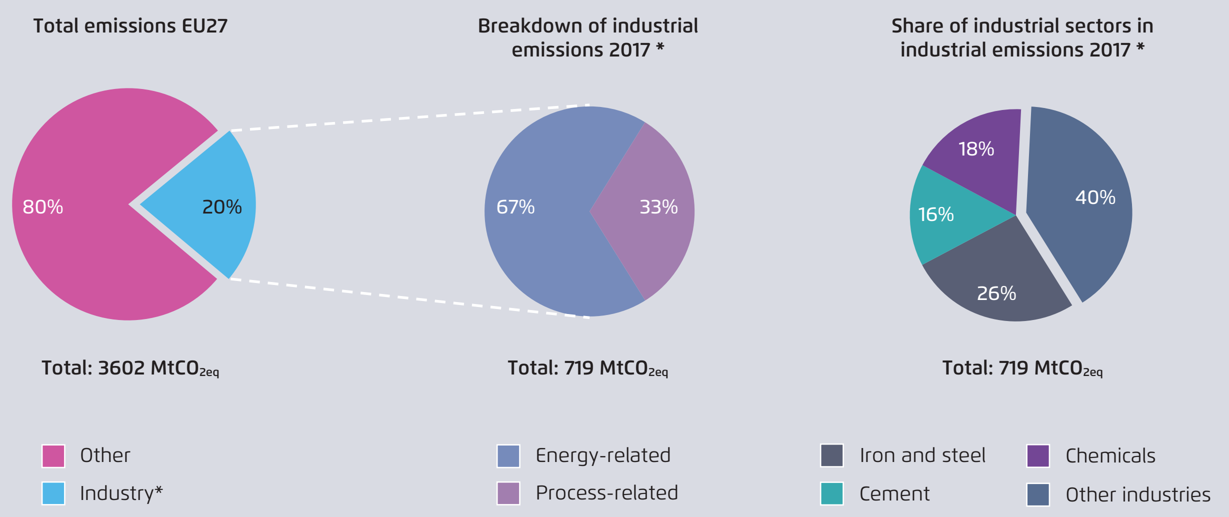
Agora Energiewende/Wuppertal Institute, 2021, based on Eurostat, 2017 — * Data for EU28 crises, it is important that the EU retains its capacity to produce basic materials for preserving integrated value chains and sovereignty.

2 The climate footprint of the manufacturing sector and the basic materials industries

In 2017, greenhouse gas (GHG) emissions in the EU27 industry totalled 719 million tonnes of CO_2 ($MtCO_2$). 481 $MtCO_2$ (or 67 per cent) were energy-related emissions, mostly from the production of electricity and heat in industrial power plants and boilers. Process-related emissions, which are generated by industrial activities such as iron-ore reduction and the calcination of limestone for the production of cement clinker, amounted to 238 $MtCO_2$ (or 33 per cent). The steel, basic chemicals, and cement sectors generate the highest volumes of CO_2 emissions, with 188, 129, and 112 $MtCO_2$ respectively. Together these sectors are responsible for 60 per cent of Europe's industrial emissions.

The GHG emissions of the basic materials industries' sectors listed in Table A.2 make up most of the EU's industrial emissions – 545 $MtCO_2$, or 76 per cent. In addition to steel, basic chemicals, and cement production this includes non-ferrous metals and foundries, other non-metallic minerals such as lime, gypsum, glass, and ceramics production as well as the production of pulp and paper.

Greenhouse gas emissions of the EU27 industrial sector in 2017 in $MtCO_{2eq}$ — Figure A.1



Agora Energiewende/Wuppertal Institute, 2021, based on EEA GHG inventory data, 2021, and E-PRTR database, n.d.

* This includes the energy-related and process-related emissions of the iron and steel industry as specified in the EEA database. In addition to that, based on our own estimates another 35 $MtCO_{2eq}$ for the production of coking coal and the power plants of the steel industry in the EU27 were added. Depending on who operates the coking plant and the power plant, these emissions are accounted under the categories 'Public Electricity and Heat production' and 'Manufacture of Solid Fuels and Other Energy Industries'. As they are directly linked to the iron and steel industry, we included them here.

GHG emissions and final energy consumption
of the basic materials industries in the EU27 and the UK in 2017

Table A.2

Sector	Direct emissions in $MtCO_{2eq}$/yr		Of which: process-related in $MtCO_{2eq}$/yr		Final energy consumption in PJ/yr	
	EU27	**UK**	**EU27**	**UK**	**EU27**	**UK**
Iron & steel*	188	13	63	3	1,131	35
Non-ferrous metals & foundries	17	1	9	0	406	27
Chemicals	129	11	62	5	2,066	140
Cement**	112	6	72	4	501	31
Other non-metallic minerals	75	3	32	2	831	69
Pulp, paper & print	23	1	-	-	1,362	76
Sectors of the basic materials industries listed here	**544**	**35**	**238**	**14**	**6,297**	**378**
Industry total (manufacturing industry)	**719**	**68**	**238**	**14**	**9,977**	**952**

Agora Energiewende/Wuppertal Institute, 2021, based on GHG emission data according to national GHG inventory data published by EEA GHG Inventory data, 2021, and own estimations; final energy consumption according to Eurostat energy balances, n.d.a, for cement according to for EU28 and the UK according to GCC Association, n.d.

* This includes the energy-related and process-related emissions of the iron and steel industry as specified in the EEA database. In addition to that, based on our own estimates another 35 $MtCO_{2eq}$ for the production of coking coal and the power plants of the steel industry in the EU27 were added. Depending on who operates the coking plant and the power plant, these emissions are accounted under the categories 'Public Electricity and Heat production' and 'Manufacture of Solid Fuels and Other Energy Industries'. As they are directly linked to the iron and steel industry, we included them here.

** Direct emissions of the cement industry were extracted from the E-PRTR database and the EEA database. Final energy consumption of the cement sector was calculated based on the GCC Association website.

3 European and international commitments to reduce emissions

In 2015, the EU became a signatory of the Paris Climate Agreement, committing itself to limit global warming to well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius. Achieving the objectives of the Paris Agreement requires industrial nations to achieve economy-wide climate neutrality by 2050 (Robiou du Pont et al., 2016).

At the EU level, the goal of domestic climate neutrality by 2050 was formally endorsed by 26 out of 27 member states in the European Council in December 2019 (European Council, 2019). This climate neutrality objective is in the process of being formalised by the European Climate Law, proposed by the European Commission in March 2020 (European Commission, 2020), but it has not yet been jointly adopted by the Parliament and Council at the time of publication. In September 2020, the Commission presented the 2030 Climate Target Plan, which aims to increase the EU's economy-wide CO_2 reduction targets from 40 per cent to at least 55 per cent by 2030 (all relative to 1990 levels). This 55 per cent reduction target was subsequently adopted by the European Council in December 2020. It is now up to the European Commission to bring forth legislative proposals to implement this 55 per cent reduction and the 2030 Climate Target Plan in 2021.

4 Industry's role in achieving the EU's new climate objectives

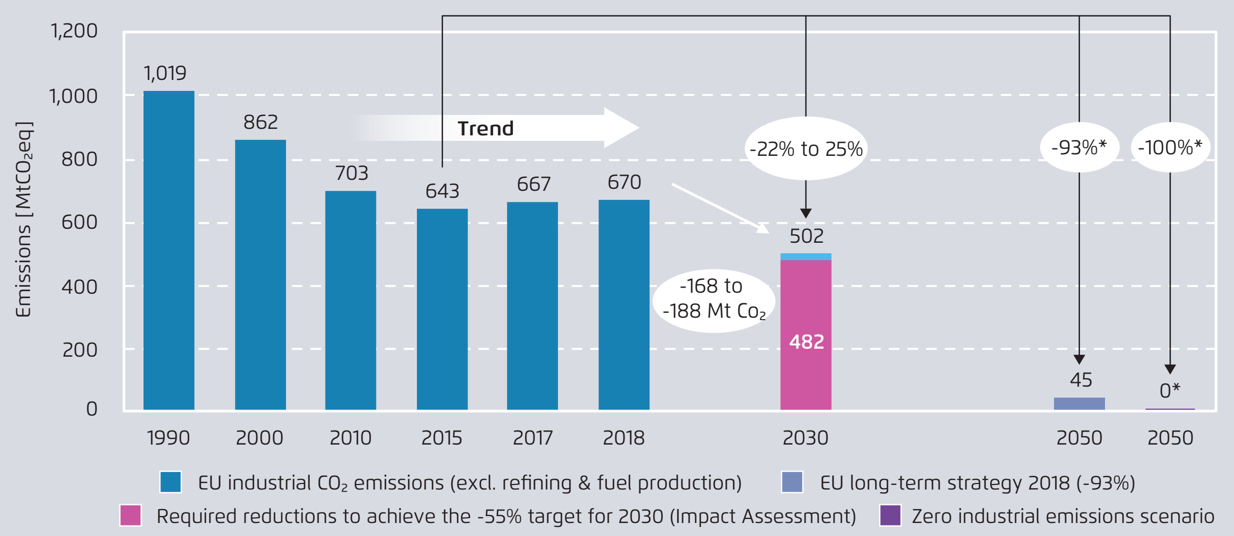
Meeting the EU's new objective of domestic climate neutrality by 2050 and a 55 per cent reduction in GHG emissions by 2030 will require swift and substantial additional efforts to decarbonise industrial processes and energy use. Studies show that climate neutrality for industry at the global level requires that, by 2060, virtually all energy-intensive industrial production will need to be based on either zero- or ultra-low-emissions technologies. Moreover, residual emissions that cannot be abated must be compensated by technologies that offer equivalent net-negative emissions (Bataille et al., 2018).

At the EU level, climate neutrality by 2050 requires the basic materials industries to reduce its GHG emissions to zero within three decades. This was illustrated starkly in the EU's strategic long-term vision for a climate neutral economy in 2050 (European Commission, 2018). It showed that, on average, energy-related emissions from industry would need to be reduced by 2050 on the order of 95 per cent. Process emissions, depending on the specific sector, would need to be reduced by 60 to 100 per cent to be consistent with economy-wide climate neutrality. Since investments in energy-intensive industrial assets tend to have operating lives of between 20 to 70 years, this requires that all investments to substitute existing or build new production capacities must use technologies that are consistent with the 2050 climate neutrality objective if stranded assets are to be avoided.

Achieving the EU's increased 2030 climate ambition will similarly require a redoubling of decarbonisation efforts. According to the Impact Assessment of the European Commission, to achieve an economy-wide 55 per cent mitigation by 2030, industrial emissions

CO_2 emitted by the EU27 industrial sector from 1990 to 2018 and proposed sector targets for 2030 and 2050

Figure A.2



Agora Energiewende, 2021, based on data from Eurostat, 2017, European Commission, 2020b & EEA, 2021

Note: Data are for CO_2 emissions only. They exclude non-CO_2 emissions from industry, from refining, solid fuel production for energy and non-energy uses.

* To achieve climate neutrality, residual emissions will have to be offset by negative emissions technologies, many of which could be developed in the industrial sector such as BECCS. By capturing and using CO_2 from other non-industry sectors, industry can provide net-negative emissions.

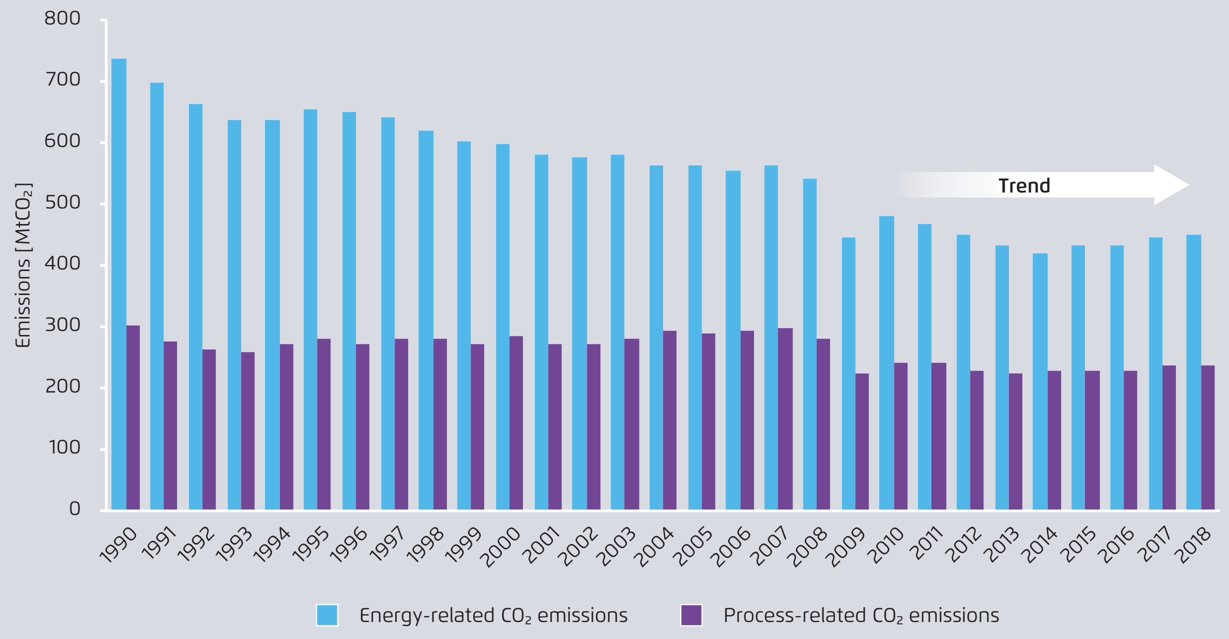
will have to be reduced by 22 to 25 per cent relative to 2015 levels (European Commission, 2020b). Since industrial emissions have been stagnant since the economic crisis of 2009, significant additional efforts will need to be made during the next decade (see Figure A.2).

A net-zero GHG emission level in many areas cannot be achieved with current technologies and production processes. For one, the potential for further improvements in energy efficiency in the steel, chemical and cement sectors is limited because most conventional technologies and processes have already reached a mature state of development.

For another, some emissions from existing production processes cannot be avoided by changing to a climate-neutral source of energy. Consider current steel production with blast furnaces, which requires coal-based coke as the reducing agent. The process emissions generated by blast furnaces are unavoidable with this production route. In cement manufacturing, most CO_2 emissions are the result of the calcination process and cannot be avoided by changing the energy source. Moreover, chemical products such as plastics are mostly made from fossil hydrocarbons today, which are released as CO_2 to the atmosphere when plastic waste is burned at the end of its lifecycle. Besides, because of the long lifetime of productive assets, future investment in conventional best available technology in Europe is at a high risk of becoming stranded in the long run. While energy efficiency will continue to be an important part of the strategy mix, addressing the stagnating levels of both energy-related and process-related emissions in the EU industrial sector will require other, transformative strategies (see Figure A.3).

For achieving climate neutrality in the basic materials industries, a comprehensive use of innovative

Historical EU27 CO_2 emissions from all industrial sources broken down by type — Figure A.3



Agora Energiewende, 2021, based on data from EEA GHG inventory data, 2021 "breakthrough" technologies and production processes – referred to in this study simply as "key low-carbon technologies" – is indispensable. The challenge for Europe is to begin deploying these technologies during the 2020s. As explained in Part D of this study, this urgency has important implications for designing appropriate policy strategies.

5 Context of the study

This study is largely based on "Climate-Neutral Industry: Key Technologies and Policy Options for Steel, Chemical and Cement." Published in German in 2019 in close cooperation with the Wuppertal Institute and supported by Navigant (Guidehouse), Becker Büttner Held (BBH), and the Institute for Climate Protection, Energy and Mobility (IKEM), it focused on the decarbonisation of the German industry. The aim of this publication is to draw on the insights of that study to discuss the decarbonisation of the European industry. General sections of the German study have been translated and slightly adapted for the European context. Other sections have been completely revised to reflect recent and specific developments of the debate on the European Green Deal, as well as the consequences of the Covid-19 crisis and the policies for economic recovery. Based on a review of the global situation, we developed a set of new policy ideas and instruments. We aggregated these in our Clean Industry Package for Europe (see Part D).

6 Parts of the study

Part B of the study highlights the challenges and opportunities of the industrial transformation to climate neutrality. It also presents the fundamental CO_2 reduction strategies for each sector, an analysis of reinvestment cycles in the EU steel, chemical and cement industries and a selection of key technologies for climate-neutral production in the basic materials industries. A detailed analysis of these key low-carbon technologies can be found in Part E.

Part C of the study discusses the necessary regulatory framework for the industrial transformation to climate neutrality. To this end, we identify a general toolbox of ten policy instruments and analyse them based on economic, legal, and political criteria. These instruments represent basic tools to forward the industrial decarbonisation and may – depending on the context – also be adapted and applied in other industrial economies.

In Part D, we apply many of the instruments that were presented in Part C to the specific context of the European policy debate. We develop a Clean Industry Package that integrates eleven policy instruments across the entire value chain for swift and coordinated implementation and describe all policy instruments and their role in greater detail.

Part E contains the study's analytical section. It presents and analyses the key technologies for climate neutrality in the steel, chemical and cement sectors. The section's fact sheets present projected production costs, respective CO_2 abatement costs, and the state of technological development. The fact sheets were created in consultation with scientists and businesses, some of whom are already operating low-carbon pilot and demonstration projects.

A publication with further information and details on the key low-carbon technologies in Part E, along with a description of ongoing pilot projects, is available as a separate online publication. The publication, carried out by the Wuppertal Institute, is titled "Detailed Presentation of Key Technologies in the Steel, Chemical and Cement Sectors".

Part B: Climate-neutral industry – opportunities, policy needs, and strategies

1 Climate neutrality as the new paradigm

2020 was the year when climate neutrality emerged as the new paradigm. Japan, South Korea, South Africa, and the EU announced net-zero greenhouse gas (GHG) emission goals by 2050. The US president-elect Joe Biden announced that the US will re-join the Paris Climate Agreement and become climate-neutral by 2050, and China, the world's largest emitter of GHG emissions, pledged carbon neutrality by 2060. This means that countries that represent around 79 per cent of the world's GDP have already pledged net-zero targets.

The long-term target of climate neutrality has direct implications for mid-term climate targets and short-term industrial policies. In December 2020, the EU submitted an updated Nationally Determined Contribution (NDC) to the United Nations Framework Convention on Climate Change reflecting the higher EU 2030 climate target of at least 55 per cent emission reduction relative to the previous 2030 reduction target of 40 per cent emission reduction against a 1990 baseline. In the run-up to the COP26 in Glasgow in December 2021, other countries are likely to follow suit and increase their respective 2030 climate targets to prepare for climate neutrality by mid-century.

This unprecedented paradigm shift will have major consequences for the basic materials industries. But what is the status quo and what are the opportunities associated with this paradigm shift? And what are the policy needs and strategies to achieve a climate-neutral industry in Europe? Some of these points will be discussed in the following section.

2 European industry at the crossroads

Large parts of Europe's basic materials industries are at the crossroads. By 2030 roughly 48 per cent of primary steel capacity, 53 per cent of steam cracker capacity, and an estimated 30 per cent of cement production capacity will reach end of their operating lifetimes (see Figure B.1).

Due to the long operational lifetimes of industrial assets, the decisions on reinvesting these production capacities will have a massive impact on hundreds of thousands of jobs, the EU's long-term economic resilience and import dependency, as well as its pathway to climate neutrality.

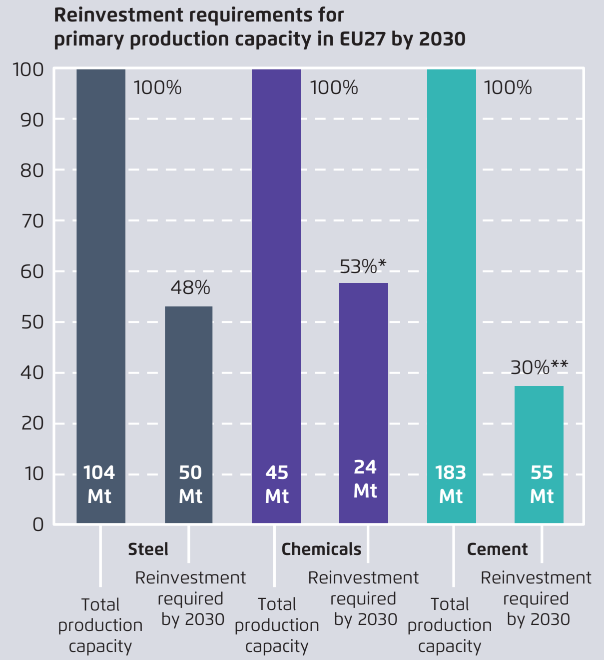
Given the EU's target of achieving climate neutrality by 2050 and a 55 per cent reduction of GHG emissions by 2030 it is evident that all major industrial investments going forward must use technologies that can operate with zero- or net-negative carbon emissions if stranded assets (i.e. the premature shutdown of well-functioning plants) and high economic losses are to be avoided. It goes without saying that this applies not only to the EU, but to all economies that envision net-zero emission targets by mid-century.

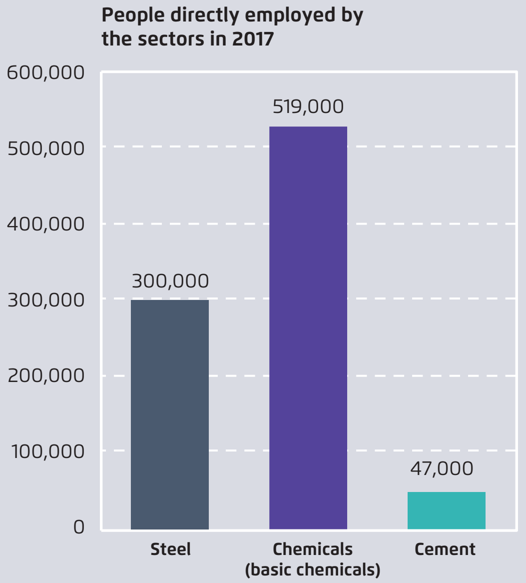
However, because a range of conditions need to be put in place along the industrial value chain to make them viable, an adequate regulatory framework is needed to foster investments with key low-carbon and circular economy technologies. To ensure that this framework is effective and efficient the respective policies should be included in a single Clean Industry Package (see Part D).

In absence of such a regulatory framework, the EU basic materials industries will remain in limbo:

Reinvestment needs by 2030 and direct employment in cement, steel and basic chemicals in the EU

Figure B.1





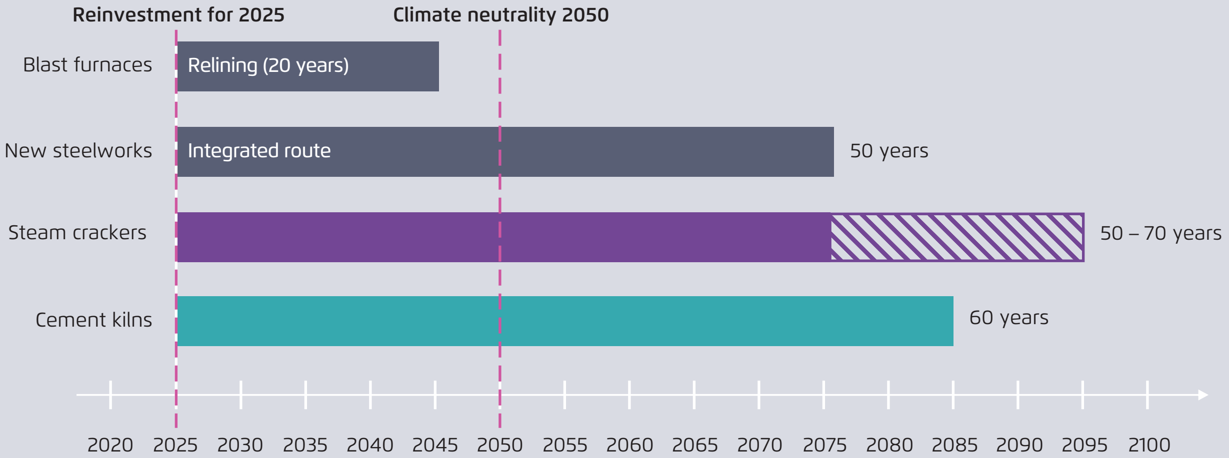
Agora Energiewende/Wuppertal Institute, 2020

* Steam crackers are normally maintained and modernised continuously so that they do not have to be replaced all at once. Nevertheless, the graph provides a rough estimate of the reinvestment needs for existing facilities.

** Cement data represent numbers for Germany only. We estimate that the reinvestment requirements for the EU27 are in a similar range.

Technical lifetime of selected primary production plants in the steel, chemical, and cement sectors scheduled to receive reinvestment in 2025

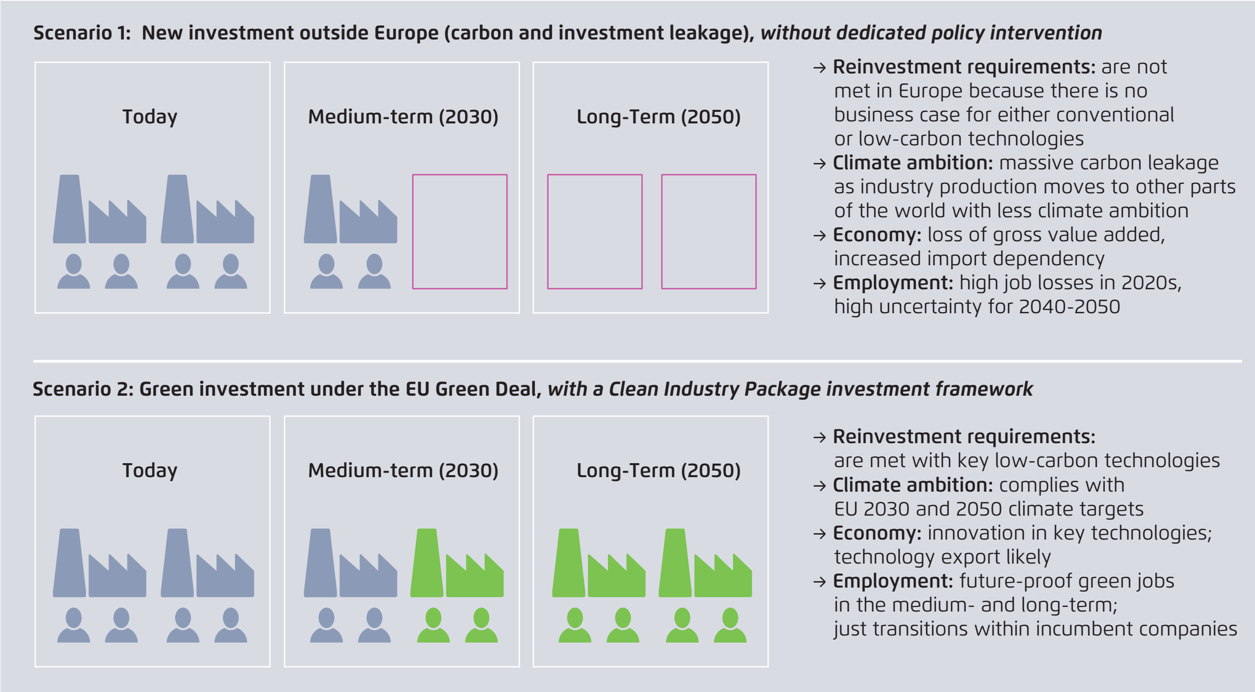
Figure B.2



Agora Energiewende/Wuppertal Institute, 2020

Two scenarios for new investment in the 2020s and their implications for climate change, the economy, and employment in the EU

Figure B.3



Agora Energiewende, 2020

currently, there's no viable business case for investment in key low-carbon technologies. At the same time, investing in conventional technologies with a level of GHG emissions that cannot be abated risks creating stranded assets under increasingly stringent GHG abatement targets and carbon prices. This difficult investment environment is aggravated by the negative economic effects of the corona pandemic.

An EU regulatory framework that fosters investments in key low-carbon technologies before 2030 would provide a major opportunity to maintain current production levels and safeguard several hundred thousand jobs while meeting the requirements of the more ambitious 2030 climate target. Moreover, such an EU regulatory framework would allow EU industry to position itself in a growing market for key low-carbon technologies and carbon-neutral products in other regions of the world.

3 Opportunities and benefits of a climate-neutral European industry

An ambitious decarbonisation strategy for basic materials industries would make an important contribution to achieving Europe's climate targets and provide an opportunity to lead the global transformation of the industrial sector during the coming, decisive decade.

3.1 Promoting a just transition and securing future-proof jobs

As described above, European industry is in a somewhat difficult situation of investment uncertainty. As a result, companies may exhaust existing assets until they are forced to shut down, endangering European production, jobs, and the integrity of supply chains. This risk is amplified by the adverse economic context in which several basic materials industries find themselves. For example, the eco-

Overview of the main opportunities of transforming the basic materials industries	Table B.1
Promoting a just transition and securing future-proof jobs	
Economic resilience and resource efficiency	
Developing critical infrastructure is the key to industrial transformation and competitiveness	
Technological leadership is the key to future markets	
Setting examples and standards can catalyse global climate ambition	
Rising demand for imported green energy can transform energy-exporting countries	

Agora Energiewende, 2021

nomic shock that resulted from the Covid-19 crisis, the threat of international dumping from excessive production capacities, and stagnant demand in mature European markets all add to these risks.

But an adequate regulatory framework to decarbonise the basic materials industries offers an opportunity to respond to these challenges by providing much of the missing regulatory certainty. By providing a robust enabling environment for investment in low-carbon alternatives, the EU has a chance to foster economic activity, innovation, and productivity and by extension to secure jobs and production in the EU. Furthermore, by reinforcing its anti-carbon leakage framework, the EU can limit the incentives for firms to offshore production of certain basic materials due to climate policy differences, further reinforcing the investment case in Europe.

With regards to the importance of a *just transition*, the starting point for industries is different from other sectors. The transformation of the basic materials industry is likely to happen *within* incumbent companies. The development and implementation of key low-carbon technologies are capital-intensive and have synergetic effects with existing industrial clusters, a fact that provides a potential advantage to existing companies. With the right regulatory framework in place, both production and jobs can be maintained on many of the existing production sites, making a just transition much easier.

3.2 Economic resilience and resource efficiency

The transition to a climate-neutral industry offers an opportunity for Europe to benefit from a more resource-efficient and circular economy. One way in which this can happen is by reducing the level of waste and pollution from the end-of-life disposal of industrial products. For example, Europe currently recycles only around 30 per cent of its annual consumption of plastics, with large amounts being either incinerated, landfilled, or released to the environment and waterways in the form of plastic litter and micro-plastic pollution (European Parliament, 2018). Similarly, construction waste, much of which consists of used concrete – containing CO_2-intensive cement – as well as steel and other energy-intensive basic materials accounted for approximately 35 per cent of all European waste production by volume in 2016 (Eurostat, 2018). While the EU has set a target for a minimum of 70 per cent of construction waste to be recovered for recycling or incineration by 2020, a large share of this waste currently is either dumped or finds its way into landfill. Moreover, recycled construction waste is currently used for low value usages such as concrete aggregate, backfill, road base, or riprap and therefore does not facilitate a reduction of the various resources needed to produce new primary construction materials (Deloitte, 2017).

In the case of steel, as much as 25 to 30 per cent of new primary steel is lost as scrap during manufacturing processes, resulting in a significant waste of primary raw materials and increased energy demand for recycling (Material Economics, 2018). Furthermore, downcycling due to metals contamination during the product lifecycle tends to reduce the degree to which new virgin material can be substituted by recycled materials, thus limiting overall secondary to primary material production ratios. But there is much potential to reduce these phenomena (see Section B5.5 and B5.6). By increasing resource efficiency and by enhancing the quality and quantity of recycling, a climate-neutral industrial sector can reduce pollution and the strain on primary material resources. A more resource-efficient and circular economy also has the potential to reduce the dependency of the European economy on imports of increasingly scarce raw materials (European Commission, 2020c).

3.3 Developing critical infrastructure is the key to industrial transformation and competitiveness

An early implementation of critical infrastructure projects for a climate-neutral basic materials industry and a credible long-term plan for their expansion can bring a substantial advantage for Europe as a future industrial production site. It is critical to transform existing industrial networks in a way that builds on the synergies that define the competitiveness of today's productive clusters. The smart transformation and expansion of infrastructure could ensure the transformation of existing production sites and attract new producers that have synergies with climate-neutral basic materials industries and their downstream businesses.

For example, if the European steel industry can be certain of sufficient and cost-competitive hydrogen supply, it will be able to transform its production sites with reactors for the hydrogen-based direct reduction of iron. Likewise, the investment in CO_2-capture equipment by the cement industry will depend on the availability of reliable infrastructure for the transport and storage of CO_2.

Hence, the development and planning of critical infrastructure for a climate-neutral basic materials industry is urgently needed to transform Europe's strategic industrial sites (Lechtenböhmer et al., 2019).

3.4 Technological leadership is the key to future markets

An early adoption of key low-carbon technologies necessary for climate neutrality would allow the European industry to define standards and position itself as a global market leader. With net-zero pledges as the new paradigm in nearly all major economies, it is likely that there will be increasing demand and competition for their development and use. The European basic materials and equipment industries must not miss that opportunity to get a head start by achieving early cost reductions and competitive advantages.

An early adoption of low-carbon technologies would offer particularly important opportunities for the machine and equipment industry. As many of the key low-carbon technologies are currently being developed in Europe, their adoption and upscaling before 2030 would drastically increase the likelihood that the European industry will supply these technologies to expanding global markets, providing domestic value creation and many quality jobs.

3.5 Setting examples and standards can catalyse global climate ambition

The development of policies that drive the large-scale deployment of key technologies in Europe can establish technology and policy pathways for the rest of the world to follow. With climate neutrality emerging as the new paradigm, many countries will be looking for best practice examples regarding the technical application and integration of low-carbon technologies, as well as appropriate policies to create an investment case for their implementation.

Although the share of Europe's industry in global emissions is only around 12 per cent (IEA, 2018), its leadership in the use of key low-carbon technologies could catalyse climate mitigation activities in other economies that far exceed the EU's own emission reduction potential. Europe's leadership with the early development and scaling of renewable energy technologies has demonstrated its capacity to trigger transformational developments in other regions of the world.

Early investment – in commercial plants as well as in pilot and demonstration projects – will bring experience with new technologies and achieve cost-reducing effects. This will reduce the investment and operating costs for building similar plants abroad, making it more likely that other countries and regions will quickly follow suit. The EU can also accelerate the global transition by helping to kick-start global markets and supply chains for vital inputs for industrial decarbonisation, such as green hydrogen, low-carbon basic chemicals (such as green ammonia or green methanol), or higher quality scrap for higher value recycled materials. Furthermore, by defining a credible pathway to phasing out conventional, CO_2-intensive industrial products in its large, domestic market, the EU can help drive global supply chains away from the most CO_2-intensive products. After all, foreign producers will want to ensure that they do not lose access to the European market.

3.6 Rising demand for imported green energy can transform energy-exporting countries

Climate-neutral basic materials industries will have to cover part of their energy demand with imported renewable electricity, clean hydrogen, and climate-neutral synthetic fuels. An early transformation of Europe's basic materials industries is key to developing partnerships with countries that can supply such renewable energy and climate-neutral energy carriers and help build sustainable business models and partnerships with companies abroad. Such pioneering projects can stimulate the creation of a world market for climate-neutral fuels over the next decades and facilitate the global transformation in the industrial and energy sectors (Schmidt et al., 2019). Many regions that could supply Europe with climate-neutral fuels are still economically dependent on the export of fossil fuels. New demand for climate-neutral fuels can provide them with a stimulus to transform their own economies.

3.7 Section conclusion

While the transition to climate neutral industry is essential for Europe to meet its overarching climate objectives for 2030 and 2050, it also offers several potential co-benefits:

→ enabling reinvestment decisions in line with climate neutrality will protect European industrial value chains and hundreds of thousands of related jobs;
→ transforming existing industrial clusters and energy systems will ensure competitiveness in a climate-neutral global economy;
→ reducing dependency on scarce and strategic materials through greater materials efficiency and circularity will increase economic resilience;
→ exploiting the need for massive reinvestment in strategic infrastructure will support the post-Covid-19 economic recovery;
→ developing technological solutions and setting standards for climate neutral production will transform international markets and catalyse higher climate ambition in other economies; and
→ demand for the import of climate-neutral energy and fuels will support the transformation of other countries and their businesses.

To exploit the opportunities that this transition presents, however, a new policy framework is needed that addresses the numerous enabling conditions discussed in Section B4 below. Part D of this document proposes a new framework and new policies that rise to these challenges.

4 Policy is needed to decarbonise Europe’s basic materials industries

There are feasible mitigation strategies (Section B5) and technologies (Part E) for the transformation of Europe’s basic materials industries. But some gaps need filling before Europe can initiate an industrial transformation to climate neutrality. In this Section, we discuss the main policy fields that need to be addressed by the EU, before moving on to examine the necessary mitigation strategies.

4.1 Policy is needed to address the upcoming reinvestment cycle

As described in Section B2, the definition of an appropriate investment environment for the deployment of key low-carbon technologies is urgent because many existing plants will soon require renovation or replacement. This is a pressing problem because the lifespans of conventional production units, once implemented, can be anywhere from 20 to 70 years (Rootzén/Johnsson, 2013). This means that, in general, major investments or reinvestments made during the 2020s will shape the productive capital stock through 2050 and possibly beyond.

The risks associated with a business-as-usual approach are well-known: companies are aware that climate constraints are becoming more stringent in the EU over time. However, if they do not have a sufficiently credible and supportive policy framework to take the risk of (re-)investing in climate-neutral key low-carbon technologies, they will tend to put off these decisions. They may prefer to operate existing assets as long as they are profitable and shut them down when required by law or when carbon prices are too high. In a worst-case scenario an increasing number of sites would close rather than become low-carbon production alternatives. This would break Europe’s integrated value chains, increase the import of carbon-intensive products, and result in permanent job losses. Europe currently employs 870,000 people in the energy-intensive cement, steel, and basic chemicals industries. It is therefore imperative that the EU and its member states develop a synergetic and effective policy framework so that energy-intensive sectors are able to plan and implement investments in innovative, climate-neutral production processes and products.

4.2 Innovative key low-carbon technologies must be brought to scale

Many of the technologies needed to transform the basic materials industries to climate neutrality, such as hydrogen-based steelmaking, electrified steam crackers, or cement kilns with CO_2 capture and

Key policy needs to decarbonise Europe’s basic materials industries — Table B.2

Policy must address the upcoming reinvestment cycle
Innovative key low-carbon technologies must be brought to scale
Climate-neutral industrial projects require support and the creation of lead markets
Green energy supply is key
Infrastructure must support climate neutrality
Circularity and material efficiency
A robust solution to the problem of carbon leakage is required

Agora Energiewende, 2021

storage facilities, are not fully mature or have yet to be proven on a commercial scale. These technologies are at different stages of development and thus require different forms of policy support.

First, for technologies that are ready for commercial scale investments, but lack sufficient track record, residual technological uncertainties represent an additional risk that is difficult to calculate for investors, increasing the challenge of financing such investments. Policymakers can address this problem with risk-mitigation instruments, such as public co-financing, loan guarantees, and support for large-scale demonstration plants (see Part D, De-risking instruments for unproven technologies).

Second, because important key technologies still need to be developed at sufficient scale and the amount of emission-free electricity and hydrogen is limited, bridging technologies can make sense to avoid reinvestment in emission-intensive plants and processes with long lifespans. For example, primary steel manufacturers could start to build plants for the production of direct reduced iron (DRI) to replace blast furnaces instead of extending their operational lifetime.[1] Initially, these plants could run on natural gas. Later, natural gas could be replaced by increasing volumes of clean hydrogen without the need for retrofitting the DRI production facility (see Part E, Steel). With this two-step process, DRI plants can be an anchor for the development of hydrogen production and transport facilities. Similarly, in the chemical sector, power-to-heat could quickly complement widespread natural gas-based heating facilities in a transition phase before they become the only unit for heat production (see Part E, Chemicals). However, a key challenge for policymakers and companies will be to sort out which intermediate solutions are genuinely compatible with climate neutrality in the long run and which ones are not. Moreover, it is important to pursue an efficient ramp up of the deployment of key-low carbon technologies to support the gradual process of developing the necessary technologies and the supporting infrastructure for the generation and transport of renewables and hydrogen, as well as the transport and storage of CO_2.

An important aspect of this evaluation is the question how the implementation and operation of key low-carbon technologies will reduce and shift GHG emissions along the value chain. The electrification of heat or the procurement of hydrogen, for example, will reduce direct emissions (so-called scope 1 emissions) of an operation, but may increase emissions at the level of electricity and hydrogen production (so-called scope 2 emissions). Moreover, the changes in the value chain will affect the CO_2 intensity of raw-materials and products (the so-called scope 3 emissions), a dimension that will affect the definition of lead markets for CO_2-efficient or climate-neutral products[2]. New standards for accounting are needed to capture these effects and define technologies, strategies and arrangements that are effective for GHG abatement in the short, and compatible with climate-neutrality in the long term (see climate-neutral production standards, Part D).

4.3 Climate-neutral industrial projects require support and the creation of lead markets

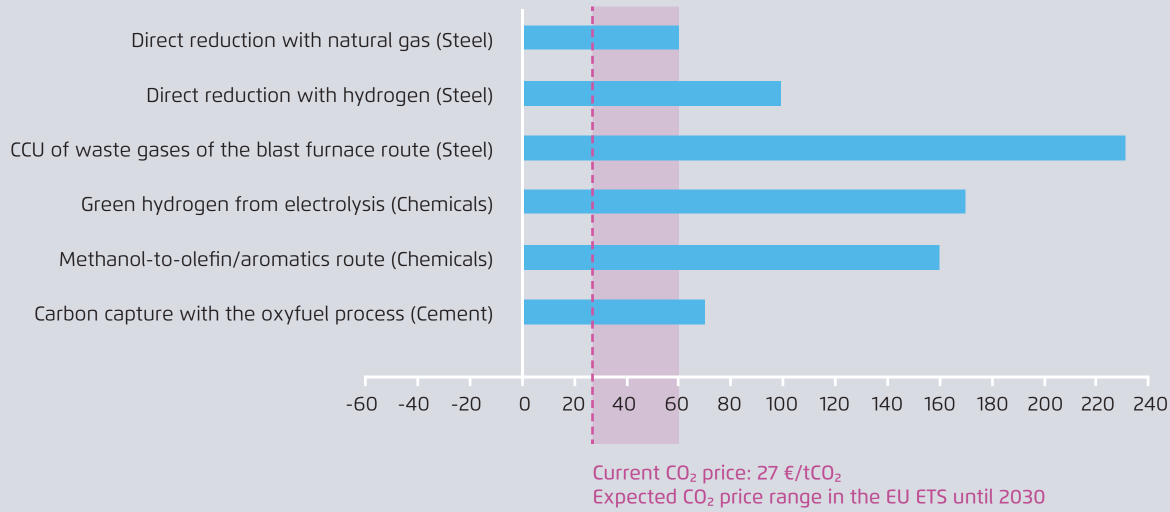
The climate-neutral production of basic materials is more expensive than current, emission-intensive processes. This is illustrated below by Figure B.4, which compares the competitiveness of key low-carbon technologies to conventional technologies. It shows the level of the CO_2 price that is needed to

1 This process is described in more detail in Part E.

2 According to the definition of the GHG Protocol, a company's GHG emissions are classified in three scopes. Scope 1 accounts for direct emissions from sources that are owned or controlled by a company, such as emissions related to productive processes. Scope 2 accounts for indirect emissions from electricity, heat, or steam purchased and used by the company. Scope 3 accounts for other indirect emissions (not included in Scope 2) that occur upstream or downstream of the value chain of a reporting company. This scope includes emissions embedded in services, raw materials and feedstock, as well as the final products delivered to the client.

Estimated CO_2 abatement costs of selected key low-carbon technologies versus today's conventional reference process for 2030

Figure B.4



Agora Energiewende/Wuppertal Institute, 2020

Note: CO_2 abatement costs depend very much on assumptions about electricity costs. For the calculation of these values, electricity costs of 60 euros per MWh were usually assumed. The estimates here are based on Agora Energiewende/Wuppertal Institut, 2019, and represent the lower bound of CO_2 abatement costs in 2030. Higher CO_2 abatement costs are to be expected before 2030 than after 2030 because the technologies must still undergo learning curves for cost reductions.

equalize costs between the respective technologies. Carbon prices of between 60 and 231 €/tCO_2 are generally needed to make these technologies competitive.[3]

By contrast, EU ETS carbon prices today are in the range of 25–35 €/tCO_2. While carbon prices are expected to rise in the coming decade in line with the EU 2030 climate target of -55 per cent, it is unlikely that they will increase to the level that is needed to make key low-carbon technologies competitive in the short term. For instance, in the scenarios that modelled a -55 per cent EU 2030 climate target, the European Commission's Impact Assessment[4] is foreseeing carbon prices from 50 to 60 €/tCO_2 by 2030 (European Commission, 2020b).

These facts, along with the high intensity of domestic and international competition in markets for basic materials, limit the potential of so-called first-mover strategies in the basic materials industries. Businesses that wish to secure long-term cost and scale advantages with an early introduction of key climate-friendly technologies have little leeway due to the intense competition and because the higher production costs of climate neutrality would drive them out of business in the short term. This needs to be addressed by adequate support policies (see Part C, Carbon contracts-for-difference).

At the same time, the government should actively push for the creation of lead markets for green basic materials. This would ensure a differentiation between clean and dirty end products, putting pressure on old technologies to be phased out of

3 Further details on the expected costs in 2030 and 2050 of the relevant technologies are summarised in Part E of this document.

4 The Impact Assessment accompanied the 2030 Climate Target Plan Communication.

future investments. Besides, it would leverage private- and public-sector willingness to pay for greener products and thus stimulate the deployment of a fuller portfolio of solutions and create the basis for scaling up key technologies beyond subsidisation in the longer term.

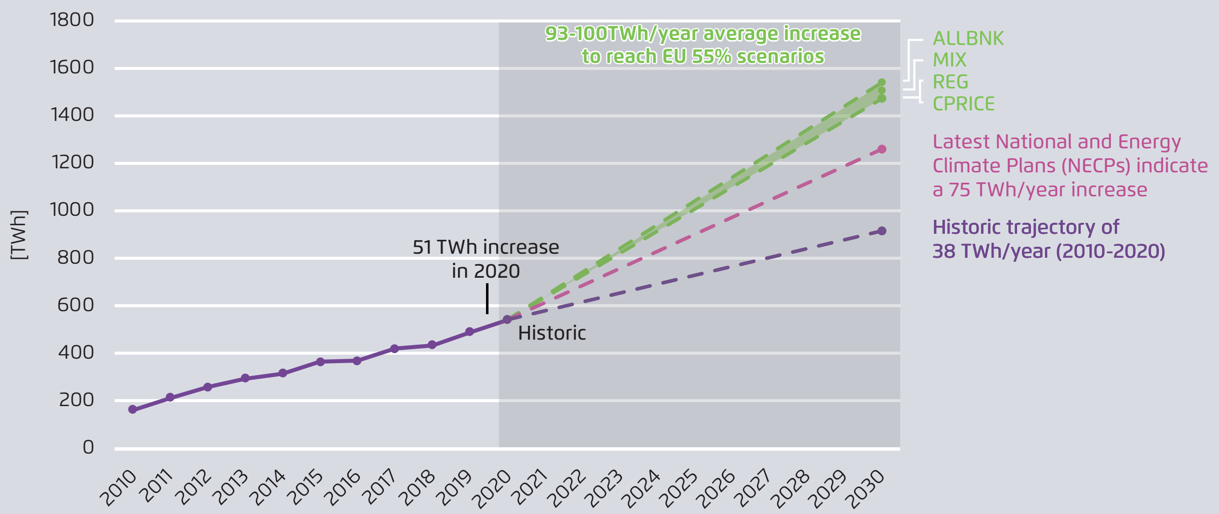
To sum up, the right mix of policy instruments is required to compensate investors for higher production costs and to create policy incentives that foster the demand and willingness-to-pay for climate-neutral basic materials and subsequent products. Possible policy instruments are discussed extensively in Part C. In Part D, we develop specific policy recommendations.

4.4 Large amounts of green energy will be required

For many of the necessary low-carbon technologies, fossil fuels must be replaced with renewable electricity or hydrogen. To establish climate-neutral basic materials industries, these alternative energy sources must be produced by low-carbon processes with an eye to near-zero emissions in the future. The use of new technologies will increase electricity demand in various ways. One example is the switch from natural gas-based steam production to electric devices such as electrode boilers, high-temperature heat pumps, and other power-to-heat technologies (see Part E). Another example is the move from blast furnaces to direct reduction facilities (DRI plants) operated with green hydrogen in steelmaking.

The success of the transformation of the basic materials industry and other sectors hinges on the future availability of affordable green electricity and hydrogen. Among other things, this requires a significant increase in Europe's renewable electricity production capacity in the coming years and decades. According to the 2030 scenarios from the European Commission (2020b), power generation from wind and solar will have to triple during the coming decade relative to the last decade to achieve an EU 2030 climate target of -55 per cent (see Figure B.5).

Wind and solar growth must almost triple to reach EU climate target — Figure B.5



Agora Energiewende, 2021, based on Ember, 2021 and 2030 scenarios from European Commission's Impact Assessment for 55% GHG cuts under Europe's Green Deal

At the same time, ambitious climate scenarios indicate that a portion of the electricity produced from renewable energy will be imported directly or indirectly in the form of hydrogen or synthetic fuels from regions with larger and more cost-effective renewable energy resources (Schmidt et al., 2019; Lechtenböhmer et al., 2019). In order to secure suitable import levels starting in the 2030s, it makes sense to develop strategic partnerships at an early stage with potential producing regions (e.g. North Africa, the Near East, South America, Australia) so that infrastructure and production plants can be built in time.

4.5 Infrastructure must support climate neutrality

A main challenge in transforming the basic materials industry is the need to build specific infrastructure to support key low-carbon technologies (Wuppertal Institute, 2018). The requirements differ depending on the technology and GHG abatement strategy:

- → New technologies that use large quantities of direct electricity (e.g. electrode boilers, electrical steam crackers, and electric arc furnaces in steel production) will require improvements in Europe's continental transmission infrastructure as well as local distribution networks, in addition to sufficient quantities of climate-neutral electricity.
- → Technologies that require large quantities of hydrogen (e.g. hydrogen-based steel production and ammonia synthesis) depend on pipeline infrastructure that transports large amounts of hydrogen from areas of favourable production to demand centres.[5]
- → Technologies based on CO_2 capture and storage (for cement kilns and BECCS[6] activities in steelmaking and the chemical industry) require infrastructure to transport the CO_2 to suitable storage facilities. This infrastructure can consist of pipelines or ships for the transport of CO_2 to marine storage locations.

Generally, there are long delays between the planning and completion of large infrastructure projects. Hence, policymakers need to start to assess and plan for the requirements early on. Infrastructure projects must begin soon, but parts of this infrastructure can be realised only with international cooperation. Already now, agreements with European and non-European partner countries (both supplier countries for carbon-free energy or offtake countries for CO_2) are needed. Without enough certainty that the required infrastructure will be available in time, investors will not invest in the key low-carbon technologies that are required for climate neutrality. Moreover, it is important to include different social groups during the planning stages to avoid potential conflicts when building the infrastructure.

4.6 Circularity and material efficiency

In light of the significant challenges of developing sufficiently large-scale renewable energy, CO_2 storage, and transport infrastructure, strategies are needed to simplify the decarbonisation of energy-intensive industries and reduce its costs. The easiest way to do this is to create a more resource-efficient and circular economy. Fortunately, the economy has much potential for adding more resource efficiency and material circularity. An influential study by Material Economics (2018) suggests that by 2050 as much as 54 per cent of the required emissions abatement effort from the steel, plastics, and cement and concrete sectors can be delivered by circular economy measures alone. As we explain in Section B5, there are numerous technical pathways for enhancing resource efficiency, material substitution, and material recirculation (enhancing the quality and quantity of recycled materials). While these strategies do not obviate the need for new, climate-neutral primary production technologies, they provide an important supplement.

5 Alternatively, it might also be possible to produce the hydrogen on-site where it is needed. In that case, however, large amounts of electricity would have to be transported, requiring increased capacity in the transmission grids.

6 BECCS stands for "bioenergy with carbon capture and storage".

A key objective for policymakers, therefore, must be to develop policy packages that unlock the full range of potential drivers of industrial decarbonisation. While carbon pricing is a fundamental element, it alone is not sufficient. Complementary policy packages must be designed. A coherent enabling environment with targeted incentives is needed to bring together resource-efficient and circular production, decarbonised primary production, key low-carbon technologies, and the competition between materials based on their embedded carbon content. These incentives are discussed in detail in Parts C and D of this study.

4.7 A robust solution to carbon leakage

In addition to competition from conventional high-carbon technologies at the local level, large parts of the basic materials industries also face intense international competition from outside the EU. This is particularly true of the chemical industry and (to a somewhat lesser extent) the steel industry. Chemical products are standardised and have relatively low transport costs, so global competition is fierce. However, the steel and non-ferrous metals sectors are also characterised by commodity products that are heavily traded in liquid international markets.

As energy and GHG emissions are significant cost drivers for these industries, the resulting competitive pressure poses specific challenges to implementing ambitious climate policies. The risk that EU producers might lose market share to CO_2-intensive foreign competition, or even migrate to locations with less strict climate mitigation policies, is often referred to as "carbon leakage". As we elaborate on in Part D, Europe currently has sector-specific policies in place to address carbon leakage. However, these policies are not sustainable and the current policy frameworks leave significant additional uncertainty surrounding the economic viability of long-lived investments in carbon-neutral assets. A critical part of a robust enabling framework for investments in climate-neutral industrial products and processes is to reform the current anti-leakage system, so that it can better protect against carbon leakage risks for existing and new climate-neutral assets. Part D of this study highlights a range of solutions that can be adopted to address this specific challenge.

4.8 Section conclusion

Putting Europe's basic materials industries on a pathway to climate neutrality by 2050 presents a range of policy challenges:

- → addressing the urgency of deploying innovative key low-carbon technologies during the upcoming investment cycle;
- → accelerating the development and broadening the portfolio of innovative key low-carbon solutions;
- → creating new financial support mechanisms for commercial-scale production with key low-carbon technologies, which are more expensive than conventional technologies;
- → de-risking capital investment in first-of-a-kind technology projects through appropriate financial instruments;
- → scaling up green electricity production to match the increased industrial demand for direct and indirect electrification;
- → developing relevant strategic infrastructure for electricity, hydrogen, and CO_2 transport and storage;
- → developing incentives for industries to pursue increased use of circular basic materials in combination with a decarbonised primary production, while developing other innovative low-carbon materials;
- → creating product design incentives to use materials – and especially CO_2-intensive materials – more efficiently in products; and
- → developing robust and sustainable solutions to carbon leakage, i.e. the risk that clean EU production will be undercut by more carbon-intensive, but cheaper, international competition.

In the aggregate, these policy needs represent the core enabling conditions that are needed to spur meaningful changes in business strategies and the implementation of investment projects in decarbonised processes and products. They therefore need to be addressed by a broad policy package, and cooperatively by both European and national decision-makers.

5 Strategies to decarbonise the European basic materials industries

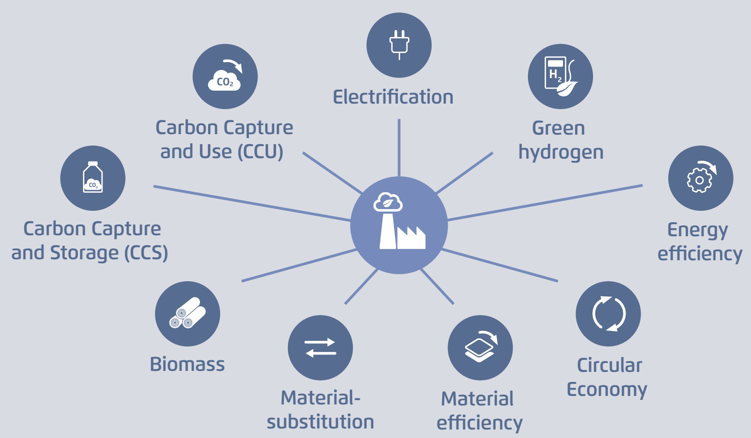
A set of strategies is required for transforming the basic materials industries to climate neutrality. Given the specific needs of different sectors, a combination of all of these strategies will be needed (see Figure B.6).

5.1 Electrification

Electrification requires the replacement of fossil fuels with electricity. As long as this electricity comes from zero-carbon or low-carbon sources, CO_2 emissions can be significantly reduced or completely eliminated. Due to decreasing costs for new renewable energy generation and the high potential for expansion – both in Europe and everywhere else in the world – electrification is of great importance for all final energy sectors.

Discussions of electrification are taking place primarily in the transport sector (electric vehicles) and in building heating (heat pumps). But electrification also has considerable potential for reducing CO_2 in the industrial sector (Lechtenböhmer et al., 2016; Schneider et al., 2018). Many sectors, especially the chemical industry, can replace much of the fossil fuel used for low- to high-temperature processes with power-to-heat technologies such as high-temperature heat pumps and electrode boilers. In the future, special solutions could be used to meet the high-temperature requirements of steam crackers, basic chemicals, and electricity-based cement manufacturing. The advantages of an electrification strategy in the basic materials industry includes the high overall energy efficiency of power-to-heat plants. This is particularly true of high-temperature heat pumps that use waste heat. Other power-to-heat technologies have high levels of energy efficiency and are more efficient than hydrogen (whose production is associated with conversion losses). The use of electricity in some applications allows a more precise provision of heat compared with combustion processes and can also contribute to efficiency gains. Moreover, because electrical and electrode boilers have fairly low investment costs, they can initially be deployed at relatively low costs, including for hybrid use, i.e. alongside existing conventional plants such as CHP plants in the chemical industry. This would

Strategies for transitioning to a climate-neutral industry — Figure B.6



Agora Energiewende, 2021

facilitate the introduction of these technologies and provides demand-side flexibility for the power system to integrate fluctuating output from renewables. The fundamental technological challenge of a widespread electrification is its significant demand for zero-carbon electricity, which requires a rapid expansion of renewable-energy capacity. In the medium to long run, however, direct electrification can reduce the demand for more electro-intensive energy carriers, such as hydrogen and e-fuels.

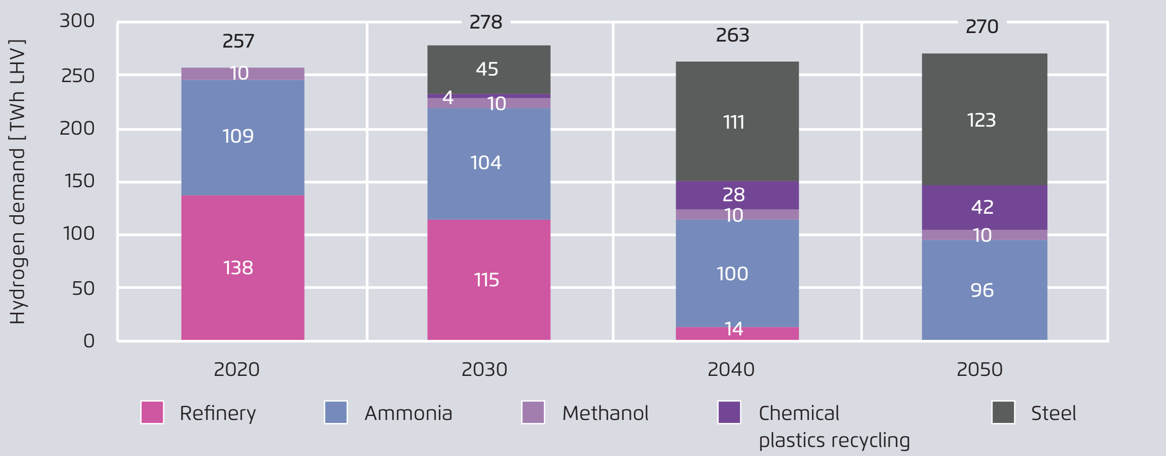
5.2 Green hydrogen

GHG-neutral hydrogen will play a significant role in supporting climate-neutral basic materials industries (Lechtenböhmer et al., 2019). The use of green hydrogen for the production of heat can be sensible or even necessary even though certain production processes are less efficient than the direct use of electricity. This applies to hydrogen-based steel production with plants for the production of direct reduced iron. Furthermore, hydrogen is needed in large quantities as a feedstock in the chemical industry in order, say, to produce ammonia.

One advantage of the hydrogen strategy is its flexibility. Hydrogen can first be produced within Europe, but as demand rises in the medium to long term it can also be imported. As long as there is public acceptance, blue hydrogen can be produced from natural gas using CO_2 capture and storage.[7] Installations to produce direct reduced iron are attractive because they can be built relatively quickly to replace older blast furnaces. Moreover, they can initially be operated with a high proportion of natural gas until sufficient quantities of hydrogen become available. The foreseeable demand for hydrogen in the basic materials industries incentivises investment in hydrogen production and the necessary infrastructure, and could help other sectors, especially shipping and aviation to reduce their emissions as well. An appropriate hydrogen infrastructure could also make the stabilisation of electrical production easier and cheaper (LBST, 2019). For example, electrolysis

7 Methane pyrolysis represents another approach to climate-friendly hydrogen production. This process manufactures hydrogen (H_2) and solid carbon (C) from methane (CH_4).

Estimated industrial hydrogen demand for the EU steel and chemicals industry — Figure B.7



AFRY, 2021

Note:The hydrogen demand for each process was based on the hydrogen required per ton of commodity coupled with a commodity demand projection based on Material Economics, 2019. For ammonia, a decrease in production due to more efficient use of fertilisers in agriculture was assumed. For steel, it was assumed that there are no reinvestments into coal-based blast furnaces from 2023 on and that 50 per cent of steel production would be met by direct reduced iron. Besides, it was assumed that refineries will be phased-out by 2050.

companies in northern Europe could buy large amounts of electricity from wind power and then transport the hydrogen to the basic materials industry.

There are several obstacles to the deployment of this hydrogen strategy. First, start-up costs are significantly higher than those of fossil fuels. Second, it depends on the construction of new infrastructure to make large amounts of hydrogen available to industry. Third, electrolytic hydrogen production requires large amounts of electricity.

5.3 Carbon capture and storage (CCS)

CCS is an alternative to switching from fossil fuels to carbon-free energy such as electricity or hydrogen. Instead, it captures and permanently stores energy- or process-based CO_2 emissions in geological formations such as empty gas fields or saline aquifers in the North Sea. In principle, CCS technology can be combined with various types of industrial processes. Plants that produce relatively large, highly-concentrated amounts of CO_2 are particularly suited to CCS in terms of economic viability and infrastructure costs. These include primary steel production[8] and steam reformers for the production of hydrogen from natural gas. CCS could also be applied with steam crackers in the chemical industry and larger plants for the production of electricity and heat, such as CHP power plants, though the CO_2 concentration in the waste gas is comparatively low. However, for the above-mentioned cases, alternative processes exist to decarbonise the production of steel, basic chemicals, electricity, and heat through direct electrification or the use of green hydrogen in the future (see Part B Section 5.1 and 5.2).

Because alternatives for substantial CO_2-abatement in the production of cement clinker are not available, CCS processes will likely be needed for the decarbonisation of this sector. Compared with other industrial plants, cement works are significantly smaller and often located in the direct vicinity of the extraction zones for limestone and clay. Costs for CO_2 capturing with oxyfuel technology are moderate, but such projects depend on an appropriate infrastructure to transport CO_2 to often distant appropriate storage sites. It might also be possible to use local geologic storage opportunities, but this depends heavily on local public support.

According to current estimates, a CCS strategy has comparatively low CO_2 abatement costs (see Part E) and generally a low requirement for green electricity. Furthermore, no extensive changes to existing production processes are required. That can be an advantage in the short to medium term, but the risk is that companies will be less rigorous in their pursuit of other innovative key technologies.

Moreover, CCS is not expected to capture 100 per cent of CO_2 (see Part E),[9] and the residual emissions would have to be offset elsewhere. The use of fossil fuels also causes GHG emissions during extraction (e.g. methane slip) and during transport and causes regional pollution. Additional CO_2 emissions can arise from the energy required for the capture, transport, and storage processes. This is why when analysing the potential of CO_2 reduction from CCS technology one must consider the capture along with the upstream and downstream processes it involves.

CCS is not limited to capturing fossil fuel emissions; it could also pave the way to achieve negative emissions via BECCS. [10] Studies by the Intergovernmental Panel on Climate Change (IPCC) show that negative emissions using BECCS could be necessary to achieve the international climate goals of the Paris Agree-

8 In primary steel production, one option to use CCS is a change from conventional blast furnaces to the HIsarna® process (see Part E).

9 Even if it is technically possible to reach capture rates of 100 per cent with some processes, the final percentage points come with significant costs.

10 CO_2 can also be removed from the atmosphere at direct-air-capture plants.

ment. This involves removing CO_2 from the atmosphere by planting sustainable biomass crops and then capturing and storing the biogenic CO_2 they release when combusted (IPCC, 2018). This can only succeed with mature, market-ready CO_2 capture technology accompanied by suitable infrastructure and secure storage facilities. Possible applications for biomass include its use in cement kilns, provided that CCS is used to capture and store their emissions. From a climate-policy perspective, it makes sense to advance BECCS both nationally and internationally.

Considering their potential to pave the way for negative emissions, a revival of the debate on the public support of CCS and BECCS technologies in the industry sector is necessary.

5.4 Carbon Capture and Use (CCU)

With CO_2 capture and use (CCU), CO_2 from industrial processes is employed as a raw material in other sectors and products. As with CCS, CO_2 capture is conceivable for large sources of emissions in the steel, chemical, and cement sectors. Potential applications for CO_2 include organic chemical products (e.g. plastics and fertilisers containing carbon) that will still need carbon in a climate-neutral world and synthetic fuels. (See the fact sheet on CCU of smelting gases from integrated blast-furnace works, Part E, Steel). As for the cement sector, a CCU strategy might be used in certain situations to store significant amounts of CO_2 in concrete, a particularly long-lasting product. (For more information, see the infobox "Recarbonation of building demolition waste"). By using captured CO_2 in concrete and other products, it is possible to reduce or even eliminate the need for CO_2 pipeline networks and CO_2 storage facilities at CCU sites.

However, one must be clear-eyed about the limitations of CCU and the necessary conditions for its application to become part of a strategy portfolio for achieving climate neutrality. First, the energy requirements of CCU applications vary considerably by sector and CO_2 use. For example, the production of chemicals or synthetic fuels from the exhaust of CO_2-intensive blast-furnaces in steelmaking (Part E, Steel) needs comparatively high levels of hydrogen. By contrast, the energy needed to bind CO_2 in mineral admixtures such as concrete is rather low (RWTH, 2019) and is already practised by some cement manufacturers (CarbonCure, 2019).

Second, the economy-wide CO_2 reduction of CCU applications depends critically on the lifespan of the product to which the CO_2 is bound. For example, fossil carbon from industrial processes in synthetic fuels or certain fertilisers would be emitted again after a short time, which is not compatible with the goal of creating a climate-neutral economy by 2050. These CCU applications are a comparatively inefficient strategy for reducing CO_2 given their high level of energy use.[11] By contrast, binding CO_2 to concrete or similar long-term products such as mattresses[12] may make more sense. Long-term CO_2 storage in building materials and consumer products has great potential to reduce CO_2 in the atmosphere.

Third, the source of the CO_2 that is re-used matters. Biogenic or direct air captured CO_2 can have very different atmospheric warming potentials over the full product lifecycle than carbon from fossil energy sources. If fossil carbon from industrial processes continues to be used in the chemical industry for a transitional period,[13] chemical recycling will be

11 For example, a passenger car that runs on synthetic fuels based on CO_2 from industrial processes (CCU) would consume five times the amount of electricity from renewable energy needed by a battery-electric vehicle (WWF, 2018).

12 Carbon2Chem, Carbon4PUR, and other projects have examined the use of CO_2 and other metallurgical gas components from steelmaking in the chemical industry. Carbon4PUR studies the binding of CO_2 and carbon monoxide in polyurethane. This is the base material for mattresses and other products. The amount of CO_2 that can be absorbed by a mattress is very limited, however.

13 Non-fossil carbon sources include CO_2 from air separation in direct-air-capture plants and sustainably produced biomass.

Infobox: Recarbonation of building demolition waste (CCU)

After water, concrete is the most commonly used material in the world (World Building Council on Sustainable Development, 2009). Significant amounts of CO_2 emissions arise from the manufacture of cement, the main component of concrete (see Part E, Cement). According to scientific studies, concrete over the course of its lifetime can absorb a fraction – sometimes up to 25 per cent – of the total CO_2 produced (HeidelbergCement 2019; Schneider, 2019; Andersson et al., 2019). This process takes place naturally and is called recarbonation. Under special conditions, the CO_2 absorption rate in the recarbonation of concrete can be increased with relatively low energy use (RWTH, 2019).

The CO_2Min project studies the manufacture of new construction materials through the recarbonation of recycled concrete from building demolition waste (HeidelbergCement 2019; RWTH, 2019). But recarbonation technology is still in its early stages and it is uncertain whether it will succeed. If technology progresses quickly, however, it might be possible in the medium to long term to re-bind a significant fraction of the CO_2 emissions from cement clinker manufacturing to new "recycled" raw input materials used in new clinker cement manufacturing, thus creating a carbon loop for part of the CO_2 emitted.

This process can also be enabled by new technologies that permit the "smart crushing" and separation of the constituents of concrete. In addition to allowing for possible circular uses of CO_2 in cement manufacturing, more efficiently recycling the coarse elements in concrete such as sand and gravel could create a material cycle that better preserves resources related to mining them. The success of this approach depends not only on technological advancements, an upgraded infrastructure for recycling demolition waste, and standards for the use of such products in construction (see Part D). The rate of flow of demolition waste to new construction and the availability of CO_2 sourcing and related transport costs are also key factors. Therefore, it is still unlikely at this stage that recarbonation and the circular use of CO_2 will offer a magic bullet solution to cement emissions without the need for CCS. A range of additional solutions to reduce the inefficient use of CO_2-intensive cement types, coupled with CCS and other low-carbon cement technologies, will likely be needed as well.

needed to close the carbon cycle. Chemical recycling prevents fossil CO_2 from being emitted again after short periods.

Finally, when evaluating CCU strategies, the amount of CO_2 saved compared with conventional processes is not the only important factor. It is also crucial that we compare them with alternative strategies for creating a climate-neutral industry. For energy-intensive CCU applications – such as those in the steel and chemical sectors – it makes sense to compare the CO_2 reduction per kilowatt-hour of green electricity with that of other options.

5.5 Circular Economy

A circular economy is a system that reuses much of the materials already in existence. Recent studies have shown that it could contribute significantly to the reduction of CO_2 emissions in the basic materials industry in the medium to long term. An analysis by Material Economics (2018) found that 75 per cent of steel demand, 50 per cent of aluminium demand, and 56 per cent of plastic demand in the EU could be covered by the recirculation of existing materials. By closing the carbon cycle, recycling reduces the CO_2 output considerably and requires appreciably less energy than the production of raw materials. In this way, the circular economy can contribute significantly to resource and energy efficiency. But stringent recycling quotas also demand changes in product design, the dismantling of products at the end of their lifespans, improved recycling logistics, and possibly altered global material flows as well. This study discusses different chemical recycling technologies, electric steam crackers, and methanol-based processes for the production of olefin and aromatics that represent important steps towards establishing circular economy models in the chemical industry (see Part E). The analysis of low-carbon technologies in Part E does not emphasise recycling in the steel industry (secondary steel production is already an established technology) or in cement production (where research on the potential and the requirements of cement and concrete recycling are still in its early stages).[14] These are nevertheless important elements of extensive and cost-effective CO_2 reductions. (For more, see the infoboxes "A circular economy in the steel industry" and "The recarbonation of building demolition waste (CCU)").

14 Technologies that could make cement recycling possible in the medium to long term are in an early phase of development (Bakker et al., 2015). For example, the manufacturer of SmartCrusher technology claims that it can enable the near complete recycling of hardened cement paste from demolition waste (Slimbreker, 2019). This and other processes could potentially be combined with the recarbonation of building demolition waste.

Infobox: A circular economy in the steel industry

In principle, steel can be endlessly recycled. Every newly produced tonne of steel from primary production increases the (global) stock of steel. Processed steel is used for many end products such as cars, machinery, equipment, and the construction of infrastructure. At the end of their lifespan, the steel parts can be retrieved, melted down, and used again, creating a materials cycle.

Recycling already plays an important role in the steel industry today. In Europe, approx. 40 per cent of the steel production in 2017 came from secondary steel (Material Economics, 2019) (see Part E, Steel.) The recycling process consists of melting scrap steel in electric-arc furnaces to produce new steel products. Compared with primary-steel production from iron ore in blast furnaces the secondary steel route requires significantly less energy (2 gigajoule versus 15 gigajoule per tonne of crude steel) (Wuppertal Institute, 2019). The same goes for CO_2 emissions (0.3 tCO_2 versus 1.7 tCO_2 per tonne of crude steel).

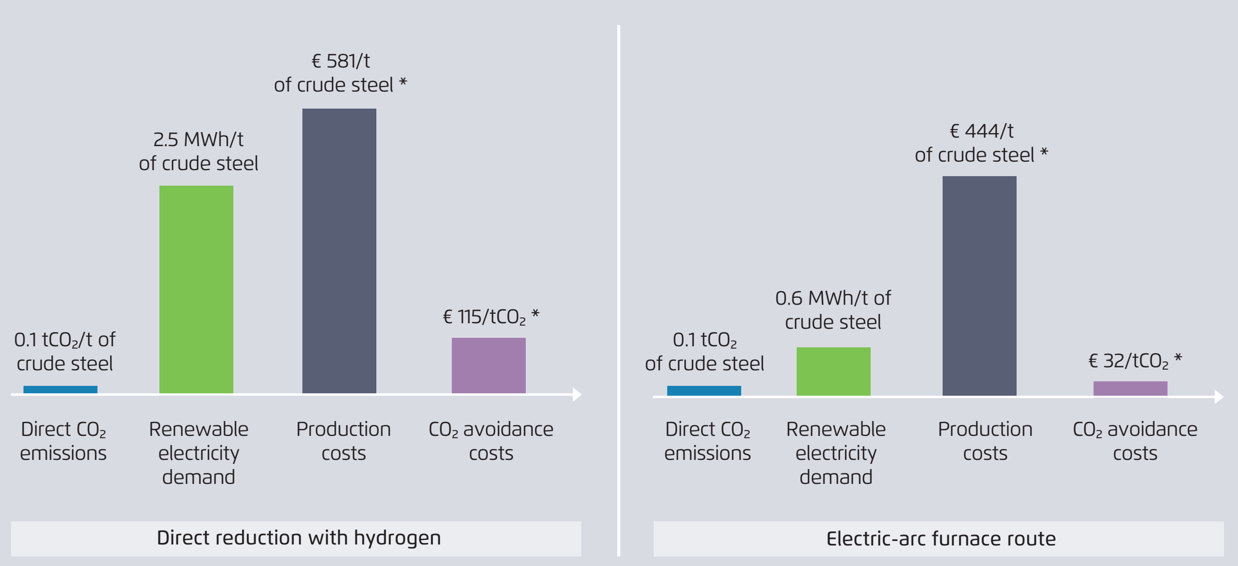
Because the secondary steel route is based on electricity, indirect emissions can be avoided in the future by decarbonising the electricity mix, producing nearly GHG-neutral steel. However, a significant increase in secondary steel production brings with it several challenges. There are large differences in the quality of steel scrap. For one, much of steel scrap is contaminated with copper. Unlike many other added elements, copper cannot be separated from steel in electric-arc furnaces. As a result, steel scrap contaminated with copper can often only be reused in reinforcement steel for concrete and in other applications where steel quality is not as important.

This is called downcycling. In order to increase the quality of secondary steel, a range of interventions are required to prevent unnecessary contamination. This includes product design requirements, improved end-of-life collection and sorting practices, and quality standards and tracing (see Part C, "Standards for recyclable products"). Because EU steel manufacturers cannot recycle all of the steel they produce (such as that used for cars sold abroad) and the total global steel demand continues to rise, primary steel production will remain necessary in the future. However, if the EU introduces a comprehensive circular economy in the steel sector, up to 70 per cent of European steel demand could be met by the secondary steel route by 2050 (versus 40 per cent today) (Material Economics, 2019). The other 30 per cent would come from primary steel production (versus 60 per cent today). Near GHG-neutral processes such as direct reduction with hydrogen exist for producing primary steel (see Part E, Steel).

But a comparison of the two virtually GHG-neutral routes shows that the requirements for green electricity are significantly lower for secondary-steel production. Primary steel production using green hydrogen requires around four times the electricity per tonne of crude steel as the secondary steel route. In addition, the estimated CO_2 abatement costs of the secondary routes for 2050 are significantly lower as well (see Figure B.8). The projected estimate shows that both steel routes will be required in the future. The higher the share of secondary steel in the total production, the less additional green electricity will be needed for creating a GHG-neutral steel industry and the lower the costs will be.

Comparison of the primary steel route with direct reduction using green hydrogen and the secondary steel route (electric-arc route) for 2050

Figure B.8



Agora Energiewende, 2019, based on data from the Wuppertal Institut and Material Economics, 2019

* Average of a cost range

Assumptions: The CO_2 avoidance costs are calculated relative to the reference process (blast-furnace route with production costs of 391 euros per tonne of crude steel and the specific emissions of 1.71 tCO_2 per tonne of crude steel). As with Material Economics, 2019, we assumed a price of 259 euros per tonne. Alongside the actual production costs, the costs contain an additional 13 euros per tonne of crude steel for reheating in the rolling process, as no by-product gases from the blast-furnace route are available.

5.6 Increasing material efficiency

Another important way to make the basic materials industry climate neutral is to deliver the same functionality and services with less material. This reduces the demand for new production plants and the energy to power them. Moreover, it reduces the costs of the transformation to climate neutrality and increases public support. Increased material efficiency can be achieved in a number of ways:

- **Reduce material losses in the manufacturing process:** Manufacturing losses in turning raw materials into finished products are estimated at around one-tenth for paper, one-quarter for steel, and two-fifths for aluminium (Milford et al., 2011; IPCC, 2014). The material wastes have to be recycled, which brings with it additional energy costs. Some options for reducing losses include modifying manufacturing processes and changing the design of individual components (Milford et al., 2011).
- **Reduce the material intensity of products:** Carruth et al. (2011) show that optimal design and production could reduce weight of many products by around one-third without limiting their performance. One impediment to this approach is the relatively high labour costs compared with material costs in most areas. Exceptions include aerospace, where the costs for the design and manufacture of lighter products and components are offset by lower fuel consumption. In the building sector, many of the structural properties of components could be achieved with significantly less material (see "Changes in construction and product standards," Part C and the infobox "Alternatives in construction").
- **Use products more intensely:** Intensifying product use means providing the same amount of service with fewer products. Some examples are the space-saving design of buildings and more durable product design. In addition, more emphasis on repairs could increase product lifespans, thereby reducing the demand for replacement products. This decreases production output and emissions in the basic materials industry (Allwood et al., 2012).
- **Steps towards a circular economy:** Increased recycling of products and materials increases material efficiency (see Circular Economy.) Some measures for increasing material efficiency may even yield negative CO_2 abatement costs.

5.7 Material substitution

In some areas, the use of substitute materials can reduce the emission intensity of products and services. One example is the use of wood for the (partial) replacement of concrete and steel in the construction of housing and certain buildings (see the infobox "Alternatives in construction"). Houses and structures that use wood instead of concrete and steel can have lower lifecycle emissions, assuming certain conditions are in place (Tettey et al., 2019; Skullestad et al., 2016; Hafner et al., 2017). Other possibilities for material substitution are bio-based, natural insulation materials (see the infobox "Insulation from sustainable raw materials") and a (gradual) switch from solid construction to lightweight construction (see the infobox "Carbon concrete"). But there are limits to material substitution when it comes to the sustainable use of wood and other crop plants as well as the suitability of replacement materials in certain applications. When evaluating individual measures for material substitution, companies should perform a comprehensive analysis of the lifecycle emissions for the materials being used. This is known as the cradle-to-cradle principle.

Infobox: Alternatives approaches to construction

Wood construction (strategy: material substitution, circular economy):
The overwhelming majority of construction materials used today – concrete, steel, bricks, glass, ceramic, plaster, and insulation materials such as polystyrene – are resource-, energy-, and CO_2-intensive. It is therefore important to try to optimise the CO_2, energy, and environmental resource intensity of the materials for construction.

In certain applications, one alternative is to use an increased share of organic materials, wood in particular. Assuming forests are harvested sustainably and depending on factors such as transport emissions, wood components typically emit less CO_2 during manufacturing and processing than cement, steel, and bricks. Moreover, wood absorbs CO_2 from the atmosphere during growth and stores it as carbon. When wood is used as a construction material, the carbon remains stored in the wood for the lifespan of the building. Thus, assuming the right conditions are in place, wood construction can be a fairly climate-friendly method for new construction, renovation, and urban densification (wood additions on existing buildings).

At the same time, it must be acknowledged that organic is not always and everywhere superior to inorganic materials. In some circumstances, the lack of sustainably harvested wood nearby, the short lifespan of structures, the need for additional reinforcing materials for large high-rise structures, or other issues such as sound insulation, thermal mass, or even fire safety can play a role in limiting the optimality of wood. In general, a location-specific and construction-wide assessment of lifecycle emissions (and other environmental indicators) is needed for each case. Hybrid construction concepts that use multiple construction materials can help to optimise environmental performance.

In Sweden and Austria, Europe's leading countries for wood construction, the share of wood in new homes is 55 per cent and 39 per cent, respectively. In Germany it is just under 18 per cent, and it is even lower in many other EU countries. But given wood's significant potential to reduce GHG emissions in construction, this represents a significant abatement opportunity. A study found that the use of wood for the supporting structure of buildings allows between 35 and 56 per cent less GHG than conventional construction methods for detached and semi-detached houses and 9 to 48 per cent less for apartment buildings (Hafner et al., 2017).

Moreover, several projects indicate that the construction of high-rise buildings that fulfil the required technical requirements (such as fire protection) is possible. These projects consist of HoHo Wien (Vienna, Austria), the largest wood high-rise building in the world and the Garmisch-Partenkirchen tax office (Germany). From the standpoint of climate change, the sustainable cultivation of wood is an absolute requirement for increasing the share of wood construction.

Other approaches:
On the next page are some additional alternatives to conventional construction.

Insulation materials from renewable raw materials (strategy: material substitution, circular economy):
Conventional insulation materials such as polystyrene, glass, and mineral wool are CO_2-intensive in the manufacturing phase and, to a lesser degree, in the disposal phase (e.g., the thermal energy recovery of polystyrene). Insulation from renewable raw materials such as flax, hemp, wood fibres, jute, sheep's wool, straw, and cellulose represent climate-friendly alternatives to conventional materials as long as the cultivation of the crops meet sustainability criteria. Relative to conventional insulation, the alternative approaches can have a significantly better CO_2 balance in the areas of raw material harvesting, production, processing, and demolition (FNR, 2017).

According to manufacturers, many insulation materials from renewable raw materials exhibit heat conductivity that is similarly low to conventional insulation (approx. 0.04 W/(m·K)) while meeting the necessary construction requirements when properly installed, including fire safety (FNR, 2017). Today, natural insulation often costs more than conventional insulation, but the cheaper price of conventional insulation does not take into account its environmental damage from CO_2 emissions. In Germany, for example, the share of natural insulation materials in construction is still comparatively low – 7 per cent (DUH, 2016).

Loam construction (strategy: material substitution, circular economy):
Loam is a widely available, alternative construction material. In contrast to many mineral-based building materials such as cement (concrete) and lime, loam does not have to be heated in an energy and CO_2-intensive process; it hardens in the air. Generally, loam-based components can be simply converted back to natural loam after the usage phase, which makes circular use possible. In this way, loam has a better eco-balance than many other mineral building materials. In 2019, Europe's largest office building made from loam (13,500 square metres, 500 employees) opened at the Alnatura Campus in Darmstadt, Germany. Its façade consists entirely of loam (Alnatura, 2018). An obstacle to the broad use of loam is its significantly higher cost, but these could fall considerably if the industrial production of loam-based components is initiated.

Building without basements (strategy: material efficiency and, if needed, material substitution):
The building of a basement demands a comparatively large amount of concrete. One of the main components of concrete is cement, which produces large amounts of CO_2 during its manufacture. By foregoing basements, the use of concrete in new constructions can be reduced.

This is already done in some cases today in order to save costs. If the loss of space is compensated by a taller construction, any increase in energy for heating and cooling must be taken into account. In urban areas, where living and storage areas are small and expensive, this probably does not represent an attractive option in the foreseeable future. In rural areas, however, it could be an option for a more climate-friendly way of construction.

Carbon concrete (strategy: material substitution):
Carbon concrete is a relatively new construction material. It serves as a replacement for reinforced concrete and significantly reduces material use. Reinforced concrete is the most-used construction material in Europe (Celsa Group, 2020) and it is predominantly used in high-rise buildings and in the construction of

infrastructure such as bridges. Because steel corrodes on contact with rain and oxygen, the steel in reinforced concrete is generally surrounded with significantly more concrete than would be necessary for the structural properties of the component. A possible alternative is carbon concrete, also known as textile-reinforced concrete. It consists of a carbon fibre or textile fibre lattice surrounded by concrete (Carbon Concrete Composite, 2019; Fraunhofer WKI, 2018). Because the grid structure materials do not rust, up to 75 per cent less concrete can be used. Moreover, textile-reinforced concrete has comparable or even better structural properties than steel-reinforced concrete (Carbon Concrete Composite, 2019). According to manufacturers, the use of carbon concrete in building construction and renovation can reduce emissions by almost 50 per cent (Carbon Concrete Composite, 2019). A further, important area of application is the modernisation of bridges built with reinforced concrete. Currently, there is still much uncertainty about whether carbon concrete is recyclable. Recent studies have shown the succesful recycling of carbon concrete under laboratory conditions (Carbon Concrete Composite, 2019). For the widespread use of carbon concrete, complete recyclability must be the goal. In 2020, the first house completely built using carbon concrete was built in Dresden, Germany. Some bridges have already been modernised using carbon concrete.

Cement substitution with lower-carbon cement (material substitution):
Sometimes material substitution or material efficiency can be achieved within a given type of material. For example, there are many types of cement and concrete products that vary widely in terms of CO_2 intensity. This means that, in many instances, it is possible to substitute more CO_2-intensive cement and concrete types with much less CO_2-intensive ones.

One of the ways this can be done is by better targeting different concrete types to different applications within a particular construction project. Often construction companies do not minimise the CO_2 footprint of the concrete they use because, to save on logistical costs, they will apply common cement types to a range of applications within a building, which in reality have very different structural performance and durability requirements. This barrier can be overcome, however, if specific incentives are put in place to encourage the optimal use of CO_2-intensive materials. For instance, labelling and/or regulatory requirements on the embedded CO_2 intensity of materials used in buildings and public works can help to shift these behaviours. Such measures are already being implemented in certain member states (see discussion in Part D of this study).

Regulatory frameworks:
There are many ways to incentivise the use of alternative construction materials and they cannot be set out in detail here. If the advantages and disadvantages of alternative construction materials are to be evaluated fairly, it is vital that regulations be adjusted to contemplate the lifecycle assessment approach in construction manufacturing, usage, and disposal. A first important step would be to take account of grey energy and grey emissions – i.e., the primary energy requirements and the CO_2 emissions arising in the manufacture of construction materials – when evaluating the energy efficiency and CO_2 balance of buildings and infrastructure projects.

5.8 Increasing energy efficiency

Increasing energy efficiency is an important strategy for significantly reducing industrial GHG emissions. In contrast to energy efficiency in cross-cutting technologies[15], energy efficiency in energy-intensive sectors is already approaching its physical limits. Due to process emissions, it is clear that energy efficiency alone is insufficient to create basic materials industries that are climate-neutral. Nevertheless, in the short to medium term energy efficiency can contribute to the reduction of energy demand and CO_2 emissions.

The replacement of Europe's existing (and aging) basic materials production plants promises meaningful efficiency potential as well. But such investments should only be made if they do not lead to the lock-in of emission-intensive processes in the long term. In some cases, it would make sense to design production plants that are flexible in handling electricity demand in order to help integrate intermittent renewable energy, even though this might have negative effects on efficiency (Agora Energiewende, 2016).

5.9 Use of biomass

Reductions in CO_2 emissions in the basic materials industry can also be achieved by replacing fossil fuels with biomass. Meaningful potential areas of biomass use in the basic materials industry are heat and the provision of feedstock for basic chemicals. Possible areas of application in the long term would be the use of biomass in combination with CCS in cement kilns to achieve negative emissions (BECCS) or as a climate-neutral carbon supplier in the hydrogen-based production of steel. Many scenarios mostly rely on the use of biomass in the industrial sector for the production of low- and medium-temperature heat. They argue that biomass can be efficiently used in this area. Moreover, there's the possibility of using CO_2 from burning biomass as a renewable source of carbon for the production of electricity-based synthetic gases.

It must be noted, however, that the potential of biomass is limited and its extent is disputed (see also Klepper/Thrän, 2019). For example, the German Federal Environment Ministry has spoken out against the cultivation of biomass solely for use as an energy source because it would create "competition for use of areas for cultivation and have negative effects on water, soil, biodiversity and nature conservation" (UBA, 2019a).

Moreover, biomass exhibits a high potential for reducing GHG emissions over its entire lifecycle only under certain conditions (Klepper/Thrän, 2019). For example, GHG emissions of biomass can be considerable over a lifecycle if many fertilisers and pesticides are used in its cultivation, if the transport routes of the harvested biomass are long and/or the conversion steps in the manufacturing process have high losses. So far, no political decision has been made about how to allocate available biomass to the industrial, transport, conversion, and building sectors in the future.

6 Key low-carbon technologies in the steel, chemical and cement sectors (overview)

The following overview briefly presents the 13 key technologies discussed in this study and assigns each to five of the nine CO_2 mitigation strategies we described in Section B5. Some of the key technologies can be assigned to more than one strategy. A comprehensive presentation of the individual technologies and processes can be found in the Sections on steel, chemicals, and cement in Part E of this study. The presentation of the key technologies does not make any claim to be exhaustive. They were selected by the authors of the study based on an assessment of their future prospects. The following short descriptions of the key technologies have been simplified to make them easier to understand.

15 Technologies are considered "cross-cutting" if they are relevant for multiple application areas or economic sectors. Such technologies include electrical motors and pumps.

Key low-carbon technologies for a (mostly) GHG-neutral steel production — Table B.3

Technology	Short description	CO_2 reduction relative to conventional technology	Possible availability
Direct reduction with hydrogen and smelting in an electric arc furnace *Strategy: green hydrogen*	This route involves a two-tiered production process. With direct reduction using hydrogen, hydrogen is used instead of coke (C) to extract iron in direct-reduction plants. This eliminates CO_2 emissions in iron ore reduction. The process produces a spongy mass known as direct reduced iron (DRI) that is then smelted into crude steel in an electric-arc furnace. (Scrap steel can be smelted together with raw steel at this stage.) If hydrogen is produced using 100 per cent renewable energy, this route is virtually CO_2-neutral.	-97 per cent	before 2025 (initially with natural gas)
Iron electrolysis and smelting in an electric arc furnace *Strategy: electrification*	The process of electrolysis reduces iron ore to pig iron in a caustic soda solution. Afterwards, an electric arc furnace smelts the crude steel. A carbon-based reduction agent is no longer required. The process promises a clear increase in energy efficiency relative to the blast-furnace route and could be nearly CO_2-free if powered mostly by renewable electricity.	-87 per cent	2040–2045
HIsarna® process in combination with CO_2 capture and storage *Strategy: CCS*	The HIsarna® process is an innovative, carbon-based smelting technology that eliminates the need for certain agglomeration steps (coking plant, sintering/pelleting) in steel production. Iron ore, which can be mixed with up to 50 per cent scrap, is reduced directly to pig iron in a single reactor. The process enables CO_2 reductions of up to 86 per cent. Moreover, because the CO_2 exhaust is relatively pure, it is particularly suitable for CCS. The captured CO_2 would then have to be transported via a CO_2 infrastructure and injected into suitable storage locations.	-86 per cent	2030–2035
CO_2 capture and utilisation (CCU) of metallurgical gases from integrated blast furnace plants *Strategies: CCU and green hydrogen*	The CCU process captures some of the smelting gases from blast furnaces and uses them for the production of reusable chemical materials (e.g., methanol, ethanol, synthetic fuels, and ammonia). The gas elements in the smelters no longer have to be burnt and could also be substituted for petroleum in the chemical industry. The low-carbon production of reusable chemical materials such as methanol (a raw material for plastic production), requires the generation of additional green hydrogen. As a result, this route demands large amounts of electricity.	-63 per cent	2025–2030

Agora Energiewende/Wuppertal Institute, 2021

Key low-carbon technologies for (mostly) GHG-neutral chemical production — Table B.4

Technology	Short description	CO_2 reduction relative to conventional technology	Possible availability
Heat and steam generation from *power-to-heat* *Strategy: electrification*	Power-to-heat helps make the electrical system more flexible and allows the direct use of electricity for the production of heat and steam. With power-to-heat, the use of fossil fuels in CHP plants or gas boilers could be avoided or reduced in the future. If 100 per cent renewable electricity is used, the heat and steam could be produced without CO_2 emissions. Both electrode boilers (for temperatures up to around 500 degrees Celsius) and high-temperature heat pumps (in combination with mechanical vapour compressors for temperatures up to 200 degrees Celsius) can be used for this approach.	-100 per cent	Starting in 2020
CO_2 capture (CCS) in combined heat and power (CHP) plants in the chemicals industry *Strategy: CCS*	By switching to carbon capture (CCS) technologies, the emissions of existing CHP plants for chemical processes could be reduced by up to 90 per cent. The captured CO_2 would have to transported away after capture via a CO_2 infrastructure such as pipelines or ships. The CO_2 could then be placed in suitable storage locations such as empty gas and oil fields in the North Sea.	-90 per cent	2030–2035
Hydrogen production using renewable energy/ electrolysis *Strategy: green hydrogen*	When producing green hydrogen, electrolysis separates water molecules into hydrogen and oxygen. Various processes exist for electrolysis: alkaline electrolysis, PEM (polymer electrolyte membrane) electrolysis and high-temperature electrolysis. If the electricity comes entirely from renewable energy, the hydrogen can be produced without emitting CO_2.	-100 per cent	2020–2030
Alternative processes such as the methanol-to-olefin/aromatics route (MTO/MTA) or electrochemical processes for olefin and aromatic production *Strategies: green hydrogen, circular economy, CCU if needed*	In the methanol-to-olefin (MTO) and methanol-to-aromatics (MTA) route, olefins and aromatics can be produced from green methanol or synthetic gas (H_2 and CO). This eliminates the need for steam crackers and the CO_2 emissions they produce. For carbon-free methanol production, green hydrogen and eventually a carbon source would be needed from non-fossil sources (such as waste plastic, biomass, or direct air capture).	-100 per cent	2025–2030
Chemical recycling: Pyrolysis or gasification of waste plastic for material use *Strategy: circular economy*	Chemical recycling makes it possible to reuse plastic waste as feedstock for the chemical industry instead of burning it. In the process, the plastic waste is converted to useful gases (gasification) or to liquid oil (pyrolysis) and then made into alternative feedstock for, say, steam crackers that replaces virgin feedstock such as naphtha. This eliminates CO_2 emissions from burning waste plastics and the manufacture of naphtha as a feedstock.	-93 per cent	2025–2030 (depending on the process)
Electrification of high-temperature heat in *steam crackers* *Strategies: electrification, circular economy*	The electrification of high-temperature heat can completely eliminate direct CO_2 emissions from steam crackers. Emissions arise from burning part of the feedstock (e.g. naphtha) for process heat (600 – 900 degrees Celsius). It is also important that alternative, non-fossil feedstock from chemical recycling (e.g. pyrolysis oil) are not burnt. In this way, the carbon contained in the feedstock can be used multiple times if needed. (See chemical recycling.)	-100 per cent	2030–2040

Wuppertal Institute/Agora Energiewende, 2021

Key low-carbon technologies for (mostly) GHG-neutral cement production — Table B.5

Technology	Short description	CO_2 reduction relative to conventional technology	Possible availability
CO_2 capture with Oxyfuel process (CCS) *Strategy: CCS*	Carbon capture using the Oxyfuel process captures a large part of the process- and fuel-related CO_2 emissions in cement clinker production. The use of oxygen for the burning process simplifies the separation and increases the capture rate of the CO_2 to around 90 per cent. The CO_2 would then have to be transported away using a CO_2 infrastructure and finally placed in a suitable storage location.	-90 per cent	2025–2030
CO_2 capture in combination with electrification of high-temperature heat in calciners (electrified LEILAC process) *Strategies: electrification, CCS*	In the LEILAC process, a special, indirectly heated steel vessel is used as the calciner. The process results in a pure CO_2 exhaust, which simplifies carbon capture. This allows some 85 to 90 per cent of total process-related emissions to be captured. The approach also enables the electrification of high-temperature heat, which eliminates energy-related emissions from the calciner. All in all, this eliminates around 77 to 80 per cent of the emissions from the clinker burning process.	-77 to -80 per cent	2025–2030
Alternative binding agents *Strategy: material substitution (here: substitution of input materials)*	Alternative binding agents allow the manufacture of concrete without the use of conventional cement clinker. By lowering the proportion of limestone, the process-related emissions can be reduced. In addition, the production processes are more energy efficient because the manufacturing process is carried out at lower temperature levels. Because the various alternative binding agents are in different stages of development, it is impossible to offer a final estimate of future market share, production costs and CO_2 reduction potentials.	up to around -50 per cent	2020–2030 (depending on the product)

Wuppertal Institute/Agora Energiewende, 2021

7 Reinvestment cycles of major EU basic materials industries represent an opportunity for a smooth industrial transformation

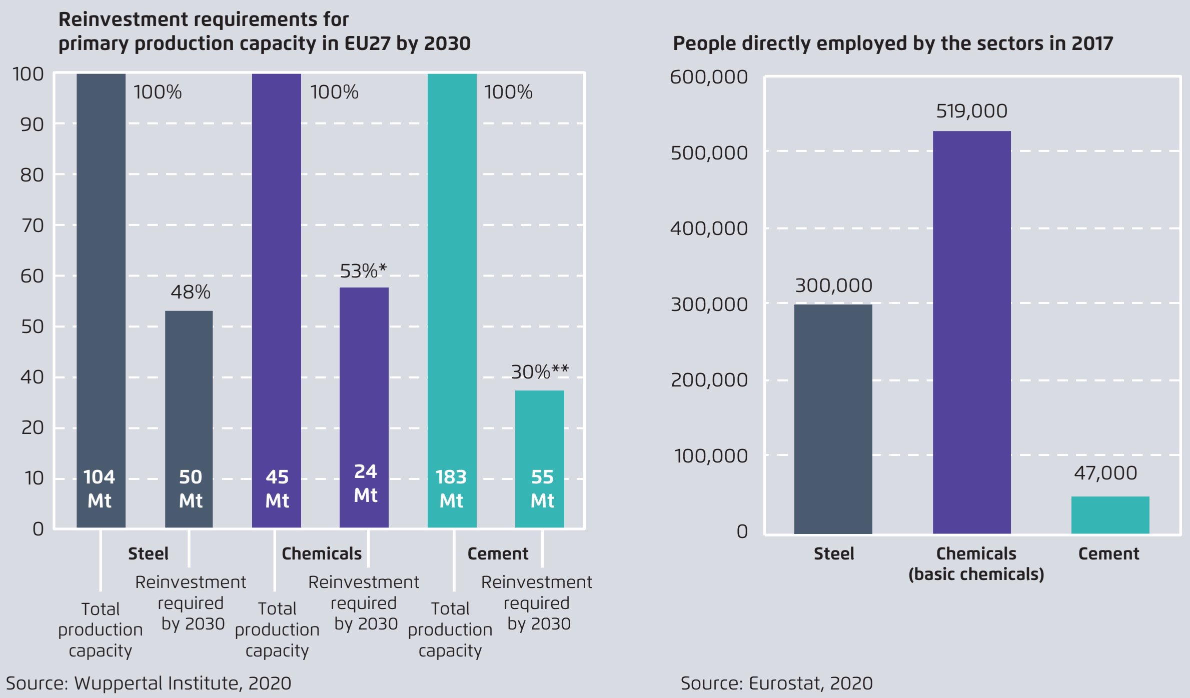
As described in Section B2, reinvestment cycles are of crucial importance for decarbonising industry. Due to the long lifetimes of industrial assets, investment decisions create long path dependencies. At a time when climate neutrality is emerging as the new paradigm, industrial reinvestments to substitute existing production capacities at the end of their lifetimes must be aligned with climate neutrality to avoid carbon lock-in and the risk of stranded assets.

The EU must take advantage of the reinvestment windows to deploy key low-carbon technologies. This is the only way to ensure an effective transition that minimises the risk of stranded assets. But the commercial availability of the necessary technologies varies from industry to industry. Accordingly, the policies for their upscaling and gradual deployment will have to reflect specific circumstances for reinvestment in each sector.

The question of reinvestment is all the more important because large parts of the EU's basic materials industries are at a crossroads. By 2030, roughly 48 per cent of primary steel capacity, 53 per cent of steam cracker capacity and an estimated 30 per cent

Reinvestment needs by 2030 and direct employment in cement, steel and basic chemicals in the EU

Figure B.9



Agora Energiewende/Wuppertal Institute, 2020

* Steam crackers are normally maintained and modernised continuously so that they do not have to be replaced all at once. Nevertheless, the graph provides a rough estimate of the reinvestment needs for existing facilities.
** Cement data represent numbers for Germany only. We estimate that the reinvestment requirements for the EU27 are in a similar range.

of cement production capacity[16] will reach the end of their lifetimes.

7.1 Reinvestment cycles in the EU steel industry

Here we focus on reinvestment requirements for primary steelmaking, specifically for the relining of blast furnaces. As the core units for iron ore reduction, blast furnaces (BF) are the most emission-intensive of integrated steel plants.

Our analysis of the capacities to be reinvested are based on a database of today's active blast furnaces and those held as a reserve. Blast furnaces are usually operated for a period of 20 to 25 years (known as a "campaign") until they need relining, a major retrofit that takes several months. Campaigns are sometimes interrupted in response to a major slump in demand.

Over the past 20 years Europe saw little investment in new blast furnaces, and none since 2008. European operators have focused on maintaining their productive capacities by regularly relining existing blast furnaces. We assume that all blast furnaces in the production stock have a remaining lifetime of twenty years based on the most recent relining date.[17]

16 The number was extrapolated from German data in absence of a full site-specific dataset for Europe.

17 Steel plant operators have some flexibility in extending the length of a blast furnace campaign, in particular if they decide not to retrofit the installation but operate it to wear and tear.

Germany produces the highest share of primary steel in Europe – 31 Mt/year, or one-third of the total. Its manufacturers emit 59 $MtCO_2$/year. France holds the second position with around 22 Mt of GHG emissions, followed by Austria, the Netherlands, Italy, Spain, Belgium, and Poland, which release 10–12 Mt of GHG emissions each.

Table B.6 shows that the first five-year period ranging from today to 2025 would require reinvestments amounting to 18 Mt of hot iron. In reality, these capacities are at risk of *not being reinvested* due to the economic effects of the corona pandemic and existing overcapacities. Some countries (Austria, the Netherlands, Spain, Poland) could be seriously affected, standing to lose as much as half of their respective capacity. For the transformation of Europe's steel industry by 2050, the 2025–2030 period is key: 30 per cent of today's existing blast furnace capacity will require retrofit or substitution, with country specific shares of up to 100 per cent. Some countries with smaller production capacities (Hungary, Romania, Sweden) will follow in the next period. From 2030 to 2035, the transformation will have impacted all countries producing primary steel. Total reinvestment needs in the period amount to 26 Mt, equivalent to 25 per cent of total primary steel capacity. The UK will see its highest reinvestment needs (61 per cent) during this period. The last five-year period, 2036 to 2040, will require reinvestments of about 28 Mt in the EU27 (27 per cent), which is similar to the previous period.

7.2 Using the reinvestment cycles in the EU steel industry for the deployment of climate-neutral technologies

For a smooth transition of the EU's steel sector, it is important that the upcoming reinvestment cycle is used to deploy key low-carbon technologies that are compatible with climate neutrality. The technology for the production of direct reduced iron (DRI) is both compatible with climate neutrality and mature enough so that it can be deployed on a commercial scale in the EU well before 2030. This is illustrated by the numerous plans and projects for DRI investments by EU steel manufacturers (Table B.7).

Given Europe's goal of achieving climate neutrality by 2050 and reducing CO_2 emissions on the order of 55 per cent by 2030, it is reasonable to assume that there will be no more investment in coal-based blast furnaces. Instead, we assume that of the blast furnace capacity slated to reach the end of its lifetime by 2030 (50 Mt of primary steel capacity), 90 per cent will be replaced by plants to produce direct reduced iron.[18] For the remaining 10 per cent, we assume the substitution by scrap-based secondary steel production plants (electric arc furnaces).

Direct reduced iron (DRI) for primary steel production: To allow for sufficient time for upscaling, planning, licensing, and implementing DRI plants, it may be necessary to postpone early reinvestment requirements.[19] This would allow primary steelmakers to replace all 45 Mt of the EU27's blast furnace capacity slated for reinvestment with DRI before 2030. Assuming a 90 per cent utilisation rate, this translates into 41 Mt of DRI production in 2030.

In a first step, DRI plants can run on natural gas, allowing for a GHG reduction of about -66 per cent relative to the integrated blast furnace route. By 2030

18 For DRI-based steelmaking, two production routes are possible. The DRI could be either smelted in electric arc furnaces for direct steel production or be smelted in a submerged arc furnace for use in existing basic oxygen furnaces in established integrated routes.

19 Blast furnaces that require relining before 2025 represent a specific challenge. Given the time for licensing and construction (2–4 years), some of the decisions regarding relining may have already been taken. At the same time, the corona pandemic may offer an opportunity for reconsidering such reinvestments and preparing a transformative approach. For operators, that could mean extending the lifetime of their blast furnaces with minor refurbishments by 3 to 10 years allowing for time to develop alternatives. Policymakers also need to establish an appropriate policy regime for accelerating reinvestment in DRI or EAF plants.

Steel emissions and reinvestment requirements per EU country — Table B.6

Country	Estimated total emissions 2017 [$MtCO_2$]	Estimated total emissions of secondary steel making in 2017 [$MtCO_2$]	Secondary steel production in 2017 [Mt/year]	Estimated total emissions of primary steel making in 2017 [$MtCO_2$]	Primary steel production in 2017 [Mt/year]	Hot iron production in 2017 [Mt/year]	Primary steel capacity to be reinvested [Mt/year]			
							2021–2025	2026–2030	2031–2035	2036–2040
Austria	13.1	0.1	0.7	13.0	7.4	6.3	2.9 (40%)	0.7 (9%)	0.7 (9%)	2.9 (41%)
Belgium	10.3	0.3	2.5	10.0	5.4	4.9		2.1 (50%)		2.1 (50%)
Bulgaria	0.1	0.1	0.7	0.0	0.0	0.0				
Czechia	7.6	0.0	0.2	7.6	4.3	3.7	2.4 (44%)	2.0 (37%)	1.0 (19%)	
Germany	58.8	1.6	12.4	57.3	31.0	27.8	4.2 (13%)	12.3 (37%)	8.2 (24%)	8.9 (26%)
Spain	10.4	1.2	9.6	9.2	4.8	4.5	2.4 (50%)		2.4 (50%)	
Finland	5.5	0.2	1.3	5.4	2.7	2.6		1.3 (50%)	1.3 (50%)	
France	22.6	0.6	4.8	22.0	10.7	10.7		5.5 (46%)	1.0 (8%)	5.5 (46%)
Greece	0.2	0.2	1.4	0.0	0.0	0.0				
Hungary	2.7	0.0	0.3	2.7	1.6	1.3			0.7 (50%)	0.7 (50%)
Italy	12.8	2.4	19.3	10.4	4.7	5.1	0.5 (5%)		2.0 (23%)	6.2 (72%)
Luxembourg	0.3	0.3	2.2	0.0	0.0	0.0				
Netherlands	12.7	0.0	0.0	12.7	6.8	6.1	2.5 (42%)	3.5 (58%)		
Poland	11.2	0.6	4.6	10.6	5.7	5.2	3.6 (47%)		2.5 (33%)	1.5 (20%)
Portugal	0.3	0.3	2.1	0.0	0.0	0.0				
Romania	4.1	0.1	1.0	4.0	2.3	1.9			3.7 (100%)	
Sweden	6.6	0.2	1.6	6.4	3.1	3.1			3.0 (100%)	
Slovakia	8.5	0.0	0.4	8.5	4.6	4.1		4.1 (100%)		
Slovenia	0.1	0.1	0.6	0.0	0.0	0.0				
Σ EU27	**187.9**	**8.2**	**65.8**	**179.7**	**95.1**	**87.2**	**18.4 (18%)**	**31.5 (30%)**	**26.4 (25%)**	**27.9 (27%)**
UK	12.6	0.2	1.5	12.3	6.0	6.0	2.1 (29%)	0.8 (10%)	4.3 (61%)	
UK + EU27	202.1	10.1	67.3	192.0	101.1	93.2	20.5 (18%)	32.3 (29%)	30.8 (28%)	27.9 (25%)

Agora Energiewende/Wuppertal Institute, 2021

Material Economics, 2019, assumes specific emissions of primary steelmaking for the EU27+UK at 1.9 tCO_2 per tonne of crude steel. Total GHG emission for the production of 101.1 Mt of crude steel was calculated at 202 $MtCO_{2eq}$. While in some EU member states coking plants and sintering are reported as part of the integrated blast furnace route, in other EU countries that is not the case. We thus assigned country-specific emissions factors according to the mean emission factor of hot-iron manufacture in the EU: 2.1 tCO_2 per tonne. This accounts for different scrap usage rates in the basic oxygen furnace and the different emission factors of crude steelmaking between the countries.

Overview of DRI plant investments announced by European steel companies — Table B.7

Project, Site	Country	Company	Status Quo	Fuel	Timeline
HYBRIT, Lulea		SSAB	Started pilot operation with clean hydrogen in 2020	Green H_2	2020: pilot plant 2026: commercial
DRI, Galati		Liberty Steel	MoU signed with Romanian government to build large-scale DRI plant within 3-5 years Capacity: 2.5 Mt/DRI/year	Natural gas, then clean H_2	2023-2025: commercial
tkH2Steel, Duisburg		Thyssenkrupp	Plan to produce 0.4 Mt green steel with green hydrogen by 2025, 3 Mt of green steel by 2030	Clean H_2	2025: commercial
H-DRI-Project, Hamburg		Arcelor Mittal	Planned construction of an H2-DRI demo plant to produce 0.1 Mt DRI/year	Grey H_2 initially, then green H_2	2023: demo plant
SALCOS, Salzgitter		Salzgitter	Construction of DRI pilot plant in Salzgitter	Likely clean H_2	n.a.: pilot plant
DRI, Donawitz		Voestalpine	Construction of pilot with capacity of 0.25 Mt DRI/a	Green H_2	2021: pilot plant
DRI, Taranto		Arcelor Mittal	Plans to build DRI plant, ongoing negatiations with Italian government	n.a.	n.a.
IGAR DRI/BF, Dunkerque		Arcelor Mittal	Plans to start hybrid DRI/BF plant and scale up as H_2 becomes available	Natural gas then clean H_2	2020s

Agora Energiewende, 2021 — Status: February 2021

we assume that sufficient amounts of clean hydrogen will be available to operate these plants with a 65 per cent share of carbon-neutral hydrogen and a 35 per cent share of natural gas (by energy content[20]). This mix will allow for an emission reduction of -89 per cent (1.6 tCO_2 of crude steel) relative to the blast furnace route, equivalent to **66 $MtCO_2$ reduction** compared with a business-as-usual scenario, in which manufacturers continue to reinvest in conventional blast furnaces.[21]

Electric arc furnaces for secondary steel production: The electric arc furnace route that produces steel from scrap is another route that is compatible with climate neutrality. We conservatively assume that 10 per cent of the primary steel production capacity requiring reinvestment before 2030 will be converted to electric arc furnaces, equivalent to an increased production of 4.6 Mt of secondary steel in 2030. The specific emission reduction per tonne of crude steel is 1.68 tCO_2 (-93 per cent), which translates into emission reductions of **8 $MtCO_2$** for 2030.[22]

Overall, this ambitious scenario allows for an emission reduction of **74 $MtCO_2$** by 2030 compared with a business-as-usual scenario with reinvestments in coal-based blast furnaces.

20 Due to the scarcity of hydrogen and the advantage of maintaining some carbon in the steelmaking process, we have decided to limit the share of hydrogen initially to 65 per cent.

21 We estimate that for this scenario around 50 TWh of green hydrogen are required in 2030. For the pre-heating of pellets another 17 TWh of electricity or green hydrogen will be required.

22 The Swedish steel company SSAB has already announced plans to replace approx. 1.5 Mt of conventional steelmaking capacity in Luleå with new electric arc furnaces to be built directly at the rolling plant in Oxeloesund by 2025.

As this analysis has shown, reinvestment decisions during the upcoming reinvestment cycle in the European steel industry will be critical for its transition. Creating an investment framework for low-carbon technologies will be key to harnessing the huge potential for GHG abatement and clean production that this strategic sector offers (see Part D).

7.3 Reinvestment cycles in the EU petrochemical industry

The transition to climate neutrality is a major challenge for the European petrochemical industry, where CO_2-intensive steam crackers play an important role. Unlike blast furnaces in the steel sector, steam crackers do not have clearly defined reinvestment cycles because they can be continuously maintained and modernised. Nevertheless, the European petrochemical industry faces some landmark decisions in the coming decade. On the one hand, emissions must be reduced to contribute to the EU 2030 climate target of -55 per cent; on the other, the ramp-up of electric vehicles and the predicted decline in refinery products could create a shortage of naphtha, which is the most important feedstock for the European petrochemical industry today.

The basic products of the petrochemical industry are so-called high value chemicals (HVC), such as olefins and aromatics, which are processed into polymers (plastics) and solvents. In Europe, the industry largely uses refinery co-products such as naphtha as input, which accounted for 78 per cent of the feedstock of the European petrochemical industry in 2017 (Deloitte, 2019). In recent years, however, cheap ethane – a co-product of surging shale gas production in the US – has been playing an increasingly important role.[23]

The major production plants for olefins and aromatics today are listed in Table B.8.

23 In the US, shale gas and its co-products have largely replaced products from oil refineries as feedstock. Due to exports of ethane to Europe, some substitution has been induced. However, in East Asia, the world's fastest-growing market, naphtha continues to be the most important feedstock.

Petrochemical production processes and their relevance in the EU — Table B.8

Process	Feedstock	Products	Relevance for petrochemical production in the EU
Steam Cracking	Naphtha, ethane, LPG, gasoil, hydrowaxes	Main products are ethylene, propylene, butadiene, and BTX; yield structure depends on feedstock	Main production process for olefins and BTX
Propane Dehydrogenation (PDH)	Propane	Propylene	Important niche technology
Fluidized Bed Catalytic Cracking (FCC)	Heavy vacuum gasoil	Gasoline and other fuels; propylene as major by-product	Relevant for propylene supply in EU
Catalytic Reforming (CR)	Heavy naphtha	Reformate fuel (gasoline), BTX as major by-product: BTX: 0.88 (t of BTX/t of naphtha) H_2: 0,03 (t of H_2/t of naphtha)	Major supply of BTX in Europe
Methanol-to-Olefins (MTO)	Methanol	Ethylene and propylene	No installation in EU
Methanol-to-Aromatics (MTA)	Methanol	Paraxylene and toluene	No industrial scale unit worldwide

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Today, steam crackers are the most important production facilities for the petrochemical industry in Europe. They are mostly integrated into local refinery complexes or connected to them via pipeline infrastructures. In the coming decades, a decline in production from refinery-embedded processes such as fluidized bed catalytic cracking and catalytic reforming can be expected due to the decreasing demand for fuels that result from a growing share of electric vehicles. As refineries supply part of the feedstocks for the chemical industry, this could make the role of steam crackers even more important in the future. However, refinery closures would also reduce supply of light naphtha, which is the most important steam cracker feedstock today.

Over the past 15 years, steam cracker operators have become partially independent of local refinery integration. For example, terminals and tank farms for ethane have been built at coastal locations to import this typically cheap co-product of shale gas production in the USA. There are also very large reserves of so-called "natural gas liquids" in the Middle East, which can be imported as convenient cracker feedstock.

For the production of ethylene, ethane crackers on the European coast usually serve as the cost reference today.[24] The cracker retrofits undertaken in the past 10 years have included measures to enable the use of ethane as an exclusive or additional feedstock. However, this has made it more difficult to cover the market for propylene and especially for butadiene and aromatics, which is reflected in an increased price spread for these products compared with ethylene. This in turn allows some of the naphtha crackers, which have a higher yield for these products, to produce economically. The dedicated production of propylene via propane dehydrogenation (PDH) plants has also gained importance in Europe in recent years. Existing plants are currently being expanded and new investments are being made in Spain and Belgium. Additional investments are also being made in Poland.

By contrast, a conspicuous reluctance to invest is observable in continental Europe. Due to the increased costs for transport and access to the new feedstocks traded on the world market, sites here are less attractive. For this reason, crackers in continental Europe – all of which are closely linked to refinery complexes – will be at a crossroads by 2035. The only option to continue production without major adjustments would be to resort to imported naphtha. Medium and heavy naphtha could become cheaper in the medium term if the introduction of electric vehicles in the passenger car sector picks up speed. However, processing these feedstocks is more CO_2-intensive than when using light naphtha (the most widespread type of naphtha in use today) and it is debatable whether this is compatible with the EU's stricter 2030 climate target of -55 per cent.

Making decisions in this complex market environment that are compatible with the long-term goal of climate neutrality will be a major challenge in the coming decades. Steam crackers play a key role because as existing core assets they have an importance that is similar to that of blast furnaces in the steel sector. Technically, steam crackers can be operated more flexibly, allowing individual lines to be temporarily shut down. Unlike blast furnaces, crackers do not run continuously for twenty years before they can be overhauled. This means that retrofits or even the replacement of individual furnaces can be carried out any time. However, steam crackers are operated at the highest possible capacity utilisation due to their high capital costs. Although crackers can be operated with proper maintenance for longer than 60 years in some cases, an observation of retrofits and closures in Europe to date shows that the furnaces are usually only operated for 35 to 50 years before they are fully replaced or shut down. Since the type of feedstock used can be changed when the furnaces are replaced, the reinvestment

24 A rare temporary exception occurred during the spring of 2020.

Steam cracker emissions and reinvestment cycles per EU country — Table B.9

Country	Total emissions of steam cracking [$MtCO_2$ in 2017]	HVC production [$MtCO_2$ in 2017]	Total capacity [Mt HVC/year]	Capacity to be reinvested [Mt HVC/year]						
				2021–2025	2026–2030	2031–2035	2036–2040	2041–2045	2046–2050	>2050
🇦🇹	0.4	0.5	1.1	-	-	1.1 (100%)	-	-	-	-
🇧🇪	4.6	6.0	5.5	-	1.0 (18%)	-	-	3.3 (60%)	-	1.2 (22%)
🇨🇿	0.7	0.9	1.2	-	1.2 (100%)	-	-	-	-	-
🇩🇪	8.5	10.7	12.8	4.1 (32%)	3.8 (30%)	2.3 (18%)	-	-	-	2.5 (20%)
🇪🇸	1.2	1.7	2.8	0.5 (18%)	2.3 (82%)	-	-	-	-	-
🇫🇮	0.4	0.5	0.6	0.6 (100%)	-	-	-	-	-	-
🇫🇷	4.2	5.6	5.1	1.2 (23%)	-	2.4 (46%)	-	1.6 (31%)	-	-
🇭🇺	0.9	1.2	1.4	0.8 (57%)	-	-	-	-	-	0.6 (43%)
🇮🇹	2.3	2.7	2.8	1.1 (39%)	-	-	0.8 (29%)	0.9 (32%)	-	-
🇳🇱	4.2	5.4	8.0	3.2 (40%)	2.0 (25%)	-	1.4 (17.5%)	-	-	1.4 (17.5%)
🇵🇱	0.8	1.0	1.5	-	1.5 (100%)	-	-	-	-	-
🇵🇹	0.6	0.7	0.7	-	-	0.7 (100%)	-	-	-	-
🇷🇴	0.0	0.0	0.4	0.4 (100%)	-	-	-	-	-	-
🇸🇪	0.6	1.0	0.7	-	-	-	-	0.7 (100%)	-	-
🇸🇰	0.0	0.0	0.5	-	0.5 (100%)	-	-	-	-	-
Σ 🇪🇺	**29.4**	**38.0**	**45.1**	**11.9 (26%)**	**12.2 (27%)**	**6.4 (14%)**	**2.3 (6%)**	**6.5 (14%)**	-	**5.8 (13%)**
🇬🇧	1.8	3.1	3.4	-	0.5 (15%)	-	0.9 (28%)	1.9 (57%)	-	-
🇬🇧 + 🇪🇺	31.3	41.1	48.5	11.9 (25%)	12.8 (26%)	6.4 (13%)	3.2 (7%)	8.4 (17%)	-	5.8 (12%)

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cycle winds up being determined by the age of the plant as well as the opportunity to adjust for new market conditions. Our estimates for the reinvestment cycles and capacities of each period can be found in Table B.9.

Due to the low level of new investments in the past 30 years, almost 90 per cent of the plants will require reinvestment by 2045, which means that they can be adapted to new feedstocks or operating methods (e.g. electric cracking) or make room for new types of plants such as methanol-to-olefin or methanol-to-aromatics. Existing naphtha or ethane crackers not yet scheduled for reinvestment by 2045 could then be operated without technical modification with products from a Fischer-Tropsch plant. As long as Fischer-Tropsch feedstock is produced with climate-neutral hydrogen and carbon dioxide, cracker operation will be compatible with the requirements of climate neutrality.

7.4 Using the reinvestment cycles in the EU petrochemical industry for the deployment of climate-neutral technologies

Many strategies exist for a climate-neutral petrochemical industry, though a full description lies beyond the scope of this study. When it comes to steam crackers, this requires the elimination of energy-related emissions through electrification or CCS and switching to climate-neutral feedstocks. However, alternative process routes such as methanol- and innovative biomass-based processes that do not rely on steam crackers are also conceivable. An alternative to the use of fossil naphtha from refineries as feedstock for steam crackers is the use of plastic waste for chemical recycling. A high-quality pyrolysis oil can be obtained from relatively pure waste with a predominant proportion of polyolefins such as polyethylene and polypropylene. The length of the hydrocarbon chains produced can be influenced by the choice of catalyst and the operating mode of the reactor in order to control the distribution of gas (ethane) and liquid (naphtha, gas oil). The technologies that are in development so far are diverse. Pyrolysis products can be used in modified flexible steam crackers, while a completely new route results from waste gasification. The resulting synthesis gas (carbon monoxide and hydrogen) can be synthesized into methanol (see the Waste to Chemicals project) and processed into olefins and aromatics in new methanol-to-olefin or methanol-to-aromatics plants.

If plastics use is to continue, closing carbon cycles with chemical recycling will be necessary in the long term to achieve climate neutrality. But the carbon cycle is not closed during the operation of a conventional cracker: CO_2 emissions are produced by burning part of the product stream or natural gas to provide the required heat energy in the cracking furnaces. To avoid direct energy-based emissions, high-temperature heat via electricity (or hydrogen) would be needed. A variety of manufacturers are working together to develop similar approaches for electric cracking (see Table B.10).

In contrast to the developments mentioned so far, which are all being pursued by established players in the petrochemical industry, bio-based plastics can be a field for SMEs as well. The spectrum here ranges from alternative feedstocks to produce established polymers (drop-in polymers) and alternative intermediates to novel polymers that can replace PET.

Although it is not clear how quickly the decline in refinery products due to the ramp-up of electric vehicles will affect the chemical industry, it is important to establish alternative climate-neutral production technologies before 2030. This will both contribute to the EU's climate target of -55 per cent by 2030 and secure the EU chemical industry's long-term competitiveness.

Overview of EU petrochemical industries' plans for commercialisation of alternative production processes before 2030 — Table B.10

Project, Site	Country	Company	Status Quo	Fuel	Timeline
Cleaning of pyrolysis oil, Geleen		Sabic	**Chemical Recycling:** Semi-commercial plant for cleaning 15 kt of pyrolysis oil from chemical recycling per year (TRL 6-7).	Waste plastics	2021: start of production
Waste to Chemicals, Rotterdam		AirLiquide, Enerkem, Nouryon, Shell	**Chemical Recycling:** production of methanol from residual waste. 220,000 t of methanol production capacity/year (TRL 6-7).	Residual waste	2020: planned start of construction
ChemCycling, various locations		BASF, Remondis	**Chemical Recycling:** production of pyrolysis oil from waste plastics in pilot plant (TRL 4-5).	Waste plastics	2019: started pilot operation
PYRECOL, Litvinov		Unipetrol	**Chemical Recycling:** construction of pilot pyrolytic unit to convert waste plastics (TRL 4-5).	Waste plastics	2020: construction of pilot plant
Carbon4PUR project, Marseille Fos		Covestro, ArcelorMittal, Recticel	**CCU in long-lived products:** pilot plant to convert metallurgical gases of steel production to polyurethane (TRL 4-5).	Waste gases	2020: construction of pilot plant
Rheticus project, Marl		Evonik, Siemens	**Electrochemical process:** Pilot plant with a capacity of 20,000 t per year for the conversion of waste gases to specialty chemicals (TRL 4-5).	Solar-driven electro-chemical reduction	2020: pilot plant started operation
E-Cracker, Ludwigshafen		BASF, Sabic, Linde	**Electrified steam cracker:** plan to build multi-megawatt demonstration plant (TRL 6-7)	Electricity	2023: demo plant

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7.5 Reinvestment cycles in the EU cement industry

There is a wide array of measures for reducing emissions along the cement and concrete value chain. These measures range from material efficiency through more efficient use of concrete and cement to alternative binders[25] and material substitution with other building materials such as wood. Another promising approach is based on the principle of material circularity: concrete from demolition is crushed and the aggregates are separated and then either re-used as cement substitute directly (unhydrated cement) or brought back to cement plants for recarbonation and recycled to be used to produce new recycled clinker. But even with recycling, the industry will still need to produce new cement clinker in the future. Roughly one-third of the emissions from clinker production (energy-related emissions) can be avoided in the future through the use of biomass or

25 For example, the clinker content of cement can be reduced by replacing a portion of the clinker with another binder such as limestone and calcinated clay substitutes ("LC3" solutions).

the electrification of kiln heating. For the remaining two-thirds of process-related emissions, however, carbon capture technologies will likely be an indispensable strategy to reach climate neutrality. This is because from today's perspective the process emissions in the clinker production process cannot be avoided. Although CO_2 capture technologies as end-of-pipe technology can also be applied to existing cement clinker production plants via retrofits, the actual location of cement clinker production plants will be an increasingly critical factor for the viability of CCS and the likelihood of its public support.

For CCS, the connection to a CO_2 infrastructure network is key for transporting CO_2 to long-term storage sites. Many cement works are located near limestone quarries far from the coasts, so there's a risk that connecting single cement works to a CO_2 pipeline infrastructure may prove difficult - even in the long-run. Besides, the use of CO_2 via CCU concepts will likely also require a CO_2 transport infrastructure, unless the CO_2 can be used in the cement plant itself.

In Norway, the UK, and the Netherlands the development of offshore CO_2 storage under the North Sea seems to face less public resistance than geological onshore CO_2 storage. Hence, it is likely that an inland CO_2 transport infrastructure will first develop close to coastal areas around those hubs. Besides, cement clinker plants close to the coast in the Baltic Sea or Iberian Peninsula could also be connected to the offshore CO_2 storage sites by CO_2 transport via ship. While there may still be reasons for sticking to

Overview of European cement companies' plans for the deployment and commercialisation of CO_2 capture projects before 2030 — Table B.11

Project, Site	Country	Company	Status Quo	Timeline
Brevik CCS project, Brevik		HeidelbergCement	The project foresees to build an industrial-scale plant to capture and store 0.4 $MtCO_2$/year in 2024.	2024: commercial CCS
ECRA-CCS project, various sites		European Cement Research Academy and various companies	The project has been studying the economic and technical feasibility of carbon capture in the cement sector since 2007. The project is currently in Phase IV which involves developing a concept for a demonstration plant (TRL 6-7)	2020–2023: building demonstration plant
Catch4climate, Mergelstetten		Buzzi Unicem-Dyckerhoff, Heidelberg Cement, SCHWENK Zement, Vicat	Plans to build demonstration plant for Oxyfuel-capture (TRL 6-7). The captured CO_2 is intended to be used to produce ‚reFuels' such as kerosene.	2021–2024: demo plant
LEILAC II, Hannover		HeidelbergCement, Cemex	Planned construction of a CCS demonstration plant that captures 0.1 $MtCO_2$/year (TRL 6-7)	2025: demo plant
LEILAC I, Lixhe		HeidelbergCement	Pilot plant has a production volume 10 t of cement clinker/hour (TRL 4-5)	2019: started pilot operation

Agora Energiewende, 2021 — Status: February 2021 existing clinker production sites (such as proximity to limestone quarries or the local customer base), each reinvestment window offers the opportunity to move clinker production to sites where a connection to a CO_2 transport infrastructure is easier and thus more likely. Consequently, the existing practice of transporting cement clinker to cement mills that only grind the clinker to cement for local markets is likely to increase in the future.

Apart from that, there are several CO_2 capture technologies available – Oxyfuel CCS, LEILAC, and post-combustion CCS technologies (see Part E, cement) – and the specific plant design needs to match the technology choice for CO_2 capturing, even if they are only to be added as part of a future retrofit.

Given the long technical lifetimes of cement plants - between 50 and 60 years – each reinvestment decision should devise an individual decarbonisation roadmap that is in line with achieving climate neutrality by 2050. In the coming decade, we estimate that around 30 per cent of existing cement clinker production capacity will reach the end of its lifetime by 2030 and will require reinvestment.[26] Several European cement companies are working on commercialising CO_2 capture technologies and long-term CO_2 storage before 2030 (see Table B.11). We assume that by 2030 around 10 cement plants that are close to the Atlantic Ocean or to navigable rivers could be connected to long-term CO_2 storage sites that are currently being developed in the Netherlands and Norway. This could reduce emissions by **9 MtCO_2** by 2030. In the future, the development of a CO_2 infrastructure could also pave the way for negative emissions via BECCS. By using a large share of sustainable biomass in its fuel mix and sequestering the biogenic carbon share, cement works that are connected to a CO_2 infrastructure can generate negative emissions.

26 These estimates represent numbers for Germany only. But we assume that the required reinvestment in the EU27 will be on a similar order.

Part C: Regulatory framework and policy instruments for the development and introduction of key low-carbon technologies

1 Introduction

Achieving the long-term goal of climate neutrality for Europe requires an industrial policy framework that incentivises the development, scaling and deployment of key low-carbon technologies. This is crucial for mitigating climate change and for positioning Europe as a leader in the global race for the development of climate-neutral technologies and sustainable industrial production hubs.
By signing the Paris Climate Agreement, virtually every country in the world acknowledged that sustainable economies and climate-friendly technologies will be needed to ensure the well-being of their citizens in 2050. Creating a climate-neutral industry holds important market opportunities in addition to environmental benefits. If Europe can get an early start, its companies stand to be pioneers in the field of climate-neutral technologies and shapers of global change.

There are many promising low-carbon manufacturing processes, and some of them have already been tested successfully in pilot projects (see Parts B and E). But if companies in the steel, chemicals and cement industries are to adopt them, they will need clear policy signals and a reliable regulatory framework. Without policy guidelines and incentives, businesses will not internalise the external costs of emission-intensive processes such as air pollution, global warming and health problems.

Individual policy instruments alone cannot cover the range of requirements for key low-carbon technologies in various stages of development. Emerging technologies require different incentives from those that are ready to be scaled at the industrial level. Moreover, the demands that policy instruments must satisfy vary by sector.

This section presents policies that can be combined into a coherent framework that applies maximum leverage for creating a climate-neutral industry. The focus is on the mechanisms of policy instruments – presenting their different approaches, strengths and weaknesses and putting them in relation to each other. Part D develops policy recommendations that can convert individual instruments into a systematic strategy. However, we do not provide specific recommendations on the definition of such strategies on the level of EU member states and their relation with a broader European enabling environment. Rather, the strategy should result from discussions between political decisionmakers, industrial representatives, trade unions and other stakeholders. By sketching out a possible policy framework, this section provides a robust foundation for those discussions.

1.1 Policy instrument criteria for a climate-neutral industry

Independent of the state of development of key low-carbon technologies, the goal of climate-neutrality in the steel, chemicals and cement sectors places particular demands on policy instruments.

→ **Send robust investment signals:** First and foremost, policy instruments must offer certainty for the planning of capital-intensive, long-term investment in new production processes. Any uncertainties about the policy framework will negatively influence business behaviour, impede innovation and leave companies reluctant to invest in new technologies. To remove these uncertainties and to create a reliable framework for the adoption of climate-neutral technologies, an array of different policies is needed. A reliable, long-term regulatory framework is also necessary so that companies invest in new climate-friendly plants and equipment when existing facilities reach the end of their operating lifetimes, as many are scheduled to do over the next ten years. Without the right policies, companies could leave European countries, leading to massive job losses (see Part D). In order to give businesses an incentive to invest in key low-carbon technologies, action must be taken now.

→ **Offset the additional costs of acquiring and operating new technologies:** Compared with conventional technologies, low-emission manufacturing processes are associated with higher costs, which can arise both at the point of investment and during operation. In today's global market, companies cannot pass these extra costs to consumers without losing out to competitors abroad. Policies are therefore needed to defray the additional costs of developing, adopting and operating low-carbon processes.

→ **Satisfy the standard requirements of policy instruments:** Alongside the above requirements, policy instruments for a climate-neutral industry must meet the standard criteria for sound governmental regulation.

- **Economic efficiency:** When distributing public funds, each euro invested must achieve the highest possible environmental and economic benefit.
- **Effectiveness and precision:** The value of a policy instrument is measured by the contribution it makes to achieving its goal (in this case: a competitive and climate-neutral industry).
- **Feasibility and acceptance:** Policies of member states must be in synergy with the European legal framework, have political support and meet requirements for transparency and accountability.
- **Support the European industry's international competitiveness:** If policy instruments for climate neutrality are to be supported by all stakeholders they must consider the special features of the industrial sectors they affect. Steel and many products of the chemicals industry are commodities – standardised, interchangeable goods that are traded internationally. European producers in these sectors face strong international competition. Transport costs generally represent only a small fraction of total prices for these goods. External costs internalised through, say, CO_2 prices, cannot be passed on to consumers in the world market as long as no comparable policy frameworks exist in other major producing countries. Higher production costs can jeopardise the competitiveness of European industry. It is crucial that policies be in place to prevent production from moving to regions with fewer restrictions for reducing emissions, - a phenomenon known as carbon leakage.[1]
  One set of policy measures that can prevent carbon leakage are border carbon adjustments, or BCAs,[2] which include countervailing duties (SVR, 2019). BCAs can be applied to emission-intensive products when imported to Europe in order to offset the higher prices of low-emission European products when competing with lower priced high-emission products from outside Europe.

1 The relocation of manufacturing to countries with less severe carbon restrictions is just one risk. Another is known as investment leakage. This occurs when global companies based in Europe decide to invest in other regions of the world. What needs to be emphasised again is the importance of a reliable, long-term regulatory framework for investment.

2 In this study, we use the term border carbon adjustment (BCA) to ensure consistency with previous publications in English language. However, in the political discussion the term carbon border adjustment mechanism (CBAM) is now used in official documents. When we refer to BCA we understand it as equivalent to CBAM.

But the adoption of such mechanisms comes with significant hurdles. First of all is the question of their compatibility with *World Trade Organization* (WTO) rules, even though exceptions from the equal treatment of domestic and foreign goods due to environmental reasons and other political aims are possible in principle. Imposing duties based on the intensity of emissions demands exact knowledge of the carbon footprint of products and therefore comprehensive carbon tracking from the emission source. Although officials could make rough assumptions based on the source of the products initially, the concrete implementation is complex. Another difficult question that needs clarifying is whether the level of environmental protection in other countries is comparable with European regulations. Exemptions for least developed countries (LDCs) will likely be necessary as well. For EU member states with exporting industries, the introduction of BCAs, as with any restriction on international trade, brings special risks. The response of trading partners whose exports would be subject to the adjustment mechanism could lead to disputes and retaliatory measures that may harm export-centered business even in sectors that are not carbon-intensive.

Moreover, the effects of policy instruments on the international competitiveness of European industry differ significantly depending on whether they target production or consumption. When selecting specific instruments, therefore, a forward-looking policy framework must take into account possible effects on international competition.

The creation of lead markets will only be successful if climate-neutral policies consider the international competitiveness of European industry while setting ambitious climate goals. Lead markets are markets or areas of technology in which industry can achieve a global competitive advantage through leadership in innovation and technology (Beise, 2001). The creation of internal demand for low-emission production technologies forms the foundation for future exports to the world market. Increasing pressure to manufacture products more efficiently and with lower emissions has created opportunities around the world and may create lead markets for low-emission industrial technologies.

1.2 Mechanisms for a climate-neutral industry

The requirements of policy instruments for a climate-neutral industry can be further subdivided into mechanisms. Four types of policy mechanisms must be adopted for a climate-neutral industry in the long term.

Initially, pressure is needed to push the affected sectors of the economy towards greenhouse-gas neutrality. At the global level, the Paris Climate Agreement provides guidance but does not imply immediate consequences or incentives for industry. The most important way to pressure the industrial sector is to internalise the external costs of CO_2 emissions. This includes the use of effective price signals, clear policy decisions and a long-term strategy for a climate-neutral industry. The central criterion for these instruments is their ability to establish low-emission business models in the market. Setting standards through regulatory laws could further strengthen policy decisions while addressing areas where experience shows that economic incentives have little effect.

The right sort of pressure to act will lead to the development, testing and adoption of key low-carbon technologies (see the technology fact sheets in Part E of this report for more information). The introduction of a circular economy is a cornerstone of sustainable industry. Policymakers must eliminate disincentives for using recycled material, create new regulations and enable the use of the technologies that are needed for a circular economy. The use of low-carbon technologies is generally associated with higher costs than conventional processes, both at the initial investment and during operation. But as long as the additional costs cannot be passed to consumers, or the required investment is too great, businesses will need financial support. In addition to supporting the provision of low-emission products, policies must encourage demand by creating public markets or incentivising private ones. Such policies help distribute the burden of creating a climate-neutral industry.

Every combination of policy instruments should cover these four mechanisms in order to effectively initiate the transformation of industry towards climate neutrality.

1.3 Forward-looking policy instruments can supplement European emissions trading

A wide spectrum of policy instruments exists that can help increase efficiency and reduce emissions in the industrial sector. The European emissions trading system (EU ETS) will play a key role alongside support policies and incentives. Many refer to the EU ETS in political debates about the necessity of augmenting the policy framework for decarbonisation (SVR, 2019). In order to leverage the greatest possible efficiency advantages and avoid carbon leakage, emissions trading should be linked globally and implemented as widely as possible (DEHSt, 2013). But even appropriate initiatives within, say, the G20 framework, are unlikely to provide an adequate outcome in the near future. Therefore, this study focuses primarily on the EU ETS in particular rather than on emissions trading in general.

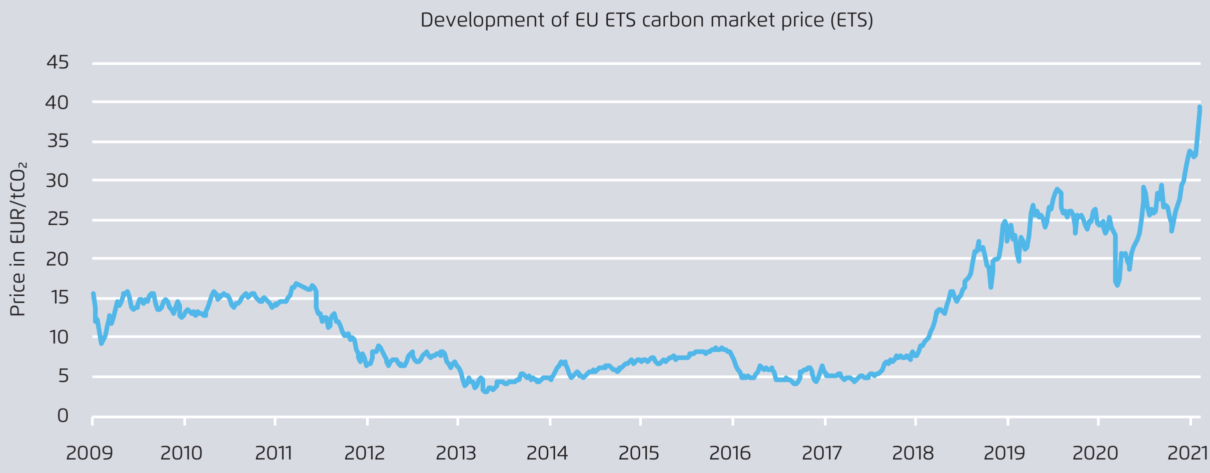
In economic theory, price signals for CO_2 are the most efficient way of securing CO_2 reductions. In the European Emissions Trading System these price signals are achieved by imposing a maximum cap on total emissions and by auctioning the corresponding emissions allowances. At current and projected prices, however, these measures will be insufficient to ensure the climate neutrality of European industry in the long term.

Carbon price trends: Carbon prices in the EU ETS have increased significantly since 2019 and are projected to increase even further. However, as argued in Part B and as demonstrated in Part E, the abatement costs for most key technologies lie well above the prices of EU emission allowances forecast for the coming years. But even if carbon prices rose significantly in the medium to long term, business expectations about price changes in the EU ETS will be decisive for investment in key low-carbon technologies. Unfortunately, the increases in carbon prices that businesses currently expect are not high enough to initiate a fundamental transformation of the industrial sector towards climate neutrality.

- → **Volatility and insecurity:** The EU carbon price depends on the regulatory framework negotiated by policymakers. But regardless of policies, emissions trading is inherently volatile, which makes it an unreliable basis for investment decisions (see Figure C.1.)
- → **Plant lifespans and investment timelines:** Unlike consumer decisions, investment in key low-carbon technologies cannot be gradually adjusted as carbon prices change. So it is crucial that long-term signals for the introduction and scaling of these technologies remain reliable over decades. By the same token, CO_2 prices must not increase so drastically as to render recent investment in conventional technologies (such as those in the chemical industry) unprofitable, forcing companies to write them off before they are amortised. Therefore, as EU carbon price signals provide gradually increasing pressure over the long term, supplemental policy instruments are needed to cover the cost differential that can justify the necessary investment in climate-neutral technologies in the short and medium term.

To summarise: the EU ETS is important for forging a path to climate neutrality. By sending EU-wide price signals for emissions, it incentivises short-term optimisations. But it is not enough to steer the long-term processes necessary for decarbonising the

Development of the carbon price in the EU Emissions Trading System from 2009 to 2021 — Figure C.1



Agora Energiewende, 2021, based on Ember, 2021

industrial sector and to cover the massive additional investment needed for developing, scaling and operating key low-carbon technologies. This is why the EU needs innovative and forward-looking policy instruments to supplement its emissions trading system. Such instrument are invaluable for triggering and directing transformative changes in the steel, chemical and cement sectors.

Infobox: EU Innovation Fund

→ **What is the EU Innovation Fund?**
The EU Innovation Fund is the successor to the NER300 programme. Its purpose and design were laid down in the EU Emissions Trading Directive (EU 2003/87/EC) and in the Commission Delegated Regulation (EU 2019/856). The goal of the fund is to support innovations in low-carbon technologies across all EU member states.

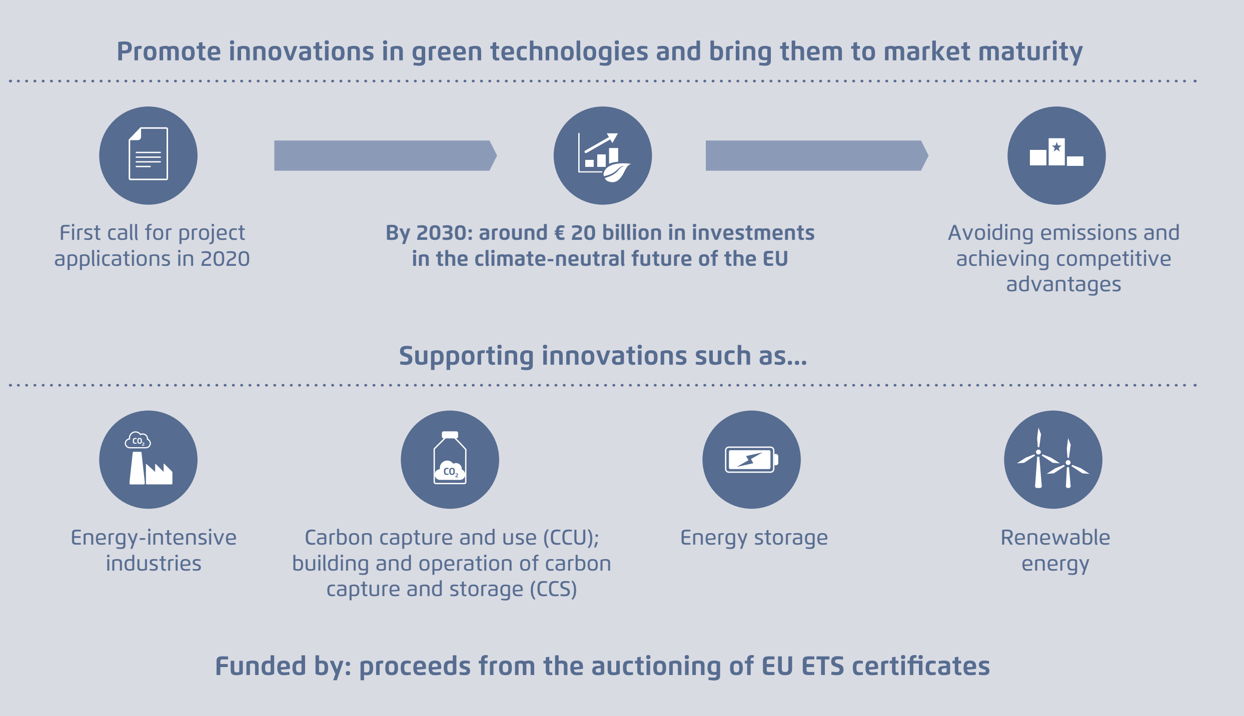
→ **What is the goal of the EU Innovation Fund?**
The goal is to support a variety of viable and innovative demonstration projects. In addition, it aims to help the European Union establish itself as a global leader in the field of low-carbon technologies.

→ **How is the EU Innovation Fund financed and what is its endowment? What does the endowment of the fund depend on?**
The EU Innovation Fund is financed with auction proceeds of the EU ETS. At least 450 million allowances[3] (EUR-Lex, 2018a; EUR-Lex, 2018b) will be auctioned for this purpose. The size of the fund depends on the level of the carbon price at the time of the auction. At an average price of around 45 euros per European emission allowance (EUA) over the next decade, the fund would amount to 20.25 billion euros.

→ **Which projects are supported?**
The fund focuses on five areas: 1) innovative, low-carbon technologies and processes in energy-intensive industries; 2) carbon capture and utilisation (CCU); 3) the building and operation of carbon capture and storage (CCS); 4) the innovative production of renewable energies; and 5) energy storage.

3 See (EU) 2018/410, art. 10a para. 8.

Operation of the EU Innovation Fund — Figure C.2



Agora Energiewende, 2021, based on European Commission, n.d.

→ **Which assessment criteria are used when selecting projects?**

The projects and sectors that can participate are specified in the calls for proposals. The following criteria are specified by the Delegated Regulation [4] (EUR-Lex, 2019a):

- effectiveness with regard to reducing greenhouse-gas emissions
- level of innovation relative to the current state of technological development
- maturity of planning and business models
- technological potential and market potential for a wide application, reproducibility and/or future cost reductions
- efficiency with regard to costs
- balance of geographical distribution

→ **Which costs can be supported and in which form?**

The fund can subsidise both capital and operating costs. As a rule, the fund can provide subsidies of up to 60 per cent of costs depending on the projects' level of risk. For projects that are already relatively close to market, conventional instruments such as loans or guarantees can also be used, although the details are still under discussion. The subsidies can be combined in principle with other EU support programmes and national initiatives. These include investEU, Horizon Europe, Enhanced European Innovation Council (EIC) pilot, InnovFin Energy Demo Projects, NER300, Connecting Europe Facility, the Modernisation Fund, the Cohesion Fund and private capital funds.

→ **Which conditions apply for receiving payments?**

The subsidy is provided based on the achievement of milestones/stage goals defined by the project. Up to 40 per cent of the subsidy can go towards project development up to the financial close, i.e. the final investment decision. Commencement of operation is another stage goal. The complete payment may be tied to the achievement of the planned reduction in emissions. In contrast to coupling the entire subsidy to achievement of the project's emission reduction goals, a staggered payment relieves the recipient from carrying the entire risk alone.

→ **When and how can applications be made?**

Starting in 2020, the European Commission will issue regular calls for proposals (EUR-Lex, 2019b).
The application phase will be divided into two parts: In the first step, applicants must present their project and apply for consideration. This involves describing the main characteristics of the project to the project commission. In the next step, applicants must provide a detailed application.
Projects that are still at an early stage can receive project development assistance after the first step as long as they have the potential to meet the selection criteria.

4 See (EU) 2019/856, art. 11.

1.4 Methods for developing and selecting instruments

The smart selection and combination of policy instruments is needed to create a long-term climate-neutral industrial sector. Relying on any single instrument will not be enough. The goal of this study is to create a policy toolbox for discussing and achieving the emissions reduction goals of the industrial sector.

In the next section, we present fact sheets for the toolbox instruments and describe an environment in which a comprehensive policy strategy for a climate-neutral industry can arise.

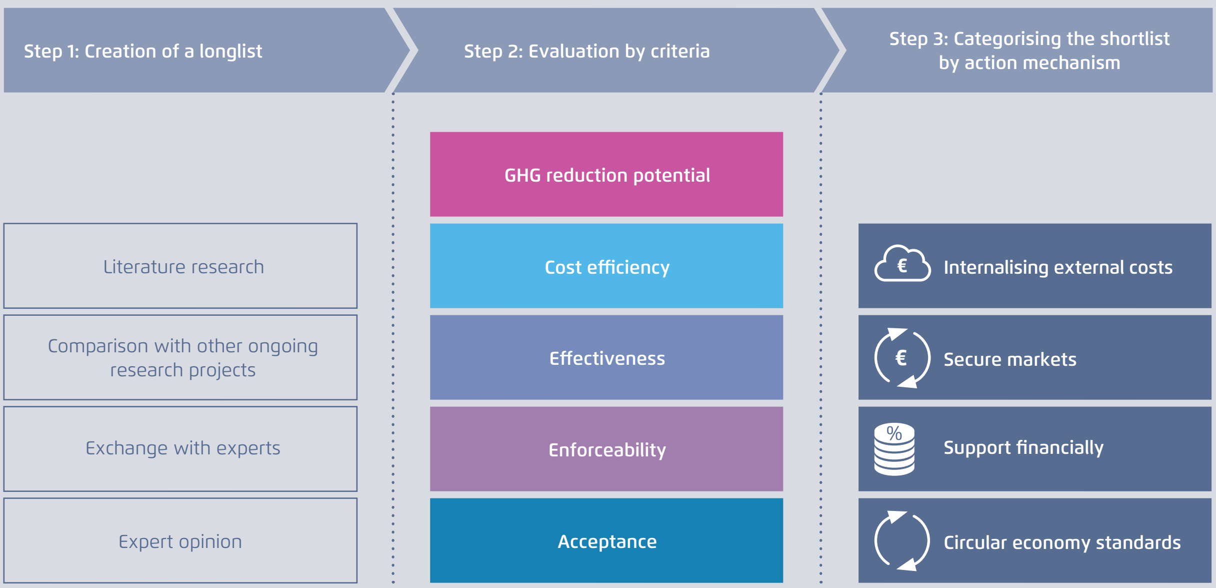
The design of policy instruments for decarbonising the industrial sector has been discussed in various research studies, advisory projects and workshops with representatives from industry, ministries, trade unions and civil society. This report is based on those discussions. To maintain a close link to existing discussions, the selection of policy instruments for the report follows a two-stage process.

First, an inventory was made of all instruments being discussed for the development and launch of low- or zero-carbon industrial processes or infrastructure needed for decarbonising European industry. We drew on a range of reports including IES, 2018; Klimaallianz et al., 2016; Ecofys/Prognos/Universität Stuttgart et al., 2017; IER/EEP/adelphi, 2017; IREES, 2017; and Ecofys, 2017. The long list of policy instruments can be found in Table C.1. The instruments discussed in the literature were divided into three categories: subsidy, charges/surcharges and standards. In order to limit the selection to particularly promising instruments, we subjected the 21 instruments in the longlist to multiple qualitative evaluations using five equally ranked criteria:

We assessed the instruments based on their potential for emission reductions (size of the sectors covered, expected range of application, ability to trigger transformative change); cost efficiency (use of resources in relation to effect); expected effectiveness for supporting key low-carbon technologies;

Process for the selection of policy instruments

Figure C.3



Agora Energiewende, 2021

feasibility and enforceability (administrative cost, legal or political hurdles); and expected acceptance among affected stakeholders. The information used for the evaluation is based on the reviewed literature and the assessments of technical experts. We did not attempt to rank or define the best instruments. Rather, our goal was to assemble a shortlist of promising, highly innovative instruments.

We subsequently discussed and adapted the shortlist over the course of multiple workshops with sector representatives. The overriding aim when selecting instruments for the shortlist was to cover the widest possible range of mechanisms needed for a climate-neutral industry, as described in Figure C.4. The instruments in the shortlist also covered the various development stages of key low-carbon technologies.[5] On the basis of these criteria, we presented ten instruments for discussion in stakeholder workshops.

5 We made an exception for instruments that purely serve to support research and development. The workshops confirmed our impression that these instruments are sufficiently covered by current policies.

Longlist of policy instruments for a climate-neutral industry

Name	Description
Support	
Tax reduction for recycled goods	Support the reuse of goods and the use of recycled materials. One way to do this is to reduce their value-added tax rate.
Reform of the tendering process for energy efficiency measures	Expand existing tenders for supporting energy efficiency from electricity to thermal efficiency and increase the coverage of additional costs.
Accelerated depreciation for investment in energy efficiency	Allow quicker accelerated depreciation of investments in energy-efficiency technologies to make them more attractive for businesses.
Carbon contracts and carbon contracts-for-difference (CCfD)	Cover incremental costs of investing and operating key low-carbon technologies by remunerating the resulting emission reductions, possibly relative to the CO_2 price.
Technology-specific research support	Help the development of specific key low-carbon technologies by subsidising R&D costs.
Accelerated depreciation for investment in GHG reduction	Reduce the effective costs of climate investment by lowering taxes to offset additional costs.
Green financing instruments	Create a credit institute to provide low-interest loans solely for financing investment in climate change mitigation.
Charges, surcharges	
Carbon price floor with border carbon adjustment	Create a rising carbon price floor to establish a plannable price signal for introducing climate technologies. Subject imports from countries without carbon pricing to a charge. Exempt exports from the carbon pricing system.
Carbon price on end products	Impose a charge on products based on the carbon intensity of the materials.
Climate surcharge on end products	Impose a climate surcharge on selected materials or their products (steel, plastic, aluminium, cement) based on volume, irrespective of the production process or origin.
Reduction of fossil fuel subsidies	Reduce direct subsidies or tax benefits for fossil fuels in order not to disadvantage climate technologies.
Reform of power markets for electricity-intensive businesses	Create electricity market instruments that mobilise demand side flexibility and sector coupling, as well as energy efficiency..
Reform of energy taxes	Tax fossil fuels based on their carbon emissions, and reduce the electricity price to make electrification more attractive.
Regulations	
Green public procurement	Ensure that public spending is made in accordance with obligatory sustainability criteria in order to create lead markets for low-carbon and GHG-neutral products.
Clean hydrogen support policies	Introduce support instruments that create a business case for clean hydrogen.
Standards for recyclable products	Require producers of consumer goods to design their products so that they are easier to recycle and reuse.
Extended producer responsibility	Introduce requirements for reverse logistics, deposit systems or fees to oblige the producers of consumer goods for recycling and waste disposal.
Ban on plastic in certain applications	Forbid plastics in disposable products and in products for which ecological alternatives exist.
Quotas for low-carbon materials	Oblige producers of consumer goods to use raw materials with a specified carbon-free share.
Changes in construction and product standards	Revise standards and supplementary regulations in the construction industry that allow the introduction of low-carbon materials and higher material efficiency.
Increased environmental requirements for chemicals	Impose stricter regulations for chemical products to favour solutions based on biomass instead of petroleum-based plastics.

Agora Energiewende, 2021, based on Navigant, 2019

Table C.1

GHG reduction	Cost efficiency	Effectiveness	Enforceability	Stakeholder acceptance

Legend: ☐ Instrument selected for the shortlist attractive ■ ■ ■ ■ □ unattractive

A shortlist of ten policy instruments Figure C.4

	Upstream	Midstream	Downstream
Internalise external costs		Carbon price floor with border carbon adjustment	Carbon price on end products Climate surcharge on end products
Support financially	Clean hydrogen support policies	Green financing instruments Carbon contracts & Carbon contracts-for-difference (CCfD)	
Secure markets			Quotas for low-carbon materials Green public procurement
Circular economy standards			Changes in construction and product standards Standards for recyclable products

Agora Energiewende, 2021

1.5 Shortlist of the policy instruments and stakeholder workshops

In the following fact sheets, every instrument is briefly described along with its mechanism, a brief legal evaluation and information on implementation.

The policy instruments described can be categorised according to various aspects. First, they can be placed into one of three levels in the industrial value chain: upstream (secure access to energy and raw materials at competitive prices), midstream (incentives and direct support for the change of production processes) and downstream (creation of secure markets and regulatory requirements). Second, the instruments can be categorised by their mechanism: internalisation of external costs, creation of secure markets, financing of additional costs and promoting a circular economy & standards. Figure C.4 provides an overview of the instruments for each system of categorisation.

The ten recommended instruments on the (shortlist) were critically discussed in six stakeholder workshops and a series of meetings with technical experts and decisionmakers. Over the course of the workshops, we presented our main interim findings from the technology fact sheets to the technical experts and to the representatives of various industries for discussion. We then presented the complete spectrum of policy instruments described in this report. The participants had the option of selecting particularly interesting instruments for more intensive discussions in small groups. We used the information and insights from these discussions to fine-tune the policy instruments.

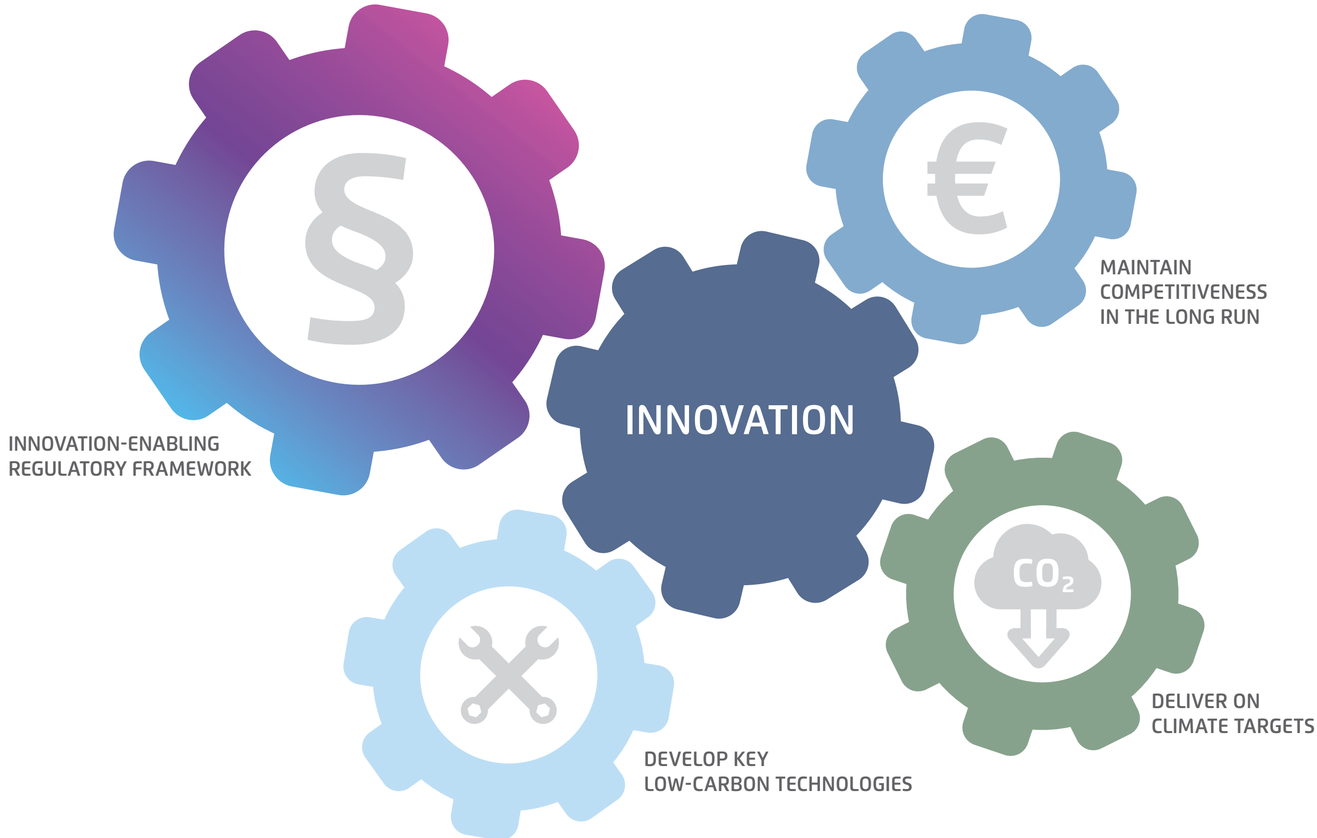
Several instruments promote incremental improvements to the efficiency of production processes and to the internalisation of the external costs of low-emission processes: the **carbon price on end products,** a **climate surcharge on end products** and the introduction of a **carbon price floor with border carbon adjustment** inside or outside the EU ETS. These instruments balance out the cost differences on a continual basis. These instruments can put pressure on industry but alone they are not enough to ensure the sweeping introduction of key low-carbon technologies. To scale market-ready technologies and secure markets for products produced with low emissions, policymakers can introduce **quotas for low-carbon materials** and **green public procurement**. The support for the investment and use of low-emission production processes can be funded by **green financing instruments** as well as **carbon contracts** and **carbon contracts-for-difference (CCfDs) or clean hydrogen support policies**. Finally, **standards for recyclable products** and **changes to construction and product standards** can promote the development and use of key low-carbon technologies and can contribute to higher material efficiency.

Approaches for the policy instruments in the shortlist — Figure C.5

Agora Energiewende, 2021, based on Navigant, 2019

2 Policy instruments

POLICY INSTRUMENTS FOR THE DEVELOPMENT AND MARKET ROLL-OUT OF KEY LOW-CARBON TECHNOLOGIES



CARBON PRICE FLOOR WITH BORDER CARBON ADJUSTMENT (BCA)

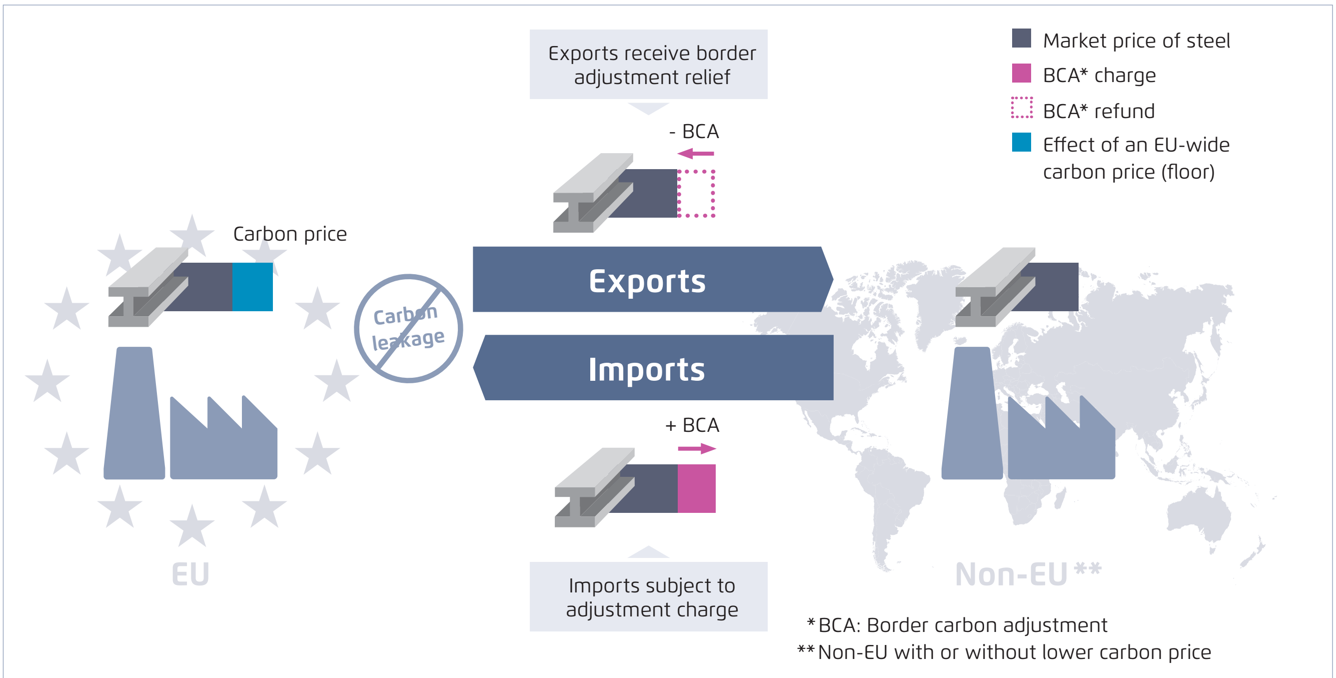
Instrument design

This instrument introduces an increasing carbon price floor in the EU ETS. The mechanism sends a reliable price signal for investments and introduces border carbon adjustment (BCA) charges on imports and reliefs for exports.

Carbon pricing through the EU ETS is an economically efficient instrument for reaching carbon reduction goals and for internalising external costs. An increasing carbon price in the EU ETS in recent years has led to substantial carbon reductions in the power sector. This is not the case in the basic materials industry, however. On the one hand, the majority of emission allowances that businesses receive are freely allocated; on the other, carbon abatement costs of key low-carbon technologies are often significantly higher than the EU ETS price. An increasing carbon price floor sends a reliable price signal and would provide investment security. In order to offset export disadvantages for the energy-intensive basic materials industry, the price of exports at the border would have to be reduced by the amount of the previous carbon charge (Border Carbon Adjustment, BCA). In addition, when significant disadvantages arise for businesses competing on the European market, it will be necessary to apply adjustment charges on imports of carbon-intensive goods within the BCA framework. This would create similar competitive conditions in the domestic market and avoid carbon leakage (SWP, 2018).

As part of its communication on the European Green Deal and the objective of carbon neutrality by 2050, the EU Commission sees BCAs as a key measure to protect industrial sectors from international carbon leakage. However, the instrument is associated with significant difficulties that pose fundamental methodological questions. For starters, should the electricity mix of a country be assumed when evaluating emissions – or can an energy-intensive company declare the purchased electricity to be zero-carbon? The difference would be decisive for, say, countries with higher shares of electricity produced by coal. In addition, there are questions about how to price carbon appropriately for imports from industrial countries and developing nations and how the implicit or explicit carbon price of climate policies in other countries can be compared to the EU ETS price. Moreover, the instrument could be misused for protectionist purposes. There is the risk that trading partners could view a border carbon adjustment as a trade restriction and respond with retaliatory measures. Trade law and trade policy disputes are therefore likely.

Mechanism of the carbon price floor with border carbon adjustment — Figure C.6



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CARBON PRICE FLOOR WITH BORDER CARBON ADJUSTMENT

A high carbon price in the EU ETS coupled with a border carbon adjustment is an efficient instrument from an economic point of view and guarantees a level playing field for industry.

INSTRUMENT TYPE

- ☐ Subsidy
- × Charge/surcharge
- ☐ Regulation

DECARBONISATION LEVER

- × Energy efficiency
- × Change of energy source
- × Process optimisation & substitution
- × Resource efficiency & material substitution

SECTOR APPLICABILITY

× Cross-cutting technologies × Steel × Chemicals × Cement × Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

Development			Market entry		Existence
Research	Scaling	Creation of green markets	Investment	Operating costs	Optimisation (plant/product)

AREA OF APPLICATION

The instrument applies to all emission sources from industrial and energy sectors registered in the EU ETS as well as to the import of carbon-intensive goods. All key low-carbon technologies whose carbon abatement costs are lower than or equal to the carbon price become competitive.

DURATION OF EFFECT

The border carbon adjustment would be coupled to the international development of emissions trading and the price development in the EU ETS. If carbon prices in other G20 economies are introduced, the BCA could potentially be lifted or applied only to other countries without a comparable carbon price level.

NECESSITY OF CARBON TRACKING

- × mandatory
- ☐ helpful
- ☐ not necessary

STATE OF THE DISCUSSION

A carbon price floor already exists in many emissions trading systems (e.g. California, Great Britain). The EU Commission and the European Council are discussing BCA as an element of the European Green Deal and as a potential direct revenue source for the EU budget. Border charges have been under discussion for a while now, but their feasibility is disputed (SVR, 2019). Exporting industries and nations are traditionally reluctant to endorse and implement border carbon adjustment measures. The instrument is supported by professional organisations (including EUROFER), governments (including FR) and the European Council, the European Parliament as well the president of the EU Commission, Ursula von der Leyen.

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

Depending on the scope of and participation in an EU ETS price floor, the total price of allowances could fall, reducing the overall effect on emissions reduction (waterbed effect[1]). To counter this, the carbon price floor should be combined with other measures, such as the cancellation of EU ETS allowances. But uncertainty around eventual tax set-offs for exports and the possibility of an inadequate carbon price floor mean that this instrument alone will not suffice to motivate large investment projects in comparatively expensive technologies. Accordingly, additional instruments besides the price floor will be needed to incentivise investment. These include quotas for low-carbon materials or carbon contracts-for-difference to promote investments in key low-carbon technologies with abatement costs above the price floor.

Financing

The additional costs stand to affect emitters registered in the EU ETS, who would then pass these on to consumers. The border charges that may potentially be levied on imports would increase prices for carbon-intensive goods. The extra income from carbon pricing could be used to support affected consumers, as it does in Canada (Engie et al., 2018).

Design options

The instrument could be formally implemented both inside and outside the EU ETS process. Within the EU ETS, the price floor could be implemented as a reserve price in the auctioning of EU allowances. But this would require amending the EU ETS directive, which is only possible with a unanimous decision by member states.[2] Outside the EU ETS, a short-term price floor could be introduced within a single nation, as in Great Britain and the Netherlands, or with like-minded neighbouring countries. A primary energy charge could balance out the difference between the price floor and the actual EU ETS price (PIK, 2018; Agora Energiewende, 2018). The border adjustment would not apply in countries with carbon pricing comparable to that of the EU. This would motivate countries who want unimpeded trade with the EU to introduce an equivalent carbon pricing regime.

The border adjustment instrument has its difficulties, however. In principle, a border adjustment can only be introduced throughout the entire EU or European Economic Area (EEA). Otherwise goods could be imported to the joint European market from EEA countries without a border adjustment system in order to get around a border adjustment in countries that do. But even were the border carbon adjustment to apply to all of the EU, the administrative costs for determining the carbon intensity of all imports and exports would be high. The data collection would be particularly complicated for processed products whose exact material composition is unknown. General assumptions could reduce the complexity, but these would have to be legally assessed. Exempting imports from countries with sufficient carbon pricing would further increase costs. It is doubtful whether the instrument conforms to WTO rules, as the brief legal assessment makes plain. Consequently, it is likely to face objections and be subject to arbitration.

Special features

As part of the EU ETS Reform, the EU could increase carbon floor prices for the covered sectors. In parallel, the EU could encourage other countries to implement a comparable price floor. This would exempt them from the border carbon adjustment mechanism and forge preferential trade relations with countries that have comparable ambitions for climate change mitigation.

1 The waterbed effect occurs when reductions in one EU country are negated by increased emissions in another. It arises because the reduction of emissions frees up emissions trading allowances, which can then be used by emitters in other countries. Starting in 2021, it will be possible for countries to cancel a number of their allowances to account for the emission-reducing effect of their domestic policies.

2 In the Emissions Trading Scheme, a portion of the allowances is auctioned on the market. The carbon price floor could be implemented as an *auction reserve price* in the EU ETS, which means that only offers above the price floor are accepted and any unsold allowances are cancelled after the auction. This would ensure that the carbon price was no lower than the price floor.

Aspects of implementation

Legal assessment

- In principle, WTO rules would allow the introduction of an EU border carbon adjustment as long as imported and domestically produced goods are treated equally. However, such a measure would not compensate exports for the higher carbon cost that they face when produced in Europe.
- WTO rules do not exclude averaged BCA calculations for foreign products. The calculations must be based on appropriate criteria, however. It is important that they do not have a discriminatory effect on the domestic system.
- A border carbon adjustment in combination with a price floor through the EU ETS would be more difficult to implement within the WTO framework. The border charge applies to a production process of the product, not to a characteristic of the product. Whether the WTO permits charges based on the production process is disputed.
- At the European level, the introduction of a carbon price floor within the EU ETS is legally possible in principle but requires an amendment to the EU ETS directive.

SWOT analysis

STRENGTHS

- The market decides across sectors on the most favourable carbon abatement technologies – very high efficiency
- Planning security for climate investment
- Energy tax reform based on a national carbon price floor can be implemented quickly

OPPORTUNITIES

- There is a clear political will to create a carbon price floor in important EU countries including France and the Netherlands
- The introduction of a price floor for EU trading partners could be an attractive option for circumventing the border carbon adjustment

WEAKNESSES

- Border carbon adjustment and exceptions can limit the effectiveness of a uniform price signal
- High administrative costs for border carbon adjustment
- Determining the carbon footprint emitted in the production of imported and exported products is very expensive
- The carbon price or carbon price floor needs to be sufficiently high (at least 100€/t of CO_2) in order to create a business case for most key low-carbon technologies

RISKS

- Border carbon adjustment may not conform to WTO rules (particularly in combination with European carbon price floor)
- Could further aggravate global trade conflict
- Countries with a carbon-intensive electricity mix could attempt to circumvent the system with green guarantees of origin, likely leading to legal disputes at the WTO

CARBON CONTRACTS-FOR-DIFFERENCE (CCFD)

Instrument design

Carbon contracts offer payments for emission reductions achieved with key low-carbon technologies to compensate for their incremental cost compared to GHG-intensive production processes. Carbon contracts-for-difference (CCfDs) complement the effects of the EU ETS and compensate for insufficient and variable carbon prices.

Key low-carbon technologies generally entail higher investment and operating costs than conventional technologies. Carbon prices in the EU ETS fluctuate and are too low to justify investments in most key low-carbon technologies. Moreover, the CO_2 price signal will not be effective if the low-carbon technologies do not receive the free EUA allocations that are awarded to conventional technologies to protect them from carbon leakage. As a result, the current EU ETS design promotes efficiency improvements of conventional technologies but does not support investments in key low-carbon technologies.

Carbon contracts and CCfDs are options that complement the EU ETS to promote and ensure transformative investments. They provide state-guaranteed payments for the CO_2-abatement obtained by key low-carbon technologies and compensate for their incremental costs relative to GHG-intensive incumbent technologies. Depending on the design and effects of the EU ETS in terms of free allocations for incumbent and key low-carbon technologies, different scenarios need to be considered, as illustrated by Figure C.7.

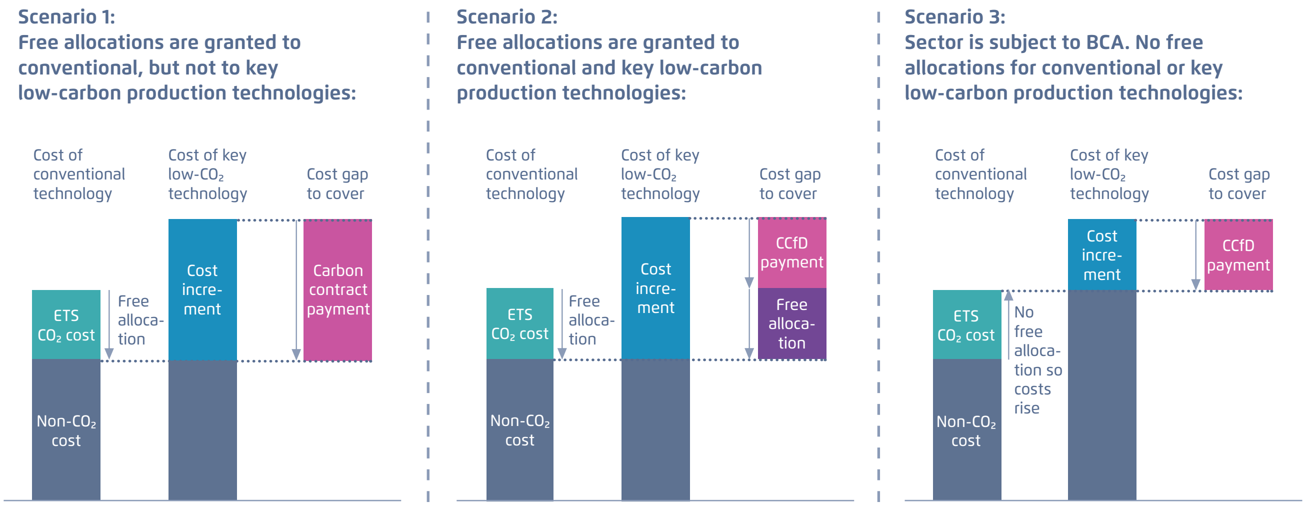
Scenario 1: Carbon contracts to compensate full incremental costs
With current regulation, most key low-carbon technologies do not receive the free allocations that are awarded to incumbent technologies. If this situation remained in place, the incremental producion costs compared to GHG-intensive technologies would not depend on the EU ETS price and have to be fully compensated by a carbon contract.

Scenario 2: CCfD in combination with free EUA allocations
If key low-carbon technologies do receive free allocations, their sale will cover part of the incremental costs that result from their operation. In this case, CCfDs must compensate for the variable difference between the market value of these allowances and the CCfD contract value that was defined to cover incremental production costs.

Scenario 3: CCfD in the context of a BCA regime
The objective of a BCA regime is to protect industry from carbon leakage without the need of issuing free EUA allocations. The result is an effective carbon price and the CCfD has to cover the difference between the effective carbon price and the CCfD contract value.

Carbon Contracts-for-Difference

Figure C.7



Note: Under the current EU ETS carbon leakage protection system, energy-intensive industries with high trade exposure receive free EUA allocations to maintain their production cost at the level of international competitors with equally GHG-intensive processes. This cost, which is largely independent from the carbon market price, is the reference for the calculation of the CO_2-abatment cost that results from producing with key low-carbon technologies. This incremental cost can be covered fully with a carbon contract (Scenario 1) or by a combination of free allocations also for key low-carbon technologies and the payment of a CCfD (Scenario 2). In case the system evolves towards a Border Carbon Adjustment (BCA) without free allocations to energy-intensive and trade-exposed industries, the production cost of GHG-intensive technologies increases and the payment of the CCfD reduces accordingly. This illustrates that the CCfD is compatible with a future BCA and increasing carbon prices but allows to mobilise urgent investments now.

Agora Energiewende, 2021

CARBON CONTRACTS-FOR-DIFFERENCE (CCFD)

This instrument reduces financing risks and incentivises investments and production with key low-carbon technologies that are compatible with climate neutrality.

INSTRUMENT TYPE

- ☒ Subsidy
- ☐ Charge/surcharge
- ☐ Regulation

DECARBONISATION LEVER

- ☐ Energy efficiency
- ☒ Change of energy source
- ☒ Process optimisation & substitution
- ☒ Resource efficiency & material substitution

SECTOR APPLICABILITY

- ☒ Cross-cutting technologies
- ☒ Steel
- ☒ Chemicals
- ☒ Cement
- ☐ Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

AREA OF APPLICATION

This instrument addresses high-volume, innovative technologies in the basic materials industry that are compatible with climate neutrality and that have moved beyond the demonstration phase. Examples include: hydrogen-based production of direct reduced iron (steel), methanol-to-olefin/-aromatics route (chemicals) and carbon capture with the oxyfuel process (cement).

DURATION OF EFFECT

Depending on technology-specific necessities, CCfDs can be structured as an interim solution to anticipate higher carbon prices and changes in EU ETS regulations or to offer stable, long-term support for capital-intensive investments like the production, transport and use of hydrogen. In any case, CCfDs should be complemented with appropriate exit strategies, such as the substitution with high carbon prices in the context of a BCA, an appropriate global agreement or the development of green lead markets that create an alternative revenue source. Depending on the specific necessities, the duration of CCfDs can vary from a minimum of five to a maximum of 20 years.

NECESSITY OF CARBON TRACKING

- ☐ mandatory
- ☐ helpful
- ☒ not necessary

STATE OF THE DISCUSSION

The carbon contract is based on an idea by Helm and Hepburn (2005). The concept of a CCfD was developed by the German Institute of Economic Research (DIW/Richstein, 2017; DIW, 2019). CCfDs are also under discussion at the European level (IDDRI, 2019). Agora Energiewende is currently developing concrete proposals for the implementation of carbon contracts for the steel, cement and chemical industry (2021, forthcoming).

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

CCfDs are suited to fill a noticeable gap in the funding world: support for the commercial scaling of innovative low-carbon technologies with operational costs that exceed those of incumbent technologies. With this capacity, CCfDs are an ideal complement to existing instruments that focus on supporting investment costs. In addition to this synergy, other potential policy interactions must be considered:

- CCfDs must be designed in synergy with policy instruments that affect energy prices, such as the cost for electricity generation, surcharges, and grid fees, as well as for fossil fuel alternatives.
- CCfDs trigger GHG abatement industries covered by the EU ETS and thus influence the balance of available EUA. These effects need to be considered when defining the EU ETS cap or the retirement, use and effect of EUA allowances that are made available by the instrument.
- Projects triggered by the CCfDs may impact the benchmark setting for the definition of free EUA allocations of existing production units.

Financing

Initially, CCfDs can be funded with existing sources, such as the EU Innovation Fund and member state budgets. Ideally, sources are combined to structure synergetic effects between CCfDs that support incremental operational costs with instruments that support investment costs. At the same time, nondiscriminatory climate surcharges on final products should be established as a reliable refinancing instrument, as discussed in the specific policy fact sheet.

Design options

The design of CCfDs must be specific to the necessities and objectives of different technologies and their context in terms of supporting infrastructure. Design options can be discussed based on the following aspects:

i) Project selection: Investments with key low-carbon technologies are site-specific and strategic for the development of key infrastructures for transformation. Initially, such investments require individually designed CCfDs with payments that cover project-specific GHG abatement costs. Over time, such project-specific support contracts may evolve to the auctioning of CCfDs.

ii) Contract duration: Contract duration should be defined based on needs, objectives and the combination with other support instruments. For projects that imply large investments and high incremental costs, longer durations are required.

iii) EU ETS interaction: EU ETS rules for free allocations have very sector-specific impacts on key low-carbon and reference technologies. These impacts and their possible evolution during the contractual lifetime must be considered in the CCfD design.

iv) Dynamisation: Incremental costs of producing with key low-carbon technologies relative to GHG-intensive technologies depend on a multitude of factors such as cost variations in energy carriers and raw materials. To minimise the resulting risk of excessive or insufficient state aid for investors and the public sector, it is useful to adjust CCfD payments accordingly. The CCfD already includes a dynamic adjustment to the carbon market price, a feature that can be expanded to cover relevant energy price or raw material indices.

v) Delivery obligations: CCfDs can be designed with or without the requirement to deliver a specified volume of GHG abatement. If investors are not obliged to the delivery of a specified contractual volume, the CCfD is a put option, a design that minimises technological and economic risks. However, in cases where the investment is an anchor for an extended value chain, e.g., the production and transport of hydrogen, it is necessary to structure appropriate obligations to support these downstream investments.

vi) Synergy with green lead markets: CCfDs aim to support the investment and operation of key low-carbon technologies with the payment of an appropriate CO_2-reduction premium. Because of the legal provisions for such state aid, further marketing and crediting of the resulting CO_2 reduction is not permitted. However, it is important to encourage companies to market and sell low-CO_2 and climate-neutral products (and the implicit CO_2 reduction) to support the development of green lead markets. Both objectives can be met by allowing investors to opt out of the CCfD payment and sell their products as green if an appropriate premium can be achieved on the market.

These aspects of CCfD design provide a provisional overview of relevant elements that need to be carefully balanced to design efficient support mechanisms for different sectors and projects.

Aspects of implementation

Legal assessment

- When designing the measure, attention should be paid to ensure that bidders abroad are not discriminated (art. III GATT, XVII GATS and art. 30, 110 TFEU).
- Depending on the financing mechanism, CCfDs may constitute a state aid acc. art. 107 TFEU. However, the notification now comes with inherent legal risks (see legal assessment for H-CfD).
- CCfDs can be implemented both at the national and European level.
- At the national level, CCfDs do not require authorisation by the European Commission, if funding is not provided by state funds.
- If a climate surcharge is used in order to finance a CCfD, then the possibility for a notification by the European Commission depends on whether the state has control over the financial resources.
- At the European level, CCfDs can for instance be financed by, say, the EU Innovation Fund and by programmes outside of the EU ETS.

SWOT analysis

STRENGTHS

- CCfDs can support innovative technologies in the critical and economically challenging phase between pilot project and market readiness (the so-called valley of death)
- Can be aligned to specific technologies and sectors
- The dynamisation of support payments with carbon price and other indices allows to minimise risks for investors and the state

OPPORTUNITIES

- CCfDs have great potential to bring key low-emission technologies to the market
- They can help establish Europe as a lead market for certain key low-emission technologies
- CCfDs can support the development of green lead markets also outside of Europe

WEAKNESSES

- Complexity of design and associated transaction costs make CCfDs best suited for large funding projects

RISKS

- Depending on design, technology and regulatory circumstances, the costs may be high
- Uncertainty on the future of the EU ETS can make contract design complex

GREEN FINANCING INSTRUMENTS

Instrument design

State measures can reduce financing costs for investment in key low-carbon technologies.

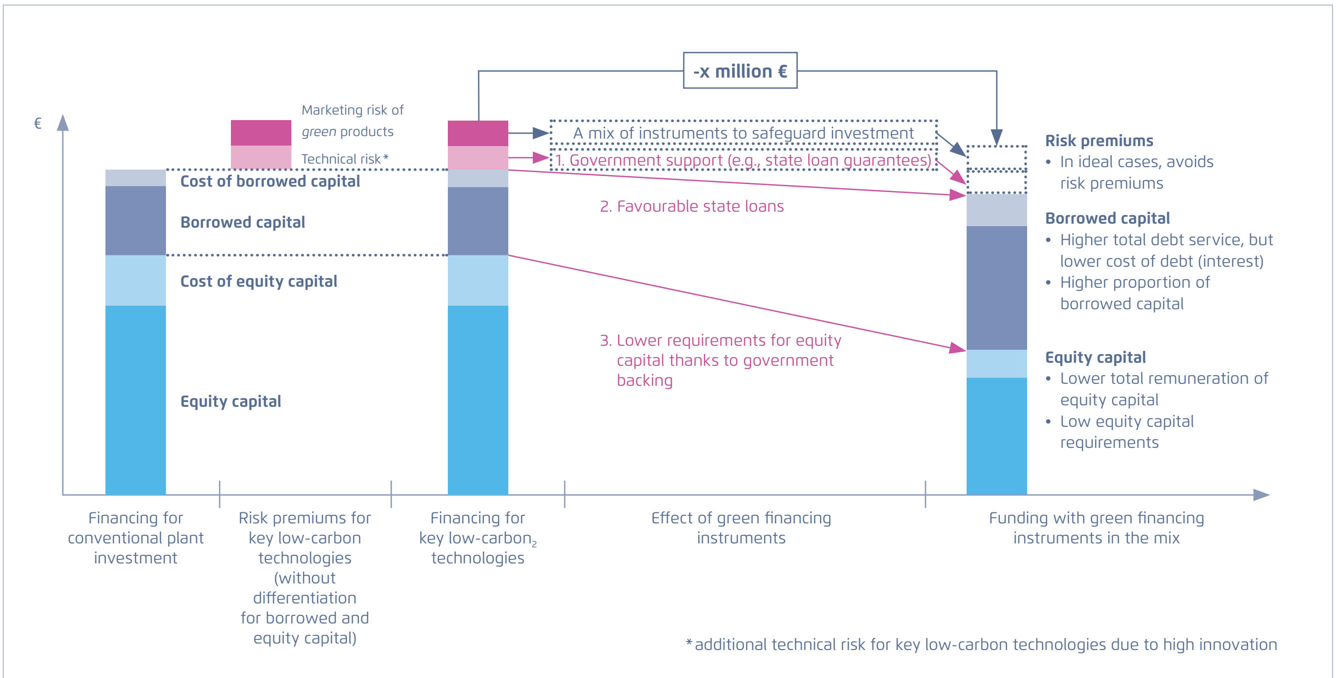
A climate-neutral industry will require significant additional investments. Instruments for reducing financing costs can significantly reduce the full costs of transformational technologies.

Approach 1: Favourable state loans
The state can pass on its low financing costs to businesses for climate-friendly investment. States generally have a significantly lower insolvency risk than companies. By assuming part of the financing costs, the state can pass on its interest advantages to businesses. This provides businesses with external capital at lower costs than those offered by private capital markets (KPMG, 2018). In addition, private capital can be leveraged with appropriate de-risking strategies. Examples are governmental guarantees or mezzanine finance products to compensate for technology risks. Demand-side and market risks can be minimised with instruments that create secure demand, such as public procurement and product quotas. Sufficient revenues for key low-carbon technologies with higher operational costs can also be guaranteed with carbon contracts-for-difference. This approach is especially relevant for technologies that are nearly market-ready (TRL 8 and 9).

Approach 2: Government guarantees to protect against the risk of failure in the final stages of technology development
The development of new technologies is associated with higher risks – and higher risk premiums – than conventional technologies. If the state takes on some of the risk in the last stages of development (TRL 5-9), the financing costs can be reduced. The state could assume the risk for demonstration plants under tightly defined criteria (e.g. in the event of a failed test and a total loss) in order to minimise the risk premiums of private lenders. With state backing, banks can grant loans at near market rates. Furthermore, the state guarantee would also send a signal to investors that the investment is fairly secure. In particular, state *green bonds* can steer additional capital to industry at lower financing costs. Businesses continue to bear the business risk but they can avoid high-risk premiums. State guarantees should not be used for funding the early phases of technological development (TRL 1–5). For those phases, research funding and venture capital (BDI/ BCG, Prognos, 2018; BCG, 2018) are the better choices.

Mechanism of green financing instruments

Figure C.8



Agora Energiewende, 2021

GREEN FINANCING INSTRUMENTS

Reduced interest rates for climate investments can supplement other decarbonisation policies.

INSTRUMENT TYPE

- [x] Subsidy
- [ ] Charge/surcharge
- [ ] Regulation

DECARBONISATION LEVER

- [x] Energy efficiency
- [x] Change of energy source
- [x] Process optimisation & substitution
- [x] Resource efficiency & material substitution

SECTOR APPLICABILITY

- [x] Cross-cutting technologies
- [x] Steel
- [x] Chemicals
- [x] Cement
- [x] Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

AREA OF APPLICATION

Approach 1 includes climate investments that make sense from a macroeconomic perspective, but not from a business perspective. Such climate investment often includes capital-intensive measures. Only technologies with near market-ready risk-return profiles benefit; new technologies with high risk premiums do not.

Approach 2 reduces financing costs for investment in key low-carbon technologies in the final stages of development (TRL 5–9).

NECESSITY OF CARBON TRACKING

- [ ] mandatory
- [ ] helpful
- [x] not necessary

DURATION OF EFFECT

Financing support only needed until climate technologies are competitive at normal market interest rates.

STATE OF THE DISCUSSION

- Green bond incentives in bank regulation: In discussion at the EU level (EU HLEG, 2018)
- Governmental provision of/backing for loans is already being practised to a degree by banks such as the KfW Development Bank in Germany and the World Bank
- Green quantitative easing is under discussion in expert circles (I4CE, 2018)
- Fiscal incentives: In Brazil, loans for infrastructure investment are subsidised with tax reductions (Oliver Wyman, 2014). To date, no known example exists in the area of climate.

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

Even if climate technologies become more economical through low interest rates, the government must create pressure to act ("demand") and secure markets for climate-friendly technologies ("support") in order to motivate businesses effectively. Alongside favourable loans, businesses also need instruments such as carbon price floors, green public procurement, and a quota for zero-carbon materials.

Financing

- *Green bond* incentives in bank regulation: An instrument that reduces regulatory demands for climate investment rather than penalising investment that harms the climate would take pressure off banks.
- The government provision of loans or loan guarantees may possibly lower costs for business development banks.
- Green quantitative easing: low costs for central banks; inflation effects possible depending on scope of money creation; extends the mandate of central banks beyond their actual remit.
- Fiscal incentives: lost government income from withholding tax to the full extent of the interest reduction.

Design options

There are various design possibilities for the instrument (I4CE, 2018).

- It can incentivise or obligate banks to buy green bonds by means of equity capital requirements.
- State development banks could provide low-interest loans themselves or secure loans from private institutes in order to mobilise private money for climate investment.
- Central banks could in turn make indirect money for climate investment available through the purchase of green bonds (green quantitative easing).
- On the fiscal side, interest rates for climate-friendly investment could be indirectly reduced by eliminating capital gains taxes.

For all design options, a uniform and ambitious definition of climate-friendly investment is needed to create the necessary financing products. The EU Commission is currently working on such a taxonomy (European Commission, 2019a).

Special features

Other instruments such as a carbon floor price or carbon contracts-for-difference (CCfDs) make climate technologies more competitive. Nevertheless, some of the necessary investments will not be profitable for businesses with loans at normal interest rates. This is where cheaper loans for climate investment come in.

Aspects of implementation

Legal assessment

- In principle, the above design options stand up to legal scrutiny.
- Policymakers must make sure that domestic and foreign suppliers are not treated differently. (See. Art. III GATT and XVII GATS.)
- As for state aid, the risks are minimal in terms of European law. Depending on the design and financing mechanism, green bonds can be qualified as state aid acc. to art. 107 TFEU. If so, it is highly likely that a notification either in accordance with the General Block Exemption Regulation (GBER) or with the ruling of the EU Commission based on the Environmental and Energie Aid Guidelines (EEAG) would be possible.
- The instrument does not impair the free movement of capital.
- The implementation of financing assistance is possible within existing law in the case of the government provision or safeguarding of loans. Green bonds require the introduction of uniform European standards and changes to equity capital requirements. Green quantitative easing requires an expansion of the legal responsibilities.

SWOT analysis

STRENGTHS	OPPORTUNITIES
• Current low interest rates in the EU mean low additional costs for the instrument • Very effective for capital-intensive technologies with a long lifespan, which includes most key low-carbon technologies and efficiency investment	• Political momentum due to the increasingly large role played by green capital investment • Proactively involves capital markets in the transformation • Non-governmental initiatives such as the *Carbon Risk Management Tool* (Carima), the *Task Force on Climate-related Financial Disclosures* (TCFD) and the *Carbon Disclosure Project* (CDP) can ease the implementation of climate measures in the capital market by providing transparency
WEAKNESSES	**RISKS**
• "Climate investment" not yet clearly defined • A low equity capital requirement increases a business's share of borrowed capital. This increases a business's debt ratio, which can downgrade its credit rating and increase the costs for all investment	• An end to the low-interest rates in the EU could significantly increase the costs of the instrument • State backing limits business risk but creates the danger of moral hazard • Mixing monetary policy and financial-market regulation with climate policy goals raises fundamental questions about the mandate of monetary policy

CLIMATE SURCHARGE ON END PRODUCTS

Instrument design

The instrument consists of a surcharge levied on selected materials (steel, plastic, aluminium and cement) by weight. The revenues go to fund other climate policy instruments.

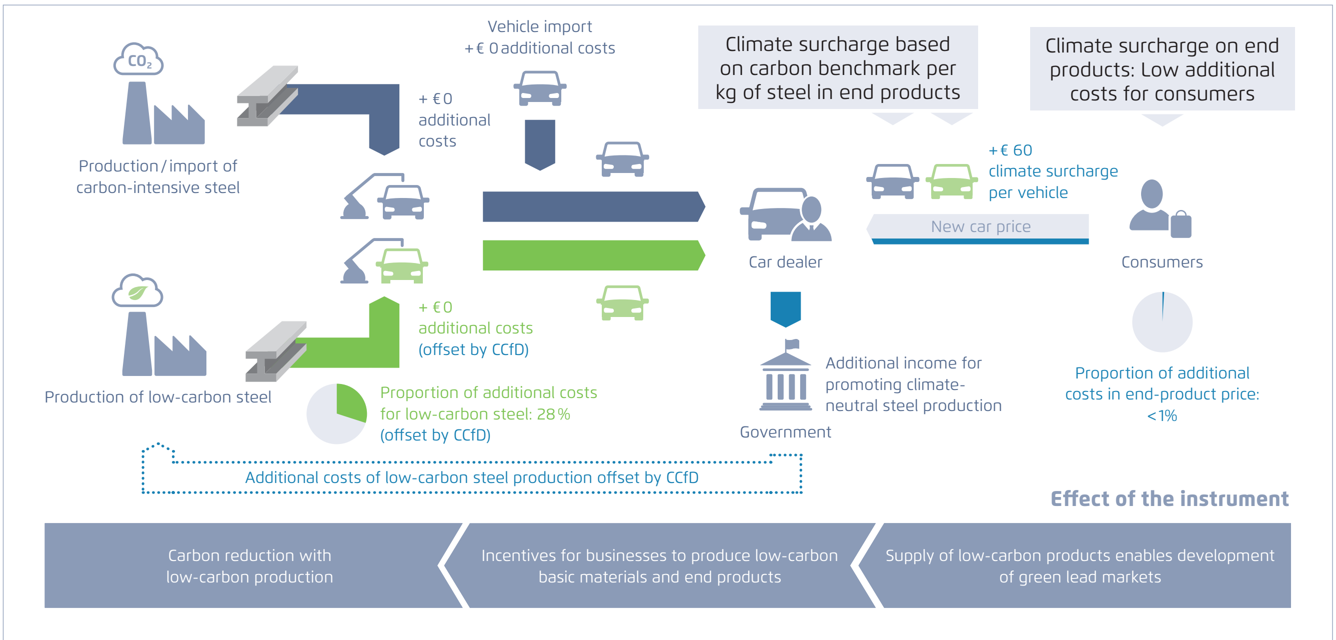
A large part of industrial GHG emissions come from the manufacture of a small range of basic materials (steel, aluminium, cement and plastics). Pricing these materials at production (say, via the EU ETS) can only be implemented in a limited way, as even small increases in price can endanger competitiveness on global commodity markets. To prevent businesses from moving abroad, basic materials producers receive the majority of their carbon allowance for free, but this reduces their motivation to produce carbon-free products.

A climate surcharge on end products targets selected materials at the point of consumption, regardless of where they are produced. When buying a washing machine, for instance, a charge would be due based on the weight of the steel used in the washing machine.

In order to reduce administrative costs, products where the charge is below a certain threshold are excluded. At first, the charge could be raised on steel, aluminium, cement and plastics. The instrument does not draw a distinction based on how much CO_2 has been released during the production process. This means that zero-carbon steel is charged the same amount as conventional steel. Unlike the carbon price on end products, the climate surcharge does not require carbon footprint tracking.

The pricing also creates an incentive to reduce the proportion of carbon-intensive materials in products. Because imported materials are subjected to the charge, but exports are not, there is no disadvantage for national products for domestic consumption and for export. This eliminates the risk of carbon leakage. The income from the climate surcharge on end products can be used for funding other climate policy instruments (e.g. CCfD).

How a climate surcharge on end products would affect steel processing in the automotive industry – an example Figure C.9



Agora Energiewende, 2021 Assumptions for calculation: 0.8 tonnes of steel per passenger car; 150 euros of additional costs per tonne of low-carbon steel

CLIMATE SURCHARGE ON END PRODUCTS

The instrument generates income for other instruments (e.g. CCfDs). There is only a small cost for end consumers, but it creates incentives for material efficiency.

INSTRUMENT TYPE

- [x] Subsidy
- [x] Charge/surcharge
- [ ] Regulation

DECARBONISATION LEVER

- [ ] Energy efficiency
- [ ] Change of energy carrier
- [x] Process optimisation & substitution
- [x] Resource efficiency & material substitution

SECTOR APPLICABILITY

- [ ] Cross-cutting technologies
- [x] Steel
- [x] Chemicals
- [x] Cement
- [x] Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

AREA OF APPLICATION

Physical goods made of materials with high carbon intensity (steel, aluminium, cement and plastics).

DURATION OF EFFECT

The instrument would remain in force as long as there is no accurate international tracking system in place for the carbon footprint of materials or as long as a worldwide alignment of carbon prices does not occur.

NECESSITY OF CARBON TRACKING

- [ ] mandatory
- [ ] helpful
- [x] not necessary

STATE OF THE DISCUSSION

Recommended by the *Climate Friendly Materials Platform*. A similar approach is being discussed by policymakers in Germany and the EU under the rubric of a plastic tax, intended primarily to eliminate waste.

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

In order to avoid a double charge, goods that fall under the climate surcharge would have to be excluded from other environmental charges such as the carbon price imposed by the European emissions trading system. Installations that are covered by the EU ETS would therefore have to be compensated financially, i.e. through the free allocation of EU ETS allowances or other mechanisms. As trade-exposed industries already receive free allowances, this condition is met, but the combination with a climate surcharge would prevent a reduction in the volumes of free EU allocation as envisaged by EU policy. As a result, current product benchmarks that define the level of free EUA allocation would need to be fixed at a level that compensates emission intensive technologies for the carbon cost that is being imposed by the climate surcharge on end products.

Financing

End consumers bear the costs, but these are low relative to the product price itself. For example, a small passenger car that would cost 60 euros more can generate significant funds to finance support instruments for transformative investments such as a carbon contract or CCfD. A moderate steering effect on material efficiency and substitution can be expected. While end consumers are not generally price-sensitive to such a small price increase, even small price signals can influence purchase decisions in business procurement of the automotive industry or retail.

Design options

In the initial version (limited to steel, aluminium, cement and plastics), the instrument is relatively simple to implement, as the charge is calculated on the basis of the weight of the materials, which serves to approximate its carbon intensity (DIW, 2016). In addition, governments already have a wealth of experiences with consumption-based charges (e.g. for tobacco, alcohol and energy). One tonne of steel in a vehicle would be charged with a flat rate, independent of the actual emissions released in its production. The charge is not due immediately on production; rather, it is passed down the value chain as part of a charge suspension procedure. The charge is only due when sold to an end consumer or a business that is not exempt from the charge. All exported products are exempt.

Specific features

The instrument has many similarities to a carbon price on end products. The difference is that the climate surcharge on end products is not pegged to the exact amount of carbon that arises from the production of a basic material. For instance, this would mean that carbon-free steel is charged just as much as conventional steel. The instrument's great advantage is that there is no need to track a product's carbon emissions.

Aspects of implementation

Legal assessment

- Introduction of a climate surcharge on end products is legally permissible in principle. A number of considerations should be kept in mind, however.
- As a charge on consumption, the instrument is compliant with WTO rule as long as the equal treatment of imported and domestically produced materials is ensured. (See art. III GATT and art. 110 TFEU.) Governments may not impose higher surcharges for imported products than for domestic products. Moreover, flat rates must also be based on verifiable and robust assumptions.
- Depending on the design, a border carbon adjustment system for products with a foreign element may be necessary – however, this is not generally permissible according to WTO rules.
- If producers included in the European emissions trading scheme are covered by the surcharge, the product's carbon footprint may be charged twice – at the point of production and the point of consumption. To avoid double charging, the climate surcharge must be compensated by a continued issuance of free allocations or an equivalent exemption from the effects of the EU ETS.
- An adjustment mechanism in the form of a free allocation of emission allowances will require a change to the EU ETS directive, namely, the rescinding of the regulation in art. 10 para. 1 RL (EU) 2018/410. It is possible that the technology benchmarks would have to be frozen at current levels.
- If needed, an adjustment mechanism can be used to justify the equal or unequal treatment of products that is deemed unconstitutional.

SWOT analysis

STRENGTHS
- Creates income for funding other instruments (e.g. CCfDs)
- The market determines material efficiency and the most favourable alternative technologies
- No carbon leakage risk because surcharge also applies to imports
- Both imported materials and those produced domestically are treated equally
- No global carbon tracking necessary
- A flat rate is not discriminatory and thus complies with world trade rules and the European law

OPPORTUNITIES
- Can be restricted to specific products (steel, cement, etc.)
- Low costs for end consumers
- Can help to create a global level playing field for transformative investments in heavy industry (e.g. if revenues are used to finance low-carbon technologies via CCfDs)
- Creates an introduction to comprehensive material pricing

WEAKNESSES
- Comprehensive implementation needed at the EU level
- An opening clause for member states may be possible, but would require changes of the EU ETS directive

RISKS
- Can lead to unwanted use of materials not subject to the charge
- Undermines the logic of a gradual reduction of free EU allowances envisioned by the EU ETS
- Uncertain whether it is permitted as an additional national measure for emitters included in the EU ETS

CARBON PRICE ON END PRODUCTS

Instrument design

The instrument consists of a surcharge based on the carbon footprint of the materials that compensates for the cost disadvantage of low-carbon products. The revenue can be used to fund other instruments.

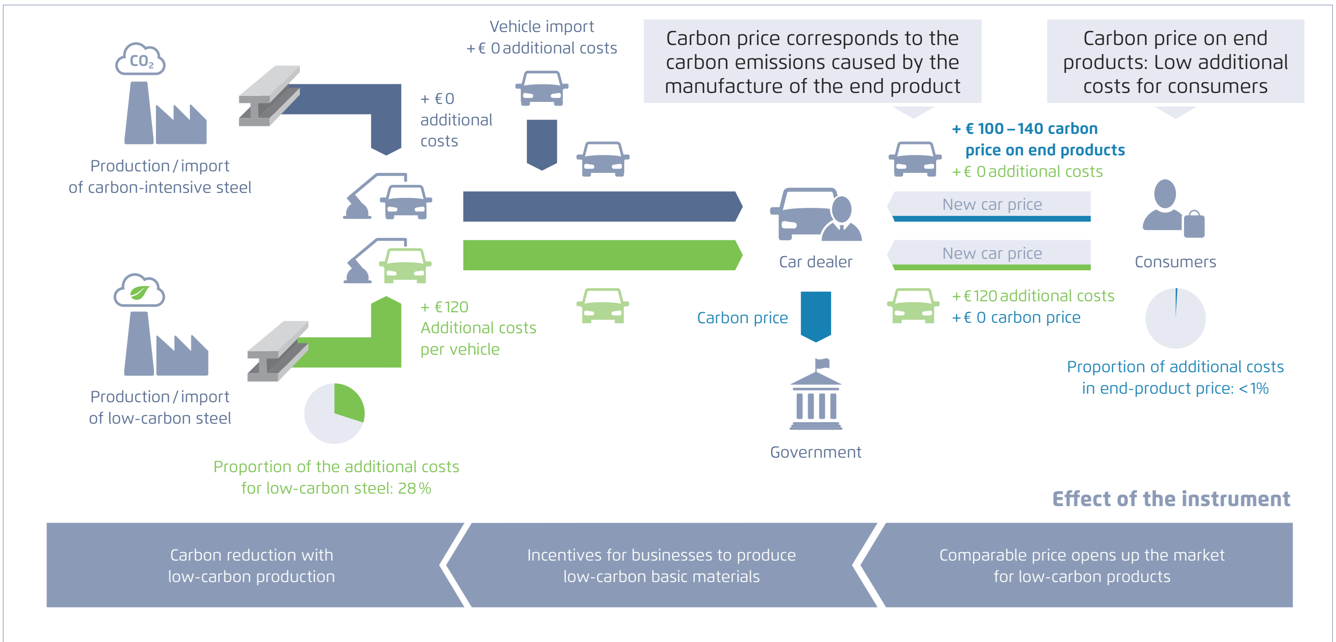
A large portion of industrial GHG emissions comes from the manufacture of materials for end consumer products (ETC, 2018a). Carbon pricing for the production of, say, plastics, aluminium or steel, can only be implemented in a limited way, as even small increases in price can endanger a company's competitiveness on the global commodity markets. Because this can lead to carbon leakage, carbon-intensive industries in the EU ETS receive the majority of their carbon allowances free of charge.

By contrast, the carbon price on end products prices the carbon emissions of materials at consumption instead of at production. For example, when purchasing a soft drink in a plastic bottle, a consumer would pay a surcharge on the carbon emissions released in the production of the bottle. A plastic bottle from carbon-neutral production would not be charged. As a result, the higher manufacturing costs (on account of, say, chemical recycling) can be passed on to the customer. In contrast to the climate surcharge on end products, where all products whether climate-neutral or not are charged by weight, the carbon surcharge is based on a specific product's carbon footprint. This means that the additional costs for the consumer remain limited. A soft-drink bottle made of carbon-neutral plastic would be less than 0.01 euro cent more expensive than those made of conventional plastics (ETC, 2018b). A carbon price would be levied on conventionally manufactured soft-drink bottles. As soon as this carbon price exceeds the additional costs of producing a carbon-neutral plastic bottle (under 0.01 euro cent), the green manufacturing technology becomes competitive on the market. Because this instrument allows the costs to be passed on directly to the consumer without competitive disadvantages, manufacturers would be incentivised to switch to carbon-neutral production methods. Because all imported end products are charged, but exports are not, there is no danger of carbon leakage. The instrument is expected to make carbon-neutral production competitive in the domestic market and to reduce the amount of carbon-intensive materials in use.

The main challenge of this instrument is that it requires the complete and seamless tracking of the carbon footprint for every product. The current costs for comprehensive carbon tracking are not acceptable, however.

How the carbon price on end products would affect steel processing in the automotive industry – an example

Figure C.10



Agora Energiewende, 2021

Assumptions for calculation: 0.8 tonnes of steel per passenger car; 150 euros of additional costs per tonne of low-carbon steel; 1.8 tCO_2 per t of conventional crude steel; carbon price of ~70 to ~100 €/tCO_2

CARBON PRICE ON END PRODUCTS

The instrument represents a minimal burden for consumers but creates incentives for producers and suppliers along the value chain to substitute materials, introduce circular economy measures and switch to carbon-neutral production processes.

INSTRUMENT TYPE

- [ ] Support
- [x] Charge/surcharge
- [ ] Regulation

DECARBONISATION LEVER

- [ ] Energy efficiency
- [x] Change of energy source
- [x] Process optimisation & substitution
- [x] Resource efficiency & material substitution

SECTOR APPLICABILITY

- [ ] Cross-cutting technologies
- [x] Steel
- [x] Chemicals
- [x] Cement
- [x] Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

Development			Market entry		Existence
Research	Scaling	Creation of green markets	Investment	Operating costs	Optimisation (plant/product)

AREA OF APPLICATION

The instrument incentivises the manufacturers of all end products covered by the carbon price to switch to low-carbon materials. This makes key low-carbon technologies such as the direct reduction with hydrogen (steel), steam from power-to-heat (chemicals) and carbon capture with the oxyfuel process (cement) more attractive.

DURATION OF EFFECT

The instrument remains in force as long as carbon-intensive materials are cheaper without it.

NECESSITY OF CARBON TRACKING

- [x] mandatory
- [ ] helpful
- [ ] not necessary

STATE OF THE DISCUSSION

Policymakers have discussed such a measure in the form of a plastic tax mainly for avoiding waste; among experts, the instrument is under discussion as a GHG-based price signal.

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

In order to avoid a double charge, goods that fall under the carbon pricing system would have to be excluded from other carbon charges such as the European emissions trading system. This could happen by ensuring that manufacturers continue to receive free EU allowances. The retention of free allowances, however, is in conflict with the EU's current policy, which is to reduce the number of free allowances over time. By eliminating the risk of carbon leakage, however, the carbon price on end products can be set significantly higher than would be the case in the EU ETS. Thus, despite the continued distribution of free allowances, more ambitious carbon pricing would be possible.

Financing

The end consumers bear the costs, but these are low relative to the product itself. For example, if the carbon price is around 85 euros per tonne, a standard passenger car containing 800 kg of conventional steel (assuming 1.8 tCO_2 per tonne of conventional steel produced) would cost around 120 euros more. At this level the additional costs for a car with low-carbon steel and conventional steel would be equal. In cement manufacturing, a CO_2 price signal of 70 to 100 euros per tonne would be needed to make low-carbon technologies competitive. The total costs for building a house would increase by only around three per cent as a result (ETC, 2018b). For foodstuffs – drinks in plastic bottles, say – the costs of a product would increase by only around one cent (ETC, 2018b). The steering effect on material efficiency and substitution would not affect the end consumer; rather, it would arise along the value chain. While end consumers are not generally price-sensitive in this way, small price signals can influence purchase decisions for business procurement in, say, automotive suppliers or the retail trade.

Design options

The design of this instrument is comparatively complex because the amount of GHG emissions that arise in the production of end consumer goods for are largely unknown. This applies particularly to imported products. In the long term, a robust international carbon tracking system would have to be introduced in order to levy the charge on specific products. The tracking system could determine how much GHG is released when, say, manufacturing a tonne of steel for a particular vehicle type. The carbon surcharge could then be calculated on this basis. In the fully fleshed-out version, the instrument would directly incentivise businesses to invest in low-carbon products because lower emissions in production would directly reduce the surcharge on their products. But carbon tracking is only realistic in the long term because of the technical challenges and the international cooperation it requires. New technologies that enable carbon footprint tracking at very low transaction costs (using blockchain technology, for example) could make this instrument possible in the future. At first, the instrument could be limited to particular materials and selected end products.

Special features

Due to the complexity of the instrument's design, a quota could be introduced in the short term for low-carbon materials in certain products – such as a requirement that passenger cars contain a certain share of direct-reduction steel. In the long term, the quota would be replaced by more flexible, broader-based GHG pricing. The climate surcharge creates similar incentives on the product side, but it can be introduced more quickly and more affordably because it doesn't require extensive carbon tracking.

The income from the instrument could be used for other climate policy measures in the industrial sector (e.g. financing CCfDs).

Aspects of implementation

Legal assessment

- In general, the carbon pricing of end products is legally permissible.
- The instrument is permitted by WTO rules as long as it complies with the non-discrimination rule in art. 110 TFEU or art. III GATT.
- The instrument nevertheless comes with significant legal difficulties due to the necessity of establishing a global carbon tracking system.
- Requires an amendment to the EU ETS Directive.

SWOT analysis

STRENGTHS	OPPORTUNITIES
• The market determines material efficiency and the most favourable alternative technologies • As a consumption charge, probably WTO-compliant • No carbon leakage risk because the charge is levied only on the end consumer	• Low costs for end consumers • Creates a global level playing field for heavy industry • The large EU market provides an incentive for carbon-free production abroad • Carbon tracking could enable better supply-chain management
WEAKNESSES	**RISKS**
• Without product-specific carbon tracking, nearly impossible to implement over the long term; comprehensive carbon tracking along the value chain is hardly possible today • Zero-carbon products for export have no direct advantage • Global cooperation is needed for carbon tracking	• Carbon tracking can be difficult in individual cases such as the chemicals industry due to complex value chains • Some designs of carbon tracking could lead to unlawful discrimination • May substitute taxed materials (e.g. plastics) with products with other CO_2-intensive products (e.g. paper) • May lead to resource shuffling by exporting countries

GREEN PUBLIC PROCUREMENT

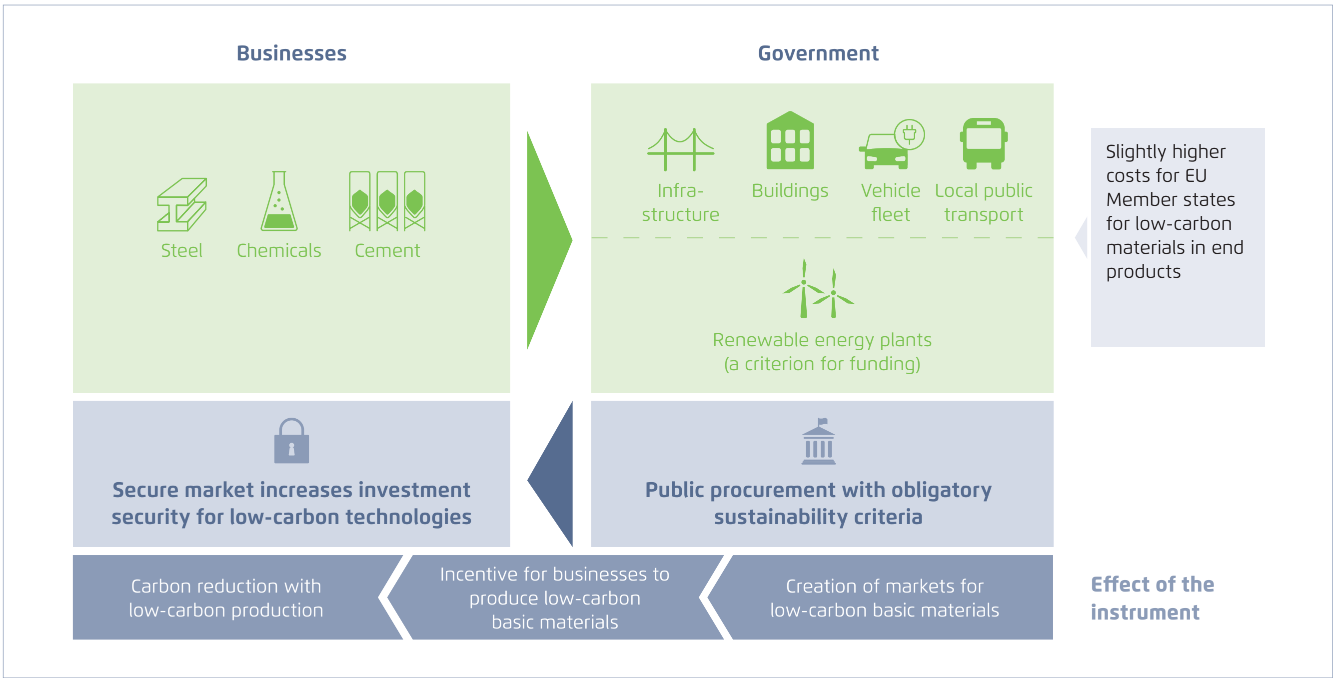
Instrument design

The instrument obliges the government to establish strict sustainability criteria for procurement. The requirement creates secure markets for sustainably manufactured products (for steel, cement and vehicles in particular).

The public sector is an important buyer of products and services. For example, Germany, the EU's largest member state, has an expenditure volume totalling over 350 billion euros per year (approx. 13 per cent of GDP). The public sector represents a substantial lever influencing the properties and production processes of the products it acquires.

So far, sustainability criteria for public procurement have only included particular product groups and are not obligatory, and as a result are not widely applied in practice. In 2015, only 2.4 per cent of public procurements took into account sustainability criteria (Chiappinelli/Zipperer/DIW, 2017). Compulsory sustainability criteria in public procurement would have a strong steering effect. To create a market for sustainable products in construction, sustainable criteria could become a standard part of public procurement in the EU. Only in certain well-justified individual cases should exceptions be made. The consistent application of sustainability criteria for buildings, modes of transport and transport services are particularly pertinent. A mandatory accounting of life-cycle costs or a mandatory quota for low-carbon/recycled materials (in construction, say) could set important impulses. A consistent, green public procurement leads to secure markets for sustainable products and thus reduces the risks for businesses investing in low-carbon production. Moreover, criteria for public procurement would also set standards for private market transactions and could complement and support CCfDs as a funding mechanism for the production of low-carbon products.

Effect of green public procurement Figure C.11



Agora Energiewende, 2021

GREEN PUBLIC PROCUREMENT

A consistent, green public procurement by the public sector would have a significant positive effect on the environment and create lead markets for green products.

INSTRUMENT TYPE

- [ ] Support
- [ ] Charge/surcharge
- [x] Regulation

DECARBONISATION LEVER

- [x] Energy efficiency
- [x] Change of energy source
- [x] Process optimisation & substitution
- [x] Resource efficiency & material substitution

SECTOR APPLICABILITY

- [x] Cross-cutting technologies
- [x] Steel
- [x] Chemicals
- [x] Cement
- [x] Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

Development			Market entry		Existence
Research	Scaling	Creation of green markets	Investment	Operating costs	Optimisation (plant/product)

AREA OF APPLICATION

In principle, sustainability criteria can be used in all areas of public procurement. A particularly high potential for GHG reduction exists in the areas of construction and transport. Among the foreseeable secure markets, the following technologies can benefit in particular: Direct reduction with hydrogen (steel), methanol-to-olefin/aromatics route (chemical), carbon capture with the oxyfuel process (cement), carbon capture and electrification of high-temperature heat in calciners (cement) and alternative binding agents (cement).

DURATION OF EFFECT

No limitation is necessary. The instrument is a sensible and effective option over the long term. The government should commit itself to using sustainability criteria for at least 20 years to ensure businesses have secure markets for their products (e.g. green steel) as they plan. Nevertheless, the sustainability criteria should be continuously adapted to technological developments.

NECESSITY OF CARBON TRACKING

- [ ] mandatory
- [x] helpful
- [ ] not necessary

STATE OF THE DISCUSSION

The idea of sustainability criteria for public procurement is not new. In 2003, the EU called on its member states to set up national action plans for creating a green public sector (European Commission, 2019b). Some states are already using sustainability criteria in public procurement. The Netherlands is one example. Governments there must apply environmental criteria when awarding public contracts (Baron/OECD, 2016).

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

Sustainability criteria can overlap with other regulations in the areas of materials and resource efficiency. But the effect would either be neutral or mutually reinforcing. For example, standards for recyclable products could make green public procurement easier.

Financing

Most public procurement takes place at the local and state levels, where financial capabilities are often extremely limited.

Design options

The instrument could be made mandatory for all procurements where the share of public funding exceeds 50 per cent. The criteria could become stricter over time. For instance, they might stipulate that 2 per cent of steel used in public building projects be green in 2022, 50 per cent be green in 2030 and 100 per cent be green in 2050. Exceptions to this rule should only be allowed in certain, well-founded cases. As for transport services, the sustainability criteria should consider not only vehicle emissions but also the incentives that shape driving and flying behaviour. The instrument could also be extended to areas where the government determines the terms for public bidding. In bids for renewable energy, for instance, EU Member States could make sustainable materials mandatory.

Aspects of implementation

Legal assessment

- The introduction of mandatory environmental criteria when awarding public contracts faces manageable legal risks.
- Alongside the equal treatment of domestic and foreign bidders, the instrument must fulfil publication and notification requirements when specifying technological regulations. See art. 2 para. 9-11 ÜtH (Agreement on Technical Barriers to Trade).
- The instrument conforms to the fundamental freedoms and the procurement directive of EU law. However, the award criteria must be connected to the object of the contract.

SWOT analysis

STRENGTHS

- Sends important signal to citizens and business that the government is leading the way
- Creation of secure markets for green products
- Highly cost-efficient if successfully implemented
- Easy to implement nationally and regionally

OPPORTUNITIES

- Emergence of lead markets for green products
- Effective changes to the production of goods
- Important signal to foreign countries
- Creating references for private markets
- Complementing other instruments such as CCfDs

WEAKNESSES

- Creates additional costs and increased complexity when awarding public tenders and determining sustainability

RISKS

- In the short term, supply shortages and limited competition can occur
- Not all product quality requirements for certain applications may be available as green products

QUOTAS FOR LOW-CARBON MATERIALS

Instrument design

The instruments requires producers of consumer goods to use a specific amount of zero-carbon materials in their end products. The measure guarantees businesses secure markets for low-carbon materials.

Many key low-carbon technologies for producing materials such as chemical recycling or steel from the direct-reduction process are almost market ready, but economically still not competitive. In order to create a secure supply (or lead markets) for low-carbon basic materials and to scale their production, the government specifies a quota for low-carbon materials – particularly those used for consumer goods such as steel.

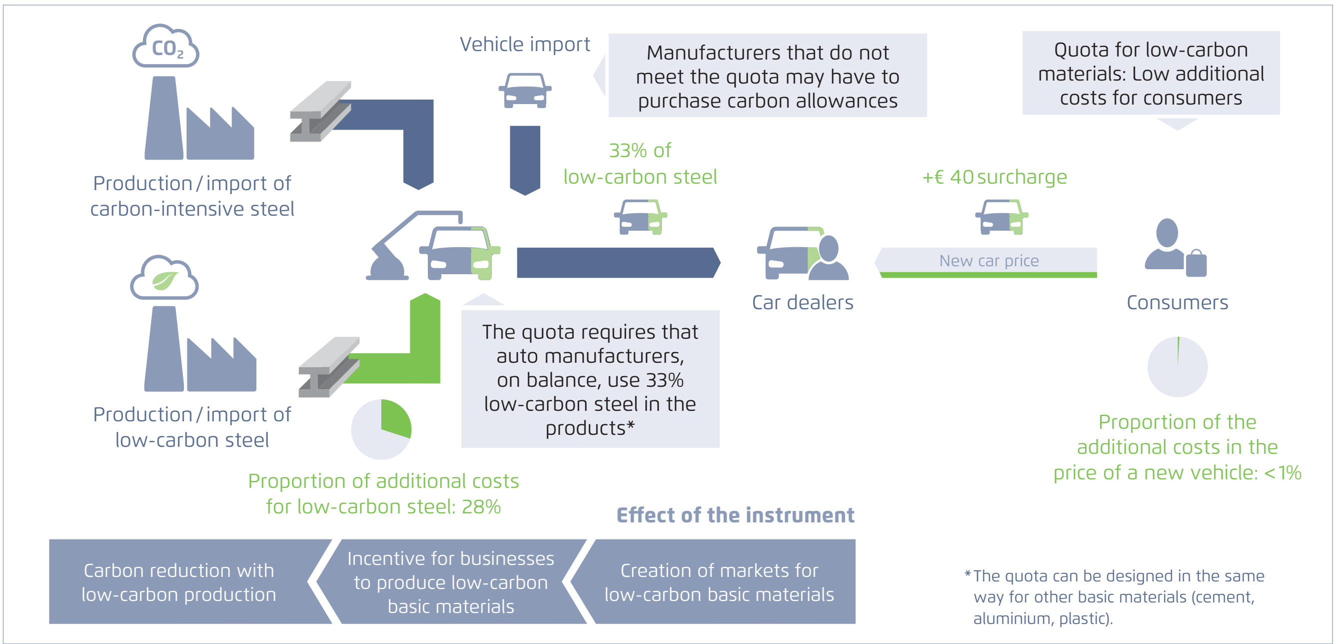
This provides manufacturers with higher investment security for climate technologies by creating a reliable market for low-carbon basic materials. The mandatory use of low-carbon materials would create demand and an appropriate price for such products. Because the quota applies to products sold in Germany and in the EU, the additional costs accrue equally for both domestic and imported products. Carbon allowances can be introduced for a transition period so as not to discriminate against manufacturers (domestic or foreign) who have no access to green materials. Imports of certified low-carbon materials can help fulfil the quota. Exports of basic materials from Europe such as metals or basic chemicals would not be affected by the regulation. This ensures the competitiveness of products made in Europe and exported abroad, and eliminates the risk of carbon leakage.

The instrument also incentivises foreign manufacturers active in the European market to use green basic materials in their end products. The demand of foreign manufacturers of consumer goods for green materials will increase the production of low-carbon basic materials abroad, even if no comparable regulations have been introduced.

The additional costs for the consumer remain limited. A passenger car made completely of green steel would cost approx. 160 euros more (ETC, 2018b). If the quota started with a proportion of five percent, the additional costs for the end consumer would be low.

How a quota for low-carbon materials affects steel processing in the automotive industry – an example

Figure C.12



Agora Energiewende, 2021 Assumptions for calculation: 0.8 tonnes of steel per passenger car; 150 euros of additional costs per tonne of low-carbon steel

QUOTAS FOR LOW-CARBON MATERIALS

A quota could be introduced quickly to bring key technologies to the market and in the long term be replaced by more flexible solutions.

INSTRUMENT TYPE

- ☐ Support
- ☐ Charge/surcharge
- × Regulation

DECARBONISATION LEVER

- ☐ Energy efficiency
- × Change of energy source
- × Process optimisation & substitution
- × Resource efficiency & material substitution

SECTOR APPLICABILITY

- ☐ Cross-cutting technologies
- × Steel
- × Chemicals
- × Cement
- × Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

Development			Market entry		Existence
Research	Scaling	Creation of green markets	Investment	Operating costs	Optimisation (product/plant)

AREA OF APPLICATION

Carbon-intensive materials in consumer goods for which zero-carbon manufacturing alternatives exist. These include the following in particular: hydrogen-based production of direct-reduced iron (steel), chemical recycling (chemicals) and carbon capture with the oxyfuel process (cement).

DURATION OF EFFECT

Recommendation by the ETC (ETC, 2018d); to date, only voluntary initiatives such as the pledging initiative for recycled plastics.

NECESSITY OF CARBON TRACKING

- × mandatory
- ☐ helpful
- ☐ not necessary

STATE OF THE DISCUSSION

In contrast to a quota, which only address a certain share of an end product, a carbon price on end products could serve as a comprehensive instrument. But production-side pricing requires an international tracking system of the carbon footprint of materials. By contrast, the quota can be introduced with limited carbon reporting in specific industries, creating immediate incentives for producers. Once a more comprehensive tracking system has been developed, however, quotas can be replaced by GHG-based pricing.

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

Price signals such as a carbon minimum price floor with a border carbon adjustment would make technologies such as power-to-chemicals or direct reduction with hydrogen more competitive in the long term. But climate-neutral investment also requires secure markets in the short term. A quota can satisfy this function by supplementing green public procurement and providing a possible option for the private sector.

Financing

Additional costs would initially be incurred by producers and passed on to end consumers. These additional costs would be relatively low for most affected goods, so that neither consumers nor producers in Europe would be significantly disadvantaged. Manufacturers could also rely on the readiness of certain customer groups to purchase more expensive GHG-neutral products (such as passenger cars made of zero-carbon -steel, similarly to Fairtrade foodstuffs).

Design options

The instrument could be designed specifically for certain materials and end products. This could reduce the administrative costs of carbon tracking but it could also lead to the selection of high-emission applications. The instrument could stipulate that a share of the steel used in passenger cars must be made with hydrogen-based production of direct-reduced iron (ETC, 2018c). A quota could also promote plastics produced from renewable carbon, such as chemically recycled plastic or bioplastic (nova, 2018). Construction companies could be obliged to fulfil quotas for low-GHG cement (ETC, 2018d).

The quota would take effect at point of sale to the end consumer. Every vehicle sold in Europe would have to demonstrate a proportion of CO_2-free steel. But for the instrument to work, a system would have to be introduced to certify that domestic and foreign manufacturers are using green steel in their products. The quota might also apply to manufacturing. For instance, one could require a European automotive manufacturer to use a certain proportion of its steel use from zero-carbon manufacture (ETC, 2018c).

Many of the production processes require investment in new plants, but the investment cycles often extend over several decades. The quota would therefore have to start low and increase over time. This would ensure that the necessary volumes of low-carbon materials are available for production. In addition, regulations would have to be created for providers that do initally not have access to low-carbon products. This might require compensatory payments or a certificate system between manufacturers.

Special features

The instrument can focus on specific production technologies and customer segments (see above). The focus will keep administrative costs low for the carbon tracking of basic materials.

Aspects of implementation

Legal assessment

- The implementation of quotas for the use of materials made from carbon-neutral production is legally permissible. Several points must be taken into account, however.
- Because quotas are intended to cover imported as well as domestic material, they must comfort with the non-discrimination rule of art. III GATT. Unlawful forms of discrimination could occur in particular with regard to the certification of imported products. The requirements for certification must be uniform for all products. Likewise, quotas may not disadvantage imported products subject to identical requirements.
- In addition, quotas can, depending on the concrete design, be subject to the requirements of the WTO agreement on technical trade barriers (the so-called TBT agreement). One would have to check whether the quotas comply with art. 5 and art. 2 no. 2.2 of the TBT agreement. Art. 2.2. stipulates that technical requirements may not limit trade any more than necessary. The risks of non-implementation also need evaluation.
- With respect to the European Law the quota may encroach the priniciple on free movement of goods and therefore requires a justification. A possible justification would be environmental protection. Moreover, the quota would have to be in line with the principle of proportionality.

- Depending on the materials and products included in a quota, European harmonisation requirements might also have to be considered.

SWOT analysis

STRENGTHS

- Creates secure markets for low-carbon products
- Fairly targeted support of central technologies for decarbonisation
- The market decides the price and production methods for zero-carbon products
- Low additional costs for end consumers
- No disadvantages for European basic materials industry because the quota on end consumption also covers imports
- No carbon leakage risk

OPPORTUNITIES

- Can be implemented quickly
- Depending on the level of the quota, substantial GHG reductions possible
- Creates an incentive abroad to invest in zero-carbon production
- Makes it possible for consumers to demand green products if businesses identify products with zero-carbon materials

WEAKNESSES

- Administrative costs for taking into account carbon-neutral basic materials (need for a certification system)
- Undesirable effects if level inappropriate or area of application unsuitable
- Assumes that producers can access low-carbon materials
- Certification system may discriminate against individual carbon-efficient manufacturers

RISKS

- Depending on the scope of materials and products, may be complex to implement; harmonisation requirements will have to be observed
- Depending on the design, it could be regarded as a non-tariff restriction on trade; compatibility needs to be assured with GATT (particularly non-discrimination rule in art. III) and the TBT agreement (particularly art. 5 and art. 2 no. 2.2)
- Manufacturers may switch to materials (from plastics to paper packaging) not included in the quota that increase CO_2 emissions
- If quota were increased too quickly, low-carbon materials would have to be imported (e.g. bioplastic from Brazil)

CLEAN HYDROGEN SUPPORT POLICIES

Instrument design

This group of instruments aims at creating a business case for clean hydrogen by closing the price gap between conventional fossil fuel-based technologies and clean hydrogen in no-regret applications.

The use of clean hydrogen will be a key pillar for decarbonisation and climate neutrality. In certain sectors such as steel and chemicals, but also as a system backup for renewables in the power sector its use will play a particularly important role (Agora, 2020). In addition, synthetic fuels made from clean hydrogen could be used in the future in the areas of air transport and shipping. The European Commission has already set out an ambitious Hydrogen Strategy that aims at reaching a target of 2x40 GW electrolysers by 2030 (European Commission, 2020d). However, concrete policy instruments to create a business case for clean hydrogen have yet to be formulated. Different types of instruments can incentivise investment in the production, transport and use of clean hydrogen.

The first instrument targets the greening of existing hydrogen demand by providing a premium to cover the incremental cost of producing clean hydrogen instead of using GHG-intensive processes, such as steam methane reforming. Such a "hydrogen contract-for-difference", could cover incremental costs of using clean hydrogen in existing methanol and ammonia production plants and compensate for variations in gas, electricity, and carbon prices that influence cost differences over time. "H-CfDs" would target industries that already use GHG-intensive hydrogen and employ them as anchors for the swift deployment and expansion of clean hydrogen production.

The second instrument supports industry with transforming their processes to generate new demand for clean hydrogen. Examples are investments in hydrogen-fueled direct reduced iron or new installations for chemical recycling, methanol and ammonia. These investments create new production facilities and face diverse incremental costs for capital expenditure and operation that can be supported with carbon contracts or CCfDs. These instruments can be designed to support the whole value chain of the production, transport and use of hydrogen.

The third option is to define quotas for the sale and use of clean hydrogen-based fuels for shipping and aviation. In response to the regulated demand, the private sector will procure adequate supply and the price will be defined by market forces.

All these instruments aim at bridging the cost gap between conventional fuels and clean hydrogen with the goal of accelerating technological development and cost reduction. Another goal of these instruments is to promote climate technologies and contribute to European technology leadership in a growing world market for these technologies.

Clean Hydrogen Support Policies — Figure C.13

Policy Instrument	Hydrogen-Contract for Difference	Carbon contracts and CCfDs	Clean hydrogen-based fuel quota
Potential application	Greening existing hydrogen production	Greening industrial processes req. green hydrogen (e.g. steel and chemicals)	Blending in aviation and maritime fuels
Remarks	Ideal for pre-existing H_2 demand with low costs for clean H_2 integration	Appropriate to support the development of new clean H_2-based value chains	Allows H_2-based fuels to compete for market demand created by the quota

Agora Energiewende, 2021

CLEAN HYDROGEN SUPPORT POLICIES

These instruments promote the scaling of hydrogen technologies and contribute to Europe's leadership in a growing global market for these technologies.

INSTRUMENT TYPE

- [x] Support (H-CfD; Carbon contracts and CCfD)
- [ ] Charge/surcharge
- [x] Regulation (clean hydrogen-fuel quota for aviation and shipping)

DECARBONISATION LEVER

- [ ] Energy efficiency
- [x] Change of energy source
- [ ] Process optimisation & substitution
- [ ] Resource efficiency & material substitution

SECTOR APPLICABILITY

- [x] Cross-cutting technologies
- [x] Steel
- [x] Chemicals
- [ ] Cement
- [ ] Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

Development			Market entry		Existence
Research	Scaling	Creation of green markets	Investment	Operating costs	Optimisation (plant/product)

AREA OF APPLICATION

Clean hydrogen will play a key role in decarbonising certain industrial processes and is a building block for synthetic fuels in aviation. In the industrial sector, clean hydrogen is fundamental to several key low-carbon technologies, such as: the hydrogen-based production of direct reduced iron (steel) and chemical recycling via the methanol- to-olefin route (chemicals).

DURATION OF EFFECT

Support instruments for clean hydrogen will lead to a gradual cost reduction for the production, transport and use of clean hydrogen. At the same time, carbon prices are expected to increase. Both processes will reduce and eventually eliminate the cost gap between clean and GHG-intensive hydrogen and produce a cost competitive European hydrogen industry. Recent studies estimate that cost parity can be achieved as early as around 2030 if the uptake of clean hydrogen is supported with adequate measures (McKinsey, 2021).

NECESSITY CARBON TRACKING

- [ ] mandatory
- [x] helpful
- [x] not necessary

STATE OF THE DISCUSSION

Hydrogen support instruments such as a Carbon contract-for-difference are mentioned in the EU Hydrogen Strategy (European Commission, 2020). In addition, a minimum quota for hydrogen-based synthetic fuels in aviation of 2% by 2030 is currently being adopted in Germany (BMU, 2021).

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

Currently, the carbon abatement costs of clean hydrogen are still very high relative to the carbon price in the EU ETS. If clean hydrogen technologies become cheaper as they undergo technology learning curves, rising carbon prices in the EU ETS can reduce the additional cost of clean hydrogen technologies. In the long run carbon prices in the EU ETS may be sufficiently high to obviate the need for further support instruments for clean hydrogen.

A significant degree of uncertainty regarding future costs still exists for buyers of hydrogen such as the steel or chemical sector. This uncertainty can, however, be attenuated by appropriate design of the hydrogen support instruments. For instance, a carbon contract or CCfD for steel manufacture with hydrogen-fueled direct reduction could cover the incremental costs of producing with clean hydrogen.

In the case of hydrogen quotas for sellers of maritime and aviation fuels the quota is a volume-based instrument and the price will result from regulatory demand.

Financing

H-CfDs, carbon contracts and CCfDs will require appropriate long-term refinancing mechanisms. One such instrument could be a climate surcharge applied on CO_2-intensive end products (e.g. steel in a car). While the additional costs in the final product are comparatively small, it could generate funds that allow for the production, transport and use of clean hydrogen in industrial processes. In the case of a clean hydrogen quota in aviation fuels, the additional costs could be borne by air travellers.

Design options

Carbon contracts or CCfDs can be designed to support investments and production with clean hydrogen-based low-carbon technologies, such as the manufacturing of climate neutral steel, ammonia, and methanol. These industries can act as anchors for investments in the production and transport of clean hydrogen. By supporting the implementation of solid and sustainable value chains, the instrument is ideally suited to initiate the development of hydrogen-based industrial networks. Top this end, such contracts need to be designed and awarded to specific sites and projects that can offer the necessary transformational spillover effects and act as seeds for the development of the hydrogen market and infrastructure that are needed for climate neutrality.

Once production and use of hydrogen become more mature, carbon contracts could be awarded in competitive auctions. This would generate competition for the production, transport and use of hydrogen, reveal new opportunities, and drive down prices.

A further evolution is to design double auctions that separate procurement auctions for clean hydrogen from auctions that allocate the contracted volumes to different industrial users. The resulting costs differences, as well as risks that result from different duration and commercial conditions of procurement and sales contracts need to be borne by a central entity that can incentivise the development of a hydrogen market. As discussed, the costs incurred by this central entity will have to be covered by appropriate re-financing mechanisms.

Specific features

Any economic support instrument for clean hydrogen must be coupled with a sustainability framework for clean hydrogen production and use. Specifically, the definition of green hydrogen needs to ensure that its production does not contribute to increasing emissions along the industrial value chain, even if considering indirect emissions from increased electricity use (scope 2) or other changes in the value chain (scope 3 emissions). Therefore rules governing guarantees of origin for clean hydrogen, the "additionality" of renewable or decarbonised energy for clean hydrogen production, and rules ensuring that clean hydrogen is first allocated to the most appropriate "no-regret" options (incl. steel and chemicals) must be developed in parallel.

Aspects of implementation

Legal assessment

- For a legal assessment of carbon contracts and CCfD, please see the respective instrument fact sheet.
- H-CfDs may constitute a state aid according to Art. 107(3) TFEU depending on the mechanism that will be used for refinancing. However, the notification of such an aid is

for now with inherent legal risks. The Guidelines on State aid for environmental protection and energy 2014 – 2020 do not provide any conditions for such aid. Moreover, it is difficult to quantify the economic significance in advance because of the volatility of the market price for the production of green hydrogen. It is also questionable whether the aid intensities according to annex 1 no. 1 (55% for medium-sized enterprises and 45% for large enterprises; 100% for bidding) are high enough to satisfy the need for such an aid.
- H-CfDs should be granted by an auction procedure in order to incentivise efficiency, which should lead to cost savings in support policies.
- If the H-CfDs cannot be entered by a foreign enterprise there is a need for a justification according to the anti-discrimination-principle. Moreover, the discrimination against other technologies (such as synthetic fuels and biomass fuels) will also need a justification according to article 3 of the German Constitution (GG).
- To prevent violations, retroactive effects with existing subsidies such as paragraphs 64a, 69b EEG2021, paragraphs 37a of the law for air quality and control (BImSchG) and 3 of the 37. Regulation for air quality and control (37. BImSchV) should be considered.

SWOT analysis

STRENGTHS	OPPORTUNITIES
• Adresses both supply and demand side of clean hydrogen • Basing support on competitve auctions enables competitve price determination • Projects can be anchors for developing hydrogen-based industrial networks	• European businesses can become leaders in this future technology, building technological leadership • Significantly reduces costs for electrolysis technology • Represents first step to creating a hydrogen economy • Instrument complements EU-ETS by targeting climate-neutral technologies
WEAKNESSES	**RISKS**
• High carbon reduction costs for clean hydrogen may lead to high long-term costs for society • The instruments requires creating institutions, regulations and oversight	• Funding the learning curve does not necessarily lead to sustained success for European industry, as the case of the photovoltaic industry shows • State aid notification by European Commission • Discriminates against other technologies

CHANGES IN CONSTRUCTION AND PRODUCT STANDARDS

Instrument design

The instrument requires the revision and adaptation of regulations and standards in order to facilitate material efficiency and substitution and increase the recyclability of construction materials.

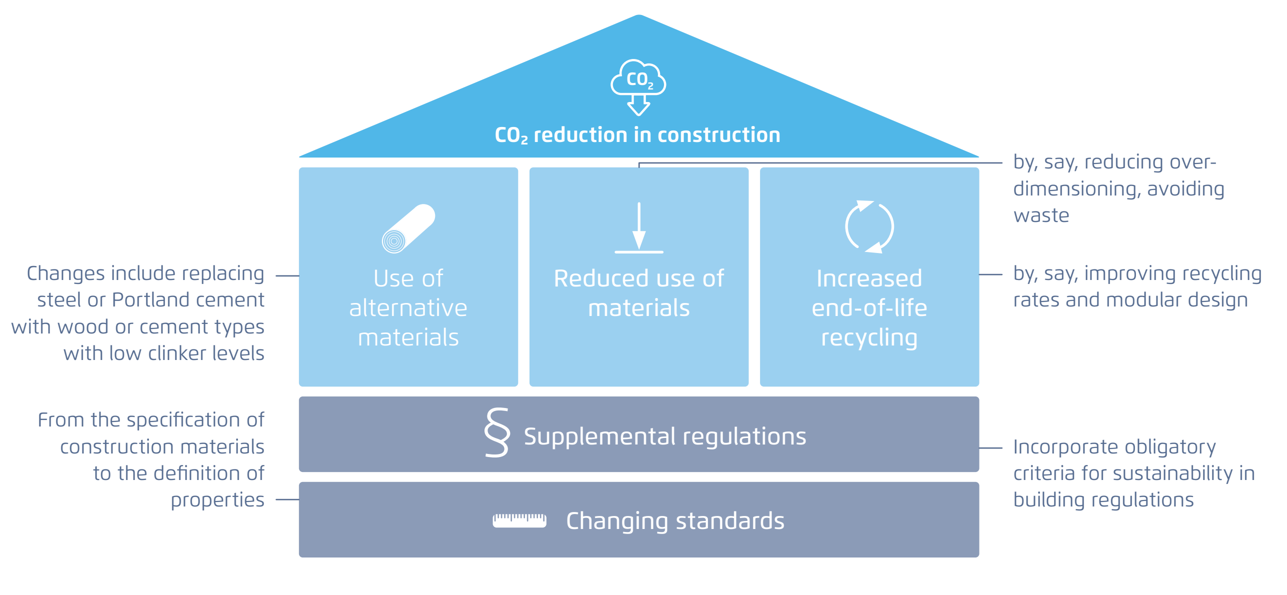
The main materials in the construction industry are steel, cement and bricks. But the manufacturing of these materials involves some of the most energy- and emission-intensive processes in the industrial sector. Achieving greenhouse-gas neutrality, especially for concrete, is an enormous challenge. It involves reducing the amount of steel and cement used in construction, increasing the use of alternative materials (e.g. wood, alternative binding agents) and increasing recyclability (by, say, avoiding composite materials) in the construction industry.

Changing standards and regulations can help reduce material use in the construction industry and improve efficiency. Changings standards from requirements for approved construction materials to requirements for required properties such as fire protection, statics and insulation enables the use of new materials (e.g. timber construction) and new compositions (cement with low clinker proportions or alternative binding agents, textile-reinforced concrete, less voluminous but stronger steel bars).

Supplementary regulations that increase material efficiency and take into account life cycle assessments (LCA) when awarding contracts (see instrument *green public procurement*) can further increase sustainability. The supplementary regulations must stipulate improved materials and the derivation of precise dimensioning. Today, dimensioning in the construction industry can exceed requirements by as much as 100 per cent (Material Economics, 2018). The regulations should be accompanied by a specification of materials, a reduction in the share of waste/scrap – today the share in construction is around 15 per cent – and the increase of sustainable and recycled materials (Material Economics, 2018).

Effect of changes to construction and product standards

Figure C.14



Agora Energiewende, 2021

CHANGES IN CONSTRUCTION AND PRODUCT STANDARDS

Revised standards and regulations in construction can lead to significant savings in materials and emissions and substantially increase the sustainability of the industry.

INSTRUMENT TYPE

- [ ] Support
- [ ] Charge/surcharge
- [x] Regulation

DECARBONISATION LEVER

- [ ] Energy efficiency
- [ ] Change of energy carrier
- [ ] Process optimisation & substitution
- [x] Resource efficiency & material substitution

SECTOR APPLICABILITY

- [ ] Cross-cutting technologies
- [x] Steel
- [x] Chemicals
- [x] Cement
- [x] Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

AREA OF APPLICATION

Construction industry, particularly new construction and demolition. Enabling the use of innovative building materials whose properties may differ, particularly cement with alternative binding agents, concrete with high proportions of recycled raw materials such as demolition material, textile-reinforced concrete, carbon concrete and wood.

DURATION OF EFFECT

No limitation necessary. The instrument will make sense and be effective at all times. EU, federal and state governments should introduce an evaluation process in which independent experts regularly assess standards and regulations on the basis of current requirements and material properties.

NECESSITY OF CARBON TRACKING

- [ ] mandatory
- [x] helpful
- [x] not necessary

STATE OF THE DISCUSSION

The instrument is currently being discussed among experts.

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

With green public procurement, some of the regulations could be implemented for the public sector. These two instruments complement each other. Ambitious carbon pricing for energy and materials could have a similar effect. It could be combined with a minimum carbon price with a border carbon adjustment. In discussions about a future building energy law, the topic of grey energy (primary energy that is necessary to construct a building) is gaining attention.

Financing

Additional costs would initially be incurred by building contractors or passed on to property tenants. For new buildings, funding could help cover the new property and efficiency requirements for construction. The avoidance of over-dimensioning could also lower costs without leading to disadvantages.

Special features

In the building sector, there is considerable potential for improved material and resource use. Material Economics (2018) has found that a recycling scenario in 2050 could cut greenhouse gas emissions by 53 per cent relative to the reference scenario.

Aspects of implementation

Legal assessment

- Changes to regulations and standards (CEN, European Committee for Standardization) governing construction materials require multiple changes to EU regulations, the Construction Products Regulation in particular. Because the sustainable use of resources is anchored in the Construction Products Regulation, the European level can account for the sustainability of products and low-carbon production when creating new regulations and standards (e.g. CEN). But this regulation is not mandatory for legislators. To become mandatory, the Construction Products Regulation and the CEN standards would have to be amended.
- WTO rules require that newly created regulations and standards be compliant with the requirements of the agreement on technical barriers to trade (TBT) (particularly art. 2, no. 2.2).
- At the national level, the legal feasibility mostly depends on the extent to which existing European harmonisation requirements are already in place. No national requirements can be made for products governed by the Construction Products Regulation, because the European harmonised standards take precedence (ECJ, ruling on 16.10.2014, C-100/13).

SWOT analysis

STRENGTHS	OPPORTUNITIES
• High precision • Sustainable use of resources already anchored in the Construction Products Regulation (though it is not mandatory)	• Significant GHG reduction potential especially in the areas of cement and steel • Can contribute to creating markets for sustainable products • Cost efficiencies due to lower material use • Material substitution in construction (e.g. more wood)
WEAKNESSES	**RISKS**
• Complex and fragmented implementation • Implementation problems due to lack of monitoring	• In the short term, the regulations can lead to increased construction costs • The industry could oppose reforms to existing standards • Compliance with the freedom of movement of goods stipulated in art. 34 TFEU and the requirements of the TBT agreement must be adhered to

STANDARDS FOR RECYCLABLE PRODUCTS

Instrument design

This instrument requires manufacturers to design products in a way that facilitates recycling so as to close material cycles and reduce carbon-intensive primary production.

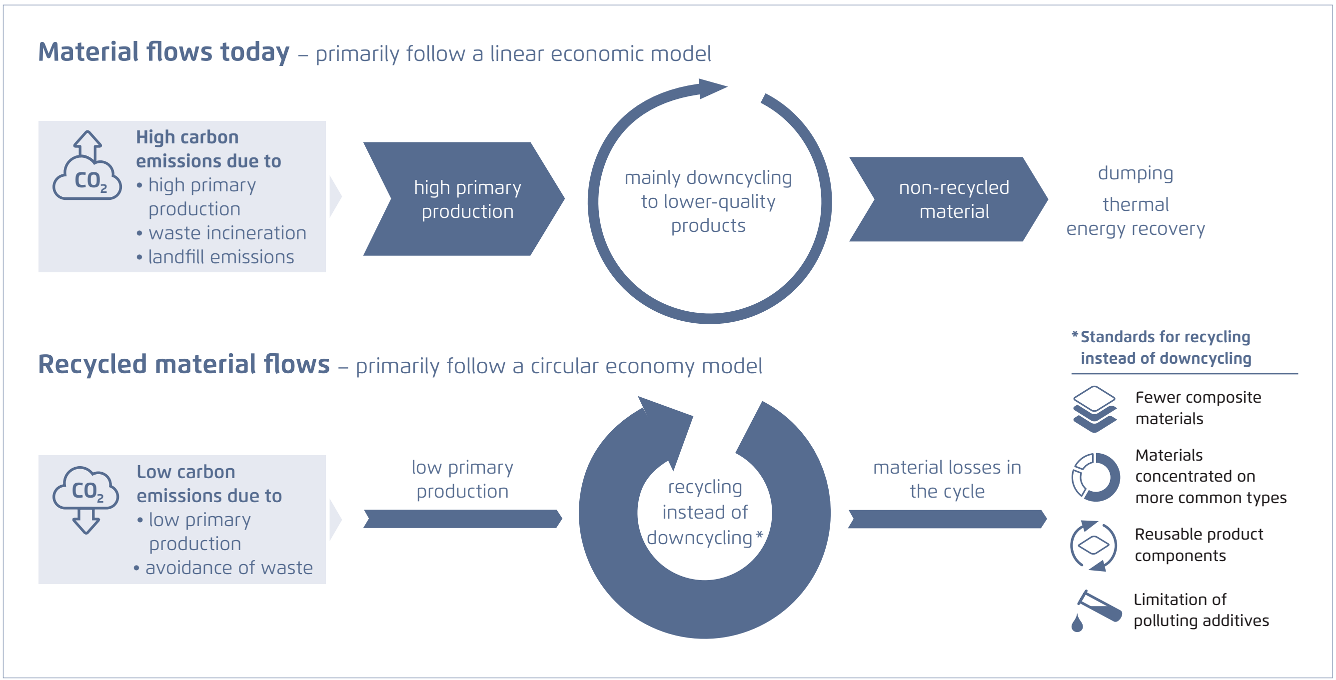
When designing products, manufacturers rarely consider material use after the end of a product's life, which severely limits recycling and component reuse (Material Economics, 2018). For example, few electrical devices exist that allow the replacement of defective components. This shortens the lifespan unnecessarily. Packaging often consists of multiple materials that are not easily separated. As a result, material recycling is limited or not economical.

To make reuse and recycling simpler and more attractive and economical, the recycling of a product must be planned into its design (IEA, 2018). The instrument is meant to lay down product-specific regulations for mandatory recycling. Among other things, the instrument's requirements would include (Ellen MacArthur Foundation, 2018):
- standardisation of product components
- product design for ease of disassembly
- limitation of composite materials
- limitation of small-sized waste
- limitation of rare materials
- limitation of colouring and additives

For steel production, the instrument addresses the contamination of steel by copper and nickel in particular. The goal must be to separate and sort different types of steel so that when melted down they can be reused. In theory, steel can be reused almost indefinitely without loss of quality.

In comparison with the steel industry, the recycling potential of construction materials is nowhere near full utilisation. For cement and concrete, technologies are now in development that will enable almost complete recycling in the future (Bakker et al., 2015; HeidelbergCement, 2019). The technologies are meant to recycle the cement, sand and gravel in concrete as well as the steel bars in its reinforced form. A large proportion of these materials could be recycled, significantly reducing the energy for extraction and production. To increase the recycling of construction materials, it would be helpful to establish a building pass system listing the materials used at each site (Madaster Platform, 2019). A certification system for recyclable construction materials could further simplify the process.

The effect of standards for recyclable products Figure C.15



Agora Energiewende, 2021

STANDARDS FOR RECYCLABLE PRODUCTS

Taking a product's end of life into account for its design enables a circular economy, with benefits that justify the regulatory costs.

INSTRUMENT TYPE

- ☐ Support
- ☐ Charge/surcharge
- × Regulation

DECARBONISATION LEVER

- ☐ Energy efficiency
- ☐ Change of energy carrier
- ☐ Process optimisation & substitution
- × Resource efficiency & material substitution

SECTOR APPLICABILITY

☐ Cross-cutting technologies × Steel × Chemicals × Cement × Circular economy

APPLICABILITY TO TECHNOLOGIES BY MATURITY LEVEL

Development			Market entry		Existence
Research	Scaling	Creation of green markets	Investment	Operating costs	Optimisation (plant/product)

AREA OF APPLICATION

The instrument can be used for goods with a low recycling quota (e.g. electrical devices and food packaging), steel products (e.g. passenger cars), construction materials (e.g. the cement, sand and gravel elements in concrete).

The instrument can incentivise the following processes/technologies in particular: the sorting of scrap steel to increase secondary steel quality (steel), chemical recycling (chemical) and the use of recycling concrete (cement).

DURATION OF EFFECT

Once high carbon prices are established so that full recycling becomes the most economical option, the more detailed regulations can be eliminated.

NECESSITY OF CARBON TRACKING

- ☐ mandatory
- ☐ helpful
- × not necessary

STATE OF THE DISCUSSION

At the EU level, individual goods are already regulated. For example, reusability and recyclability have been criteria for passenger car approval since 2005. In 2018 the EU parliament enacted the Eco-Design Directive, which established rules for the energy efficiency of devices and for increasing their reusability and recyclability.

Legend: ■ Primary effect ■ Secondary effect

Instrument details

Possible interactions

In spite of this instrument, the production of new materials will remain necessary. This is why the incentivisation of low-carbon production – through, say, higher carbon prices – will continue to be important. In order to fully utilise the instrument's recyclability standards, regulations – for waste separation, say – may have to be tightened in the long run. In principle, the benefits of recycling must always be weighed against its costs. The benefits can lie in the avoidance of GHG or in the recovery of valuable raw materials. Recycling processes that stand in the way of this principle can be disregarded. Thus, in the medium term, the energy and CO_2 intensity of material production and material disposal at the end of a building's service life could also be taken into account.

Financing

The extra costs in the manufacturing of consumer goods could be passed on to the end customer. But in the long term waste disposal costs for consumers would also fall. Ultimately, the costs would decrease over the medium term because the exchange of defective components reduces new purchases.

Economically, longer product lifespans could lead to reductions in private consumption. For countries with few raw material resources, more resource efficiency is a macroeconomic opportunity, however, as it decreases the import dependency of those countries.

Design options

There are various options when designing regulations for recycling standards (CEPS, 2018). One is the vertical regulation of individual products. Another is the horizontal regulation of specific aspects across product groups, such as the requirement that all product batteries be easily removable. Voluntary agreements with manufacturers and dealers could initiate changes to product design in the short term.

Further questions would need answering about the details of the instrument, including measurement methods, adherence monitoring and import handling. Furthermore, the regulations must be flexible enough not to hinder innovation (CEPS, 2018).

The following measures could help simplify the mechanical recycling – and to some degree – the chemical recycling of plastic:

- Limits to composite materials
- Limits to colourings and additives if needed
- Limits to individualised reusable deposit bottles if needed (PwC, 2011)
- Adaptation of product and (if needed) construction standards to enable the manufacture of plastics with a high share of recycled materials for broad application

The following measures could help recycle steel products without loss of quality (Material Economics, 2018):

- Mandatory separation of steel and copper waste flows (e.g. during vehicle scrappage)
- Mandatory product design allowing copper and steel components to be separated mechanically as simply as possible

The following measures could help recycle construction materials:

- A landfill ban for the coarse fraction of demolition materials (sand and gravel) in order to establish material cycles and to contribute to the conservation of resources
- A ban on fine fractions of demolition materials (cement paste and hardened cement paste) as filling material in road construction, provided technologies exist in the future for their recycling (downcycling)
- Adaptation of product and construction standards so that construction materials with a high share of recycled elements can be approved for use

Special features

For this kind of regulation, many more detailed regulations needing continuous adjustment are necessary at the product and material levels. These create high administrative costs. Even with very high carbon prices, additional regulations will be necessary, particularly in areas where price incentives barely reach. Regulatory provisions are necessary for a fast start of a circular economy. Furthermore, the instrument serves raw-material security by reducing resource consumption.

Aspects of implementation

Legal assessment

- The introduction of mandatory product-specific regulations is legally possible at the European level, but it assumes a change in the Construction Product Regulation and the EU Ecodesign Directive. At the national level, permissibility depends particularly on whether European harmonisation requirements already exist that take precedence.
- Product-specific regulations must comply with WTO rules regarding the agreement on technical barriers to trade (TBT) (particularly Art. 2 No. 2.2).
- European law already allows product-specific requirements regarding, say, reusability or recyclability. (See art. 15 para. 6 in conjunction with appendix 1 of the Ecodesign Directive and art. 3 para. 1 in conjunction with appendix 1 no. 7 of the Construction Products Regulation.) Specifying such requirements is not yet mandatory for legislators. A mandatory requirement, therefore, would need a change to the Ecodesign Directive and the Construction Products Regulation.
- The permissibility of product-specific requirements at the national level assumes that no harmonisation requirement exists at the EU level. (On the precedence of the Construction Products Regulation, see the ECJ ruling of 16.10.2014 – C-100/13 Commission/Germany.)
- Other possibilities alongside mandatory, product-specific requirements are voluntary commitments by the manufacturer. Measures within the remit of the EU Ecodesign directive must be approved by the European Commission. (See art.18 of the directive.)

SWOT analysis

STRENGTHS

- Reduced waste incineration and carbon emissions
- Reduced production of new material
- Increased lifespan of products
- Increased security of raw materials
- Increased qualities in secondary steel production and reduced carbon-intensity in primary steel production
- At the European level, product-specific requirements (e.g. recyclability) are possible though not mandatory.

OPPORTUNITIES

- Recycling and re-use have a positive macro-economic effect
- More conscious consumers and an end to throwaway society
- Europe could seek to amend the Ecodesign Directive and the Construction Products Regulation

WEAKNESSES

- Relatively fine regulations are needed that must be adapted frequently

RISKS

- Regulation that is too inflexible hinders product innovation
- Lack of control and penalties can limit effect
- Product prices may increase

3 Conclusion

The ten policy instruments on the shortlist represent a theoretical basis with significantly different approaches for incentivising the transition to a climate-neutral industry. They are meant to serve as possible starting points for discussions about industry decarbonisation – not only in the EU, but potentially also other regions of the world.

However, as the analysis made plain, there is no one silver bullet that can incentivise the roll-out of key low-carbon technologies alone. While a border carbon adjustment is viewed by some as an efficient instrument, there are a number of important questions that need to be answered: How can the real carbon footprint of imported goods be verified? Are rebates for exported goods into markets without a comparable CO_2 price signal compatible with current WTO regulations? And will the CO_2 price be high enough to incentivise investment in key low-carbon technologies? And technicalities aside, how will the introduction of such a mechanism be viewed politically by other important trading partners such as the US and China? Finding answers to those questions will likely require time before such an instrument can be implemented.

Similarly, while being an interesting option in theory, a carbon price on end products would require complete global CO_2 tracking for every end-product component. A swift implementation of this instrument thus seems rather unlikely, but it could become a meaningful option in the portfolio of instruments once global CO_2 tracking becomes possible (e.g. through blockchain technology). Instead of focusing on one instrument, we need to develop a comprehensive and adequate policy mix that unlocks the full decarbonisation potential at each part of the value chain.

Given the strength and weaknesses of the different instruments what is a sensible way to combine them? How do they interact with another? And how do they fit into the existing European policy landscape? These questions will be addressed in the next section where we formulate concrete policy recommendations in the form of a Clean Industry Package for Europe.

Part D: A Clean Industry Package for the EU

1 Introduction

Under the 2030 Climate Target Plan and the European Green Deal, the European Commission has recommended that the EU reduce its greenhouse gas emissions by -55% by 2030 (relative to 1990 levels) and achieve economy-wide climate neutrality by 2050 (European Commission, 2020a).[1] Achieving these targets is technologically and economically achievable with the right policies in place (Agora Energiewende & Oeko Institute, 2020a). Meeting them will also keep the EU on track to fulfil its commitment to climate neutrality under the Paris Agreement. During the post-COVID19 recovery, more ambitious climate action can boost the economy by stimulating investment in green infrastructure and technology, creating new jobs and laying the foundations for long-term industrial competitiveness.

The **European industrial sector has a vital role to play in delivering this vision of the European Green Deal**. Direct emissions from the EU27's industrial sector accounted for 719 $MtCO_{2eq}$ in 2017, equivalent to 20% of annual net EU greenhouse gas emissions (Eurostat, n.d.)[2]. By far, the greatest emitters are the cement, steel and chemicals sectors, making up approximately 60% of the total. By 2050, the EU will need to reduce its combined industrial emissions by approximately 95% and offset residual emissions with carbon sinks to achieve climate neutrality.

1 This chapter has already been published in October 2020 prior to the EU Council decision in December 2020 to adopt an EU 2030 climate target of -55 percent GHG emissions reduction.

2 The figure excludes emissions from energy sectors such as upstream power and heat production, refining, and solid fuel production.

The **transition to a climate-neutral industrial sector can contribute to economic recovery and secure long-term prosperity**. Between 2020 and 2030, between 30 and 53% of the EU's aging industrial plants in the cement, steel and steam cracker sectors will require major reinvestment and refurbishment.[3] Existing, high-carbon technologies must be replaced with low-carbon technologies. Moreover, significant investment is needed in strategic infrastructure such as clean power, hydrogen, biomass and carbon capture and storage. New skills and jobs will be required to facilitate this transition to innovative, climate-neutral technologies and business models. The next 5 to 10 years thus represent a major window of opportunity in which Europe can combine the transition to climate neutrality with economic recovery and long-term stability. Given the urgency posed by the climate crisis, member states must begin to make these investments during the next several years and the EU must follow up with robust legislative policies.

Border carbon adjustments and expected carbon prices will not be sufficient to initiate investments in climate neutrality over the next 10 years. The industrial sector has yet to invest in key low-carbon technologies at industrial scale. This is not primarily because of international competition but because carbon prices are not expected to be high enough during the next decades to justify the economics of these technologies. Even with carbon prices averaging 45-60 €/tCO_2, as proposed in the recent Impact Assessment of the 2030 Climate Target Plan, nearly all of the key low-carbon technologies would not be profitable. Moreover, carbon prices or border adjustments alone will not create the conditions needed for investment in clean power, hydrogen, CCS infrastructure and other technologies. Likewise,

3 See Wuppertal Institute (2020, forthcoming).

the development of efficient, circular value chains requires lifting a range of price and non-price barriers.

With between 30 to 53% of the EU's energy-intensive industrial assets will be up for major reinvestments during the next 5 to 10 years, policy-makers must act now. The EU needs a strong regulatory framework that provides clear incentives for investment along the entire value chain, from infrastructure and production to final products and recycling.

With genuinely transformative policies, the EU can shift the course of global efforts to decarbonise industry. From vehicle emissions standards to energy labelling, the EU is a recognised leader in environmental regulation. Recently, the People's Republic of China put forward its own plan for achieving carbon neutrality by 2060 (NYT, 2020). By demonstrating what is feasible in so-called "hard to abate" industrial sectors, the EU can also have an outsized influence on policy to decarbonise industry globally, including among major emitters like China, whose industry accounted for 5.17 gigatons of CO_{2eq} emissions in 2014, or 46% of China's total for that year (UNFCCC, n.d.). Moreover, if the EU acts boldly now, it can become a technology leader and effectively set the global standards for climate-neutral production and products.

The purpose of this paper is to explain why the legislative package which will be proposed in 2021 to implement the 2030 Climate Target Plan and the European Green Deal must consist of a transformative and comprehensive policy package to drive investment and job creation in clean industrial technologies. The next section explains in more detail why a policy package is required. Section three then sketches some concrete proposals for a Clean Industry Package.

2 Why the EU needs a Clean Industry Package now

There are three basic reasons why the EU needs a Clean Industry Package:

→ Continuing current policies until 2030 will lead to high-carbon technology lock-in in the medium term and will put jobs at risk in the short-term because there will be no credible business case for clean investment.
→ The EU is ready to begin investing in a portfolio of key low-carbon technologies during the next 5 years.
→ Only a coordinated set of policies across the value chain can ensure that the necessary investments will be made.

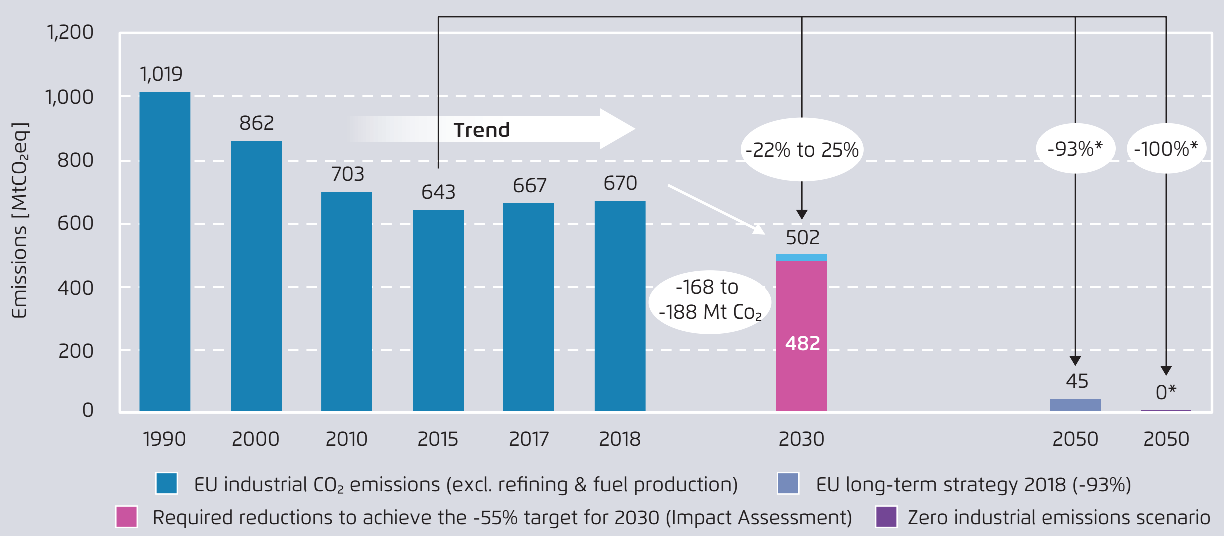
2.1 Continuing current policies until 2030 will lead to high-carbon technology lock-in and put jobs at risk

To stress again, the industry sector accounted for 719 $MtCO_{2eq}$ (or 20%) of the EU27's emissions in 2017. The total is even higher if one considers indirect emissions sources. To achieve the -55% emissions reduction target by 2030 and reach climate neutrality by 2050, the EU will need to make significant steps towards reducing its industrial emissions. For example, meeting the 2030 target will require the EU27 to cut its industrial CO_2 emissions by between 22 and 25% relative to 2015 levels (Figure D.1).

In one sense, this is not a very significant increase in expected business as usual reductions, since the introduction of the Clean Energy Package and the 2018 carbon market reforms are already expected to decrease industrial emissions by 18% by 2030 relative to 2015 levels. The European Commission's Impact Assessment of the 2030 Climate Target Plan has shown that the most energy-intensive industry sectors in the EU Emissions Trading Scheme (EU ETS) could deliver a 29.4% reduction in emissions by simply adopting the best available current technolo-

CO_2 emitted by the EU27 industrial sector from 1990 to 2018 and proposed sector targets for 2030 and 2050

Figure D.1



Agora Energiewende, 2021, based on data from Eurostat, 2017, European Commission, 2020b & EEA, 2021

Note: Data are for CO_2 emissions only. They exclude non-CO_2 emissions from industry, from refining, solid fuel production for energy and non-energy uses.

* To achieve climate neutrality, residual emissions will have to be offset by negative emissions technologies, many of which could be developed in the industrial sector such as BECCS. By capturing and using CO_2 from other non-industry sectors, industry can provide net-negative emissions.

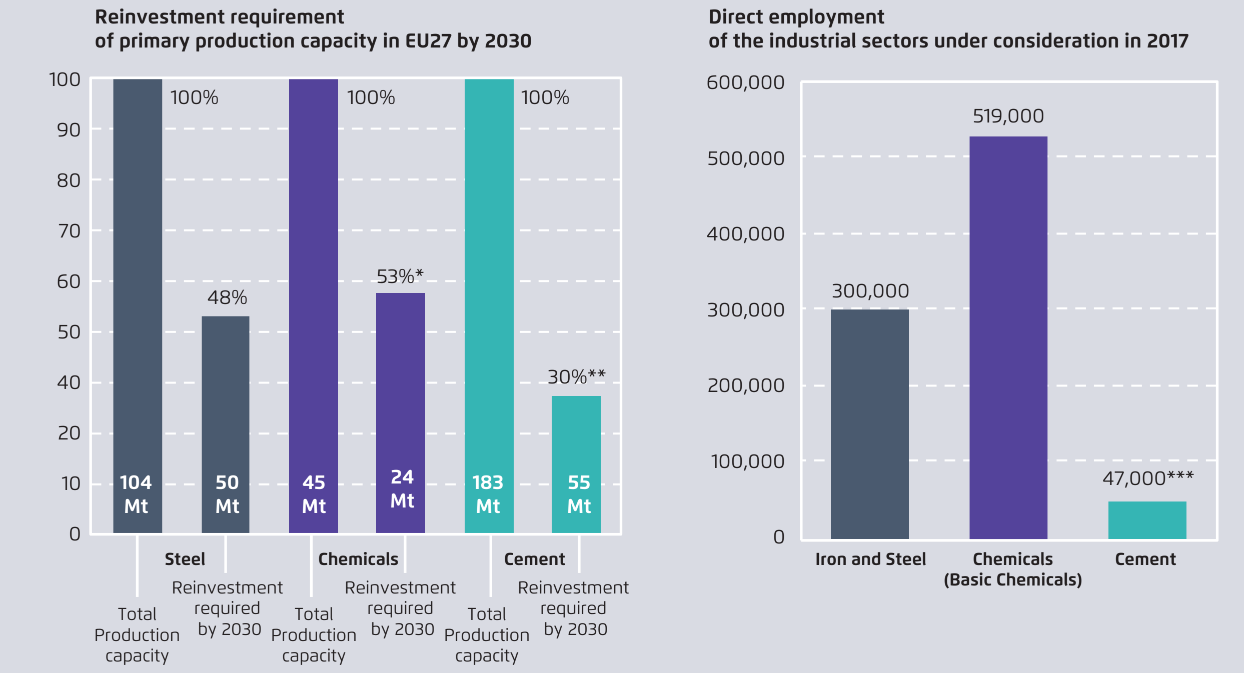
gies, which are already used by 10% of EU installations.

But what matters is not only that the EU industry reduces emissions by 2030 but also, more importantly, how it does so. The EU's overarching goal must be to reduce industrial CO_2 emissions by ~95% by 2050. In one scenario, the EU industry could reduce emissions by approximately 25% by 2030 through a range of marginal improvements to the efficiency of existing technologies. But doing so would have the perverse effect of locking in technologies and energy sources unable to achieve climate neutrality by 2050. It is critical, therefore, that the 2030 goal is met with low-carbon technologies that are compatible with climate neutrality in 2050. Policymakers must encourage the industrial sector to invest during the next 10 years in ambitious abatement options for climate neutrality in 2050. This means implementing policies that go beyond the ETS.

The EU's energy-intensive industrial assets are slated for major reinvestment and refurbishments during the coming decade. It is imperative that the sector makes new investments in technologies that are compatible with climate neutrality by 2050 (Figure D.2). Based on the ages of current plants, some 48% of blast furnaces (primary steel), 53% of steam crackers, and roughly 30% of cement kilns will require modernisation to remain in operation and avoid carbon leakage. A policy framework is urgently needed to make sure that the right climate-neutral investments are made. Otherwise, the industry risks stranding its assets and increasing the costs of achieving its climate targets.

The flip-side of this equation is that the upcoming investment cycle in energy-intensive industries presents a unique opportunity for advancing the EU's economic recovery, provided that the right policies are in place.

Reinvestment needs by 2030 and direct employment in cement, steel and basic chemicals in the EU   Figure D.2



Agora Energiewende/Wuppertal Institute, 2020

* Steam crackers are normally maintained and modernised continuously so that they are not completely replaced at one time. However, the need for reinvestment gives a rough impression of the need to modernise existing facilities.
** Indicative: Cement data represent numbers for Germany only. We estimate that the reinvestment requirement for EU27 is in a similar range.
*** Own estimate for 2017 based on Cembureau 2015

2.2 The EU is ready to begin investing in a portfolio of climate neutrality-compatible solutions

Despite the lack of progress in reducing emissions, the European industry has at its disposal a growing number of key low-carbon technologies and other levers to reduce emissions. Though some technologies are not fully mature, there is no reason why the EU cannot begin to deploy some key technologies already during the next 5 to 10 years.

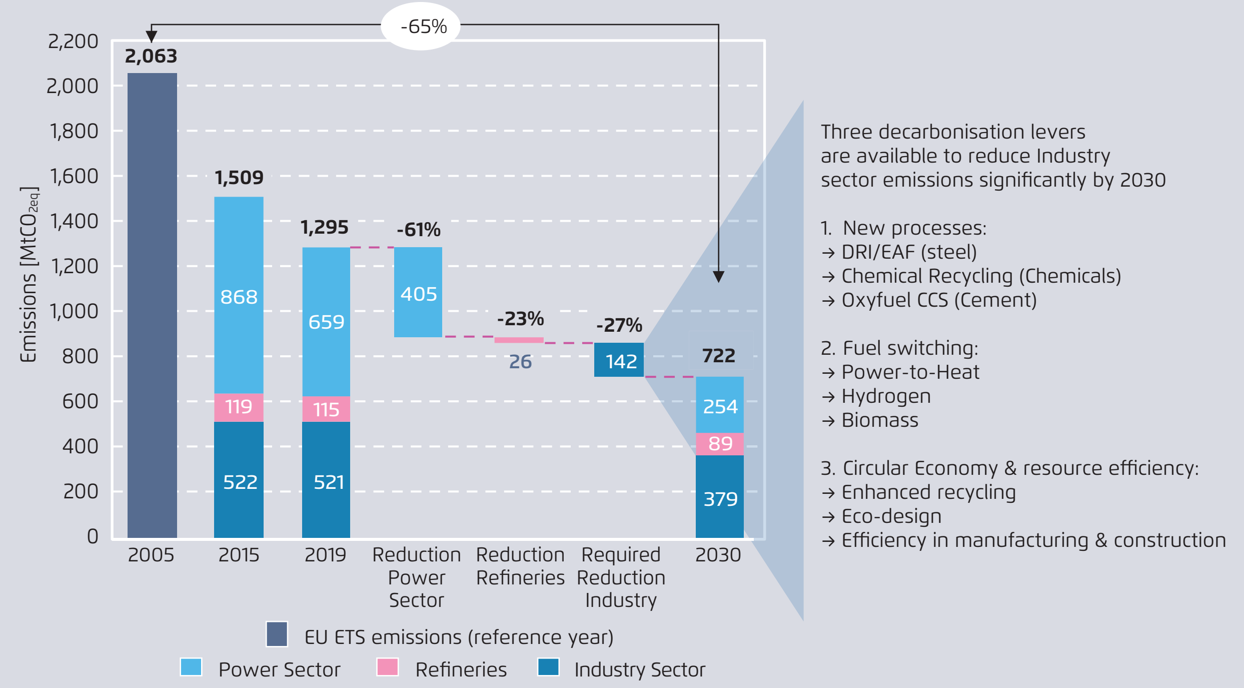
Figure 3 shows estimates for the necessary emissions reductions by industry in the EU ETS. Using data from the European Commission and European Environment Agency, we estimate that energy-intensive industries will need to reduce their emissions by approximately 27% by 2030 relative to 2019 levels. The figure lists three broad categories of solutions that can be deployed to achieve these reductions in a manner compatible with climate-neutrality in 2050:

First, industries can reduce emissions significantly by **starting to commercialise key low-carbon production technologies**. These include direct reduced iron (DRI) for steel production, chemical recycling, and carbon capture and storage (CCS) in the cement industry, which are all near-zero-carbon technologies and have sufficient technological maturity for commercial-scale deployment during the next 5 years.

Second, industries can achieve massive reductions by **fuel switching** from fossil fuels to net-zero alternatives such as direct electrification with

Expected emissions reductions from EU ETS industry under a -55% 2030 EU climate target and decarbonisation levers to deliver those reductions

Figure D.3



Agora Energiewende, 2021, based on data from Eurostat, 2017, European Commission, 2020e & EEA, 2021

Note: Emissions that relate to industrial processes such a coking plants and power plants for industrial use are accounted for in the industry sector and not in the transformation sector. ETS emissions in 2005 are notional base year emissions with respect to the 2030 target, i.e. they account for the change in the ETS scope and size of the EU since 2005.

decarbonised electricity, biomass, and, clean hydrogen in steel and chemicals production.

Third, **circularity and efficiency in the use of basic materials** (such as steel, aluminium, plastics, cement and concrete) have the potential to reduce emissions in energy-intensive industries by up to 50% by 2050 (Materials Economics, 2018). While some of these measures will not have an effect until after 2030 due to long product lifetimes, a number of measures can already begin to yield benefits before then.

Implementing these solutions at the 30–53% of cement, steel and chemical production sites slated for refurbishment during the next decade can dramatically shift industrial production facilities towards climate neutrality.

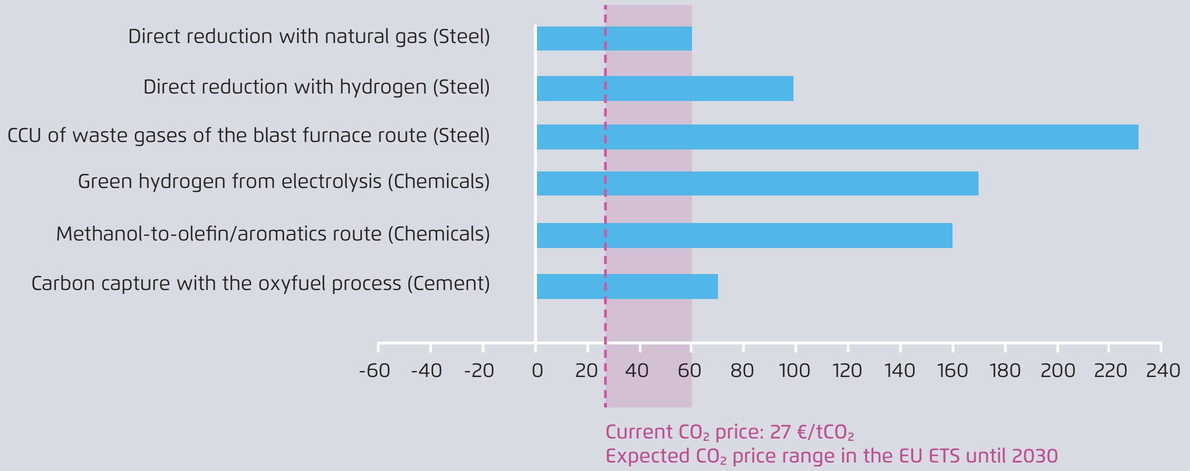
2.3 A coordinated set of policies along the value chain is needed

Border Carbon Adjustments are often proposed as sufficient solutions to kick-start the low-carbon transformation of the industrial sector. But, as noted previously, this is far too simplistic. One of the main reasons is that companies that use low-carbon technologies must compete not only with foreign producers but also with domestic manufacturers using conventional technologies. This requires carbon prices that are higher than those currently planned.

Figure D.4 shows that the current carbon price – 27 €/tCO_2 – is well below the levels required to drive investment in breakthrough technologies. Not even the 45-60 €/tCO_2 proposed by the European Commission's Impact Assessment on the 2030 Climate

Estimated CO_2 abatement costs of selected key technologies versus today's conventional reference process for 2030

Figure D.4



Agora Energiewende/Wuppertal Institute, 2019

Note: CO_2 abatement costs depend very much on assumptions about electricity costs. For the calculation of these values, electricity costs of 60 euros per MWh were usually assumed. The estimates here are based on Agora Energiewende/Wuppertal Institut, 2019 and represent the lower bound of CO_2 abatement costs in 2030. Higher CO_2 abatement costs are to be expected before 2030, compared to after 2030, because the technologies must still undergo learning curves for cost reductions.

Target would be high enough to ensure the proper investments.

But even if carbon prices rose enough for these technologies to be profitable in the short term, uncertainty surrounding ETS pricing would still create a barrier to investment. After all, the ETS price has fluctuated dramatically, going as high as 30 and as low as 0€/tCO_2, and there is no guarantee that it will remain high. Additional instruments to support the economics of expensive key low-carbon technologies are therefore needed.

The conditions needed for the industrial sector to invest in decarbonisation measures go beyond the simple question of carbon price levels or the risk of carbon price volatility, however. Specific needs can be identified along the value chain:

→ **Upstream:** The industrial sector needs reliable access to clean energy and basic materials at competitive prices via new infrastructure. It also requires additional infrastructure planning and financing for industrial clusters and cross-border, pan-European solutions when appropriate.
→ **Midstream:** The industrial sector needs the right economic and financial conditions in order to develop, implement and operate investments in key breakthrough technologies and in order to address the risks of carbon leakage.
→ **Downstream:** The industrial sector needs demand and scalable markets for decarbonised and circular products, markets that have internalised the higher costs of decarbonised products, and incentives to integrate the circular economy and resource efficiency all along the value chain.

A detailed discussion of these requirements is beyond the scope of this paper, but Table D.1 summarises the ten most urgent considerations.

The new European Commission has already proposed policies that could, if well-implemented, address some – but not all - of the industrial sector's specific

10 essential conditions for industry to transition to climate neutral products, processes and business models

Table D.1

Upstream	Midstream	Downstream
→ Access to sufficient, affordable clean energy → Access to key infrastructure (e. g. hydrogen, clean power & CCS) → Planning, financing and regulation of energy networks, esp. to support industrial clusters	→ Investment risk mitigation for unproven technologies → Recovery of higher operating cost of ultra-low carbon technologies. → Protection from carbon leakage under higher carbon & production costs	→ Funding costs of decarbonisation internalised in final product prices → Standards and demand for climate- neutral basic materials → Stronger incentives to increase the quantity and quality of recycling → Incentives for material CO_2-efficiency in final product design, manufacturing & construction

Agora Energiewende, 2020

* These carbon pricing systems generally apply to fossil-fuel emissions not covered by the EU ETS and include varying exemptions, especially for the industry due to competitiveness concerns.
** Effective carbon rates, including carbon taxes, energy taxes and price of emission permits, but excluding emissions from the combustion of biomass in the emissions base.
*** Provided that targets are not met.

needs. These include the Hydrogen Strategy, the Sustainable Products Policy Initiative and the Circular Economy Strategy. However, to create a business case for truly climate-neutral investments, these broad initiatives must be turned into strong economic and regulatory incentives.

In some areas, such as infrastructure planning in key industrial clusters, implementing instruments to support the high operating costs of ultra-low carbon technologies or creating new markets for ultra-low carbon products, the Commission has yet to make concrete proposals. Accordingly, key gaps still need filling.

3 Policy needs for a comprehensive European "Clean Industry Package"

The preceding section outlined the reasons for the key conditions needed to kick-start investment in climate-neutral production, products and business models. In general, these conditions cannot be created by the industry sector itself. Rather, the EU will need to create them by enacting new policies. This section proposes a Clean Industry Package of eleven key policies to satisfy these conditions.

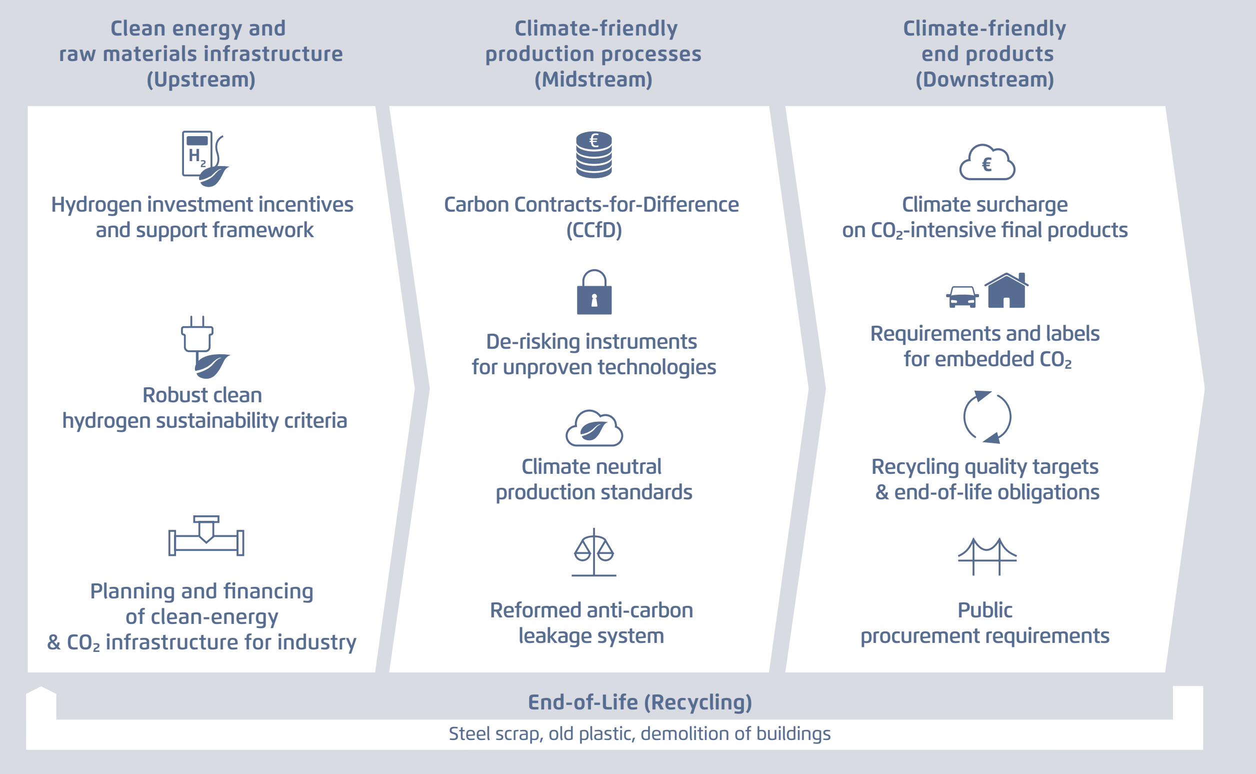
Figure D.5 summarises the eleven key policies that we propose. The policies are broken down by their position in the value chain, i.e. upstream, midstream and downstream.

3.1 Upstream policies

The key conditions for enabling the transition of the upstream value chain are:

- → access to sufficient, affordable clean energy
- → access to key infrastructure (e.g. hydrogen, clean power and CCS)
- → the planning, financing and regulation of energy networks, especially to support industrial clusters

Policy needs at the different parts of the value chain | Figure D.5



Agora Energiewende, 2020

To meet these needs, we identified the following policy priorities for EU and member-state policymakers:

Policy need 1. Economic support instruments to create a business case for investments in clean hydrogen production infrastructure:

If a decarbonised industrial energy infrastructure is to be built, it needs a business case to exist. For clean hydrogen production and transport, policymakers must create demand for a product that is currently more expensive than existing alternatives. Three main types of instruments can incentivise investments in the production and transport of clean hydrogen.

The first is to provide a **feed-in premium**, or what we might call a "hydrogen contract-for-difference," to support the production of competitive clean hydrogen. This is a payment that would be given to producers to close the price gap between clean hydrogen and existing hydrogen that is already produced in Steam Methane Reformers today. "H-CfDs" might be appropriate for supporting early-stage investments in greening the existing production of hydrogen and thus for specific industrial processes that already use hydrogen, where it is only a matter of switching from "grey" to "green" energy sources.

The second type of instrument is to provide *downstream industrial users of hydrogen* with a more comprehensive **carbon contract-for-difference**. This could either be used to cover the cost of switching from grey to green hydrogen (e.g. for existing hydrogen use in ammonia and fertiliser production) or to support the transformation of industrial technologies and processes, generating a previously non-existent demand for clean hydrogen.

For example, steel producers require major investments to move from conventional blast furnace-based processes (which use coking coal) to DRI/EAF-based steel production processes (which use hydrogen). Similar examples also exist for breakthrough technologies in the chemicals sector (e.g. low-carbon ammonia or H_2-based methanol-to-olefins routes). These downstream users will face higher investment and operating costs when switching to hydrogen in new production processes. They will require support to cover the incremental cost of these new investments and operating costs. Simply providing clean hydrogen at the price of "grey" hydrogen will not be enough to justify the economics of these new low-carbon operations. Hence, a carbon contract for difference, offered at the level of the industrial hydrogen user, is a more appropriate instrument in these cases.

A key factor for introducing clean hydrogen to the industrial sector is to account for investment needs in both upstream hydrogen production and in downstream hydrogen offtake. This is especially necessary for steel or chemicals manufacturing and other industries that must invest in new industrial processes while upstream hydrogen production is being developed. These investors need to see hydrogen infrastructure investments moving ahead with high certainty to be able to move ahead with their own site transformations. Similarly, upstream infrastructure providers will also need to see firm commitments and policy instruments such as CCfDs being created to be able to invest in upstream infrastructure with confidence. Close coordination of policy support relating to both the supply infrastructure and downstream investment decisions to create demand will be essential for the design of effective support instruments.

The third and final option is to set **clean hydrogen quotas** on sellers of maritime and aviation fuels. Here the private sector absorbs the cost of blending a share of renewable fuels in the end product. This option is not appropriate for industry because the higher cost of hydrogen blending would make it difficult to compete with foreign competitors that do not use renewable hydrogen.

A possible difficulty posed by quota systems – one experienced by renewable energy support schemes (IEA, 2011) – is that the price of quotas tends to fluctuate based on supply and demand, which themselves depend on other government policy interventions. On the plus side, quota systems avoid the need for direct subsidisation, allowing the internalisation of innovation costs in broader market prices for transport fuels.

A number of actions at the EU level can help member states implement one or more of the above three instruments both effectively and sustainably:

- → The EU Environmental and Energy Aid Guidelines for State Aid, to be revised in 2021, must unambiguously open the door to the three options, including H-CfDs, CCfDs for industrial users of clean hydrogen and quotas for clean hydrogen-based fuel blending.
- → Reform of the Renewable Energy Directive, and supporting regulations, to clarify the conditions under which member states can support investments and scaling up of clean and decarbonised hydrogen (more on this below, Cf. point 2).
- → Development of European Projects of Common Interest, integrating hydrogen development and the transformation of industrial processes in the steel and chemicals sectors, as a model for future projects.

Besides direct support mechanisms, a broader set of conditions must be in place to enable hydrogen in the energy system and direct electrification in the industrial sector. For example, national governments may also need to review power market design, hydrogen gas infrastructure regulations and taxation policies that facilitate the effective introduction of direct and indirect electrification in the industrial sector.

Policy options to support investments into clean hydrogen — Figure D.6

Policy Instrument	Hydrogen-Contract for Difference	Carbon contracts and CCfDs	Clean hydrogen-based fuel quota
Potential application	Greening existing hydrogen production	Greening industrial processes req. green hydrogen (e.g. steel and chemicals)	Blending in aviation and maritime fuels
Remarks	Ideal for pre-existing H_2 demand with low costs for clean H_2 integration	Appropriate to support the development of new clean H_2-based value chains	Allows H_2-based fuels to compete for market demand created by the quota

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Policy need 2. A robust sustainability framework for clean hydrogen production and use

To develop clean hydrogen that does not contribute to increasing emissions along the industrial value chain (scope 3 emissions[4]), the EU will also need a robust sustainability framework. This could be made part of a revised Renewable Energy Directive and related regulations on the definition of renewable hydrogen. A robust sustainability framework for clean hydrogen would need to set rules determining when hydrogen production is classifiable as "clean" and eligible for state aid. These include:

- → rules governing guarantees of origin for clean hydrogen;
- → rules governing the "additionality" of renewable or decarbonised energy for clean hydrogen production;[5]
- → rules ensuring that clean hydrogen is allocated first to the most appropriate "no-regret" options, beginning with steel and chemicals;
- → rules governing the safety of hydrogen deployment and the technical requirements of transport pipelines.

Policy need 3. Planning and financing of decarbonised energy infrastructure, especially for industrial clusters

Presently, responsibility for the planning and funding of public utility electricity and public gas infrastructure falls to the National Energy and Climate Plan (NECP) under the EU's Energy Union Governance Regulation, where it is then delegated to entities at the national level. Introducing hydrogen, carbon capture and storage and clean power infrastructure for the decarbonisation of industry requires revisions to existing national governance systems. At a minimum, future versions of National Energy and Climate Plans should include planning and reporting on the financing of strategic industrial infrastructure – which the existing NECP template does not explicitly cover.

Much of the infrastructure planning and development will need to begin by focusing on the micro-scale,

4 That is to say, emissions that result from producing hydrogen with non-zero carbon electricity.

5 "Additionality" means that the renewable hydrogen is sourced from additional renewable energy production in the EU instead of from existing or new renewable power resources dedicated to decarbonising power for other end usages.

i.e. at the industrial clusters in each member state and on solutions for decarbonising them. Ideally, member states should develop decarbonisation strategies for industrial clusters in accordance with existing regulations. Such strategies should be summarised in future NECP revisions and serve as a reference point for other planning and EU financing instruments such as NECPs, Regional Just Transition Plans, Projects of Common Interest approvals, state aid approval requests, etc.

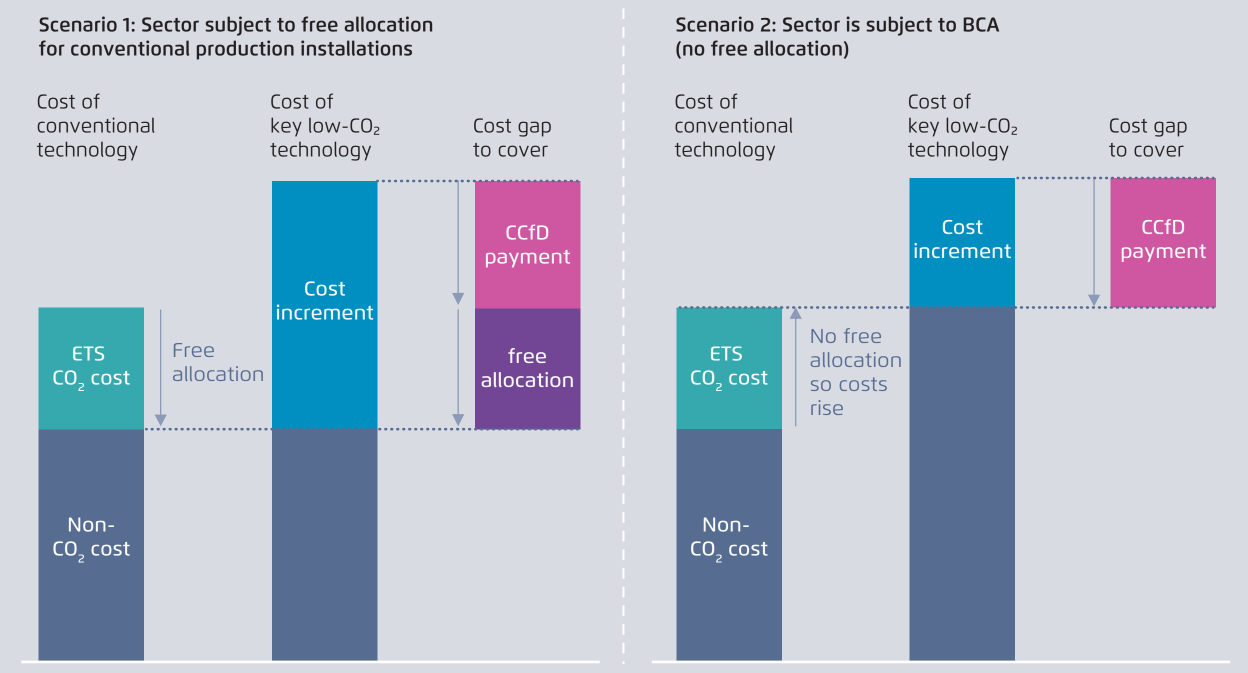
Cross-border infrastructure will also become increasingly relevant to the decarbonisation of industrial sites and clusters across Europe. Decarbonised industrial energy and the CO_2-storage and transport infrastructure are critical for European policies such as the Trans-European Networks for Energy regulation ("TEN-E") and the Projects of Common Interest framework. The need for a decarbonised industrial energy infrastructure must be reflected in national and regional planning processes.

3.2 Midstream policies

The preceding sections identified three key requirements for the midstream part of the value chain:

- → Investment risk mitigation for unproven technologies
- → Recovery of the higher operating costs for ultra-low carbon technologies
- → Protection from carbon leakage under higher carbon & production costs

The CCfD mechanism with two anti-leakage policies (free allocation vs BCAs) — Figure D.7



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Note: Under the current EU ETS anti leakage system, the EU's energy intensive industries with high trade exposure receive free EUA allocations to maintain the production cost at the level of international competitors with equally GHG intensive processes. This cost thus also represents the reference for the calculation of carbon specific cost differentials of key low-carbon technologies. This incremental cost can be covered with a combination of free allocations also for key low-carbon technologies and the payment of the CCfD. In case the system evolves towards a Carbon Border Adjustment without free allocations to energy intensive and trade exposed industries, the cost for producing or importing products produced from GHG intensive technologies would increase and the payment of the CCfD, without free allocations to key low-carbon technologies, will be sufficient to cover the cost gap. This illustrates, that a CCfD is compatible with a future border adjustment and increasing carbon prices but allows to mobilize urgent investments now.

We identified the following EU-level policy priorities for meeting these requirements.

Policy need 4. An EU policy framework for carbon contracts-for-difference to cover the higher operating costs of key technologies

Carbon contracts-for-difference (CCfD) would be awarded only to projects implementing technologies deemed compatible with achieving economy-wide climate neutrality by 2050. In effect, they are a guarantee that the EU or the host member state will cover the difference between the actual EU ETS carbon price and the carbon price required for the project to be profitable.

Figure D.7 illustrates how a CCfD works using either free allocation or border carbon adjustments as the main anti-leakage measure.[6]

Payments to the projects would be calculated based on the difference between the EU-ETS carbon price and a pre-agreed "strike price," the breakeven carbon price necessary to make the low-carbon technology project commercially viable in relation to a given conventional technology. At the end of each year, the project owner reports the annual production level.

If the carbon price average was below the strike price, the project receives the difference multiplied by a) the production cost using the low-carbon technology multiplied by b) the abated emissions from the new technology (relative to a conventional benchmark). Conversely, if the carbon price is above the strike price, then the project owner pays back a share of the "excess" income.

In sum, CCfDs help cover the operational cost gap between conventional and climate-neutral or ultra-low carbon technologies. But they also help stabilise revenue streams by eliminating the CO_2 price risk for project investors. In this way, they help significantly improve the economic viability and bankability of projects.

Given their urgency, CCfDs for industry would initially need to be awarded at the member-state level. They would nevertheless require a strong European enabling policy framework. EU-level CCfDs should be developed as soon as possible to ensure that Europe does not experience a two-speed rollout at the member-state level.

An EU-level mechanism would bring other advantages as well: diversification of geographical and technological deployment, increased competition between technologies at auctions, solidarity with member states unable to pay for domestic CCfDs in the short term and facilitating the planning of pan-European infrastructure for industrial clean energy and CO_2 storage (avoiding a two-speed Europe).

Specifically, the EU should put in place the following elements:

- → Open the door to national CCfDs under revised Environmental and Energy State Aid Guidelines. The conditions under which member states could develop a policy with likely approval must be clear.
- → Develop guidance for minimum CO_2 performance benchmarks and relevant sustainability criteria to ensure that CCfDs are allocated only to projects that are genuinely compatible with the goal of climate-neutrality by 2050.
- → Introduce guidance and possible technical support on how to ensure that project costs are evaluated correctly, do not lead to overpayment and do not minimise the risks of internal market distortions.
- → Reform EU ETS provisions on free allocation and benchmarks in order to simplify CCfD implemen-

6 Technically, a third scenario is also possible: the national government could sell previously allocated allowances to the project and pay the full cost difference of the decarbonised technology. This scenario occurs when key-low carbon technologies do not receive free allocations.

Box 1: CCfDs would be affordable for member states

In view of the budget constraints due to the COVID-19 crisis, some national governments may be concerned about the costs of carbon contracts-for-difference. In reality, however, such fears are mostly unfounded.

Initial estimates for the cement and steel sector are shown in Figure D.8 below. The data explore two pathways for decarbonising steel and one for decarbonising cement. For steel, option one describes a first step towards climate-neutral production. It begins by investing in natural gas-based DRI technology, which will reduce emissions by ~66%. (Over time, clean hydrogen will replace natural gas.) The second option consists of immediately introducing much higher levels of clean hydrogen for DRI, which will reduce emissions by 89% relative to conventional blast furnaces. For cement, the option is based on an oxyfuel process with CCS at 90% capture rates.

Figure D.8 presents the mid-range cost estimates up through 2030, with an assumed CO_2 price of 45€/tCO_2 and an average wholesale power price of 60 to 70€/MWh. Actual site costs could differ depending on local conditions

Cost estimate for financing CCfDs of a hypothetical member state representing ~10% of the EU's primary steel or cement production

Figure D.8

	Breaktrough technology	Breakeven CO_2 price range & central estimate for 2030*	CCfD payment per tCO_2 avoided @ETS= 45€/tCO_2	Support per tonne primary steel/cement		10% of EU27 primary production		Annual costs for CCfD (for greening 10% of EU market
STEEL	DRI (NatGas) (-66% t CO_2/t steel)	71 – 49: 60€/tCO_2	15€/t CO_2	17€/t CO_2	x	10Mt/yr	=	0.17 bn €/yr
STEEL	DRI (Green H_2) (-89% t CO_2/t steel)	165 – 99: 132€/tCO_2	87€/t CO_2	132€/t CO_2	x	10Mt/yr	=	1.32 bn €/yr
CEMENT	Oxyfuel-CCS (-90% CO_2/t cement)	131 – 70: 101€/tCO_2	56€/t CO_2	31€/t CO_2	x	16Mt/yr	=	0.50 bn €/yr
	CO_2 reductions refer to conventional process (steelmaking; cement)	Green Power price = 60€/MWh – 70€/MWh	Assumes 45€/t CO_2 average price in EU ETS			2017 EU primary steel (cement) production = 95 Mt (159 Mt)		Number will vary for bigger or smaller member states & depending on capacity supported

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Note: Actual technology breakeven costs may differ from these estimates, depending on site-specific characteristics. The required CCfD strike price and thus per unit cost can be lowered if combined with other support/funding. Costs depend critically on ETS CO_2 price, H_2, and power price assumptions, and size of national market. Exact emissions reductions per technology can vary depending on site specifics.

The projected annual payments to cover the incremental costs of CCfDs suggest that the costs are fairly moderate for individual member states. For example, a large member state, representing, say, 20% of the total EU market for primary crude steel and Portland cement, and looking to convert 50% of its national production capacity to climate neutrality-compatible processes, would need to calculate between 170 million to 1.32 billion €/yr for primary steel (depending on the share of gas vs. hydrogen in DRI production) and roughly 500 million €/yr for cement (to shift production to oxyfuel and CCS technologies). These amounts would be sufficient to cover the clean-energy modernisation needs during the next 10 years for the steel and cement sectors in Europe.

The above example was for a larger member state, but most EU member states do not produce more than 5% of the total EU supply of either cement or primary steel. In principle, therefore, these member states could convert their steel and cement sites to clean energy for less than 50% of the estimated cost.

Other factors can also affect costs. In practice, CCfDs are not likely to be the only support instrument, and infrastructure costs may be partially paid by other instruments. For example, the EU ETS Innovation Fund or national innovation funding tools would likely contribute to the capital cost of some projects, thus reducing the need for CCfDs to cover 100% of additional costs. In such circumstances, the above cost estimates would be on the high side. At the same time, costs would be higher if support is given to other sectors, such as certain basic chemicals or non-ferrous metals. Changes to assumptions regarding ETS or power prices could also increase or decrease the results, direction depending.

tation by member states and eliminate disincentives.

→ Identify new funding sources – either from ETS auctioning revenues and/or from a climate surcharge on basic materials – to fund large-scale European CCfD projects.

Policy need 5. Financial de-risking instruments for capital expenditure in first-of-a-kind, large-scale investments

While CCfDs are an effective instrument for covering the operating cost gap between key low-carbon and conventional industrial technologies, they do not necessarily address the "capex risk" from the large-scale deployment of new unproven technologies. For this, CCfDs may need to be supplemented by capital de-risking tools. These instruments can take different forms. However, some powerful tools already exist at the EU level. One such tool is the EU ETS Innovation Fund, which provides up to 60% of the additional costs of large-scale demonstrators for innovative low-carbon projects in any sector.[7] Another useful tool is InvestEU, which provides loan guarantees that help reduce the risk of investment in innovation and in "strategic" projects in Europe.

But though both of these tools are already in place, they also are relatively small and are spread thinly across many sectors and priorities. For example, the EU ETS Innovation Fund is expected to offer €8-11 billion over the ten-year period to 2030 (roughly 1 billion per year) over all sectors of the energy system.[8] InvestEU can be leveraged since it provides loan guarantees rather than grants. However, its size was reduced dramatically during

7 See https://ec.europa.eu/clima/policies/innovation-fund_en

8 See https://ec.europa.eu/clima/policies/innovation-fund_en

the recent EU Recovery and Budget negotiations.[9] Other initiatives, such as the proposed liquidation of the EU Coal and Steel Fund, make up only a small slice of the total pie.

To boost these instruments, the EU must devise additional funding mechanisms. An EU-wide climate surcharge on products with large amounts of basic materials sold in the EU market is one solution. An additional source of funding could be new revenues from ETS auctions. These could stem from expanding the ETS to additional sectors beyond maritime and aviation fuels. They might also come from the elimination of free allocations for certain sectors (such as those moving to border carbon adjustments).

Policy need 6. Set standards for climate-neutrality compatible production of basic materials

While carbon contracts-for-difference and financial de-risking mechanisms to support innovation will be essential for financing breakthrough technology projects, the EU also needs to send a clear signal dissuading new investments in industrial plants and technologies that are incompatible with achieving climate neutrality by 2050. Otherwise, EU companies may invest in half measures that reduce emissions in the short run but lock in technologies that cannot deliver economy-wide neutrality by mid-century.

The best way to tackle this problem is via setting standards for basic materials that are compatible with climate neutrality. Such standards are necessary for several reasons, including:

- → clarifying the project eligibility criteria for CCfDs (see above)
- → facilitating the creation of lead markets for climate neutral materials
- → facilitating green public procurement of climate neutral basic materials
- → providing a clear signal about the direction of future EU policy requirements to avoid lock-in of "half way solutions" that are not compatible with climate neutral industry in 2050.

Once standards are set, the EU could determine CO_2 performance requirements for major reinvestments and for license extensions of existing plants after a given date, say, 2030. Revisions to the EU's Industrial Emissions Directive could make the best available reference technologies post-2030 consistent with climate neutrality criteria.

Since IED regulations can take several years before coming into effect followed by a long, sometimes, 4-year phase-in period, new standards should seek to set climate neutrality requirements for all major new investments or license extensions after 2030. Doing so would send a very clear signal to industries, encouraging them to prioritize their decarbonisation strategies and steer a course towards climate neutrality during the coming investment cycle.

Policy need 7. A robust package of anti-carbon leakage policies, enabling long-term alternatives to free allocation and state aid

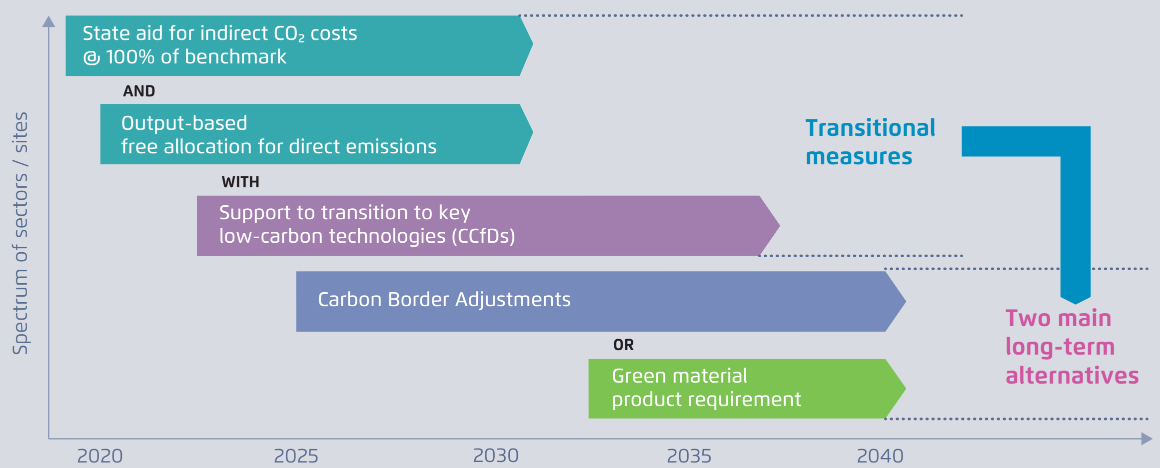
Under existing policies, the EU ETS Directive provides two main measures for tackling the risk of "carbon leakage," i.e. when production, jobs and emissions move to countries with lower carbon prices. The first is the free allocation of emissions allowances to sectors at risk of carbon leakage, which include energy-intensive industries.[10] The second is

9 See https://ec.europa.eu/commission/priorities/jobs-growth-and-investment/investment-plan-europe-juncker-plan/whats-next-investeu-programme-2021-2027_en

10 See European Commission (2018): Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 (consolidated text, incorporating revisions).

Short, medium and long-term policy tools for carbon leakage protection

Figure D.9



Agora Energiewende, 2019

the possibility of state aid payments to compensate for higher electricity prices. But with higher carbon prices and declining free allowances likely in the future, these solutions will need to be revised and then eventually phased out in favour of alternatives. (See Box 2.) When it comes to maintaining a uniform carbon price along the value chain, phasing out free allocation and state aid will unlock additional downstream incentives for abatement. The phase-out can also help remove distortions created by certain regulations (such as the disincentive to substitute clinker for cement). [11]

11 If free allocation is to be continued, then efforts may be needed in some sectors to revise existing benchmarks and prevent distortions. For example, in the case of cement, the existing practice of providing free allocation for clinker production (rather than cement) could have a distortionary effect. This is because is it fairly easy to substitute clinker with other materials, such as calcined clays, etc. Under high carbon prices, free allocation based on clinker production would provide companies with an incentive not to adopt this option. Subsuming cement under a border carbon adjustment or a product carbon requirement and phasing out free allocation would avoid the problem.

In the medium term, therefore, the EU will need to replace its current carbon leakage instruments with more sustainable and more effective alternatives. In the absence of a G20 agreement on a global carbon price, two basic options exist: border carbon adjustments, which equalize carbon prices at the border, or carbon product requirements on all goods (imported or domestic) sold in EU. Unless a global carbon price agreement is reached, the EU will have to choose one of the two (or perhaps some combination thereof).

The exact speed with which the EU would need to move to these long-term alternatives will depend on how quickly free allocation and state aid cash payments become unsustainable in the EU ETS. This, in turn, depends on whether the EU decides to enlarge the ETS. As explained in Box 2 below, the point of unsustainability could be reached at any time between the mid-2030s and 2042.

In the short run, however, both border carbon adjustments and carbon product requirement present significant challenges. Carbon product requirements will not be able to be introduced immediately. Such policies are generally appropriate only once certain technologies become well-established. Likewise, border carbon adjustments require significant new administrative enforcement development and face political hurdles at the domestic and international level.

A likely scenario is that border carbon adjustments in the near term will be impossible for all but a small handful of sectors and, even then, will require a cautious and gradual introduction. Instead, a transitional arrangement will be needed that relies on existing state aid and free allocation systems that incorporate longer-term solutions like border carbon adjustments or carbon product requirements. Figure D.9 summarises the broader anti-leakage policy package needed in the short, medium and longer term.

In the short-term, the following specific reforms will be needed:

- Free allocation must be continued at the full technology benchmark for sectors not subject to a border carbon adjustment, but **adjusted ex-post** based on true output ("output-based allocation"). Currently, free allocation is determined ex-ante based on past output.
- **Reforms to state aid guidelines** are needed that limit support to electricity-intense sectors. Maximum aid levels should be linked explicitly to the carbon price and allowed to rise to 100% of the full technology benchmark for prices above 30€/tCO_2.
- Border carbon adjustments and carbon product requirements must be gradually implemented for the relevant candidate sectors. This requires monitoring and reporting infrastructures, mechanisms to account for foreign carbon policies, mechanisms to provide export rebates, diplomatic efforts to reduce opposition and retaliation, etc.

Depending on the specific policy package design proposal, the EU may need to undertake additional reforms. These include:

- reforms to eliminate the need for a cross-sectoral correction factor (depending on whether the EU expands the ETS);
- changes to certain product benchmarks to avoid disincentives for clinker substitution (if free allocation is continued in the cement sector); and
- rule changes that allow member states to provide cash payments instead of free allocation to sites receiving CCfDs without losing their allocated ETS allowances (provided that free allocation continues in sectors subject to CCfDs).[12]

12 In a free allocation system, the question is whether a free allocation should continue for ultra-low carbon sites receiving CCfDs, or whether a cash payment would be simpler, allowing allocations to be sold to raise the necessary revenues for the member state or the EU fund.

Box 2. The limits of the existing anti-carbon leakage system

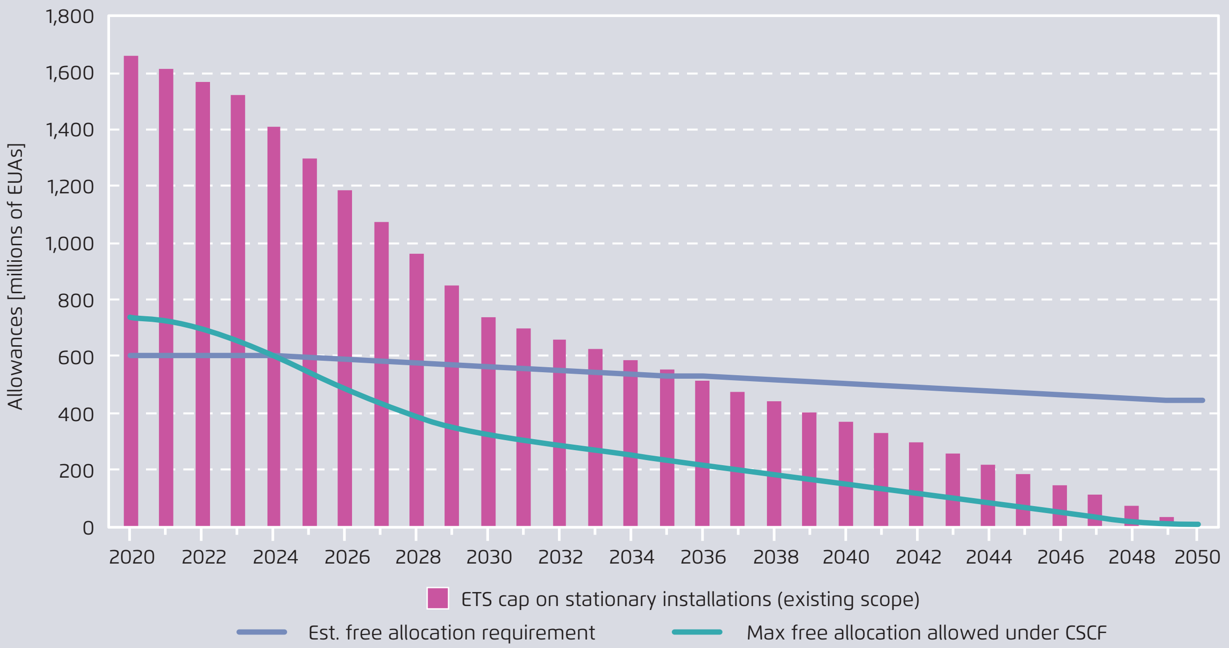
Under current ETS anti-leakage rules, free allocation is provided based on past activity levels multiplied by CO_2 performance benchmarks based on the average of the best 10% of installations producing a given product in the EU. But the free allocations can be revised downwards if the total level of free allocation exceeds 46% of the total EU ETS allocation (including both free and auctioned allowances), whereupon a "cross-sectoral correction factor" (CSCF) kicks in. Furthermore, electricity-intensive sectors, such as producers of non-ferrous metals, are eligible to receive cash compensation for up to 75% of additional electricity costs arising from the ETS.[13]

While the system has avoided leakage fairly well so far, more ambitious climate policies would sharply decrease the total number of ETS allowances over the next 10 years. Consequently, even if the CSCF were reformed to allow for a share of free allocation higher than ~46% of the cap, the share of free allocation would still grow very quickly – potentially consuming up to 75% of the total number of allowances by 2030 and 100% by 2037. This indicates that free allocation is not a sustainable solution to carbon leakage in the

13 See European Commission (2012): Guidelines on certain state aid measures in the context of the greenhouse gas emission allowance trading scheme post 2012. Adopted on 22.05.2012. Official Journal C154, 05.06.2012, p. 4

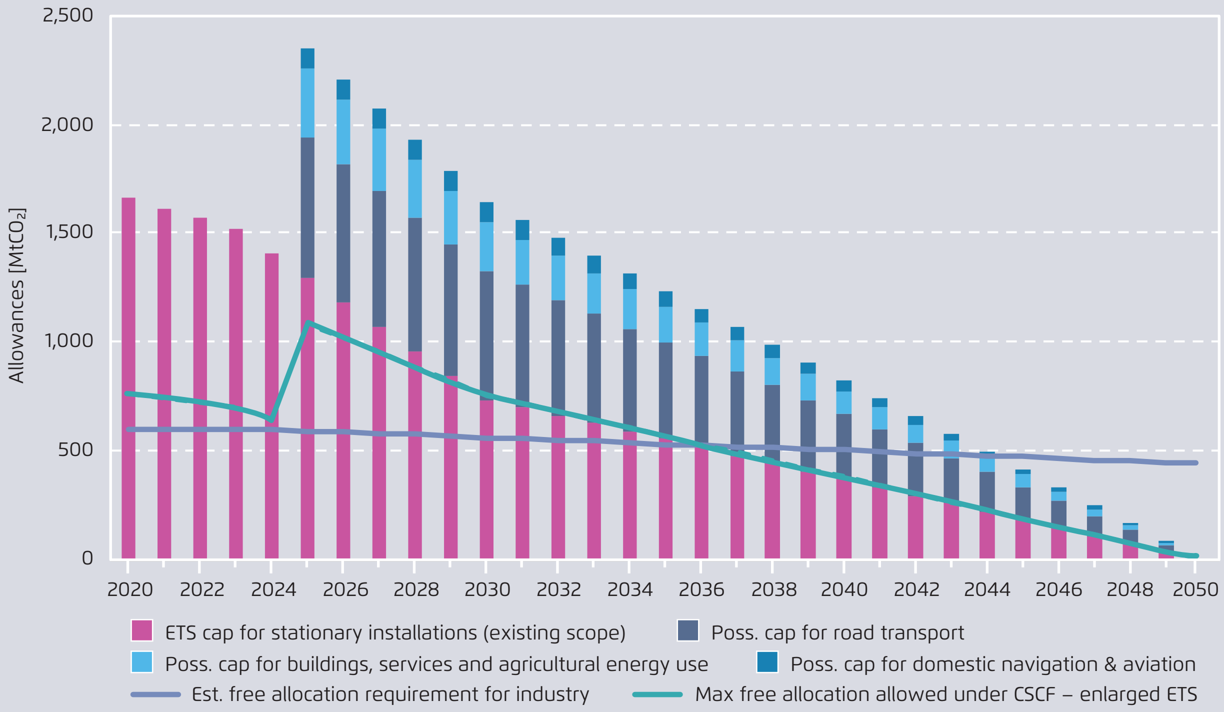
Free allocation and the EU ETS emissions cap with an EU-wide -55% in 2030 and climate neutrality in 2050 target

Figure D.10



Agora Energiewende, 2021. Own estimates based on data from EEA, 2021 and European Commission, 2020b.

Free allocation and the EU ETS emissions cap assuming ETS extension to buildings and transport   Figure D.11



Agora Energiewende, 2021. Own estimates based on data from EEA, 2021 and European Commission, 2020b.

medium term.[14] Even in the short term, strong growth in the free allocation share would tend to put pressure on the residual auctioning share of allowances, which currently supports several dedicated funds and provisions in the broader EU ETS policy framework.

Another option would be to include in the EU ETS fossil use sales for the transport and buildings sectors. This would increase the total allowances available each year (Figure D.11). If the EU significantly enlarges the ETS, the existing free allocation mechanism could be retained for much longer than possible in the current system. Nevertheless, the EU would still need to transition to an alternative system at some point down the line.

Another problem with the existing EU ETS anti-leakage system is that free allocation is given prior to firms' production decisions and unless production varies very significantly (more than +15% or –15%) from past activity levels, there is no ex-post adjustment to align free allocation to actual production levels at the end of the year. Under very high carbon prices, this could create an incentive for a certain percentage of installations

14 This is true even if energy-intensive sectors reduce their emissions to zero, since the producers would still need to be protected from the additional cost of climate-neutral products relative to conventional ones. Under a free allocation system, low-carbon technologies would probably require free allocations at the full conventional benchmark, although cash payments might also be an alternative. In the absence of a dedicated funding source, however, this too would likely be an unsustainable solution in the long term.

to reduce their production by a given percentage, import a share of the production no longer produced in Europe, and sell the surplus allocations on the market. This phenomenon is known as "operational carbon leakage." Incentives for operational leakage can be eliminated by introducing ex-post adjustments to the level of free allocation given each year based on the actual production from the preceding year (more on this below).

A third problem with the existing carbon leakage system is that, under current state aid guidelines, which expire in 2020, a maximum of 75% of indirect ETS costs can be offered to compensate electricity-intensive sectors. At future carbon prices of 45-60€/tCO_2, the absence of 100% compensation can have a major impact on the competitiveness of electricity-intensive products because they compete in international commodity markets with strong competition from non-EU countries. For example, in 2018, the EU imported basic unwrought and semi-finished aluminium products equivalent to 42% of total EU aluminium production for that year (Eurostat, n.d.).

3.3 Downstream policies

The preceding sections identified four key requirements for the downstream segment of the value chain:

→ funding costs of decarbonisation internalised in final product prices
→ standards and demand for climate-neutral basic material
→ stronger incentives to increase the quantity and quality of recycling
→ incentives for increased material CO_2-efficiency in final product design, manufacturing and construction

We identified the following policy priorities at the EU level to meet these requirements.

Policy need 8. A climate surcharge on material-intensive final products

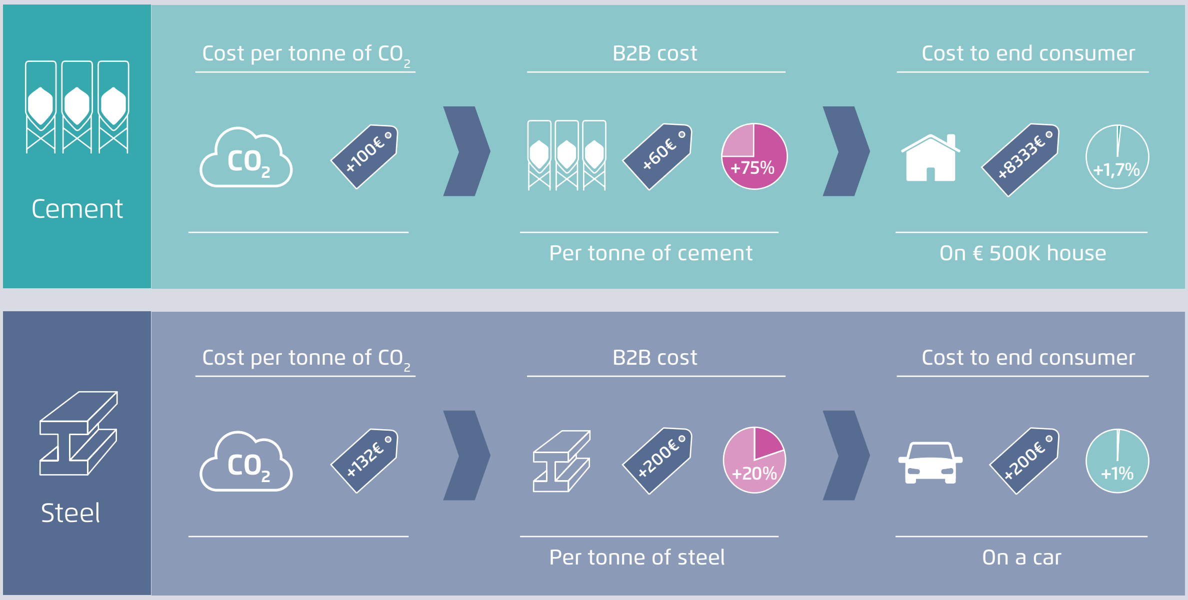
If scaled at the EU level, CCfDs and related policies will probably require a new dedicated funding source. In general, it is desirable that any new funding source is ultimately paid for by the final consumer of the products, so that the sector would be "self-funding." The ideal solution would therefore be a climate surcharge to be placed on final products that have very high levels of energy-intensive basic materials such as steel, cement or basic chemicals.

The list of such products could be long or short depending on how broad or narrow policymakers wish to make the tax base. But even a narrow tax base for a limited number of products such as new buildings, new motor vehicles and plastic packaging items would be able to both cover a large share of the consumption of steel, cement and plastic chemicals. For such products, the contribution rates would be very low, typically in the order of less than 1% of the final product cost,[15] thus reducing any risk of undermining market demand. Carbon leakage would not be possible either, since all products sold in the internal market, including imports, would be subject to the charge, while exports could be exempted (See Figure D.12).

15 These are based on our own estimates.

How the cost of carbon in upstream basic materials translates into price increases in downstream products

Figure D.12



Agora Energiewende, 2020, adapted from illustration of Energy Transition Commission, 2018

Climate surcharges could be levied at the national or the European level. Indeed, the EU has already proposed a plastics tax to pay for part of the European recovery fund post-Covid19 – "Next Generation EU". The EU could expand this approach to a broader set of products containing large shares of carbon-intensive basic materials.

Policy need 9. Requirements to improve recycled basic material quality and material efficiency in manufacturing

One of the biggest barriers to boosting the circular economy for basic materials such as steel, non-ferrous metals and plastics is the degraded quality of secondary scrap and plastic. This limits the share of recycled materials that can be used to substitute new virgin materials. Since the products that are manufactured or built today will be the recycled scrap available 10, 20 or even 50 years from now, the issue is urgent.

We have identified three ways to incentivise the improvement of material quality:

→ The EU could reform recycling legislation for basic materials to include **stronger incentives for material quality conservation**. This could be done via reforms to sectoral legislation under the EU Waste Framework, such as the End-of-Life Vehicles Directive, the Waste Framework Directive and the Construction and Demolition Waste policy framework. Reforms could take different shapes, but options should include minimum recycled content requirements, additional material quality separation, collection and tracing requirements and incentives for Extended Producer Responsibility schemes to set quality goals alongside quantity objectives.

- The EU could **ban or otherwise disincentivise products with low recyclability or poor material efficiency performance** – akin to existing practices for energy using products. This could include, for instance, incentives to reduce the number of polymers that plastic products contain, ensuring that products such as vehicles, machines or buildings are designed with longevity and ease of disassembly in mind, banning or disincentivising (via labelling) material-intensive construction and design.
- The EU could revise construction and vehicle waste legislation to **adopt minimum requirements for end-of-life de-construction, sorting and tracing**. This should include, as a minimum, tighter limits and regulations on the demolition of and sorting of waste from buildings and construction and tighter limits and regulations on the shredding of vehicles.

Policy need 10. "Climate neutrality-compatible" product labelling and eco-design requirements for embedded carbon

Assuming that carbon contracts for difference and climate-neutral compatibility requirements for the production of intermediate materials after 2030 are in place to drive investment upstream, there are two ways that the EU can support the creation of lead markets and demand for low-carbon basic materials:

- **Low-CO_2 product labelling for basic materials.** Common EU-wide labelling can help foster purchaser confidence in the environmental integrity and climate-neutrality compatibility of basic materials. The label can be used as a reference point for leading private-sector purchasers who wish to advertise their green credentials. Since production technologies for intermediate basic materials are updated only every 20-30 years, these labels should not use the A-F rating, like the one used by the EU's Energy products under Energy labelling. Rather, because non-marginal change is required, and the EU must be careful not to incentivise "lock in" of half-way solutions to climate neturality, the relevant label should only indicate "climate-neutrality compatibility". This solution would thus be more akin to the current EU's "Eco-labelling" system, rather than its "Energy labelling". The resulting standards could potentially be used in a variety of legislative instruments, such as the environmental standards set under the Construction Product Regulation, Green Public Procurement Directive or the Industrial Emissions Directive.
- **Design requirements for final products** containing large amounts of basic materials. To create a more complete set of incentives, the EU should set **minimum requirements for embedded CO_2 in final products**, beginning with buildings and vehicles. One of the strengths of embedded carbon requirements is that they address material intensity, choice of materials, choice of recycled vs. primary materials, etc. They can also help tackle important sources of waste due to overestimation of materials needs in construction and inefficient manufacturing processes. These regulations could follow the example of leading member states such as France, Sweden, Finland, and Denmark and require that member states adopt policies that require all new buildings to have embedded carbon below a given tCO_2/m^2 threshold (adjusted for certain features of the building), with tightening standards over time. Indeed, the EU has begun trialling its own evaluation system for measuring building LCA emissions, known as LEVEL(s). This could be used a a technical basis for further requirements on member states to adopt mandatory requirements on new construction across the EU.

The change could be adopted via amendments to the Construction Products Regulation[16] and the creation of a new product regulation for construction products.

16 See https://ec.europa.eu/growth/industry/sustainability/ecodesign_en

Box 3. Examples of eco-design requirements for lifecycle carbon assessment (LCA) limits and new construction labels

Although many private and local government LCA initiatives exist (Bionova, 2018), national LCA labelling and eco-design policies have recently begun to emerge at the EU member-state level (Zero Waste Scotland, 2019).

For example, France's "E+C- labelling" scheme is a state-backed system that reports the full LCA emissions (and energy performance) of new buildings. Under the label, new buildings must report a) total energy consumption, and b) total lifecycle CO_2 emissions, including energy use and embedded emissions in construction materials.[17] Based on this label, from 2021, a reform of the existing thermal energy regulation on buildings[18] will impose maximum binding limits on each of the above measurements. The limits for embedded CO_2 emissions are expressed in $kgCO_2/m^2$, with an assumed 50-year building lifetime. Certain adjustments then factor in other relevant criteria (e.g. climatic zone, parking spaces, etc). While the limits are not extremely strict at the moment, the regulation defines limits below the minimum for buildings to receive a higher performance label. This is done to create a reference point for more ambitious clients and construction companies. It is expected that the binding limits will progressively be tightened over time.

In 2018, Sweden's National Board of Housing, Building and Planning (Boverket) introduced a new regulation for climate declarations of buildings, effective from 2022. It will include mandatory reporting requirements for most buildings and binding limits for climate impacts expressed in $kgCO_2$ e/m^2 BTA[19] (Boverket, 2020). Since 2015, Denmark has been offering a freely available lifecycle assessment tool for buildings. It will shortly be publishing a set of voluntary sustainability classes. These are intended to try out monitoring and evaluation tools before the introduction of mandatory requirements in the building regulations in 2023 (Zero Waste Scotland, 2020). Similarly, Finland launched a public consultation in 2018 on how to approach whole-life carbon footprinting. This will become mandatory for new buildings by 2025 (Zero Waste Scotland, 2020).

Meanwhile the EU itself has been trialling, since 2018, the new LEVELS framework, which attempts to develop a harmonised European methodology for evaluating the sustainability performance of buildings across several indicators, including embedded CO_2 emissions in materials. The EU could potentially build on this framework to introduce mandatory measures as has been done in the above-mentioned member states.

17 See XPAIR (2020) and Batiment à Energie Positive & Reduction Carbone (RE2020), « Le label E+C- et la Réglementation Environnementale 2020 : Votre guide technique !, » https://blog.batimat.com/e-c-label/

18 See the Regulation on Thermal Energy use in Buildings ("Reglementation Thermique 2020").

19 BTA refers to "bruttoarea," which is broadly equivalent to "Gross Floor Area" (or GFA).

Policy need 11. Green public procurement requirements for basic materials

EU public procurement legislation from 2014 already permits [20] – but does not require – environmental criteria to be used in public procurement for the domestic market. Following the distinctions made by Chiappinelli, Zipperer & DIW (2017), two basic approaches for the EU could potentially be envisaged and implemented via a reform of the Public Procurement Regulation:

- The EU could set **declining maximum CO_2 limits on specific materials** that are eligible for use in public projects. A similar approach has also been adopted by Buy Clean California[21] in the United States, which forbids certain CO_2-intensive materials in public projects when the scope 2 emissions are above a given threshold. This approach has the effect of supporting the phase-out of CO_2-inefficient products.
- The EU could introduce **mandatory life-cycle CO_2 performance criteria** in assessing projects, based on harmonised European methodology. Under the Most Economically Advantageous Tender system, environmental criteria can be explicitly monetised, with the better environmental performers receiving a reduced, "fictive" bid price. The Dutch Public Infrastructure Authority already uses a lifecycle assessment tool ("Dubocalc") and a shadow price of 50€/tCO_2e to calculate fictive bids. The lifecycle assessment method is based on the Environmental Product Declaration Standards EN 15804 and EN 15978, with national adaptations (Zero Waste Scotland, 2020). To support this more generally across the EU for basic material products, the EU should certify compliant methodologies and databases and require member states to implement these systems.

20 See European Commission (2014): Directive 2014/24/EU on public procurement and repealing Directive 2004/18/EC; Directive 2014/25/EU on procurement by entities operating in the water, energy, transport and postal services sectors and repealing Directive 2004/17/EC.

21 See https://www.dgs.ca.gov/PD/Resources/Page-Content/Procurement-Division-Resources-List-Folder/Buy-Clean-California-Act

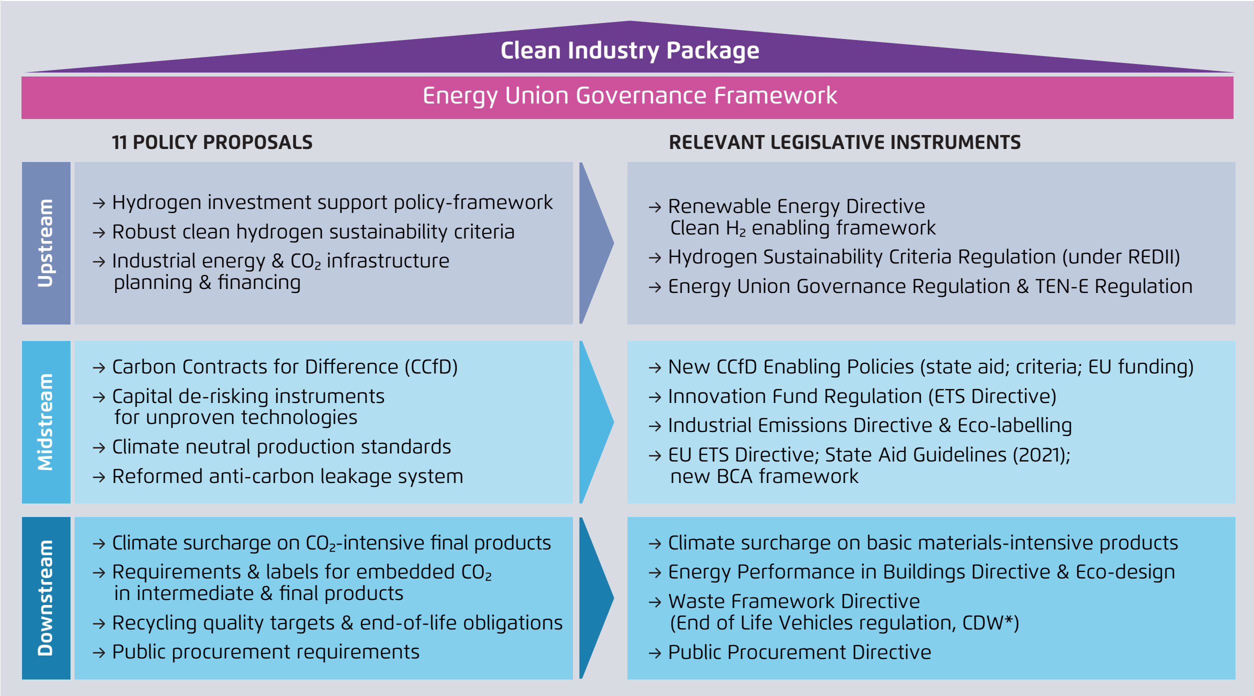
4 Summarising the 11 proposals for a Clean Industry Package

The previous section has laid out a detailed list of specific proposals for policies that together could constitute something approximating a Clean Industry Package for Europe. They are not meant to be a shopping list but, rather, are an attempt to address specific conditions for putting Europe's energy-intensive industrial sector on a path to climate neutrality by 2050. The policies are intended to be, and, in many cases, depend fundamentally on being, part of a package in order to have maximum effectiveness.

We have shown in several instances that policy effectiveness will depend on national-level and sub-national-level interventions. Helping member states to activate these levers of policy – facilitating a broad and inclusive "one-speed" transition across the EU27 – will require a combination of both "harder" legislative instruments together with other "softer" policies that enable, harmonize and provide technical and capacity-building support.

What legal architecture should this combination of policies take? Should they be combined in, say, a "clean industry directive"? A dedicated clean-industry directive is probably not required. With the exception of the introduction of border carbon adjustments and the new CCfD policy, most of the necessary policies could be introduced by reforming existing regulatory instruments. Yet a risk of this approach is that the overarching vision of a comprehensive and coherent package gets lost in the detail. To keep its eye on the big picture, the EU will need to consider the role of **new governance tools** for industrial decarbonisation, both as it prepares legislation and over the longer term.

Policies and legislative instruments to implement the Clean Industry Package — Figure D.13



Agora Energiewende, 2020

Note: CDW stands for Construction and Demolition Waste

Figure D.13 summarises the eleven policy recommendations and maps them onto existing EU-level legislative instruments. The figure shows that, save for CCfDs and eventual border carbon adjustment legislation, virtually all of the proposed instruments could be attained through reforms to existing legislative tools.

Furthermore, virtually all of these legislative files have been proposed for revision under the Green Deal and the 2030 Climate Target Plan. This represents a golden opportunity to implement the proposed policies. At the same time, however, important elements that are not part of the legislative files on the table – notably an enabling framework for carbon contracts for difference and the development of robust standards for climate-neutral materials – must not be forgotten.

Part E: Key low-carbon technologies in the steel, chemical and cement sectors

1 Introduction and methodology

This part of the study describes 13 key low-carbon technologies that can play a significant role in the production of low-carbon basic materials in the steel, chemical and cement sectors. These technologies stand to reduce GHG emissions and most of them are compatible with the creation of a climate-neutral industrial production.

In addition to an introductory overview of each sector with information on current CO_2 emissions, production volumes, employment and reinvestment requirements, we provide 13 comprehensive fact sheets, one for each of the key low-carbon technologies. The fact sheets contain information on current pilot and demonstration projects, CO_2 reduction potentials and abatement costs, earliest possible availability and cost estimates.

The information is based on the studies and calculations that are documented in the publication **Climate Neutral Industry: Detailed Presentation of the Key Technologies for the Steel, Chemicals and Cement Industries.** This publication is a technical supplement that was initially developed for a decarbonisation study on German industry (see point 4 below) and is now used as a basis for the development of assumptions and projections that are representative of the European industry as a whole.

The information in the fact sheets has been developed based on the following sources and strategies:

1. **Scientific literature:** The assumptions and reference data used for calculations and projections were generally based on scientific studies. Where applicable, the fact sheets relied on information from papers in established academic journals such as *Applied Energy* and *Energy Procedia*. The fact sheets also refer to studies that use recent data, including *Integrated Energy Transition* (dena, 2018), *Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry* (Material Economics, 2019) and *The Future of Hydrogen* (IEA, 2019).

2. **Assumptions and results of internal calculations:** For numerous key technologies, we carried out our own internal calculations of expected future production and CO_2 abatement costs based on published scientific studies. Detailed information about our calculations and the underlying assumptions are contained in the aforementioned technical supplement.

3. **Stakeholder review process:** All technology fact sheets underwent a two-stage review process with stakeholders in the German industry. First we presented preliminary versions of the technology fact sheets at stakeholder workshops with participants from businesses, industry associations, science and government. Based on the discussions and input, we revised the fact sheets and sent them to selected companies, associations and scientific institutions for further comments. We then took into consideration the comments and conducted an additional review of the literature before producing the final versions of the fact sheets.

4. **Adapting the technology fact sheets to the EU27:** The technology fact sheets were initially developed and reviewed in cooperation with German stakeholders and published in the 2019 study *Climate-Neutral Industry: Key Technologies and Policy Options for Steel, Chemical and Cement*. This

German-language study focused specifically on decarbonising industry in Germany. For the current study, we assessed the same key low-carbon technologies for the EU as a whole. To ensure the compatibility of the technology fact sheets with European reality, we performed some modifications:

- The CO_2 abatement potential and electricity requirements of key low-carbon technologies were scaled for a Europe-wide deployment. For the calculations, we relied on the 2017 production and emission levels from the steel, chemical, and cement sectors.
- Certain pilot and demonstration projects that were announced since the publication of the German study in 2019 were added to the technology fact sheets. We updated the earliest possible market readiness of certain technologies where appropriate.
- For consistency's sake, we chose to not change the specific emission and cost figures for the reference technologies. This means that the maximum CO_2 reduction potential in the EU27 of each low-carbon technology was calculated according to the average specific emission levels of German plants.

Data sources for individual elements of the technology profiles:

- **Pilot and demonstration projects:**
  Information on pilot and demonstration projects was obtained from operating companies and/or participating research institutions, as well as from appropriate websites and press releases.

- **Maximum CO_2 reduction potentials:**
  We estimated the theoretical maximum CO_2 reduction potentials of key low-carbon technologies for 2030 and 2050 by defining the rate at which low-carbon technologies can replace existing GHG-intensive production plants. The projections are based on an estimate of the earliest possible availability of the key low-carbon technologies (derived from the technology readiness level (TRL)), as well as the projected reinvestment requirements of existing installations. Because we estimated only the theoretical potential, we did not take into account possible economic or societal barriers, such as the availability of infrastructure or the supply of sufficient quantities of electricity or hydrogen. Moreover, we did not consider competition between different low-carbon technologies, which would limit their individual contribution to GHG abatement.

- **CO_2 abatement costs:**
  Data on CO_2 abatement costs are based on calculations that compare the production costs of key low-carbon technologies with conventional GHG-intensive technologies and on findings from the technical literature. In view of the considerable uncertainties about future CO_2 abatement, we provided plausible cost ranges.

- **Earliest possible availability (technology readiness level, TRL):**
  Assumptions about the earliest possible availability of individual technologies are based on the academic literature and on information from companies and research institutions involved in pilot and demonstration projects. The current state of development of individual technologies is assessed by the internationally used TRL rating system. With this approach, technologies that are still in the research and laboratory stage are classified as TRL 1 to 3. Technologies that have entered the pilot phase receive the rating of TRL 4 or 5, while technologies that are in the demonstration phase are TRL 6 or 7. Technologies that are mostly mature are in the range of 8 to 9. However, the TRL alone does not say anything about commercial viability, i.e. the ability of a technology to compete with conventional technologies.

The aim of the technology fact sheets is to assess and compare the complex physical and economic aspects of key low-carbon technologies and create a basis for discussions of their role and deployment. We are aware that the abbreviated presentation represents a simplification, but we nevertheless hope that the synthetic compilation supports constructive dialogue. We would like to thank all the associations and companies that took the time to review and improve these fact sheets. Any errors that still exist are solely those of the authors.

Notes on the fact sheets:

- We had to settle on a selection of key low-carbon technologies to feature in the fact sheets. This selection is incomplete and omits potentially important future technologies for a climate-neutral basic materials industry. For example, while we assess the electrolytic production of hydrogen, we do not present other (nearly) climate-neutral types of hydrogen production such as the use of CCS for steam reforming (blue hydrogen) or methane pyrolysis (turquoise hydrogen). We also omit various strategies to promote a circular economy (e.g., cement recycling), material substitution (e.g., the use of wood instead of cement and concrete in construction) or material efficiency. But we do consider these alternative strategies in Part B of the study.
- The cost calculations or estimates in these fact sheets are geared towards private businesses. For example, we apply a discount rate of 8 per cent, which is typical for private investors, rather than the much lower social discount rate used in economic analyses.
- Cost calculations are based on electricity price assumptions of 60 to 70 euros per MWh for 2030 and 50 to 60 euros per MWh for 2050.[1] More details on assumptions and calculations are contained in the aforementioned technical supplement.
- For both the reference technologies and the key low-carbon technologies, we considered only direct[2] emissions generated during their operation. Unless otherwise noted, we did not take into account upstream emissions (which occur, for example, in the extraction of fossil fuels or in the construction of new production plants) and downstream emissions from the use and disposal of products. We chose this perspective because direct CO_2 emissions constitute the largest source of emissions and because of the uncertainties regarding upstream and downstream emissions.
- Estimates of future costs are based on 2020 prices.
- For some key technologies, an integrated view is necessary. For example, assumptions about hydrogen production from renewables play a central role in calculating the production and CO_2 abatement costs of some of the technologies presented here. Likewise, the development of a closed carbon cycle economy in the chemical industry will require the combination of chemical recycling and electrified steam crackers.
- We invite all experts to provide us feedback regarding our assumptions and calculations so that we can further refine our evidence base for key low-carbon technologies.

1 Electricity costs vary across EU member states. We assume that the companies in the basic materials industries will continue to benefit in the future from significant reductions in certain electricity price components such as grid charges and levies for the financing of renewable energy plants.

2 Direct emissions do not include the emissions from electricity production.

2 Steel

2.1 Steel industry overview

Steel is a material that is used in many different industries. Much steel is used in infrastructure (especially in the transport and construction sectors), where it remains for many years.

Steel production can be divided into two categories: primary production, based on iron ore, and secondary production, based on scrap steel. Globally, the integrated blast furnace is the most common process for reducing iron ore to hot metal, while the electric-arc furnace is the preferred process for melting and purifying scrap steel. Both processes are used in Europe.

As referenced by official industry classification (NACE 24.1), the EU27 steel industry employed around 304,000 people in 2017 and directly produced an annual gross value added of 23.7 billion euros.[1] In 2017, steel production in the EU27 totalled 161 Mt.[2] Of this, 59 per cent was manufactured with integrated blast furnaces (referred to as blast-furnace route below), whereas 41 per cent was produced in electric-arc furnaces (EAF). The energy demand of each process differs. EAF can only process steel that has already passed through the energy-intensive reduction step from iron ore to pig iron in blast furnaces. In Europe, energy use in the primary route totals around 15 GJ per t of crude steel for reduction and smelting and 2 GJ per t of crude steel for EAF smelting. The steel plant in Hamburg represents a special case in Europe as it is the only plant that uses natural gas for the production of direct reduced iron as a primary feedstock for steel production (see Table E.1 on the following page).

Crude steel is rarely the product sold by steel mills. Rather, most manufacturing output consists of semi-finished steel made by hot-rolling crude steel into sheets, rods, beams, pipes and other products.

The vast majority of steel producers both manufacture the steel and perform the hot-rolling, so the volume of crude steel trade is quite low, though crude steel is available for import from other countries. The trade of rolled products is far more significant. Overall, the EU net trade balance of steel is rather balanced. However, since 2016 the EU became a net importer and in 2017 net imports amounted to roughly 3 Mt of steel. The largest domestic buyers of European steel by volume are the construction industry (35 per cent), the automotive industry (19 per cent), mechanical engineering (12 per cent), metal ware (14 per cent) and pipe manufacture (11 per cent).[3]

In 2017, EU27 steel and iron production directly emitted 188 $MtCO_2$.[4] Most of these emissions can be traced back to the blast-furnace process. As with energy use, specific emission levels noticeably differ between primary and secondary production (see Table E.1.).

By 2030, 48 per cent of EU27 blast furnace capacity needs refurbishment which requires replacing and investing in an equivalent to 50 Mt of hot metal capacity.[4]

Direct CO_2 emissions from the steel industry in the EU27 (+UK) in 2017
188 $MtCO_2$ (+12 $MtCO_2$ in the UK)

Steel production in the EU27 (+UK) in 2017
161 Mt of crude steel
(+7.5 Mt of crude steel in the UK)

Steel demand in 2017 (EU28)
159 Mt of finished steel

Reinvestment required for blast furnaces by 2030
Approx. 48 per cent of blast furnaces, i.e. a total of 50 Mt of annual hot metal production capacity)

Directly employed in 2017 (EU27)
304,000

Greenhouse-gas-neutral steel production

Creating a steel production that is mostly greenhouse gas (GHG)-neutral represents a great challenge, but it is technologically possible. There are already some promising approaches for producing GHG-neutral steel in the future. This section describes those approaches in detail. One important approach is to increase the share of steel from secondary production (melting down scrap steel in electric arc furnaces) because its carbon emissions are already fairly low and requires comparatively little energy.[5] If green electricity and biomass (biogenic carbon) are used[6], this route can potentially become carbon-neutral in the long term.

A greater challenge is GHG neutrality in primary steel production. The main reason is the high level of carbon emitted during the blast-furnace process. Below, we describe the most important process steps along with their carbon emissions.

Reference case (integrated blast-furnace route)

The main process for primary steel production is the extraction of iron from iron ore. Iron ore and coke are fed into the blast furnace where carbon (C) reduces iron ore (Fe_2O_3 and Fe_3O_4) to liquid pig iron (Fe) in a reaction with temperatures as hot as 2,200 °C. The main components of the metallurgical gases generated by the coking plant, the blast furnace and the basic oxygen furnace are CO_2 and carbon monoxide (CO). The CO is then used in other processes of the integrated blast-furnace route, where it is ultimately converted to CO_2.

Coke, produced in coking plants from high-quality coal, fuels the blast furnace and serves as a reduction agent. Fine iron ore is first processed in a pelleting or sintering plant to create the particular aggregation needed for blast furnaces.

After the blast furnace, the molten iron passes through a basic oxygen furnace, where oxygen removes impurities in the material. This results in process-related carbon emissions. Several additional steps are needed before the iron ore is finally converted into crude steel.

Carbon emissions arise at various points along the blast-furnace process. Today, total direct CO_2 emissions per t of crude steel in most plants in Europe – not considering the indirect emissions from electricity use – amount to approximately 1.7 t[7], of which some 1.4 t arise at the blast furnace, 0.2 t at the basic oxygen furnace, and 0.1 t, in the coking plant.

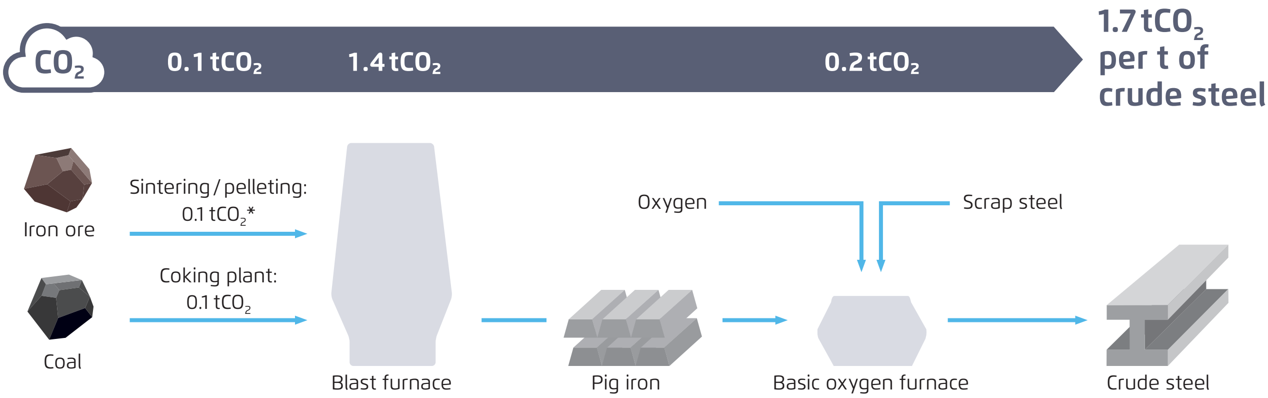
Various steel production processes in comparison in 2017 (EU27) — Table E.1

Steel production route	Share of steel production	Annual production of crude steel	Primary energy source	Energy required per t of crude steel	Direct carbon emissions per t of crude steel	Direct carbon emissions, crude steel total
Integrated blast-furnace route*	59%	95 Mt	Coal	15 GJ*	1.8 tCO_2*	171 $MtCO_2$
Electric arc furnace route**	41%	66 Mt	Electricity	2 GJ	0.07 tCO_2	4.6 $MtCO_2$
Natural gas direct reduction*	0.3%	0.6 Mt	Natural gas, electricity	13 GJ*	0.5 tCO_2*	0.3 $MtCO_2$

Sources: World Steel, 2018, and internal calculations of the Wuppertal Institute, 2021

*Primary steel routes, 12% scrap assumed in each case
**Secondary steel route, > 95 % scrap use

Process steps and carbon emissions of crude steel production (integrated blast-furnace route) Figure E.1



* Assumption: Use of furnace gas from the blast furnace; therefore no additional accounting of CO_2 emissions needed

Possible key low-carbon technologies

Direct reduction with hydrogen

The hydrogen-based production of direct reduced iron[8] is an alternative technology for producing steel. In this process, hydrogen (H_2) substitutes coke as chemical reducing agent and therefore eliminates CO_2 emissions from the process. The only by-product is water (H_2O). It is also possible to use natural gas (CH_4) as the reduction agent, with increasing proportions of hydrogen over time. A direct reduction process that uses mostly green hydrogen as a reducing agent will emit around 97 per cent less carbon than the blast-furnace route. But green hydrogen requires large amounts of renewable electricity for electrolysis. In addition, some carbon is needed to facilitate the metallurgical process. Biogas can be used to ensure a climate-neutral carbon source.

Iron electrolysis

Iron electrolysis is an electricity-intensive process that makes the reduction of iron ore possible without carbon-based reduction agents. As long as carbon-neutral electricity is used, iron electrolysis can be near zero-carbon.

HIsarna with carbon capture and storage (CCS)

The HIsarna® process uses coal as an energy source and reduction agent, but instead of the blast furnace it deploys a special reactor that smelts iron ore at very high temperatures. The innovative process is particularly suitable for combination with CCS because its exhaust gas consists of comparatively pure CO_2. Unlike the blast-furnace route, HIsarna with CCS can capture and store up to 86 per cent of carbon emissions from the steel production.

Carbon capture and use of metallurgical gases

The carbon capture and use (CCU) concept consists of recycling various components of the blast-furnace route (including CO_2, CO and H_2) for the production of basic chemicals such as methanol and ammonia. Moreover, CCU can be added to existing steel smelting plants. For the complete use of the carbon monoxide (CO) and CO_2, however, large amounts of additional hydrogen are required. As long as all the electricity used to produce hydrogen comes from renewable sources, reductions in CO_2 of 50 to 78 per cent relative to the blast-furnace route without CCU are possible.

2.2 Direct reduction with hydrogen and melting in electric arc furnaces (instead of the blast-furnace route)

Direct reduction plant using natural gas, steelworks Hamburg, ArcelorMittal — Photo: ArcelorMittal

With direct reduction, iron ore pellets are reduced in hydrogen-based DRI plants. The process results in sponge iron (direct reduced iron, DRI) and water. The sponge iron (together with scrap, if needed) can then be melted into crude steel in an electric arc furnace. If hydrogen is produced using 100 per cent renewable energy, this route is virtually carbon-neutral. The DRI process requires a certain share of (bio)methane as a carbon-containing energy carrier for the formation of foamed slag.

Pilot and demonstration projects

Commercial

HBIS (Hebei, China)
Hebei Iron & Steel Group China, Tenova
Outlook: Production of 0.6 Mt DRI per year starts in late 2021.

The Energiron DRI technology will use a mixture composed of 30 per cent of metallurgical gases from the existing integrated steel plant and 70 per cent of hydrogen from external sources. The residual CO_2 will be recovered by a CO_2 removal unit and reutilised in downstream processes (CCU).

Commercial

tkH2Steel (Duisburg, Germany)
Thyssenkrupp
Outlook: Plant is expected to be completed by 2025; capacity of 1.2 Mt of hot metal per year.

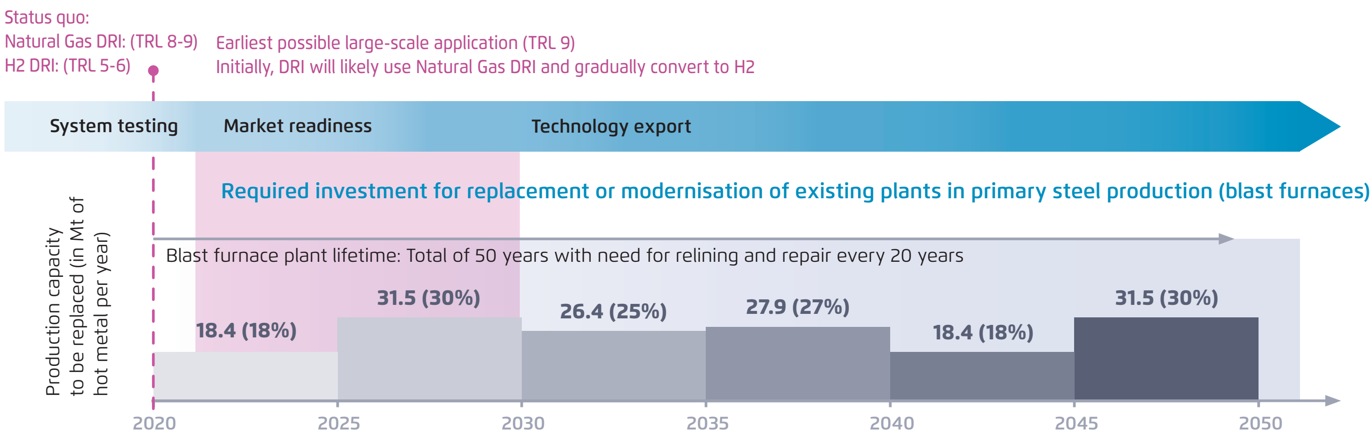
The plant for the H_2-based production of direct reduced iron will be built with an integrated melting unit, a submerged arc furnace. This concept of a so-called Blast Furnace 2.0 allows to produce hot metal for use in the existing basic oxygen furnace. As long as hydrogen is not available in sufficient quantities, the plant will operate using natural gas.

Pilot, Commercial

HYBRIT project (Lulea, Gaellivare, Sweden)
SSAB, LKAB and Vattenfall
Status: Hydrogen-based DRI pilot plant with a production capacity of 10,000 t per year was commisioned in 2020 (TRL 5).
Outlook: SSAB wants to offer fossil-free steel by 2026.

The hydrogen needed for the H_2 DRI plant will be produced on-site, largely by renewable energy. SSAB announced to build commercial-scale DRI plants in Gaellivare with a capacity of 1.3 Mt DRI per year in 2026 and 2.7 Mt DRI per year in 2030.

Required reinvestment and earliest possible market readiness for key low-carbon technologies



Required investment

The required investment in primary steel production by 2030 must substitute blast furnaces with an annual production capacity of approx. 50 Mt of hot metal (approx. 48 per cent of total capacity). We have assumed that blast furnaces will require significant investment 20 years after their last relining.

Technology development

The commercial use of the technology (TRL 9) is technically possible before 2025, as the announcements above illustrate. Starting with natural gas instead of hydrogen allows reducing carbon emissions by around 66 per cent right away. Increasing shares of hydrogen can later be blended with natural gas with minor adjustments to the plants.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1 to 9 (TRL 9 = ready for market).

Steel

Technology
Direct reduction with hydrogen (H_2 DRI)

Current stage of development
Announcements of commercial plants

Expected readiness for use
Before 2025 (possibly beginning with natural gas)

Maximum CO_2 reduction in the EU27

2030	2050
66 $MtCO_2$ per year	**166** $MtCO_2$ per year

2030: Direct reduction with natural gas and a 65 per cent share of green H_2

CO_2 abatement costs

2030	2050
60–99 €/tCO_2	**85–144** €/tCO_2

2030: 60 €/tCO_2 with 100% natural gas-based direct reduction;
99 €/tCO_2 with hydrogen-based direct reduction (lower range)

Renewable electricity and infrastructure requirement
- H_2 DRI route (2050): 3.3 MWh/t of crude steel
- Large-scale hydrogen production
- Creation of a H_2 infrastructure (consisting of pipelines and, if needed, ships and ports)

Challenges
For this technology, large amounts of carbon-free electricity are needed for the production of green hydrogen (3.3 MWh/t of crude steel or 2.5 MWh with partial use of methane). DRI plants are thus more likely to start with natural gas before 2025. Converting the current blast-furnace capacity to H_2 DRI would result in a significant additional electricity demand.

Possible policy instruments
- Carbon price and border carbon adjustment
- Carbon contracts or CCfDs
- Green public procurement
- Quotas for low-carbon materials
- Clean hydrogen support policies

Evaluation of compatibility with Paris climate agreement
The technology can be market ready before 2025, making significant carbon reductions possible fairly early. Green hydrogen can make steel production virtually carbon-neutral. Until the large-scale availability of green hydrogen, increasing shares of hydrogen can be blended with natural gas to make high carbon reductions (> 66 per cent) possible.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Integrated blast-furnace route		**Direct reduction with H_2**
1.71 tCO_2/t of crude steel	**-97%** Specific emission reduction	**0.05** tCO_2/t of crude steel
391 €/t of crude steel (2019)	**+36 to +61%** Specific additional costs	**532–630** €/t of crude steel (2050)

Central assumptions for determining the range of production costs (2050)

Assumption		Lower range	Upper range
Specific capital costs of crude steel from H_2 DRI (DRI plant, E-furnace)		€ 40/t of crude steel	€ 40/t of crude steel
Operating costs for use of green hydrogen		€ 105/t of crude steel	€ 191/t of crude steel
Assumption:	Costs of providing hydrogen (green)	€ 2.78/kg	€ 5.04/kg
Consisting of:	Electrolyser and full load hours (FLH) Electricity costs Costs of transporting hydrogen	€ 250/kW – 3,000 FLH € 50/MWh € 0.35/kg	€ 500/kW – 6,000 FLH € 40/MWh € 2/kg (H_2 import)
Operating costs of electricity use in the steel works (incl. substitution of lost metallurgical gases)		€ 59/t of crude steel	€ 71/t of crude steel
Assumption:	Electricity price	€ 50/MWh	€ 60/MWh
Other costs (work, 17% scrap, alloys, lime, biomethane)		€ 328/t of crude steel	€ 328/t of crude steel
Production costs of low-carbon crude steel		**€ 532/t of crude steel**	**€ 630/t of crude steel**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

2.3 Iron electrolysis and smelting in electric arc furnaces (instead of the blast-furnace route)

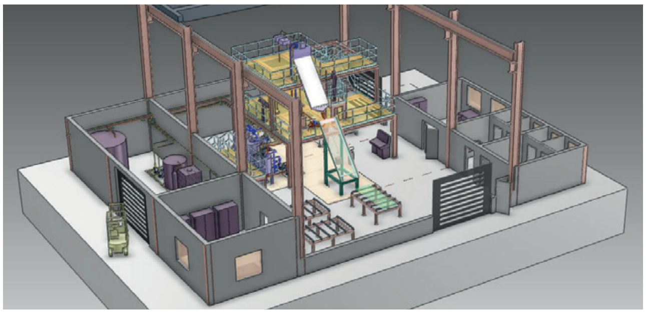


Illustration of the SIDERWIN pilot plant currently in construction in Maizières-lès-Metz Illustration: ArcelorMittal

In alkaline iron electrolysis, iron ore is reduced to iron in a caustic soda solution at a temperature of 110°C and then melted to produce crude steel in an electric arc furnace. The process does not require a carbon-based reduction agent, promising to increase energy efficiency relative to the blast-furnace route and to be carbon-neutral, provided that renewable electricity is used throughout the process. An alternative is to conduct the electrolytic process of molten iron ore at high temperatures.

Pilot and demonstration projects

Pilot

SIDERWIN (Maizières-lès-Metz, France)
ArcelorMittal, CMI, EDF and others
Status: Development and construction of a pilot plant (2017–2022) in northern France (TRL 4).

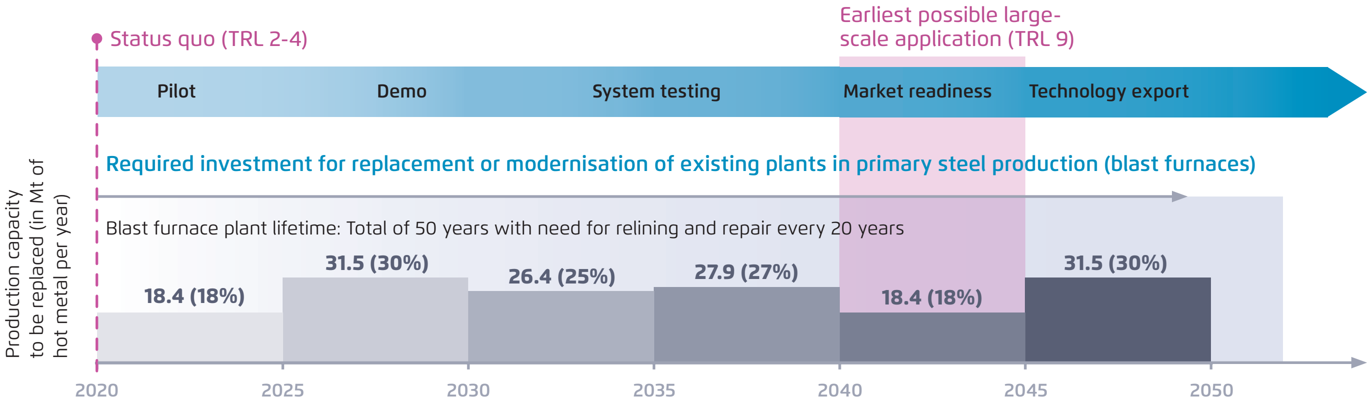
A consortium led by ArcelorMittal is working on the development of an experimental plant for iron electrolysis using the electrowinning process. The goal is the development and testing of a prototype for an electrolysis cell. The project investigates the use of renewable electricity through flexible operation and electricity network integration. The project also examines whether lower quality iron oxide or waste materials containing iron can be used as the input material for electrolysis.

Pilot/demo

Boston Metal (Woburn, USA)
Boston Electrometallurgical Corporation
Status: In 2021, the start-up raised 50 million US dollars from investors to develop the technology (TRL 4).
Outlook: The company is planning to build a demonstration plant that produces 25,000 t of metal per year.

The start-up Boston Electrometallurgical Corporation (Boston Metal; founded in 2012) is working on the commercialisation of molten oxide electrolysis, a process developed at MIT (Massachusetts Institute of Technology). Iron ore (Fe_2O_3 and Fe_3O_4) can be converted directly to its elementary components oxygen (O_2) and molten pig iron (Fe) in a special electrolysis cell without a carbon-based reduction agent.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment
The required investment in primary steel production by 2030 must substitute blast furnaces with an annual production capacity of approx. 50 Mt of hot metal (approx. 48 per cent of total capacity). We have assumed that blast furnaces will require significant investment 20 years after their last relining.

Technology development
If the technology develops optimally, the commercial use of the technology (TRL 9) may be possible by 2040. Some demonstration plants may exist in Europe before that.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1 to 9 (TRL 9 = ready for market).

Steel

Technology
Iron electrolysis and smelting in electric arc furnaces

Current stage of development
construction of a pilot plant (TRL 4)

Expected readiness for use
2040-2045

Maximum CO_2 reduction in the EU27

2030	2050
0 $MtCO_2$ per year	**149** $MtCO_2$ per year

CO_2 abatement costs

2030	2050
unknown	**170–292** €/tCO_2

Renewable electricity and infrastructure requirement

- Alkaline iron electrolysis (2050): 2.5 MWh/t of crude steel
- the construction of a special electricity infrastructure may be necessary

Challenges
Alkaline iron electrolysis requires large amounts of renewable electricity. The extent to which electrolysis can be flexibly implemented amid the variability of renewable energy feed-in still requires further study.

Possible policy instruments

- Support for research
- Quotas for low-carbon materials

Evaluation of compatibility with Paris climate agreement
This technology is a promising long-term option. However, as of 2020, the technology is not expected to be market ready until 2040. The technology is thus unlikely to contribute significantly to emissions reduction in Europe by 2050 since most blast furnaces in Europe will require reinvestment before 2040 when they should be replaced with a key low-carbon technology that is compatible with climate neutrality 2050.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Integrated blast-furnace route		**Alkaline iron electrolysis**
1.71 tCO_2/t of crude steel	**-87 %** Specific emission reduction	**0.22** tCO_2/t of crude steel
391 €/t of crude steel (2019)	**+65 to +112 %** Specific additional costs	**645–828** €/t of crude steel (2050)

Central assumptions for determining the range of the production costs (2050)

Assumption	Lower range	Upper range
Specific capital costs of crude steel using alkaline iron electrolysis	€ 154/t of crude steel	€ 269/t of crude steel
Assumption: CAPEX-ULCOWIN process	€ 900/t annual iron capacity	€ 3,350/t annual iron capacity
Assumption: CAPEX electric arc furnace	€ 128/t annual steel capacity	€ 128/t annual steel capacity
Operating costs of electricity use in the steel works	€ 145/t of crude steel	€ 174/t of crude steel
Assumption: Electricity price	€ 50/MWh	€ 60/MWh
Other costs (raw ore, 17% scrap, alloys, lime, coal)	€ 334/t of crude steel	€ 371/t of crude steel
Compensation for lost metallurgical gases	€ 12/t of crude steel	€ 14/t of crude steel
Production costs of low-carbon crude steel	**€ 645/t of crude steel**	**€ 828/t of crude steel**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

2.4 The HIsarna® process combined with carbon capture and storage (instead of the blast-furnace route)

HIsarna® pilot plant, Tata Steel in IJmuiden — Photo: Tata Steel

The HIsarna® process is an innovative, carbon-based smelting reduction process that eliminates the agglomeration stages (coking plant, sintering/pelleting) in steel production. The iron ore, which can be mixed with up to 50 per cent scrap, is reduced directly to pig iron in a single reactor. The process is particularly suitable for combination with CCS because its exhaust gas consists of comparatively pure CO_2. Carbon reductions of up to 86 per cent are possible. The electricity use of the HIsarna process is around 0.5 MWh per t of crude steel and hence comparatively low.

Pilot and demonstration projects

Pilot

ULCOS (Ijmuiden, the Netherlands)
Tata Steel, ThyssenKrupp, ArcelorMittal, voestalpine and others
Status: Diverse tests carried out on the pilot plant (TRL 3-4).

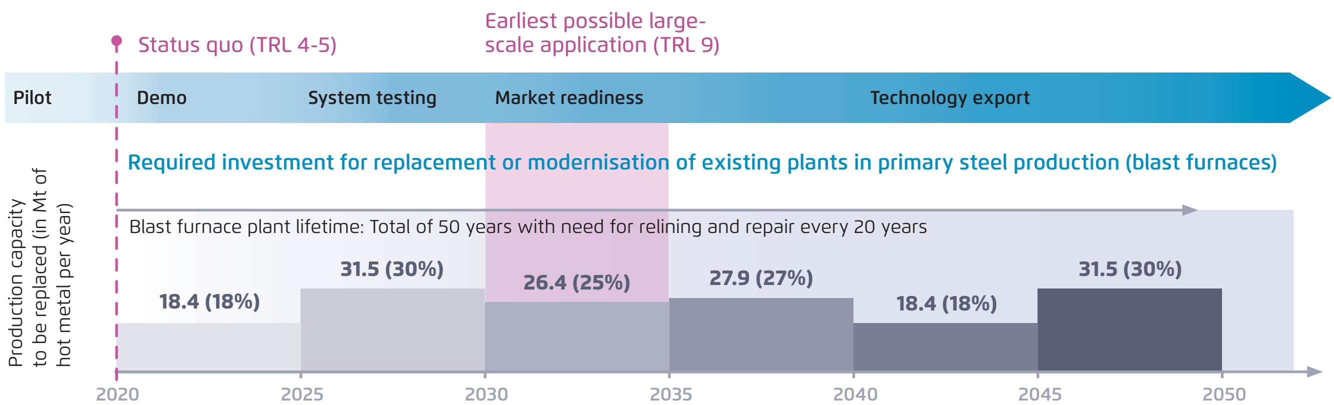
The pilot plant has a nominal annual capacity of 60,000 t of crude steel. Four short-term tests for the production of pig iron and steel have been carried out since 2011. A long-term test from 2018 has integrated the HIsarna® reactor into existing steelmaking plants.

Demo

HIsarna® (Jamshedpur, India)
Tata Steel
Status: Demo plant in planning (TRL 5)
Outlook: Expected to be completed by 2022.

The construction of a demonstration plant is planned with an annual capacity of 400,000 t of pig iron.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Reinvestment requirement
The required investment in primary steel production by 2030 must substitute blast furnaces with an annual production of approx. 50 Mt of hot metal (approx. 48 per cent of the total capacity). We have assumed that blast furnaces will require significant investment 20 years after their last relining.

Technology development
If the technology develops optimally, the earliest possible large-scale implementation (TRL 9) will not be until 2030. Furthermore, a CO_2 infrastructure for transporting and storing CO_2 would have to be introduced in time.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1 to 9 (TRL 9 = ready for market).

Steel

Technology
HIsarna® with CCS

Current stage of development
Pilot plants (TRL 4-5)

Expected readiness for use
2030 - 2035

Maximum CO_2 reduction in the EU27

2030	2050
0 $MtCO_2$ per year	147 $MtCO_2$ per year

CO_2 abatement costs

2030	2050
unknown	25–45 €/tCO_2

Renewable electricity and infrastructure requirement

- HIsarna (2050): 0.5 MWh/t of crude steel
- Construction of CO_2 pipelines
- CO_2 transport on inland water vessels
- CO_2 storage facilities

Challenges

Although HIsarna and CCS can reduce CO_2 emissions by 86 per cent, the remaining 14 per cent still require abatement. For the use of CCS, various questions regarding infrastructure for transport and storage of CO_2 and their public acceptance need to be clarified. Moreover, transnational partnerships with EU countries (e.g. the Netherlands, Norway) that are willing to store CO_2 in offshore sites are necessary to facilitate the implementation of CCS.

Possible policy instruments

- Carbon price and border carbon adjustment
- Carbon contracts and CCfD
- Green public procurement
- Quotas for low-carbon materials

Evaluation of compatibility with Paris climate agreement

HIsarna in combination with CCS enables significant CO_2 reductions of 86 per cent and could be a comparatively low-cost option. Because the technology is not likely to reach the market until 2030 or later, it is not expected to be available for the upcoming investment window for approx. 48 per cent of blast-furnace capacity in Europe before 2030. Accordingly, the technology will only be viable in Europe as a later supplemental option.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Integrated blast-furnace route		**HIsarna® with CCS**
1.71 tCO_2/t of crude steel	-86 % Specific emission reduction	0.24 tCO_2/t of crude steel
391 €/t of crude steel (2019)	+9 to +16 % Specific additional costs	427-454 €/t of crude steel (2050)

Central assumptions for determining the range of the production costs (2050)

Assumption	Lower range	Upper range
Specific capital costs for crude steel with HIsarna reactor	€ 53/t of crude steel	€ 53/t of crude steel
Assumption: CAPEX Brownfield Investment HIsarna	€ 300/t annual steel capacity	€ 300/t annual steel capacity
Assumption: CAPEX CCS technology at reactor	€ 128/t annual steel capacity	€ 128/t annual steel capacity
Operating costs for carbon capture, transport, storage	€ 38/t of crude steel	€ 64/t of crude steel
Assumption: Carbon capture, transport & storage	€ 41/tCO_2	€ 69/tCO_2
Operating costs of electricity use (incl. the substitution of lost metallurgical gases)	€ 11/t of crude steel	€ 14/t of crude steel
Assumption: Electricity price	€ 50/MWh	€ 60/MWh
Material costs (raw ore, 17% scrap, alloys, lime)	€ 324/t of crude steel	€ 324/t of crude steel
Production costs of low-carbon crude steel	**€ 427/t of crude steel**	**€ 454/t of crude steel**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

2.5 Carbon capture and use (CCU) of smelting gases from integrated blast-furnace works (retrofitting of existing blast furnaces)

Carbon2Chem® pilot plant, Duisburg Photo: thyssenkrupp AG

The CCU process captures a portion of the metallurgical gases arising from the blast-furnace route and uses them for the production of chemicals such as methanol, ethanol, synthetic fuels and ammonia. The gases captured in this process no longer have to be burnt and their use in the chemical industry substitutes the use of crude oil. However, the low-carbon production of chemicals such as methanol (a raw material for plastic production) requires the additional production of green hydrogen, which makes this route very electricity-intensive.

Pilot and demonstration projects

Pilot

Carbon2Chem® (Duisburg, Germany)
Thyssenkrupp, BASF, Covestro, Linde and others
Status: Operation of a pilot plant for the production of methanol.
Outlook: As all individual parts of the pilot plant are market ready, it is not necessary to build a demo plant.

The primary goal is to use the carbon and hydrogen molecules in the metallurgical gases generated by the coking plant, blast furnace and basic oxygen furnace as raw materials for chemical products. Green hydrogen, methanol, ammonia, and higher quality alcohol have already been produced on-site from smelting gases in the pilot plant.

Pilot

Steelanol project (Ghent, Belgium)
ArcelorMittal, LanzaTech
Status: Construction of a pilot plant.
Outlook: CO_2 savings potential is limited because the plant converts only the CO in smelting gases and leaves the CO_2.

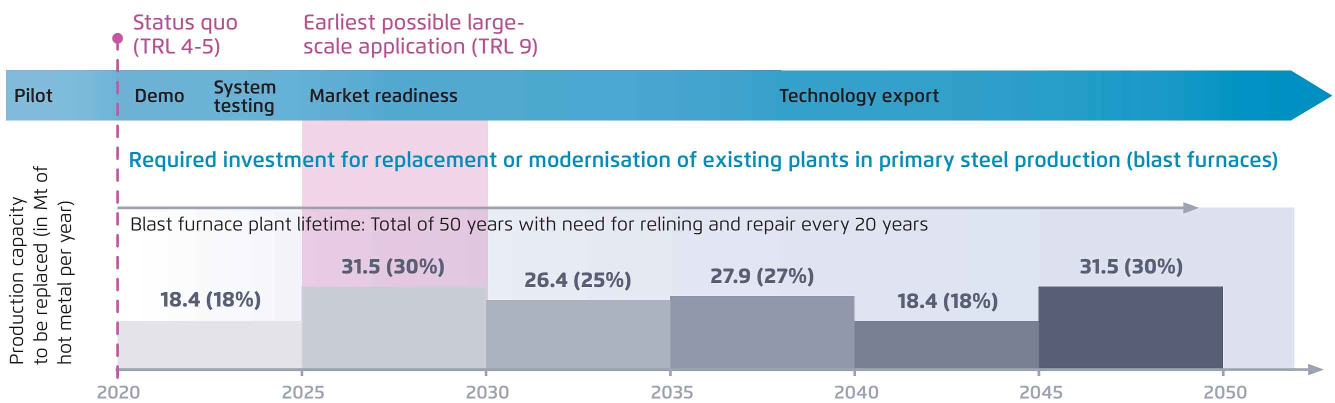
In a biochemical process developed by Lanzatech, bacteria convert the 25 per cent share of carbon monoxide in the smelting gases into ethanol, which will be used as a fuel (mixed with petrol).

Pilot

Carbon4PUR (Marseille, France)
Covestro, Recticel, ArcelorMittal, Dechema and others
Status: Planned construction of a pilot plant with a capacity of 20 t per year.

The goal of the Carbon4PUR approach is to convert the CO_2 and carbon monoxide elements of the smelting gases in the integrated blast-furnace route into raw materials for the production of polyurethane.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment

The required investment in primary steel production by 2030 must substitute blast furnaces with an annual production of approx. 50 Mt of hot metal (approx. 48 per cent of the total capacity). We have assumed that blast furnaces will require significant investment 20 years after their last relining.

Technology development

Because all individual parts of the Carbon2Chem pilot plant are essentially ready for large-scale implementation, the construction of a demonstration plant is not necessary. If the proper regulatory framework is in place, the industrial retrofitting of blast-furnace plants could begin in 2025.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1 to 9 (TRL 9 = ready for market).

Steel

Technology
CCU of smelting gases from the blast-furnace route

Current stage of development
Pilot plants (TRL 4-5)

Expected readiness for use
2025–2030

Maximum CO_2 reduction in the EU27

2030	2050
26 $MtCO_2$ per year	**85** $MtCO_2$ per year

2030: Provided that the CO_2 reduction in the chemical sector (MTO route) is completely credited to steelmakers 32 $MtCO_2$ can be reduced

CO_2 abatement costs

2030	2050
231–439 €/tCO_2	**178–379** €/tCO_2

2030/2050: Abatement costs seen from a cross-sector perspective including CO_2 reduction in the chemical sector

Renewable electricity and infrastructure requirement
- CCU in the blast-furnace route (2050): 3.6 MWh/t of crude steel
- Establishing a H_2 infrastructure (pipelines and possibly ships and ports)
- Integration into local industry clusters is a sensible approach

Possible policy instruments
- Carbon contracts or CCfDs
- Clean hydrogen support policies

Challenges
Generally, CCU makes sense for the blast-furnace route only if it contributes to a total reduction in emissions despite the high energy requirements. Given the scarcity of renewable energy, CCU concepts should be critically compared to other key low-carbon technologies that are available before 2030, such as direct reduction with hydrogen.

Evaluation of compatibility with Paris climate agreement
CCU approaches should be considered holistically. Since CCU in the steel sector consumes high levels of electricity and the CO_2 capture rate is limited (50 to 78 per cent max.), CCU is suitable at best as a bridge technology for retrofitting the gas collection system in the blast-furnace route. In addition, the captured carbon should be stored in materials with long lifetimes (e.g. plastics). CCU is a comparatively expensive carbon reduction option.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Integrated blast-furnace route		**Blast-furnace route with CCU**
1.71 tCO_2/t of crude steel	-50% (-63%)* → Specific emission reduction	**0.85** tCO_2/t of crude steel (0,64)* tCO_2/t of crude steel
391 €/t of crude steel (2019)	+63 to +119% → Specific additional costs	**637–858** €/t of crude steel (2030)

*Provided that CO_2 reduction in the chemical sector (MTO route) is completely credited to steelmakers

Central assumptions for determining the range of the production costs (2030)

Assumption CCU 2030	Lower range	Upper range
Production costs of the conventional blast-furnace route	€ 391/t of crude steel	€ 391/t of crude steel
Specific capital costs for CCU retrofitting	€ 13/t of crude steel	€ 13/t of crude steel
Assumption: CAPEX CCU (smelting gas, methanol synthesis)	€ 129/t annual steel capacity	€ 129/t annual steel capacity
OPEX electricity use for CCU processes (€ 60–70/MWh)	€ 30/t of crude steel	€ 35/t of crude steel
Costs of providing H_2 for methanol synthesis	€ 310/t of crude steel	€ 526/t of crude steel
Assumption: Cost of providing hydrogen (green)	€ 3.34/kg (see H_2)	€ 5.67/kg (see H_2)
Other material costs	€ 68/t of crude steel	€ 68/t of crude steel
Proceeds from the sale of methanol	€ -175/t of crude steel	€ -175/t of crude steel
Production costs of low-carbon crude steel	**€ 637/t of crude steel**	**€ 858/t of crude steel**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

2.6 End notes and bibliography

List of end notes

1 Agora Energiewende/Wuppertal Institute, 2021, based on Eurostat, 2017.

2 Internal calculations from Wuppertal Institute/Agora Energiewende based on Worldsteel, 2018.

3 Eurofer, 2018.

4 Wuppertal Institute, 2021.

5 In the short to middle term, demand for steel will increase globally, requiring continued primary steel production. Due to the limited amount of high-quality scrap steel in the EU, an increase in the proportion of the secondary steel route is possible but limited in the short term. However, the availability of high-quality scrap steel can be significantly increased through better sorting.

6 With today's technology, a carbon carrier that oxidises to CO_2 in electric arc furnaces is required to foam the slag. Carbon carriers can also be of biogenic origin.

7 Wuppertal Institute, 2021. These emissions are based on the CO_2 emissions of the crude steel production via the blast-furnace route in Germany, which is close to the best available technology benchmark. In the EU, the CO_2 emissions of the integrated blast furnace route currently amount to 1.8 tCO_2 per t of crude steel. The emissions cover all aspects of crude steel production, but exclude the CO_2 emissions of downstream processes such as hot and cold rolling for the production of semi-finished and finished steel products.

8 The calculations in this part have been carried out based on green hydrogen from electrolysis with only renewable energy. In principle, it is also possible to use decarbonised hydrogen from steam reforming with CCS (blue hydrogen) and methane pyrolysis (turquoise hydrogen).

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3 Chemicals

3.1 Chemical sector overview

The chemical industry manufactures a multitude of products that are used in a wide range of applications. The products range from plastics and rubber to fertilisers and specialty chemical products such as food additives. Due to high energy requirements and the comparatively high CO_2 emissions, the production of basic chemicals is particularly relevant for climate protection.

The chemical industry is an important economic sector in Europe: In 2017, it directly employed around 1.1 million people and generated a gross added value of 143 billion euros.[1] Producers of basic chemicals generated approx. 58 per cent of that gross value added[2] and employed approx. 519,000 people in 2017.[3]

Direct CO_2 emissions from the chemical industry in the EU27 (+UK) in 2017
129 $MtCO_2$ (+11 $MtCO_2$ in the UK)

Chemicals production in the EU27 (+UK) in 2017
40.2 Mt of HVC (high value chemicals)
(+5.3 Mt of HVC in the UK)

Chemicals demand in 2017 (EU28)
40.7 Mt of HVC

Reinvestment required in basic chemicals by 2030
Approx. 53 per cent of the total capacity (steam crackers with a capacity of 24.1 Mt of HVC per year)

Directly employed in 2017 (EU27)
1.1 Mio. employees (519,000 in basic chemicals)

The production of basic chemicals is the beginning of the value chain in the chemical industry, excluding the extraction of raw materials such as crude oil and salt. In terms of energy use, the petrochemical industry, ammonia, and chlorine production are the most relevant branches. All three make important contributions to the production of polymers – which in turn form the main components for the production of plastics: While petrochemicals provide the molecular building blocks for plastics production, ammonia and chlorine are only used in some polymers. In addition, chlorine is important as a reactant in the petrochemical industry. Ammonia represents the basis for further added-value chains in the production of fertiliser, but also for other products such as lightweight plastics.

In 2017, the production of High Value Chemicals (HVC)[4] in Europe amounted to approx. 40.2 Mt.[5]

In the EU, the production of basic chemicals is concentrated in few locations. The most important CO_2 sources in the chemical industry are industrial power plants, steam crackers, and hydrogen production via steam reforming of natural gas. The industrial power plants operated at integrated locations are mainly combined heat and power (CHP) plants, since those locations demand high levels of process steam and electricity for chemicals production. The steam is used both as a heat carrier and for hydrogen production. Steam crackers are another important CO_2 source in the chemical industry.[6] They are the starting point for the petrochemical industry and thus for the plastics value chain.[7]

The required investment in steam crackers by 2030 includes plants with an annual production capacity of approx. 24 Mt of HVC (approx. 53 per cent of total capacity).[8] The CO_2 emissions of the EU27 chemical industry declined by 52 per cent between 1990 and 2017 and totalled approx. 129 $MtCO_2$ in 2017.[9]

Greenhouse gas-neutral basic chemicals

The conversion of current production processes to a greenhouse gas-neutral (GHG-neutral) production of basic chemicals represents an enormous challenge. On the one hand, chemicals production has the highest energy requirements amongst all industry sectors – 573 TWh in 2017 – with 55 per cent of this requirement currently covered by the use of fossil fuels (63 per cent natural gas, 26 per cent oil and petroleum products and 11 per cent coal).[10] Although the direct use of renewable electricity and the electrification of process heat (e.g. via power-to-heat) could in principle avoid emissions from the combustion of fossil fuels, a greater renewable energy generation capacity must be built first, in order not to simply transfer CO_2 emissions to the power sector.

On the other hand, the petrochemical industry cannot be decarbonised in the conventional sense, because it requires carbon as a feedstock for its products even in a GHG neutral world. Therefore, the industry must eliminate feedstock based on fossil fuels such as crude oil and natural gas and use renewable carbon sources instead, as well as avoiding non-CO_2 GHG emissions. Because renewable carbon sources such as biomass and captured CO_2 from the air are limited and expensive, closing the carbon cycles (e.g. through chemical recycling) to develop a circular carbon economy is paramount to achieving GHG neutrality. Through the use of renewable carbon sources, the chemical industry can contribute to the reduction of (fossil) CO_2 emissions in other sectors. For instance, the incineration of plastic waste that was initially produced from renewable carbon sources would merely release CO_2 that had previously been removed from the atmosphere.

To illuminate the challenges for avoiding fossil CO_2 and to better understand existing technological approaches, three of the most carbon-intensive processes in basic chemicals sector are described below along with alternatives that are mostly CO_2-neutral.

Reference process (electricity and steam from natural gas CHP plants)

For the production of basic chemicals, large amounts of electricity, steam and process heat are required. In 2017, the low and medium temperature heat requirement (up to 500°C) of the EU27 chemical industry amounted to approximately 340 TWh_{th}.[11] We estimate that a significant share of this heat requirement (150 to 160 TWh_{th}) is generated by mostly natural gas-based CHP plants with an estimated installed electrical capacity of 22 GW_{el}. In total, we estimate that the emissions of the industrial power plants in the EU27 chemical industry amounted to roughly 55 $MtCO_2$ in 2017.[12]

Possible key low-carbon technologies

Steam generation from power-to-heat

Power-to-heat (PtH) allows the direct use of electricity to generate heat and steam. In the process, the use of fossil fuels in CHP plants or gas-fired boilers can be reduced or replaced. If 100 per cent renewable electricity is used in PtH plants, the steam generation is carbon-neutral.[13]

CO_2 capture in CHP plants

Existing CHP plants can be retrofitted with carbon-capture technologies that can sequester most CO_2 emissions. Depending on the technology, a capture rate of up to 90 per cent is possible.

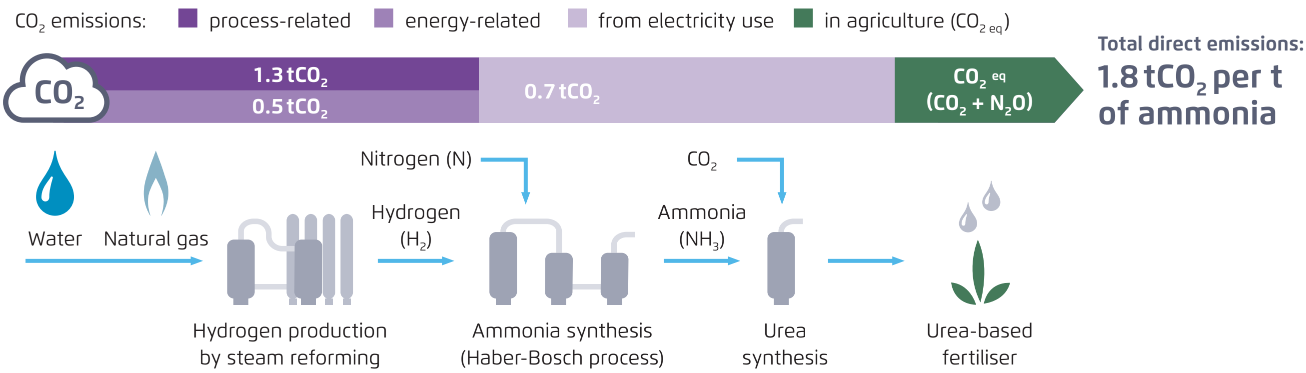
Another large CO_2 source is the synthesis of ammonia, with emissions of approx. 24 $MtCO_2$ in 2017.[14]

Reference process (ammonia synthesis)

For ammonia synthesis, large amounts of hydrogen (H_2) are necessary. Today, these are largely produced from natural gas and water through steam reforming. As a result, process-related emissions of 1.3 tCO_2 per t of ammonia arise from the reaction of natural gas (CH_4) with steam (H_2O). When heating the hot steam to around 400 to 500°C, some of the natural gas combusts as well, which produces energy-related emissions of 0.5 tCO_2 per t of ammonia.[15]

In the next step, ammonia (NH_3) is produced via ammonia synthesis using the Haber-Bosch process from hydrogen (H_2) and nitrogen (N) separated from the atmosphere. While no direct emissions arise, the compression processes require considerable amounts of electricity, whose generation produces emissions of 0.7 tCO_2 per t of ammonia.[16] Ammonia production in Europe amounts to approx. 13.4 Mt per year.[17] Today, ammonia is used mainly for producing nitrogenous fertilisers. Part of fertiliser production occurs

Process steps and CO_2 emissions from ammonia synthesis as part of the fertiliser value chain — Figure E.2



via the synthesis of urea (CH_4N_2O) from ammonia (NH_3) and the CO_2 generated by the steam methane reforming process (see Figure E.2).

When fertilisers are used in agriculture, direct emissions of CO_2 and nitrous oxide (N_2O) arise as a result.

Two measures are necessary for carbon-neutral fertiliser production in the future[18]: the use of renewable carbon sources for the production of urea (biomass or direct air capture), because only the amount CO_2 that was removed from the atmosphere is emitted; and the avoidance of CO_2 emissions during hydrogen production.

Possible key low-carbon technology

Hydrogen from electrolysis (green H_2)

Using water electrolysis, renewable energy can be used to split water into its components of hydrogen (H_2) and oxygen (O_2). In this way, the CO_2 emissions released in conventional hydrogen production via steam reforming can be avoided. Green hydrogen can not only provide an important contribution to CO_2 reduction in the chemical industry; it also plays a central role in the GHG neutrality of other industries, such as steel manufacturing (direct reduc tion with hydrogen) or heavy transport. Less electricity-intensive alternatives for this are the production of hydrogen via steam reforming in combination with CCS (blue hydrogen)[19] or using the methane pyrolysis process (turquoise hydrogen).[20]

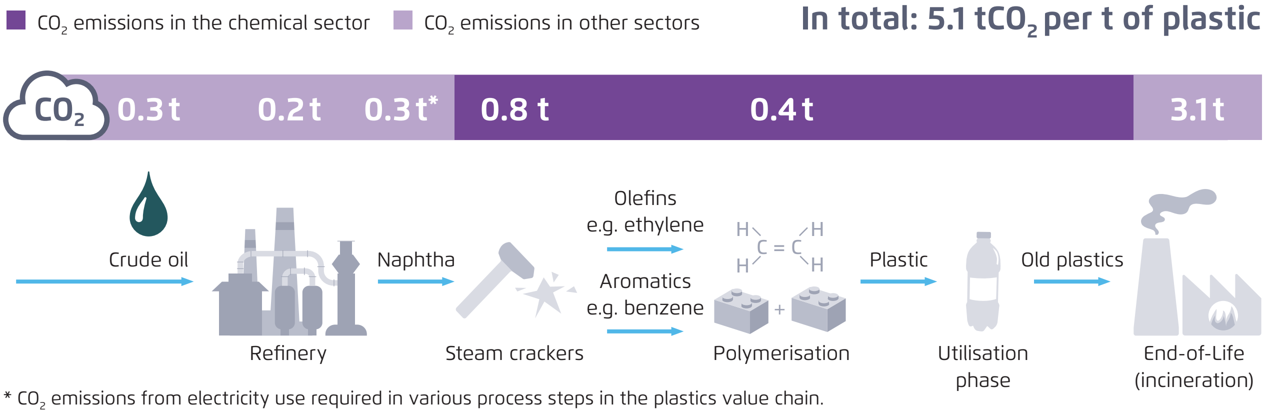
Reference process (plastics value chain)

Alongside technologies for low-carbon steam production and green hydrogen for ammonia synthesis, GHG-neutral feedstock will play a key role for HVC and their products such as plastics. Because even in a GHG neutral world, carbon will continue to be needed for chemical products. In 2017, direct CO_2 emissions along the plastics value chain in the EU27 amounted to approx. 181 $MtCO_2$[21]. About 8 $MtCO_2$ are emitted in refineries during the naphtha production process, 32 $MtCO_2$ during the production of HVC in steam crackers, 16 $MtCO_2$ during the manufacture of intermediate products and polymerisation, and 125 $MtCO_2$[22] in the incineration (thermal recycling) of plastic waste. Due to the high emissions arising from the plastic waste incineration, this step must be considered together with the chemical production process. It is necessary to understand the integration of chemical production and waste disposal to develop alternative circular carbon economy models that ensure climate neutrality. Below we describe the process steps of the plastics value chain along with the CO_2 emissions arising from them (see Figure E.3).

Today, the primary basic raw material for plastic is crude oil. In this process, emissions of 0.3 tCO_2 per t of plastic production occur from the energy demand

Process steps and CO_2 emissions in the plastics/synthetics value chain

Figure E.3



* CO_2 emissions from electricity use required in various process steps in the plastics value chain.

to produce oil and from flaring excess methane. In refineries today, a distillation process is used to produce various products such as naphtha (hydrocarbon chains with 5 to 12 carbon atoms). For naphtha production,, temperatures in excess of 200°C are necessary, involving emissions of 0.2 tCO_2 per t of plastic production.

Naphtha is the main feedstock in the EU petrochemical industry, with 78 per cent of the total.[23] Naphtha is broken down in steam crackers into shorter chain hydrocarbons. Naphtha is broken down in steam crackers into shorter chain hydrocarbons such as olefins (ethylene, propylene, and butadiene), and aromatics (benzene, toluene and xylene). To run the splitting process in the steam cracker, high temperatures of 600–900°C are required. Part of the product mix from the steam cracker is burnt to provide the required heat. This leads to energy-based emissions of 0.8 tCO_2.[21]

The next step uses steam and heat to process the olefins or aromatics into a wide range of plastics in the polymerisation process. These include very different plastic types such as polyethylene and polypropylene, polyvinylchloride and foam plastics, coatings, rubber and many other products. Depending on the product, CO_2 emissions also vary; in this step, 1 t of plastic generates approx. 0.4 tCO_2.[21]

After use, most of the products from the chemical industry are collected for waste disposal. Only a portion of all plastics – such as reusable plastic bottles – are mechanically recycled and reused. In 2017, 30 per cent of all plastic waste was recycled.[24] More than half of the plastic waste is incinerated in waste-to-energy plants or used as alternative fuel, for example in cement production kilns. In the process, 3,1 tCO_2 per t of plastic waste are released.[21] Although electricity and heat are generated in the process, which replace some fossil fuel use in the power sector, other material recycling processes should be developed to establish a circular economy with closed carbon cycles.

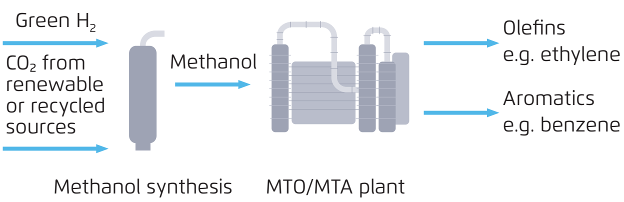
If CO_2 emissions of 0.3 tCO_2 from the electricity used in the process are considered, total emissions of approx. 5.1 tCO_2 / t plastic (polyethylene) arise. However, of that only 1.2 to 1.5 tCO_2 comes from the chemical industry (steam cracking, polymerisation, electricity for various processes), while the rest (refining, incineration of plastic waste) is allocated to the energy sector.

Possible key low-carbon technologies

Methanol-to-olefin/aromatics route (MTO/MTA)

In this route, green methanol is used as a feedstock in so-called MTO/MTA plants for the production of olefins and aromatics instead of splitting fossil naphtha in a steam cracker. The green methanol is manufactured using climate-friendly hydrogen and CO_2 from renewable carbon sources (biomass or direct air capture), chemical recycling, or from fossil CO_2 from industrial processes (see Figure E.4). In this way, the energy-related emissions from the steam crackers can be saved. And if the CO_2 comes from non-fossil sources, the thermal energy recovery of the plastic waste can be (virtually) climate-neutral.

Process steps for the MTO/MTA route Figure E.4



Chemical recycling of plastic waste

Chemical recycling allows the industry to forgo the incineration of plastic waste, which releases large amounts of CO_2, and to convert the part of the plastic waste that cannot be mechanically recycled into feedstock (pyrolysis oil, methanol) for the chemical industry. There are two mature processes for chemically recycling of mixed plastics. In the first, plastic waste is pyrolysed, producing pyrolysis oil similar to naphtha that can replace naphtha as a feedstock in steam crackers. In the second, plastic waste is gasified along with additional, climate-friendly hydrogen, to produce green methanol for the MTO/MTA route. Chemical recycling avoids emissions from incinerating plastic waste and manufacturing fossil-based naphtha.

Electrification of steam crackers

The electrification of steam crackers using green electricity makes it possible to avoid the combustion of part of the feedstock (e.g. naphtha or pyrolysis oil from chemical recycling) and thus emissions from the steam cracker.

3.2 Heat and steam production from power-to-heat (substitution of fossil steam production in gas boilers and CHP plants)

Electrode boilers in the combined heat and power plant at the industrial park, Höchst, Frankfurt Photo: Infraserv GmbH & Co. Höchst KG

Power-to-heat – besides contributing to making the electrical system more flexible – enables the direct use of electricity for the production of heat and steam. This reduces the use of fossil fuels in CHP plants or gas-fired boilers. If 100 per cent renewable electricity is used, power-to-heat can replace them completely. Potential technologies include electrode boilers (200–500°C) and high-temperature heat pumps, possibly in combination with mechanical vapour compression (< 200°C).

Pilot and demonstration projects

System testing

Electrode boiler: (Frankfurt (Main), Germany)
Infraserv Höchst, Parat
Status: Two electrode boilers have been in operation since 2014, each with an output of 20 MW (TRL 8–9).

The 10-kV electrode steam boilers – with an output of 20 MW each – were supplied by Parat and are operated by Infraserv Höchst.

System testing

Electrode boiler: (Premnitz, Germany)
Enerstorage, Parat
Status: Two electrode boilers have been in operation since 2014, each with an output of 20 MW (TRL 8–9).

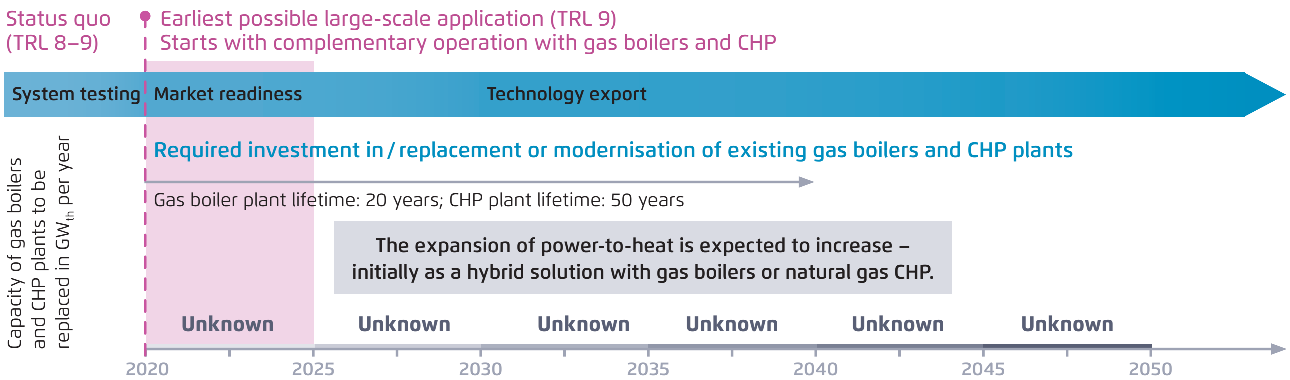
The electrode boilers from Parat are operated by Enerstorage GmbH, the contracting party for power-to-heat plants. The first project is being carried out in partnership with EEW Energy from Waste. The Premnitz site is one of 18 waste incineration plants operated by EEW in Germany.

Demo

DryFiciency project (Uttendorf, Austria)
Agrana Staerke, Wienerberger
Status: planned demonstration of high-temperature heat-pump systems.
Outlook: An 80 per cent reduction of energy and a 75 per cent reduction of CO_2 emissions in industrial drying processes shall be shown.

The DryFiciency consortium has the goal of developing solutions for upgrading unused waste heat flows to process heat flows for temperatures up to 160°C. DryFiciency is testing the 400-kW, high-temperature heat pumps (TRL 7) under real production conditions in industrial drying processes in two European industrial companies (Agrana Stärke and Wienerberger).

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Reinvestment requirement

The required investment for gas boilers CHP is split between many operations. The cumulative figure is unknown. The standard service life of a gas boiler is around 20 years. In certain applications, it is significantly longer.

Technology development

Electrode boilers have reached technical market readiness (TRL 8–9) are available for large-scale commercial deployment. High-temperature heat pumps (TRL 7) can be rolled out on a large-scale starting in 2025 at the earliest, provided that technology develops optimally. Before 2030, a complementary operation with CHP plants or gas boilers can lead to significant CO_2 reductions.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1 to 9 (TRL 9 = ready for market).

Chemicals

Technology
Steam from power-to-heat (electrode boilers)

Current stage of development
E-boilers: system testing until market readiness (TRL 8–9); heat pumps (TRL 7)

Expected readiness for use
E-boilers (from 2020); heat pumps (from 2025)

Maximum CO_2 reduction in the EU27

2030: **24.7** $MtCO_2$ per year

2050: **76** $MtCO_2$ per year

CO_2 abatement costs

2030: **-54–40** €/tCO_2

2050: **76–131** €/tCO_2

Assumption for 2030: Hybrid operation with natural gas CHP (PtH: 2,000 hours per year)

Renewable electricity and infrastructure requirement

- Electrode boilers: approx. 1 kWh_{el} per kWh_{th}
- Heat pumps: approx. 0.33 kWh_{el} per kWh_{th}
- Improvement of grid connections
- Distribution grids (if needed)
- Storage (if needed)

Possible policy instruments

- Carbon price and border carbon adjustment
- Reform of network charges
- Reform of levies and surcharges

Challenges
A broad use of PtH for steam production would take enormous amounts of electricity, requiring a rapid increase in renewable energy capacity. If 100 per cent of the low- and medium temperature heat demand (up to 500°C) of the EU27 chemical industry for 2017 (approx. 340 TWh_{th}) was provided by electrode boilers (65 per cent) and heat pumps (35 per cent), an additional electricity demand of approx. 260 TWh_{el} would arise.

Evaluation of compatibility with Paris climate agreement
The steam production from PtH plants can completely eliminate CO_2 emissions from fossil steam production as long as 100 per cent renewable electricity is used. Until the electricity mix is completely decarbonised, complementary operation with boilers or CHP plants can cut CO_2 emissions provided that PtH plants are always used when the emission factor in the electricity mix drops below 220 g CO_2/kWh.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON$_2$ TECHNOLOGY
Steam from fossil CHP or gas boilers		**Steam, from PtH (electrode boiler)**
223 g CO_2/kWh_{th}	-100% Specific emission reduction	**0** g CO_2/kWh_{th}
3.5 ct/kWh_{th} (2019)	+49 to +83% Specific additional costs	**5.2–6.4** ct/kWh_{th} (2050)

Central assumptions for determining the range of the production costs (2030/2050)

Hybrid operation 2030 (assumptions for electrode boilers)	Lower range	Upper range
Specific capital costs for electrode boilers	€ 125/kW	€ 300/kW
Utilisation in full-load hours (FLH)	2,000 FLH per year	2,000 FLH per year
Average electricity price with 2,000 FLH	€ 15/MWh	€ 25/MWh
Production costs of low-carbon steam production 2030	**2.3 €-ct/kWh_{th}**	**€ 4.4-ct/kWh_{th}**
Full operation 2050 (assumptions for electrode boilers)	**Lower range**	**Upper range**
Specific capital costs for electrode boilers	€ 100/kW	€ 250/kW
Utilisation in full-load hours (FLH)	8,000 FLH per year	8,000 FLH per year
Average electricity price with 8,000 FLH	€ 50/MWh	€ 60/MWh
Production costs of low-carbon steam production 2050	**€ 5.2-ct/kWh_{th}**	**€ 6.4-ct/kWh_{th}**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

3.3 Carbon capture (CCS) at the CHP plants of the chemical industry

Fortum Oslo Varme's CCS pilot plant, Oslo Photo: Fortum Oslo Varme AS

By retrofitting carbon capture (CCS) technologies, the emissions of existing CHP plants for the production of electricity and heat for chemical process can be reduced by up to 90 per cent. The CO_2 must then be transported via a CO_2 infrastructure, e.g. pipelines or inland shipping, and placed in a suitable storage location (e.g. in depleted oil and gas fields in the North Sea). The additional electricity demand for carbon capture can be met by electricity that the CHP plants produce themselves.

Pilot and demonstration projects

Pilot

Fortum Oslo Varme's CCS project (Oslo, Norway)
Fortum
Status: Carbon capture at the waste-to-energy plant without sequestration (TRL 4).
Outlook: Implementation decision for large-scale realisation is still pending, but the project is expected to be launched in 2023 or 2024.

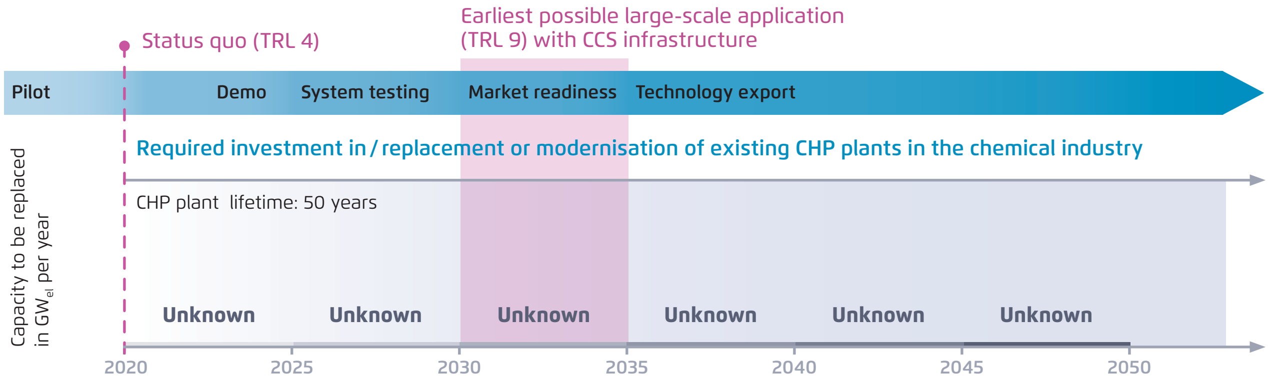
In the future, around 400,000 t of captured CO_2 from the waste-to-energy plant in Klemetsrud in Oslo will be transported by ship to an intermediate storage site. The carbon dioxide is then transported by pipeline to an offshore storage site under the sea floor in the North Sea. This will accept CO_2 emissions from various sources as part of the Norwegian *Northern Lights* project. Due to the biogenic element of the waste, this procedure can achieve some degree of negative emissions.

Study

ADP TA 8001 (Gaojing, China)
Beijing Jiaotong University
Status: Feasibility study (TRL 1-2).
Outlook: The study is complete.

The study investigated the extent to which electricity and heat production in China can be ensured by natural gas-based CHP with CCS.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required reinvestment

The required investment in CHP plants in the chemical industry was not assessed in this project. Usually these plants remain in operation for 50 years.

Technology development

The relatively low level of technological maturity of CHP plants with CCS (TRL 4) means that commercial application is likely to be realistic only after 2030.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1 to 9.

Chemicals

Technology
CHP plants with CCS

Current stage of development
Pilot plants (TRL 4)

Expected readiness for use
2030–2035

Maximum CO_2 reduction in the EU27

2030	2050
0 $MtCO_2$ per year	**49.5** $MtCO_2$ per year

Assumption for 2030: CO_2 reduction contribution with first demo plants

CO_2 abatement costs

2030	2050
unknown	**45–93** €/tCO_2

Electricity and infrastructure requirement

- Additional electricity requirement for changing all natural-gas CHP to CCS: 29 TWh_{el}
- Pipelines or ships for CO_2 transport
- Availability of secure long-term CO_2 storage

Challenges

The future social acceptance of CO_2 transport and storage is uncertain. Transporting CO_2 would be associated with high infrastructure costs (i.e. pipeline) for locations without access to a port (transport with ships). In addition, the market readiness of the technology is only expected in 2030, while there may be some reinvestment requirement before 2030 already.

Possible policy instruments

- Carbon price and border carbon adjustment
- Carbon cotracts or CCfDs

Evaluation of compatibility with Paris climate agreement

By installing carbon capture systems on CHP plants in the chemical industry, up to 90 per cent of the CO_2 arising can be captured. A large-scale application is only likely after 2030, however. Once connected to a CO_2 infrastructure, biomass-fired CHP plants with carbon capture technologies could contribute to negative emissions via Bio-Energy and CCS (BECCS).

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON$_2$ TECHNOLOGY
Heat-driven natural gas CHP		**CHP plant with CCS**
297 g CO_2/kWh_{th}	**-90 %** Specific emission reduction	**33** g CO_2/kWh
7.0 €-ct/kWh (2019)	**+17 to +36 %** Specific additional costs	**8.2–9.5** €-ct/kWh (2050)

Central assumptions for determining the range of the production costs (2050)

Assumption		Lower range	Upper range
Electricity production costs for natural gas CHP		7.0 €-ct/kWh_{th}	7.0 €-ct/kWh_{th}
Assumptions:	Type of plant	GCC	GCC
	Plant size	20 MW	20 MW
	Utilisation in full-load hours (FLH)	5,000 FLH	5,000 FLH
	Natural gas price	€30/MWh	€30/MWh
Operating costs of carbon capture, transport and storage (CCS)		€ 1.2-ct/kWh_{th}	€ 2.5-ct/kWh_{th}
Assumption:	CO_2 avoidance costs (CCS)	€ 45/tCO_2	€ 93/tCO_2
Production costs of low-carbon steam production 2050		**€ 8.2-ct/kWh_{th}**	**€ 9.5-ct/kWh_{th}**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

3.4 Hydrogen production from renewable energy/electrolysis (replacement of steam reforming for hydrogen production)

GrinHy pilot plant for high-temperature electrolysis, Salzgitter
Photo: Salzgitter AG

When producing green hydrogen from electrolysis, electricity is used to separate water molecules into hydrogen and oxygen. There are various types of electrolysis: alkaline, polymer-electrolyte membrane (PEM) and high-temperature electrolysis. When the electricity for electrolysis is entirely from renewables, the hydrogen production is carbon-neutral.

Pilot and demonstration projects

Demo

Green ammonia: (Puertollano, Spain)
Iberdrola, Fertiberia and NEL
Status: Plant commissioning is expected for 2021 (TRL 6-7). The PEM electrolyser will have a capacity of 20 MW.

Iberdrola is building an integrated system with a 100 MW photovoltaic plant, a lithium-ion battery system with a storage capacity of 20 MWh and one of the world's largest PEM electrolysers. The green H_2 will be used in Fertiberia's ammonia plant to manufacture green fertilisers.

Pilot

Refhyne (Wesseling, Germany)
Shell, ITM Power, SINTEF, thinkstep
Status: Construction of a pilot plant for PEM electrolysis with 10 MW (TRL 5–6).
Outlook: Technology will be tested for possible use in other sectors.

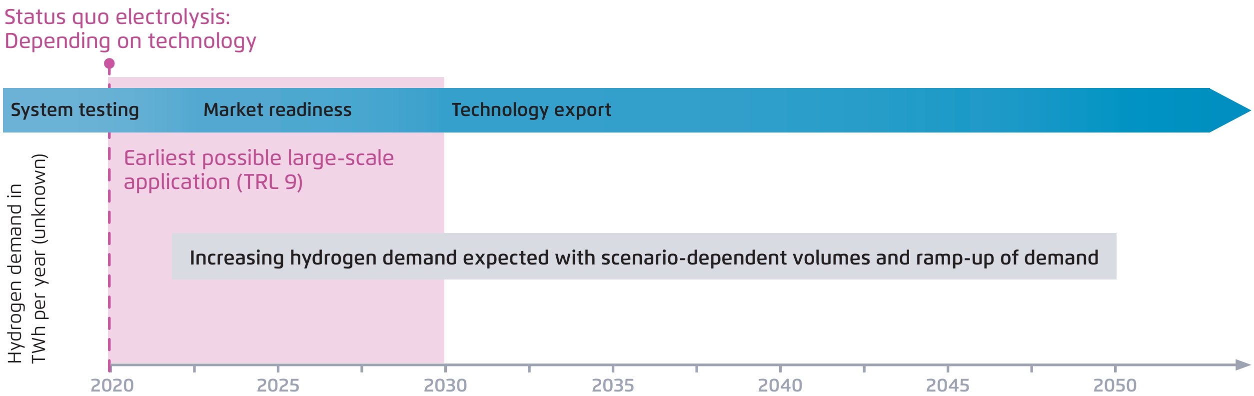
The refinery in the Rhineland requires around 180,000 t of hydrogen annually, most of which currently comes from steam reforming using natural gas. The new plant can produce an additional 1,300 t of green hydrogen annually. The production is completely integrated into the refinery process and is used, say, for the desulphurisation of conventional fuels.

Pilot

GrInHy 2.0 project (Salzgitter, Germany)
Sunfire, Salzgitter AG, Paul Wurth and Tenova
Status: Operation of the GrInHy pilot plant for high-temperature electrolysis until 2019 (TRL 4–5).
Outlook: Operation of the GrInHy 2.0 pilot plant for high-temperature electrolysis (TRL 6) until 2022.

GrInHy 2.0 is a pilot high-temperature electrolysis plant that will be operated with a capacity of 720 kW_{el} for at least 13,000 hours resulting in the production of more than 100 t of green hydrogen. It will also use waste heat sources from steel production at Salzgitter AG and thus reach an energy efficiency of 84 per cent.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment

It is nearly impossible to estimate the required investment due to the diverse production processes for hydrogen electrolysis. It is foreseeable that new investment will be needed because the demand for hydrogen from electrolysis will increase strongly in the future.

Technology development

If technology develops optimally, hydrogen electrolysis can be available for commercial use starting in 2025. Today, low-temperature electrolysis and the likely more efficient high-temperature electrolysis are at different stages of development, at TRL 8–9 and TRL 6–7, respectively.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1–9 (TRL 9 = ready for market).

Chemicals

Technology
Green hydrogen from electrolysis

Current stage of development
Alkaline electrolysis (TLR 8-9); PEM electrolysis (TRL 6-7) and high-temperature electrolysis (TRL 4-5)

Expected readiness for use
2020–2030

Maximum CO_2 reduction in the EU27

2030	2050
75 $MtCO_2$ per year	**73** $MtCO_2$ per year

2030: we assume a demand for green/clean H_2 in the steel, chemicals and refinery sector of 278 TWh. By 2050 total green hydrogen demand of these sectors amounts to 270 TWh and refineries will be phased out.

CO_2 abatement costs

2030	2050
170–430 €/tCO_2	**110–360** €/tCO_2

Calculation of the CO_2 abatement costs based on the CO_2 reduction compared with the reference process of steam reforming

Renewable electricity and infrastructure requirement
- 2050: 1.25 MWh_{el} per MWh_{th} of green H_2
- 2030: 1.4 MWh_{el} per MWh_{th} of green H_2
- With central production or import: dedicated H_2-pipelines are necessary
- Effect on the electricity network

Challenges
The production of green hydrogen demands large amounts of additional renewable electricity at moderate costs. For climate neutrality in the industry sector, we assume a no-regret hydrogen requirement of approx. 270 TWh in 2050. For exclusively green H_2, approx. 338 TWh of renewable electricity would be required.

Possible policy instruments
- Clean hydrogen support policies
- Green financing instruments
- Carbon price and border carbon adjustment

Evaluation of compatibility with Paris climate agreement
Besides reducing CO_2 by 100 per cent over that of conventional hydrogen, green hydrogen can play a key role in decarbonising many industries including steel, chemicals and maritime and aviation transport. Due to high demand for renewable electricity, the import of green hydrogen from non-EU countries with high renewable energy potential makes sense.

Technologies in comparison

CONVENTIONAL TECHNOLOGY **Steam methane reforming**		KEY LOW-CARBON TECHNOLOGY **H_2 from electrolysis**
9 kg CO_2 / kg H_2	-100 % Specific emission reduction	**0** kg CO_2 / kg H_2
1.8 € / kg H_2 (2019)	+56 to +178 % Specific additional costs	**2.8–5.0** € / kg H_2 (2050)

Central assumptions for determining the range of the production costs (2050)

Assumptions	Lower range	Upper range
Specific capital costs of electrolyser	€ 250/kW_{el}	€ 500/kW_{el}
Conversion efficiency (lower heating value)	82 %	74 %
2050 domestic		
Full-load hours; Ø electricity price	3,000 FLH; € 50/MWh	3,000 FLH; € 60/MWh
Cost of provision of green hydrogen 2050 (domestic)	**€ 2.8/kg H_2**	**€ 4.3/kg H_2**
2050 import		
Full-load hours; Ø electricity price	6,000 FLH; € 25/MWh	6,000 FLH; € 40/MWh
H_2 transport (without distribution)	€ 1.35/kg H_2	€ 2.00/kg H_2
Cost of provision of green hydrogen in 2050 (import)	**€ 2.9/kg H_2**	**€ 5.0/kg H_2**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1.)

3.5 Alternative processes such as the methanol-to-olefin/aromatics route (MTO/MTA) or electrochemical processes for olefin and aromatic production (replacement of olefin and aromatic production in steam crackers)

Carbon2Chem® pilot plant, Duisburg Photo: thyssenkrupp AG

In the methanol-to-olefin (MTO) and aromatics (MTA) route, olefins and aromatics can be produced from green methanol or syngas (H_2 and CO). These production pathways could replace steam crackers and the associated CO_2 could be saved. For methanol production, we recommend using green H_2 and, in the long term, CO_2 from renewable or recycled sources (feedstock from plastic waste, biomass, CO_2 from direct air capture).

Pilot and demonstration projects

Pilot MTO/MTA

Carbon2Chem® project (Duisburg, Germany)
Thyssenkrupp, BASF, Covestro, Linde, Evonik, Siemens, Fraunhofer-Institute
Status: Operation of pilot plant for methanol manufacture in Duisburg (TRL 4-5), with all the individual components (TRL 9).

The cross-sector network of the steel, chemical and energy industries seek to establish CCU processes and use metallurgical gases (including the CO_2 they contain) from steel production as a feedstock for chemical products. Excess electricity from renewable energy will be used as one of the energy sources.

Pilot

Carbon4PUR project (Marseille, France)
Covestro, ArcelorMittal, Recticel, DECHEMA
Status: Construction of a pilot plant in Marseille Fos.
Goals: Obtain polyurethane from smelting gases.

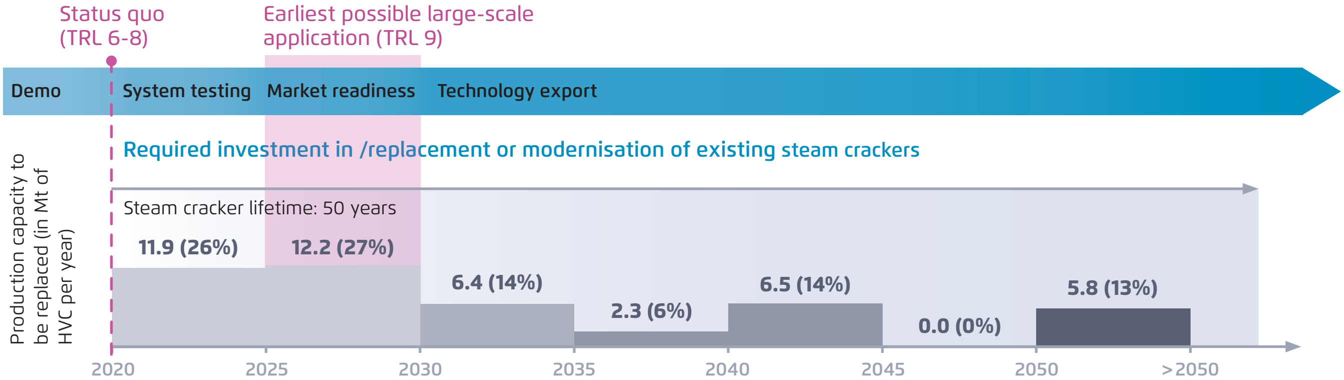
The project develops the conversion of industrial exhaust gases with mixed CO/CO_2 flows into polyurethane plastics. The process can produce end products such as rigid foams, building insulation or coatings.

Pilot Electro-chemical process

Rheticus project (Marl, Germany)
Evonik, Siemens
Status: Construction of a pilot plant in Marl.
Vision: Operate a plant with a capacity of up to 20,000 t per year where exhaust gases from industrial processes are converted into special chemicals or fuels.

The first step is the solar-powered electrochemical reduction of CO_2 and H_2O to obtain syngas, which is used in the test plant to manufacture butanol or hexanol. The manufacture of other special chemicals or fuels is also possible. In the future, flexibly sized plants could be installed where CO_2 is emitted on a large scale, i.e. at biomass power plants and biogas facilities.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment

The required investment in steam crackers by 2030 includes plants with a production of approx. 24.1 Mt of HVC (approx. 53 per cent of total capacity). Normally, steam crackers are continuously maintained and modernised, rather than replaced all at once. Nevertheless, the required investment provides a rough idea of the modernisation needs of old plants.

Technology development

If technology develops optimally (TLR 9), large-scale deployment would be possible starting between 2025 and 2030. Today, the MTO (TRL 8) and MTA processes (TRL 6) are already in advanced stages of development. The MTO route was originally developed for using coal as a feedstock and is already in use in other countries (e.g. China).

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1–9 (TRL 9 = ready for market).

Chemicals

Technology
Methanol-to-olefin/aromatics route (MTO/MTA)

Current stage of development
MTO (TRL 8); MTA (TRL 6)

Expected readiness for use
2025–2030

Maximum CO_2 reduction in the EU27

2030	2050
unknown	**181** $MtCO_2$ per year

2050: CO_2 reductions incl. waste incineration plants (energy sector)

CO_2 abatement costs

2030	2050
160–355 €/tCO_2	**84–515** €/tCO_2

2030/2050: indicated CO_2 abatement costs only apply to MTO
2050: weighted average MTO/MTA: € 122–615/tCO_2

Renewable electricity and infrastructure requirement
- 22.7 MWh per t of olefin (of which 21.5 MWh for green H_2)
- 36.5 MWh per t of BTX (of which 34.6 MWh for green H_2)
- Syngas storage, if needed

Possible policy instruments
- Carbon contracts or CCfDs
- Clean hydrogen support policies
- Green public procurement
- Quotas for low-carbon materials
- Carbon price and border carbon adjustment

Challenges
For extensive CO_2 reductions, methanol-based processes (MTO, MTA) require large amounts of renewable electricity. If 100 per cent of current plastics production (31.6 Mt of olefins and 8.6 Mt of BTX in 2017) was produced using the MTO/MTA route, around 1032 TWh of additional electricity would be needed, 978 TWh in the form of green H_2.

Evaluation of compatibility with Paris climate agreement
In principle, MTO/MTA should be evaluated from a holistic perspective (life cycle assessment). Under ideal conditions (100 per cent renewable electricity, non-fossil carbon source), MTO and MTA can avoid (virtually) all CO_2 emissions in the plastics life-cycle (from production to recycling) and thus close the carbon cycle. The use of CO_2 from industrial processes (e.g. steel, cement) is also conceivable during the transition.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Naphtha steam cracking + Waste incineration plants		**Methanol-to-olefin route+ Carbon from direct air capture**
4.5 t CO_2/t of HVC	-100 % Specific emission reduction	**0** t CO_2/t of HVC
842 €/t of HVC (2019)	+45 to +277 % Specific additional costs	**1,223–3,176** €/t of HVC (2050)

Central assumptions for determining the range of the production costs (2050)

Assumptions	Methanol import	Domestic production
Specific capital costs for direct air capture (DAC)	€ 248/t of HVC	€ 248/t of HVC
Specific capital costs of methanol synthesis	€ 135/t of HVC	€ 135/t of HVC
Specific capital costs of methanol-to-olefin plant	€ 19/t of HVC	€ 19/t of HVC
Fixed operating costs	€ 138/t of HVC	€ 138/t of HVC
Costs for H_2 supply	€ 620/t of HVC	€ 2540/t of HVC
Assumptions: Ø electricity price H_2 production	€ 25/MWh	€ 60/MWh
Transport costs for methanol	€ 31/t of HVC	–
Costs for providing electricity (with import only MTO)	€ 31/HVC	€ 95/HVC
Production costs for climate-neutral HVC production:	**€ 1223/t of HVC**	**€ 3176/t of HVC**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

3.6 Chemical recycling: Pyrolysis or gasification of plastic waste for material use (replacing the combustion of plastic waste in waste incineration plants and substituting primary feedstock from fossil sources)

Pilot plant for chemical recycling, Ennigerloh Photo: Recenso GmbH

Chemical recycling makes it possible to re-use plastic waste as feedstock in the chemical industry instead of burning it. In the process, the plastic waste is converted to synthesis gas (gasification) or to liquid oil (pyrolysis) and then made into alternative feedstock that replaces fossil feedstock (e.g. fossil naphtha). In this way, the CO_2 emissions from burning plastic waste and the use of naphtha as a feedstock can be eliminated. In order to create a climate-neutral petrochemical industry, chemical recycling must be combined with other processes in the long term (electric steam cracking, methanol-to-olefin).

Pilot and demonstration projects

Demo Pyrolysis

Cleaning of pyrolysis oil (Geleen, the Netherlands)
Sabic
Status: Planning of semi-commercial plant for cleaning approx. 15 kt of pyrolysis oil per year.
Outlook: Production to begin in 2021.

The recycled polymers of Sabic will be manufactured from a pyrolysis oil-based raw material produced from mixed plastic waste. Sabic is introducing this alternative raw material to its production facility in Geleen. The resulting polymers will be supplied to customers such as Unilever and Tupperware Brands.

Demo Gasification

Waste to Chemicals Rotterdam (the Netherlands)
Air Liquide, Enerkem, Nouryon, Port of Rotterdam, Shell
Status: Plant in planning.

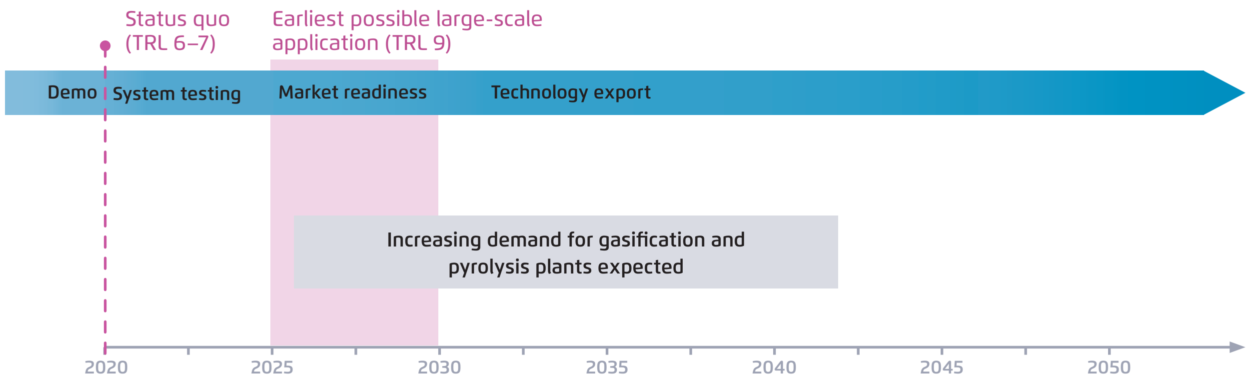
The waste-to-chemicals plant will produce methanol from residual waste. Up to 360,000 t of residual waste can be converted into syngas and then into 220,000 t (270 million litres) of methanol.

Pilot Pyrolysis

ChemCycling (various locations, Germany)
BASF, Remondis, Plastic Energy, Recenso
Status: Pilot plant for direct oiling of Recenso GmbH in operation (Ennigerloh, Germany).

Production of pyrolysis oils from plastic waste, which can be processed in steam crackers. In this way, the use of fossil naphtha in the steam cracker can be reduced. In 2018, the first products based on pyrolysis oils from the pilot plant were manufactured in Ennigerloh.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment

The introduction of chemical recycling would require new gasification and pyrolysis plants for the conversion of plastic waste into feedstock. The extent to which existing waste incineration plants or steam crackers can be replaced depends on a multitude of factors and cannot be determined here.

Technology development

Both pyrolysis and the gasification route exhibit a high degree of technology development (TRL 6–7). Both processes are therefore expected to be market ready in the period from 2025 to 2030. Large-scale use would be possible as long as the conditions for chemical recycling in the EU27 ensure economic viability.

The Technology Readiness Level (TRL) describes the maturity of the technology on a scale from 1–9 (TRL 9 = ready for market).

Chemicals

Technology
Chemical recycling (pyrolysis, gasification)

Current stage of development
Demonstration plants (TRL 6-7)

Expected readiness for use
2025–2030

Maximum CO_2 reduction in the EU27

2030	2050
6.2 $MtCO_2$ per year	**79** $MtCO_2$ per year

2050: CO_2 reductions incl. waste incineration plants (power sector)

CO_2 abatement costs

2030	2050
-58*–60 €/tCO_2	**11–49** €/tCO_2

2030: *Non-integrated pyrolysis route; cost depends on naphtha price
2050: integrated pyrolysis route (incl. electric steam cracker + MTO)

Renewable electricity and infrastructure requirement
- Electricity requirement for integrated pyrolysis: 6.8 MWh per t of HVC (2 MWh for green hydrogen)
- Collection and logistics system for suitable plastic waste

Possible policy instruments
- Standards for recyclable products
- Quotas for low-carbon materials
- Carbon price and border carbon adjustment
- Green financing instruments

Challenges
The use of pyrolysis oil in steam crackers is already economically attractive, but for complete closure of the carbon cycle, chemical recycling must be combined with other processes (electr. steam crackers and MTO). Based on the availability of waste plastics in 2050, chemical recycling could result in an electricity requirement for renewables amounting to approx. 129 TWh.

Evaluation of compatibility with Paris climate agreement
Chemical recycling is an essential element for building a circular carbon economy and thus central to achieving a (mostly) GHG neutral chemical sector. As long as 100 per cent of the electricity used is renewable, CO_2 emissions from burning plastic waste and the many manufacturing steps of fossil naphtha can be almost completely eliminated.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Naphtha steam cracking+ Waste incineration plants		**Pyrolysis + electric steam crackers + methanol-to-olefin**
4.5 t CO_2 / t of HVC	**-93 %** Specific emission reduction	**0.3** tCO_2 / t of old plastics
842 €/t of HVC (2019)	**+6 to +25 %** Specific additional costs	**890–1,050** €/t of HVC (2019)

Central assumptions for determining the range of the production costs (2030)

Assumption of pyrolysis + conv. steam crackers without MTO (2030)	Lower range	Upper range
Specific capital costs of pyrolysis plant	€ 14/t of HVC	€ 14/t of HVC
Specific capital costs of steam crackers	€ 74/t of HVC	€ 74/t of HVC
Specific supply costs of natural gas	€ 20/t of HVC	€ 20/t of HVC
Fixed operating costs	€ 40/t of HVC	€ 40/t of HVC
Specific supply costs of waste	€ 483/t of HVC	€ 483/t of HVC
Assumptions: Supply costs for waste (old plastics)	€ 304/t of waste	€ 304/t of waste
Specific costs for supply of electricity	€ 29/t of HVC	€ 34/t of HVC
Assumptions: average electricity price	€ 50/MWh	€ 60/MWh
Production costs for low-emission HVC production:	**€ 659/t of HVC**	**€ 664/t of HVC**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

3.7 Electrification of the high-temperature heat in steam crackers (replacement of the burning of fossil raw materials in the steam cracker)

A pilot plant does not yet exist.

The electrification of the high-temperature heat can completely eliminate direct CO_2 emissions from steam crackers. The emissions currently arise from burning a part of the feedstock (e.g. naphtha) or natural gas in order to provide the necessary process heat (600–900°C). electrified steacm crackers, the alternativel feedstock from chemical recycling (e.g. pyrolysis oil) would not have to be burned, which would allow to close the carbon cycle without significant losses. (See chemical recycling.)

Pilot and demonstration projects

Demo

E-Cracker (Ludwigshafen, Germany)
BASF, Sabic, Linde
Status: Partners applied for funding at the EU Innovation Fund and national decarbonisation fund.

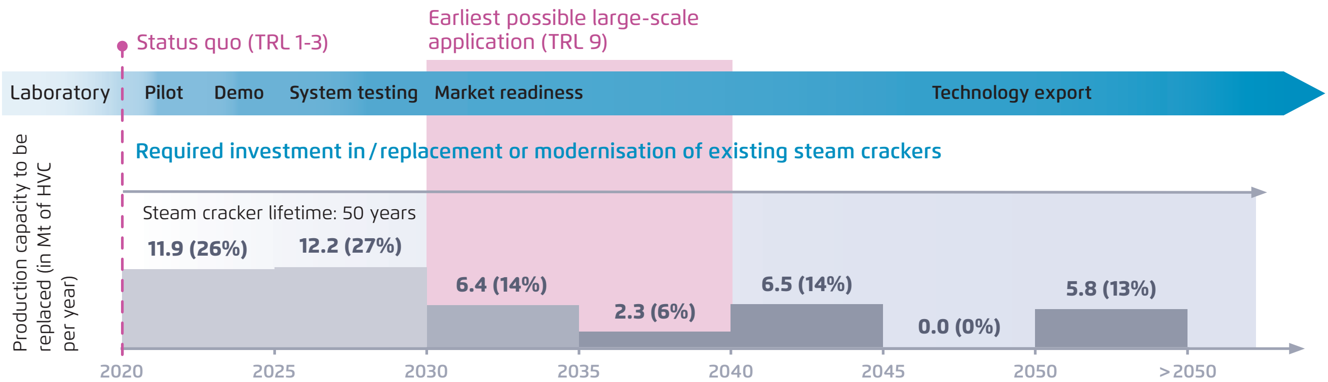
The parties are evaluating construction of a multi-megawatt demonstration plant of an electrically heatable steam cracker at BASF's Ludwigshafen site, targeted for start-up as early as 2023, subject to a positive funding decision. This would allow the substitution of fossil fuels that are burned today to supply the required high-temperature heat.

Laboratory

Cracker of the Future (three-country cooperation)
BASF, Borealis, BP, LyondellBasell, Sabic, Total, Brightlands Chemelot Campus
Status: Testing of the sustainable technical and economic possibilities of the technology and a prompt implementation.
Outlook: Roadmap for the development and use of electric cracker technology.

A consortium from six petrochemical companies operating in the trilateral region of Flanders, the Netherlands and North-Rhine-Westphalia, led by Brightlands Chemelot Campus, is conducting research on the operation of electric steam crackers supplied with electricity from renewable energy for producing basic chemicals such as ethylene, propylene, butadiene and aromatics. The partner companies agreed to invest in appropriate research and development and to share knowledge. The collaboration is a result of the trilateral strategy of the chemical industry between the German VCI, the Belgian Essenscia and the Dutch VNCI.

Required reinvestment and earliest possible market readiness of key low-carbon technology



Required investment

The required investment in steam crackers by 2030 includes plants with a production of approx. 24.1 Mt of HVC (approx. 53 per cent of total capacity). Normally, steam crackers are continuously maintained and modernised, rather than replaced all at once. Nevertheless, the required investment provides a rough idea of the modernisation needs of old plants.

Technology development

Laboratory scale plants do not appear necessary for market readiness because the basic functionality of electric crackers is well understood and the challenges lie more in the construction of an industrial plant. The construction of a pilot or demonstration plant is likely to be possible between 2020 and 2030.The technology is likely to be market ready (TRL 9) starting in 2030.

The Technology Readiness (TRL) describes the maturity of a technology on a scale from 1–9 (TRL 9 = ready for market).

Chemicals

Technology
Electrically heatable and feedstock-flexible steam crackers

Current stage of development
Laboratory phase (TRL 1-3)

Expected readiness for use
2030–2040

Maximum CO_2 reduction in the EU27

2030	2050
0 $MtCO_2$ per year	**32** $MtCO_2$ per year

CO_2 abatement costs

2030	2050
73–121 €/tCO_2	**11–49** €/tCO_2

Assumption 2050: Embedded in a circular economy

Renewable electricity and infrastructure requirement
- 2.5 MWh/t of HVC
- Total electricity requirement for electric steam cracking of 40.2 Mt of HVC: 101 TWh
- increased expansion of electricity network

Possible policy instruments
- Reform levies and surcharges
- Reform of network charges
- Carbon price and border carbon adjustment:
- Green financing instruments
- Support for research

Challenges
By the time the technology is market ready (2030 at the earliest), a large portion of the investment in new steam crackers could have already been made. As a result, retrofitting electric heating systems and an increased flexibility with respect to the feedstock (pyrolysis oil, biomass, etc.) should be considered. In addition, the direct electricity requirement would be relatively high (2.5 MWh/t of HVC).

Evaluation of compatibility with Paris climate agreement
This technology makes sense particularly in combination with chemical recycling within a circular economy. On the one hand, the emissions at the steam cracker can be reduced by 100 percent. On the other hand, it would not be necessary to combust part of the carbon contained in the alternative feedstock from plastic waste to provide heat, which under ideal conditions allows closing the carbon to cycle without significant losses.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Naphtha steam cracker		**Electrically heated steam cracker**
0.80 t CO_2 / t of HVC	-100 % Specific emission reduction	**0** t CO_2 / t of HVC
842 €/t of HVC (2019)	+15 to +18 % Specific additional costs	**968-993** €/t of HVC (2050)

Central assumptions for determining the range of the production costs (2050)

Assumptions	Lower range	Upper range
Specific capital costs for electric steam crackers	€ 60/t of HVC	€ 60/t of HVC
Cost of provision of naphtha	€ 752/t of HVC	€ 752/t of HVC
Fixed operating costs	€ 29/t of HVC	€ 29/t of HVC
Electricity costs	€ 127/t of HVC	€ 152/t of HVC
Assumptions: average electricity price	€ 50/MWh	€ 60/MWh
Return on saved fuel	–	–
Production costs for low-emission HVC production:	**€ 968/t of HVC**	**€ 993/t of HVC**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

3.8 End notes and bibliography

List of end notes

1 Agora Energiewende/Wuppertal Institute, 2021, based on Eurostat, 2017.

2 The European Chemical Industry Council (CEFIC), 2018.

3 Eurostat, 2017.

4 "HVC" refers to products from naphtha steam cracking. Ethylene and propylene are the main components, but benzene, toluene, and xylene (BTX) are included as well. 1.97 t of HVC contain one t of ethylene.

5 Wuppertal Institute, 2021. Includes HVC production from steam crackers and refineries.

6 The GHG emissions of steam crackers are only accounted for by the chemical industry if they are being operated by chemical companies. In case they are being operated as part of a refinery, their emissions are accounted for by the energy sector.

7 Apart from steam crackers, catalytic crackers and steam reforming plants within refineries also produce basic chemicals as by-products that are further processed in downstream processes.

8 Wuppertal Institute, 2021. Generally, steam crackers are continuously maintained and modernised but not completely replaced. As a result, reinvestment expenditure does not happen all at once but is spread over a longer period. Nevertheless, the required investment for the coming years indicates the extent to which old plants have to be modernised or replaced by plants with new technologies.

9 European Environment Agency, 2021.

10 Eurostat, 2017. Includes energy requirements from the chemical and petrochemical industries.

11 Agora Energiewende/Wuppertal Institute, 2021, internal calculations.

12 Agora Energiewende/Wuppertal Institute, 2021, internal calculations.

13 Other CO_2-neutral alternatives are the use of biomass or hydrogen for CHP. We do not consider these options because of the limited availability of sustainable biomass and (for the time being) hydrogen. Moreover, the use of biomass and hydrogen in other applications promises greater benefits to the climate.

14 Internal calculations based on ammonia production from the United States Geological Survey (USGS), 2017, and on an emission factor of 1.8 t CO_2/t ammonia.

15 Material Economics, 2019.

16 The required electricity causes an indirect emission of 0.7 tCO_2 per t of ammonia. The emissions must be accounted for by the industrial power plants of the chemical industry or the power sector.

17 United States Geological Survey (USGS), 2017.

18 When using fertilisers that contain reactive nitrogen compounds, considerable nitrogen oxide emissions (including nitrous oxide, an extremely potent greenhouse gas) and water pollution can occur. Accordingly, the challenge is not just to replace natural-gas-based ammonia and fertiliser production for a route using green hydrogen but also to significantly reduce the use of synthetic nitrogen fertilisers.

19 The introduction of CCS is associated with substantial hurdles for social acceptance. CCS also requires the establishment of extensive infrastructure for the transport and permanent storage of CO_2.

20 In the methane pyrolysis process, natural gas is split in a high-temperature reactor into hydrogen and carbon. In the process, solid carbon is produced that can either be used for other purposes (e.g. for battery manufacture) or disposed of in landfills. This hydrogen is called turquoise. The process is in an early stage of development and it cannot be predicted whether, when and at what cost hydrogen can be produced in large volumes with this method.

21 Internal calculations based on data from the Wuppertal Institute for Germany, 2019. According to the calculations and assumptions of the Wuppertal Institute, the production of each t of HVC generates 1.4 tCO_2 emissions (0.2 t in the refinery, 0.8 t in the steam cracker and 0.4 t in the polymerisation process) as well as 3.1 t CO_2 when incinerated in waste-to-energy plants.

22 Internal calculations of the Wuppertal Institute. It should be noted that the heat and the electricity that are generated in waste-to-energy plants offset GHG emissions from heat and electricity generation with primary fossil fuels. As a result, the net emissions for the combustion of plastics in waste-to-energy plants are lower than 125 $MtCO_2$ per year. However, in a future energy system consisting entirely of renewable electricity, this offsetting disappears.

23 Deloitte, 2019.

24 European Parliament, 2018.

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4 Cement

4.1 Cement sector overview

Direct CO_2 emissions from the cement industry in the EU27 (+UK) in 2017
112 $MtCO_2$ (+6 $MtCO_2$ in the UK)

Cement production in the EU27 (+UK) in 2017
159 Mt of cement in EU27 (+8.6 Mt of cement in the UK)

Cement demand in 2017 (EU28)
168 Mt of cement

Reinvestment required for cement by 2030
We estimate that approx. 30 per cent of the total capacity will require reinvestment by 2030

Directly employed in 2017 (EU27)
47,000 employees

Cement is a binding agent that is an essential element of concrete and mortar and ranks among the most-used construction materials worldwide. As a result, the cement industry holds a decisive position in the value chain of the construction industry. The cements produced by the cement industry are clearly defined in European-wide and national standards. The European standard DIN EN 197-1, for so-called normal cements, divides the cement into five main types (CEM I – CEM V), which are differentiated based on the per cent by weight of cement clinker and other components (e.g. slag, pozzolan, fly ash) into 27 normal cement types.

In 2017, approx. 159 Mt of cement were manufactured in the EU27[1], generating a gross value added of around 5.1 billion euros.[2] Compared with steel and basic chemicals, the trade intensity of cement is low. The cause of this is primarily the high transport costs relative to the product price. Accordingly, the main part of cement transport happens on the roads in a transport radius of up to 250 km, although the importance of longer transports using (inland) shipping is increasing.

The European cement industry includes a mix of medium-sized and large companies with a total of around 47,000 employees.[3] In 2017 cement clinker was produced at roughly 190 different sites across the EU27.[1] Locally available raw materials (limestone, clay) and low-cost transport options to reach demand markets are central factors for cement plant locations.

In 2015, cement usage in Europe broke down as follows: buildings (50 per cent), civil engineering (30 per cent) and maintenance (20 per cent). Most of the cement is processed into ready-mixed concrete (approx. 48 per cent), followed by precast concrete (28 per cent) and mortars and plasters (24 per cent).[4]

EU cement production has a high energy cost share of 35 per cent per t of cement. Fuels are used mainly for the energy-intensive burning of cement clinker. In 2017, 54 per cent of the cement industry's thermal energy use came from fossil fuels. But the cement industry also uses alternative fuels such as old tyres, waste oil, animal meal, and plastic waste. The share of these alternatives has been continually rising since the 1990s. In 2017, 46 per cent of the thermal energy use came from alternative fuels.[5] Roughly 10 to 15 per cent of the overall energy requirement comes from electricity. The electricity goes primarily to grinding raw materials and cement.

The direct specific CO_2 emissions (i.e. without contribution from electricity use) from cement varies across Europe and amounts to an average of 0.65 tCO_2/t of cement. For the subsequent technology fact sheets the average for Germany of 0.61 tCO_2/t of cement was the base for the calculations. Overall direct emissions of cement manufacture in the EU27 amounted to 112 Mt in 2017.[1]

Based on the required reinvestment of the German cement industry by 2030 which is estimated at 30 per cent, we assume the reinvestment requirement at EU level to be in a similar range.

Greenhouse-gas-neutral cement sector

Decarbonising the cement sector represents a great challenge. This is mostly because of the process-related CO_2 emissions that arise during the calcination process, when limestone is heated to produce calcium oxide (or lime), the principal ingredient of cement clinker. From today's perspective, the use of carbon capture and storage (CCS) and possibly carbon capture and use (CCU) technologies are unavoidable.

A further difficulty is that most cement plants are in rural areas close to mining areas for limestone and clay. The construction of a comprehensive CO_2 infrastructure in rural areas would be necessary for transporting the captured CO_2 to offshore storage sites.

Process-related emissions amount to approx. 65 per cent of the emissions per t of cement. The remaining 35 per cent (fuel-related emissions) come from burning fossil and alternative fuels to provide the high-temperature process heat. In principle, this proportion can be significantly reduced or even completely eliminated by electrification, green hydrogen or other greenhouse gas-neutral fuels such as biomass and synthetic gas. With the use of CCS or CCU[6] for the capture of process-related and fuel-related emissions, negative emissions would be possible if mainly GHG neutral fuels that do not contain carbon of fossil origin are used. Below, the conventional cement production process is described in order to provide the basis for understanding key low-carbon technologies (see Figure E.5.).

Reference process

For the binding properties of cement, cement clinker is the key component. Depending on the type of cement, other materials are mixed with the cement clinker in varying proportions. The manufacture of cement clinker is responsible for a total of 94 per cent of the overall (i.e. direct plus indirect) CO_2 emissions of cement manufacture.[7] The current normal average proportion of cement clinker in Europe of 74 per cent cement (or a clinker factor of 0.74) is used for the following assessment.

Cement clinker is manufactured from a ground mixture of approx. 75 per cent limestone and 25 per cent clay. Put simply, its manufacture can be divided into two central, energy-intensive steps: The pre-heated raw material is initially calcinated at approx. 900°C (burned). In modern cement plants, this takes place in the calciner, upstream of the rotary kiln. Approx. 60 per cent of the total heating is required for the calcination process, which today is provided by the burning of fossil and alternative fuels. In the process, an average of 0.13 tCO_2 per t of cement arise from fuel combustion. 90 to 95 per cent of the limestone ($CaCO_3$) in this process step is already converted to burnt lime (CaO) and carbon dioxide (CO_2) (calcination), resulting in additional, process-related CO_2 emissions of 0.36 tCO_2 arising in the calciner.

In the next step, the material mixture is heated in the rotary kiln to 1,450°C where it is fused together (sintered) and then cooled in the clinker cooler.
In the rotary kiln, direct, fuel-related emissions arise (0.08 tCO_2 per t of cement) as well as other process-related emissions (0.04 tCO_2 per t of cement).

In a later step, the cement clinker is ground and possibly mixed with other main components such as slag to produce cement. For one t of cement, direct emissions of around 0.61 tCO_2 result. But this does not take into account the indirect emissions for the use of electricity in the drying and grinding processes.

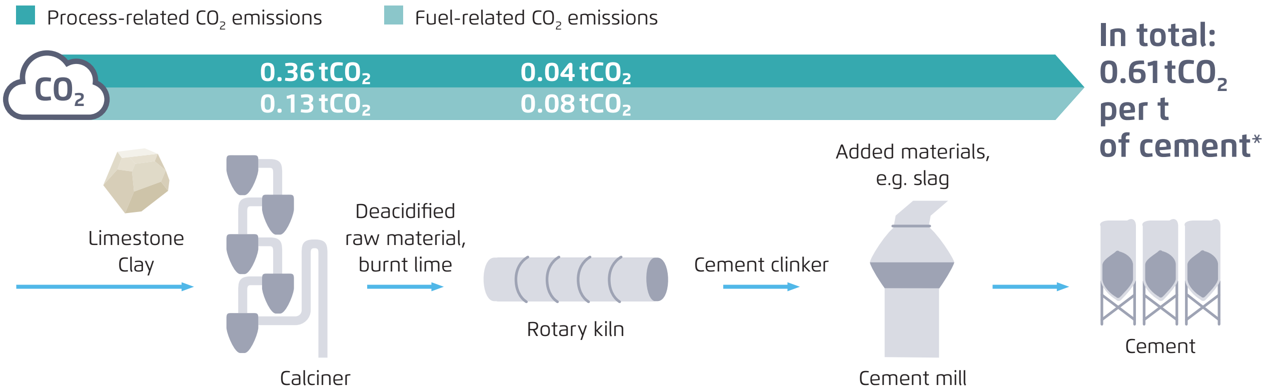
Possible key low-carbon technologies

CO_2 capture with Oxyfuel-CCS

CCS includes the capture, transport and permanent storage of the CO_2 emissions arising from the cement clinker manufacture. In the Oxyfuel process, the combustion process in the rotary kiln and in the calciner is carried out with a mixture of oxygen and recycled CO_2 instead of air. This makes the separation of the CO_2 from the exhaust gas flow easier and increases the CO_2 capture rate. In this way, approx.

Process steps and direct CO_2 emissions from cement production

Figure E.5



* Assumption: All information is based on cement with a clinker proportion of 74 per cent.

90 per cent of the whole process and fuel-related emissions can be captured. If Oxyfuel-CCS is combined with a share of biogenic fuels (BECCS) cement works can become climate-neutral (when they use a share of around 25 per cent of biogenic fuels - or even carbon-negative when they use more than a 25 per cent share of biogenic fuels).

CO_2 capture and electrification of the high-temperature heat for the calciner (LEILAC)

In an approach followed by the LEILAC project[8], the calcination process step is carried out in a special, indirectly heatable steel vessel. This allows the process-linked emissions to be captured in a relatively pure CO_2 flow, which reduces the energy required for CO_2 capture and purification. In principle, this approach also allows the electrification of calciners by heating the steel vessel electrically instead of with fossil burners. But this approach requires large amounts of electricity. With this technology, approx. 77 to 80 per cent of the total emissions from the kiln can be reduced.

Alternative binding agents

Alternative binding agents allow the manufacture of concrete without the use of conventional cement clinker. The various existing approaches for alternative binding agents differ strongly regarding input materials and production processes and therefore cannot be discussed in detail here.[9] A central aspect is reducing the share of limestone to lower process-related emissions. Some alternative binders are also less energy-intensive, because the manufacturing process takes place at a lower temperature level, and the thermal energy requirement for calcination is also lower with reduced limestone content. Being a non-CCS option, cement produced with alternative binding agents can lower CO_2 intensity up to 53 per cent relative to conventional cement (whose clinker share is around 74 per cent).[10] Alternative binding agents can also be combined with CCS technology. Doing so would reduce the electricity requirement for carbon capture and transport as a result of the lower CO_2 emissions. However, it is expected that the application of alternative binding agents will remain limited to niche markets in the medium term because some of the properties of the final products deviate from industrial norms.

Other promising approaches exist – different post-combustion technologies (CCS)[11], the recarbonation of building demolition (CCU) or textile-reinforced concrete – but they are not part of our assessment.

4.2 CO_2 capture with the Oxyfuel process (CCS)

Pilot plant Oxyfuel clinker cooler, cement works Hanover, HeidelbergCement
Photo: Steffen Fuchs, Heidelberg/Germany

The Oxyfuel process is a process for carbon capture for the cement clinker burning process carried out using a mixture of oxygen and recycled CO_2 instead of air. This makes the capture of carbon from the exhaust gas flow easier and in practice allows the capture approx. 90% of the total emissions. The CO_2 would then have to be transported via a CO_2 infrastructure, e.g. pipelines or ships for locations near rivers, and ultimately placed in suitable storage locations (e.g. in depleted oil and gas fields in the North Sea).

Pilot and demonstration projects

Demo

Catch4climate (Mergelstetten, Germany)
Buzzi Unicem-Dyckerhoff, HeidelbergCement, SCHWENK and Vicat
Status: Planning to build demonstration plant on a semi-industrial scale (TRL 6).

The consortium CI4C (Cement Innovation for Climate) was created in 2019 and is cooperating closely with the federal state of Baden-Wuerttemberg. Their aim is to create the basis for a large-scale application of CO_2 capture technologies in cement plants enabling the use of CO_2 as a raw material in other processes (CCU, CCS). The captured CO_2 will be used to produce synthetic fuels such as kerosene for airplanes.

Demo

ECRA-CCS project (EU project)
ECRA, HeidelbergCement
Status: The project is currently in phase IV – developing a concept for an industrial-scale demonstration plant and applying for an EU grant to fund construction.

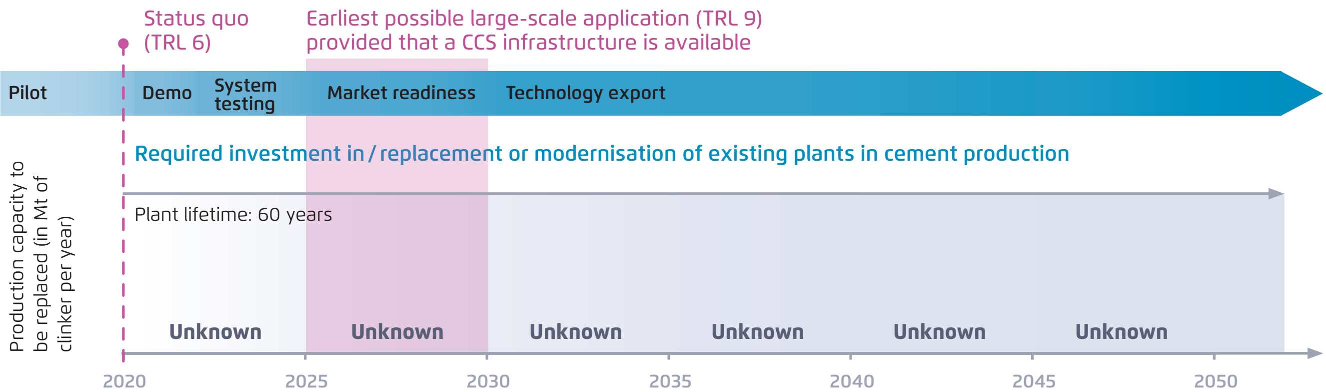
The *European Cement Research Academy* (ECRA) has been studying the technical and economic feasibility of carbon capture in cement manufacture since 2007. Talks are currently being held on a suitable location in Germany for the construction of a demonstration plant for an industrial-scale test operation.

Pilot

CEMCAP project (Hanover, Germany)
HeidelbergCement, German cement works association (VDZ)
Results: Evidence for Oxyfuel clinker cooling; development of Oxyfuel burner and calciner.

An Oxyfuel cooling system for clinker was successfully installed and tested. Laboratory tests have been carried out on an Oxyfuel-compatible burner and calcinator. A model of a complete Oxyfuel plant was created.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment

By our estimates, the reinvestment requirement in the cement industry by 2030 includes plants with a capacity of approx. 55 Mt of cement clinker per year (approx. 30 per cent of the total capacity). The number was extrapolated from German data in absence of a full site-specific dataset for Europe.

Technology development

If technology develops optimally, commercial use (TRL 9) can be envisaged by 2025. However, carbon capture requires a CO_2 infrastructure to transport the CO_2 away to offshore storage sites, which is why retrofitting cement plants near the coast and rivers (transport by ship) appears likely as an initial step.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1–9 (TRL 9 = ready for market).

Cement

Technology
Carbon capture with the Oxyfuel process

Current stage of development
Planned construction of demo plants (TRL 6)

Expected readiness for use
2025–2030

Maximum CO_2 reduction in the EU27
2030: **8.5** $MtCO_2$ per year
2050: **101** $MtCO_2$ per year

CO_2 abatement costs
2030: **70–131** €/tCO_2
2050: **65–87** €/tCO_2

Renewable electricity and infrastructure requirements
- 0.25 MWh per t of cement (incl. capture, purification and compression of CO_2)
- CO_2 infrastructure
- secure long-term CO_2 storage
- Oxygen production plant

Challenges
The public acceptance of CO_2 transport and storage is uncertain, especially for sites far away from potential offshore storage sites. The Oxyfuel process demands a some additional renewable electricity. For 50 per cent of the EU27 cement production (approx. 80 Mt) the Oxyfuel process with CCS would create an additional electricity requirement of approx. 20 TWh.

Possible policy instruments
- Carbon price and border carbon adjustment
- Carbon contracts or CCfDs
- Green public procurement
- Quotas for low-carbon materials
- Reform levies and surcharges

Evaluation of compatibility with Paris climate agreement
A successful further development of this technology can contribute to siginificant CO_2 reductions from cement manufacturing worldwide if the required CO_2 infrastructure is constructed. With 100 per cent GHG-neutral fuels, such as biomass from sustainable sources, negative emissions are possible.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Conventional cement manufacturing		**Carbon capture with Oxyfuel**
0.61 tCO_2/t of cement	-90 % Specific emission reduction	**0.06** tCO_2/t of cement
46 €/t of cement	+78 to +104 % Specific additional costs	**82–94** €/t of cement

Central assumptions for determining the range of the production costs (2050)

Assumption	Lower range	Upper range
Capital costs for reference cement work	€ 15/t of cement	€ 17/t of cement
Specific capital costs of retrofitting Oxyfuel	€ 7/t of cement	€ 10/t of cement
Assumption: CAPEX Oxyfuel for 1 Mt of cement clinker per year	€ 100 million	€ 130 million
Operating costs of cement production incl. carbon capture in the cement works	€ 41/t of cement	€ 46/t of cement
Assumption: average electricity price	€ 50/MWh	€ 60/MWh
Costs for CO_2 transport and storage	€ 33/tCO_2	€ 38/tCO_2
This consists of: CO_2 transport costs (inland and seagoing vessels)	€ 23/tCO_2	€ 28/tCO_2
North Sea storage	€ 10/tCO_2	€ 10/tCO_2
Production costs of low-carbon cement	**€ 82/t of cement**	**€ 94/t of cement**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

4.3 Carbon capture in combination with the electrification of high-temperature heat for calciners (electrified LEILAC process)

Pilot plant of the LEILAC reactor in the Lixhe cement plants, HeidelbergCement
Photo: Paul Poels, Meerlo/the Netherlands

In the LEILAC process, a special, indirectly heated steel vessel is used as the calciner. As a result, a pure CO_2 exhaust gas flow simplifies the capture of CO_2. This way captures approx. 85 to 90 per cent of total process-related emissions. It also enables the electrification of high-temperature heat production, which eliminates the fuel-related emissions from the calciner. The total reduction is around 77 to 80 per cent of kiln emissions.

Pilot and demonstration projects

Demo

EU project LEILAC II (Hanover, Germany)
HeidelbergCement, Cemex, Calix
Outlook: Demonstration plant (TRL 6-7) is expected to be ready by the end of 2023 and the overall project will run until 2025.

After the success of the first project phase, LEILAC II is now designing a CO_2 capture pilot plant that can capture 100,000 tCO_2 per year. This corresponds to 20 per cent of the cement plant's capacity. The project design phase will be completed in June 2021.

Pilot

EU project LEILAC (Lixhe, Belgium)
HeidelbergCement, Calix
Status: The pilot plant in Lixhe has a production volume of 10 t of cement clinker per hour and was used for the first time in April 2019 (using fossil fuels).

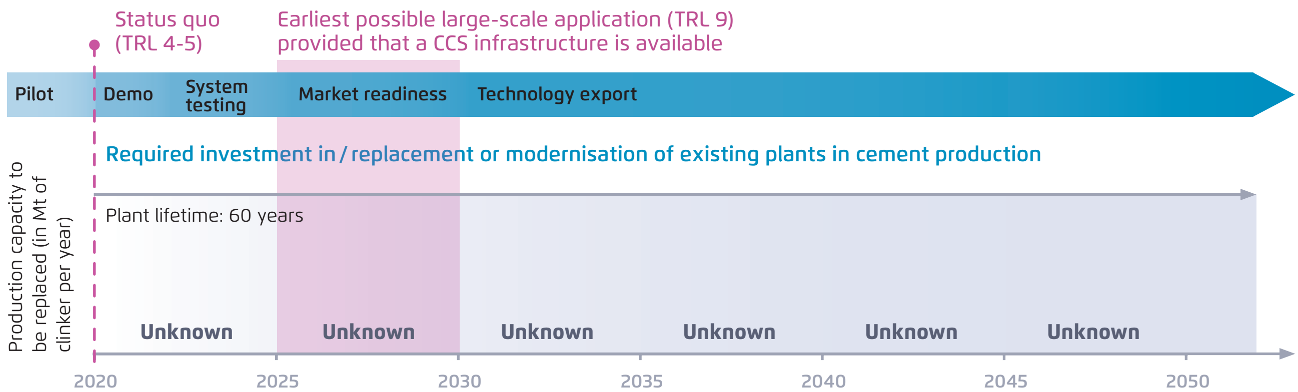
The project, which ran until 2020, had the goal of developing and testing a special calciner. The raw material is indirectly heated and calcinated in a (fossil-fueled or electrically heated) steel vessel. The aim was to show that 240 t of raw material per day can be processed.

Concept

CemZero (Gotland, Sweden)
Cementa/Vattenfall
Status: Energy and mass balance for an electrical cement plant with LEILAC (without CCS).
Outlook: Pilot plant testing for electricity-based cement manufacture (plasma technology).

The focus of the project does not lie on LEILAC but on plasma technology. A recent study produced an energy and mass assessment for a completely electrified cement plant using the LEILAC technology in cement clinker production.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment

By our estimates, the reinvestment requirement in the cement industry by 2030 includes plants with a capacity of approx. 55 Mt of cement clinker per year (approx. 30 per cent of the total capacity). The number was extrapolated from German data in absence of a full site-specific dataset for Europe.

Technology development

If technology develops optimally, the large-scale use (TLR 9) of the LEILAC technology (in the fossil-heated approach) will be possible between 2025 and 2030. The electrically heated system can be available by 2030.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1–9 (TRL 9 = ready for market).

Cement

Technology
Carbon capture and electrification of high-temperature heat for the calciner

Current stage of development
Pilot plants (TRL 4)

Expected readiness for use
2025–2030

Maximum CO_2 reduction in the EU27
2030: **7.4** $MtCO_2$ per year
2050: **88** $MtCO_2$ per year

CO_2 abatement costs
2030: **unknown**
2050: **73–112** €/tCO_2

Renewable electricity and infrastructure requirement
- Electricity requirement of the electrified LEILAC process: 0.54-0.71 MWh per t of cement
- Electricity network expansion, if needed
- CO_2 infrastructure
- Availability of secure CO_2 storage

Possible policy instruments
- Carbon price and border carbon adjustment
- Carbon contracts or CCfDs
- Green public procurement
- Quotas for low-carbon materials
- Reform levies and surcharges

Challenges
The public acceptance of CO_2 transport and storage is uncertain, especially for sites far away from potential offshore storage sites. The electrification of high-temperature heat production demands a significant amount of additional renewable electricity. For 50 per cent of the EU27 cement production (approx. 80 Mt) the electrified LEILAC process with CCS would create an additional electricity requirement of approx. 43–57 TWh.

Evaluation of compatibility with Paris climate agreement
This technology enables the capture or avoidance of approx. 77–80 per cent of total emissions from cement production. When combined with 100 per cent GHG-neutral fuels for rotary kilns, the technology can eliminate a total of 90–93 per cent of emissions. An advantage of electrifying calciners is that they obviate the need for scarce or expensive GHG-neutral fuels (biomass, synthetic methane).

Technologies in comparison

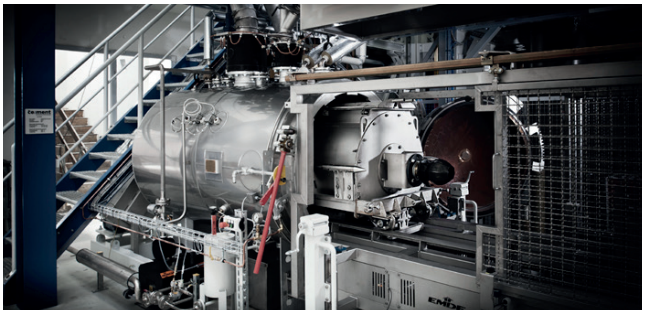
CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Conventional cement manufacturing		**LEILAC with electrification**
0.61 tCO_2/t of cement	-77 to -80 % → Specific emission reduction	**0.12–0.14** tCO_2/t of cement
46 €/t of cement	+74 to +119 % → Specific additional costs	**80–101** €/t of cement

Central assumptions for determining the range of the production costs (2050)

Assumption	Lower range	Upper range
Productions costs for reference cement plants	€ 46/t of cement	€ 46/t of cement
Capital costs of the LEILAC calciner and CO_2 purifying and compression plant	€ 0.8/t of cement	€ 3.8/t of cement
Assumption: CAPEX-LEILAC calciner in addition to regular investment	€ 0	€ 40 million
Assumption: CAPEX-CO_2 purifying and compression plant	€ 9.5 million	€ 9.5 million
Operating costs for electricity use	€ 27/t of cement	€ 42/t of cement
Assumption: Electricity price	€ 50/MWh	€ 60/MWh
Saving of primary fuels through the use of electricity	€ -5/t of cement	€ -5/t of cement
Costs for CO_2 transport and storage	€ 33/tCO_2	€ 38/tCO_2
Production costs of low-carbon cement	**€ 80/t of cement**	**€ 101/t of cement**

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

4.4 Alternative binding agents



Autoclave in the Celitement pilot plant Photo: Markus Breig, ©KIT

Alternative binding agents enable the manufacture of concrete without the use of conventional cement clinker. A lower share of limestone can reduce process-related CO_2 emissions. The production processes of some alternative binding agents are less energy-intense than those of conventional cement. Because the alternative binding agents are in different stages of development and market introduction, future market share, production costs and CO_2 reduction potentials cannot be estimated with certainty.

Pilot and demonstration projects

Pilot

Celitement (Karlsruhe, Germany)
Schwenk Baustoff- Group, KIT
Status: Pilot plant in Karlsruhe in operation since 2011, producing up to 100 kg/day.
Outlook: Industrial reference plant in planning.
CO_2 reduction potential: Up to 50 per cent compared with Portland cement (PLC), whose clinker proportion is greater than 95 per cent.

The Celitement binding agent has nearly the same hydration properties, strength development and final strength as conventional cement. The same raw material can be used in production, but the production process is more complex.

On the market

Solidia Technologies (Piscataway, New Jersey)
Status: Recently entered the market for non-load-carrying components such as paving stones and roofing tiles.
CO_2 reduction potential: 30–70% relative to PLC.

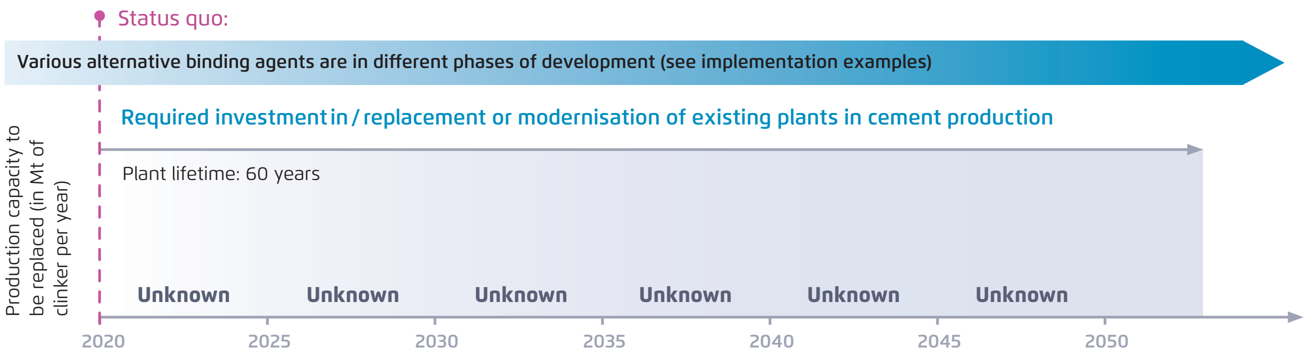
Because the hardening takes place in a CO_2-rich atmosphere and not through contact with water, the products work as a CO_2 sink. But this also means that the technology is primarily suitable for precast elements that are thin enough to be penetrated by CO_2.

On the market

Ternocem (various locations)
HeidelbergCement
Status quo: The EU project EU-Binder successfully produced wall panels in Ternocem.
CO_2 reduction potential: 20–30% compared to PLC.

Ternocem is a cement containing mostly belite and includes more aluminous raw materials and ferrite than Portland cement. Because less limestone is processed, the process CO_2 emissions decrease.

Required reinvestment and earliest possible market readiness of the key low-carbon technology



Required investment

The application of alternative binding agents is currently limited, and will probably remain so in the medium term. Until 2030, a limited amount of cement clinker production could be transferred to the production of alternative binding agents or be replaced by plants that produce them.

Technology development

Alternative binding agents are in different stages of research and development or are in a very early stage of market introduction.

The Technology Readiness Level (TRL) describes the maturity of a technology on a scale from 1–9 (TRL 9 = ready for market).

Cement

Technology
Replacement of conventional cement clinker with alternative binding agents

Current stage of development
Various; depends on product

Expected readiness for use
2020–2030 (depending on product)

Maximum CO_2 reduction in the EU27

2030	2050
unknown	unknown

CO_2 abatement costs

2030	2050
unknown	unknown

Infrastructure requirement
- Far-reaching effects on the infrastructure are not expected

Challenges
The properties of alternative binding agents deviate somewhat from those of conventional cements, which makes extensive tests and standardisation processes necessary. There is still need for research regarding the long term and regional availability of raw materials and their effects on the environment.

Possible policy instruments
- Changes in construction and product standards
- Green public procurement
- Quotas for low-carbon materials
- Carbon price with border carbon adjustment

Evaluation of compatibility with Paris climate agreement
Alternative binding agents represent a non-CCS option for a significant reduction of specific CO_2 emissions (up to 53 per cent) and can be regionally/globally important if CCS cannot be implemented. The high degree of uncertainty regarding future scaling potential, areas of application and market penetration rates is a problem.

Technologies in comparison

CONVENTIONAL TECHNOLOGY		KEY LOW-CARBON TECHNOLOGY
Conventional cement manufacturing		**Alternative binding agents**
0.61 tCO_2/t of cement	in % Specific emission reduction	unknown
46 €/t of cement	in % Specific additional costs	unknown

Costs and cost factors of alternative binding agents

Alternative binding agent	Information on (today's) costs and cost factors
Calcium hydrosilicate binder (e.g. Celitement)	Reduced lime and energy requirement. But the manufacturing process is more complex.
Carbonated calcium silicate (e.g. Solidia)	Costs are comparable with conventional cements.
Belite-ye'elimite-ferrite cements (e.g. Ternocem)	Costs for raw materials lie above those required for Portland cement.
Ye'elimite cements	Commercially available in China for 40 years. Due to the high proportion of aluminium-rich raw materials, more expensive than conventional cements.

Source: Compiled by the Wuppertal Institute based on various sources. (See the reference to the publication in Part E.1).

4.5 End notes and bibliography

List of end notes:

1 Analysis based on E-PRTR, 2017.

2 Calculations by Agora Energiewende/Wuppertal Institute, 2021, based on Eurostat, 2017.

3 Analysis based on Cembureau, 2015.

4 Material Economics, 2019.

5 Cembureau, 2020.

6 With respect to CCU, such approaches only lead to long-term emission reductions when the carbon remains in products over a long time period.

7 Material Economics, 2019. With regard to the direct emissions, the proportion is even higher, as the remaining 6% largely results from the provision of electrical energy (indirect emissions).

8 LEILAC, 2018.

9 See CSI/ECRA, 2017, and Scrivener et al., 2018, for a more extensive description.

10 This produces a CO2 reduction of between roughly 20 per cent and 70 per cent relative to Portland cement (with a clinker content > 95 per cent). This means that a reduction of up to 53 per cent is possible relative to the reference base selected here (cements with a clinker content of 74 per cent). It should be noted that very high reduction potentials are only reported for individual approaches – see the section on Solidia cement in the technology fact sheet – and a large part of this potential for reduction results from special additional processing (i.e., hardening the cement using carbonisation).

11 When using post-combustion technologies such as chemical absorption, no change in the clinker burning process is necessary. Instead, the complete, unchanged exhaust gas is captured, and the CO2 is removed from it.

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