DECARBONISATION PATHWAYS FOR THE EU CEMENT SECTOR

Technology routes and potential ways forward

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Summary of key findings

The EU has, under the *European Green Deal*, committed to achieving greenhouse gas neutrality by 2050 to be in line with the Paris Agreement long-term temperature goal to keep global temperature rise well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit it to 1.5 degrees Celsius. This poses a great challenge for the hard-to-abate industry sectors. The EU cement industry has made progress in the past three decades to reduce its emissions by 15% since 1990. Such reductions have been achieved through the implementation of some well-established mitigation measures, often bringing economic benefits to the producer as a result of fuel savings and raw material efficiency. While acknowledging these improvements, the challenge ahead is substantial. Traditional mitigation potentials such as energy efficiency and fuel switch have, at this point, largely been exploited; yet the EU cement industry has a long way to go to achieve carbon-neutrality by 2050.

Traditional mitigation measures do not target the main emissions associated with cement production which result from the chemical process of limestone calcination in the clinker kiln, accounting for about 60% of emissions. Most mitigation measures to date are directed at energy-related emissions. Targeting process emissions will require the expansive roll-out of some emerging technologies which are not yet technically fully developed or economically feasible in the short- to mid-term.

This study aims to (a) identify and analyse the key emerging technologies and their key barriers, (b) assess the potential of the identified key emerging technologies through a scenario analysis, (c) propose a concept of accelerating *mitigation ambition* based on the results, and (d) derive high level policy recommendations for potential ways forward.

The study develops four different scenarios through a bottom-up modelling exercise: the *reference scenario* (R-S), the *accelerating current technologies scenario* (ACT-S), the *high innovation capture scenario* (HIC-S) and the *high innovation processes scenario* (HIP-S). The R-S serves as a comparative proxy to the three mitigation scenarios. In the ACT-S scenario, the full potential of current commercially available mitigation measures is explored. Lastly, two high innovation scenarios assess the potential of two different technology routes, where each route focusses on one main emerging technology. The HIC-S explores a future highly dependent on carbon capture and use technology (CCS/U), whereas the HIP-S looks at a future less dependent on CCS/U, but more so on alternative innovative practices such as novel cements and new clinker substitutes.

The purpose of such set-up is to analyse the relative potentials of different technology routes, and to identify key aspects to be considered to identify the optimal one. Given the high level of uncertainty in terms of technological development and market penetration of the key emerging technologies, establishing the priorities for the sector at an early stage can help direct investments in research and pilot testing, infrastructure development and raw material supply chains.

The study finds that both high innovation scenarios achieve Paris/near Paris-compatibility by 2050, but the two routes differ in terms of implementation. The HIC-S results in the highest mitigation potential, achieving 92% emission reductions by 2050 compared to a R-S scenario. Correspondingly, the HIP-S scenario reveals similar potential, reaching 88% in the same year. A CCS/U focused route could allow for cement production to continue with current practices but would require substantial infrastructure development alongside uncertainties that come with the technology itself. The HIP-S would mean a complete shift in how cement is being produced – both in terms of technology and supply chains. In addition to that, the technical feasibility of respective technologies remains uncertain. The high innovation scenarios are compared to Paris-compatible benchmarks indicating what would be considered Paris-compatible for the sector. Doing so, a significant gap is revealed in 2030, while Paris, or near-Paris compatibility, is achieved by 2050 (Figure 1).

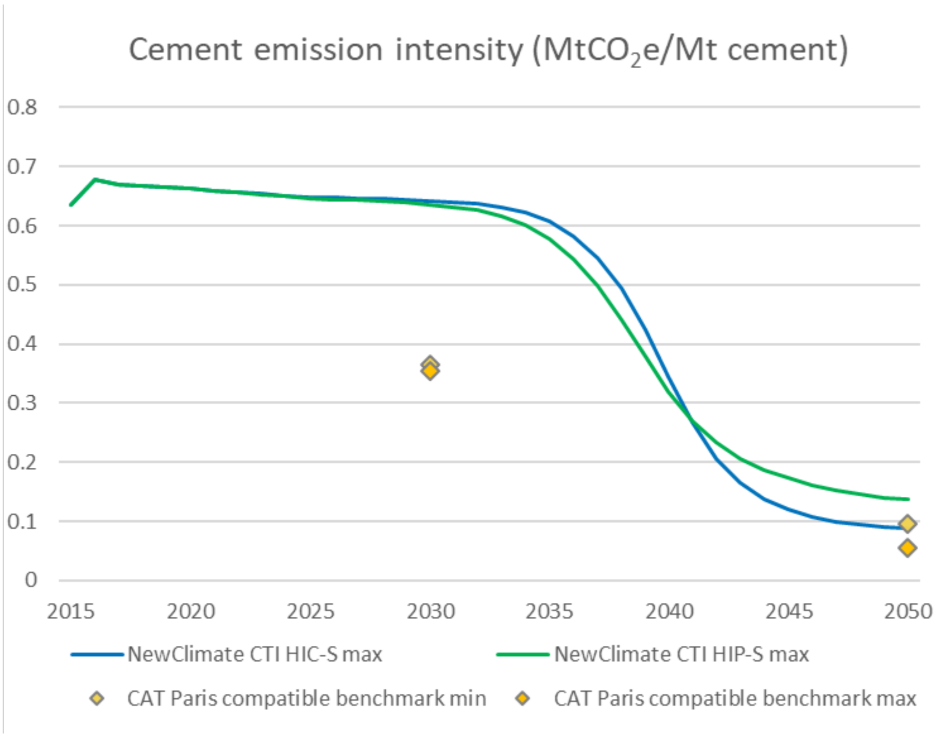

Figure 1. Cement emission intensity ($MtCO_2e$/Mt cement) in the EU cement sector. The graph compares to results of the high innovation scenarios in this study with Paris compatible benchmarks developed by the Climate Action Tracker (CAT) (Climate Action Tracker, 2020).

A noticeable trend that differs from similar studies is the lack of emission reductions in the mid-term (2030). The results show an initial increase in emissions toward 2030 caused by innovative technologies only being introduced after 2030, combined with an overall rise in cement production driven by increasing demand. Based on technology specific assessments, it is judged that the status of development of key emerging technologies will require a ten-year period of pilot-testing and infrastructure development before full roll-out can be expected. That is, albeit technological readiness might be in place, aspects including market maturity and raw materials supply chains development are expected to require time and to delay the full deployment of innovative technologies. For these reasons, a large inconsistency with the 2030 benchmark is obtained, which has a larger focus on technological maturity rather than the creation of an enabling environment (Figure 1).

If novel technologies are to reach the required level of maturity by 2030, urgent action in the near term is needed. To identify an optimal technology route for the decarbonisation of the EU cement sector, the interaction between different technologies and their techno-economic requirements in different regional contexts should be considered. Further, the sufficient allocation and distribution of resources needed for research and development must be ensured. Early policy planning could play an important part in preparing the sector for a rapid and smooth roll-out of technologies once they mature.

Given the limited emission reductions before 2030, this analysis suggests alternative ways to increase ambition and set objectives in that time frame, particularly related to NDC updating processes and long-term strategy (LTS) planning. In the short term (2025), a sector-level dialogue could be initiated where a roadmap for the decarbonization of the EU cement sector could be determined, reflecting the objectives of the European Green Deal. In the mid-term (2030-2035), a further conceptualization of the ambition level could be ensured through a dedicated investment plan in R&D, pilot projects and regulatory adjustments, building on existing and upcoming programmes and initiatives. In the long term (2050) a stringent transformation could happen through the systematic introduction of novel techniques and practices. The latter would require adjustments to the legislative framework, and continuous updates for long-term planning ensuring a common vision between the public and private sectors.

Contents

1 Introduction: The challenge ahead

A tremendous challenge ahead but promising opportunities for international cooperation

The cement sector represents one of the most challenging, *hard-to-abate* sectors in the context of an economy-wide zero-carbon transition. Traditional cement making using clinker emits high levels of process emissions and requires substantial amount of heat, currently predominately provided by carbon-intensive fossil fuels such as coal. No alternative production technologies exist as of 2020 that combine technological maturity and economic cost-competitiveness, while ensuring similar output quality as traditional cement making. Most countries have implemented alternative measures to reduce the primary demand of traditional cement, however only to a very limited extend.

In this context, the European Union's (EU) cement sector faces similar challenges and uncertainties as all countries worldwide. Contrary to other sectors such as electricity supply, no country has so far emerged as an international or regional frontrunner. While this points at the significant challenge ahead, international cooperation and knowledge sharing between countries and private actors become evidently important to accelerate existing efforts to advance the cement sector's decarbonisation. The countries' economic recovery responses to the COVID-19 pandemic might directly impact the sector's development depending on the share of green, low-carbon investments in the sector.

Cement's high density and low product value result in high commodity transport costs and limit its regional and global trade. This lower risk of replacing domestic cement with cheaper foreign products potentially facilitates effective collaboration among public and private actors to develop zero-carbon technologies and practices across borders.

The objective of this study is to contribute to the ongoing policy discussion on the future development of the EU cement sector while identifying options for cooperation and replication in other countries. Specifically, the study has three main aims:

- ✓ The study develops **an analytical framework for assessing different technology routes** towards 2050. The authors use the framework to assess the impact of future technology uptakes over time such as CCS/U or novel cements, starting from the current development stage of key technologies and practices in the EU and worldwide. For this purpose, the authors directly build on relevant literature to apply the analytical framework in the context of the EU's cement sector.
- ✓ The study proposes **a concept of accelerating "*mitigation ambition*"** in the EU's cement sector by 2030 and 2050 considering the sector's challenges, barriers, and uncertainties. This conceptualisation gains particular relevance in the context of both the updating of Nationally Determined Contributions (NDCs) in 2020 as part the 'ratchet mechanism' of the Paris Agreement and the first-time submissions of Long-Term Strategies (LTS) expected in 2020.
- ✓ The study derives high-level **policy recommendations** to approach cement sector planning processes towards 2025, 2030, and 2050 and identifies some options for cooperation between the EU and other countries, as well as private actors.

Methodological approach

The analytical framework explores different scenarios of the EU's cement sector evolution until 2050, accounting for different potential technology routes and respective market penetration over time. The authors develop four stylized scenarios (*Reference*, *Accelerating Current Technologies*, *High Innovation Capture*, and *High Innovation Processes*) building up on existing available literature and best practice case studies (Scrivener, John and Gartner, 2016; ECRA, 2017; EU Calc, 2019; Fleiter *et al.*, 2019; Material Economics, 2019; Cembureau, 2020; Climate Action Tracker, 2020).

The authors use the Climate Transparency Initiative's *2020 CTI Simulation Tool for the European Union* developed by Climate Works Foundation and Climact for the scenario analysis (Pestiaux, J., Lalieu, S., Schobbens, Q., Monteith, S., Plechaty, D., Cronin, C. and Menon, 2020). The CTI is an excel-based bottom-up tool.

The **Methodological annex** to this study provides a more detailed explanation of this study's approach and underlying scenario assumptions.

2 The status quo of the European Union's cement sector

2.1 The landscape of policies and legislation at EU level

The European Commission has released two overarching, interlinked strategies to foster the EU's economy and industrial sectors towards carbon neutrality by 2050: The *Green Deal* released in December 2019 and the *A New Industrial Strategy for Europe* released in March 2020 (European Commission, 2019, 2020a). The former formalizes the ambition for the EU's climate neutrality by mid-century while the latter supports the industry towards this overarching objective. For this purpose, the *Industrial Strategy* lays out several key pillars for the industrial transformation such as digitalisation and large-scale investments in emerging technologies.

In the context of the EU's cement sector, both strategies frame the Commission's approach to industrial policy that consists of regulatory frameworks, financial incentives, and Member States' own industrial targets, strategies and policies as key drivers (Hodges and Woods, 2020). The cohesion between industrial policies in EU Member States however remains incomplete given the lack of competency at the EU level to promote a more uniform industrial policy landscape (Hodges and Woods, 2020).

Several directives and emissions trading regulate some key issues

The European Union has the competency to regulate key areas of industrial production through directives on pollutant emissions from industrial installations (*Industrial Emissions Directive* or 2010), industrial thermal energy use (*Renewable Energy Directive* of 2009, revised in 2018), or reuse, recycling or recovery of construction and demolition waste (*Waste Framework Directive* of 2009). EU Member States transpose these directives and respective minimum requirements into national legislation. Each country remains flexible on how exactly to achieve these minimum requirements and whether to go beyond them.

Besides these directives, the sector is included in the *European Union's Emission Trading System* (EU ETS), the main instrument to drive decarbonisation. The scheme distributes free allocation to industrial installations including cement clinker plants based on CO_2 intensity benchmarks in the ongoing Phase III and forthcoming Phase IV (2021-2030). Installations with higher emission intensities than the allocated free allowances must purchase additional allowances via auctions or from other, more efficient installations. Latest analysis indicates reductions in the cement clinker sector's total emissions over the course of Phase III (2013-2020) (Marcu *et al.*, 2019). Uncertainty remains about whether these reductions have actually been driven by the EU ETS or other factors such as the economic recession in 2008-2009, especially if one considers the cumulative surplus of free allowances for clinker cement installations throughout the entire timeframe.

A range of financing mechanisms will start operation in 2020 and 2021

As for financial incentives, three key mechanisms will shape the EU funding for research and development, demonstration, and roll-out of low-carbon infrastructure over the next decade.

The *Horizon Europe Framework Programme* (2021-2027)[1] represents an EUR 80.9 billion research and innovation programme succeeding Horizon 2020, including a funding focus on 'Low-Carbon and Clean Industry' under the "Digital, Industry and Space" cluster that comprises low-carbon technologies for cement making. Uncertainty remains on the specific budget for the seven-year period given latest discussions to cut its funds from EUR 94.4 billion as proposed by the European Commission in June 2020 in the context of the post-coronavirus economic stimulus plan (Kelly, 2020).

The *Innovation Fund* (2020-2030)[2] financed by EU ETS auction proceeds of up to EUR 10 billion (depending on the carbon price in EU ETS auctions between 2020-2030) supports up to 60% of additional capital and operational costs linked to the demonstration phase of eligible, innovative projects selected in annual calls for proposals. The fund particularly focuses on low-carbon technologies and processes in energy intensive industries such as cement making, including CCS and CCU.

The *Modernisation Fund* (2020-2030)[3], also financed by EU ETS auction proceeds of EUR 6.2-9.3 billion (depending on the carbon price in EU ETS auctions between 2020-2030), fosters the accelerated uptake of low-carbon technologies in ten lower-income EU Member States.

Ambitious member state level action

On a member state level, several countries have set ambitious individual targets and strategies for the decarbonisation of the industry and cement sectors. Sweden aims for carbon-neutral cement to be on the market by 2030, and for it to be used everywhere in the country by 2045 (RISE, 2020). Some key drivers behind such transition will be sustainability requirements on public procurement and an increased public spending on the development of innovative technologies such as CCS and electrification (Cementa, 2018).

As part of the Climate Action Plan 2050, Germany aims to reduce industry emissions by 49-51% by 2030, compared to 1990 levels. To achieve that target, the government will work with the industry to develop a research and development programme aimed at the reduction of process emissions (BMU, 2020). CCS is recognised as a necessity for heavy industries like cement to reach carbon-neutrality by 2050 (Amelang, 2020). Further, through its National hydrogen strategy, Germany aims to establish hydrogen as an alternative energy carrier to achieve decarbonisation in the "hard-to-abate" sectors. Investments in research and capacity building should bring industrial scale solutions by 2030 (German Government, 2020).

2.2 Reference Scenario until 2050: a future locked into high emissions

The Reference Scenario (R-S) presents the expected evolution of the European Union's cement sector assuming the continuation of sectoral trends before the outbreak of the COVID-19 pandemic (pre-COVID). Ongoing improvements in energy efficiency, including the long-term phase out of wet clinker kilns, are expected to continue as a result of existing polices and savings in fuel costs. Modest improvements in fuel switch to alternative fuels and the clinker-to-cement ratio are other advancements considered.

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[1] More information available under: https://ec.europa.eu/info/horizon-europe-next-research-and-innovation-framework-programme_en

[2] More information available under: https://ec.europa.eu/inea/en/innovation-fund

[3] More information available under: https://ec.europa.eu/clima/policies/budget/modernisation-fund_en

The R-S in this study is developed with the purpose to function as a comparative proxy, relative to the explorative scenarios. As such, it does not intend to forecast the impact of existing policies. The *Methodological annex* further explains all underlying modelling assumptions in more detail.

This study makes no attempt to quantify the impact of the COVID-19 pandemic on the EU cement sector in 2020 and beyond. Such quantification remains unsound as of September 2020 given a lack of data, the ongoing dynamic of the pandemic, and general uncertainties in production trends going forward. The following Section provides some indicative analysis on the pandemic's potential impact.

EU's cement sector emissions peak around 2040 due to reduction in cement production

The European cement sector has seen recent progress in terms of CO_2 emission reductions, which have been reduced by 15% since 1990 (Cembureau, 2020). The reductions have been achieved through the implementation of energy efficiency and other commercialised mitigation measures, such as the reduction of the clinker-to-cement ratio, and the increased use of alternative fuels. Much of the potential from those measures has now been harnessed, and although there still is capacity for further improvement, the emission reduction curve has flattened in recent years and has even slightly increased as a result of a growing production. In the R-S, emissions continue to increase and peak in 2038 at 131 $MtCO_2e$/year as shown in Figure 1, followed by a slow and only slight decrease towards 2050 reaching 124 $MtCO_2e$/year. Compared to 2015 levels, that corresponds to an 20% and 14% increase respectively. The rise in emissions leading to 2038 is a result of an increased cement production but is partly offset by some minor improvements in energy efficiency, fuel switch and clinker substitutes. The cement production in the R-S is not affected by any demand-side measures such as material substitution and efficiency and is to a large extent driven by an increase in GDP.

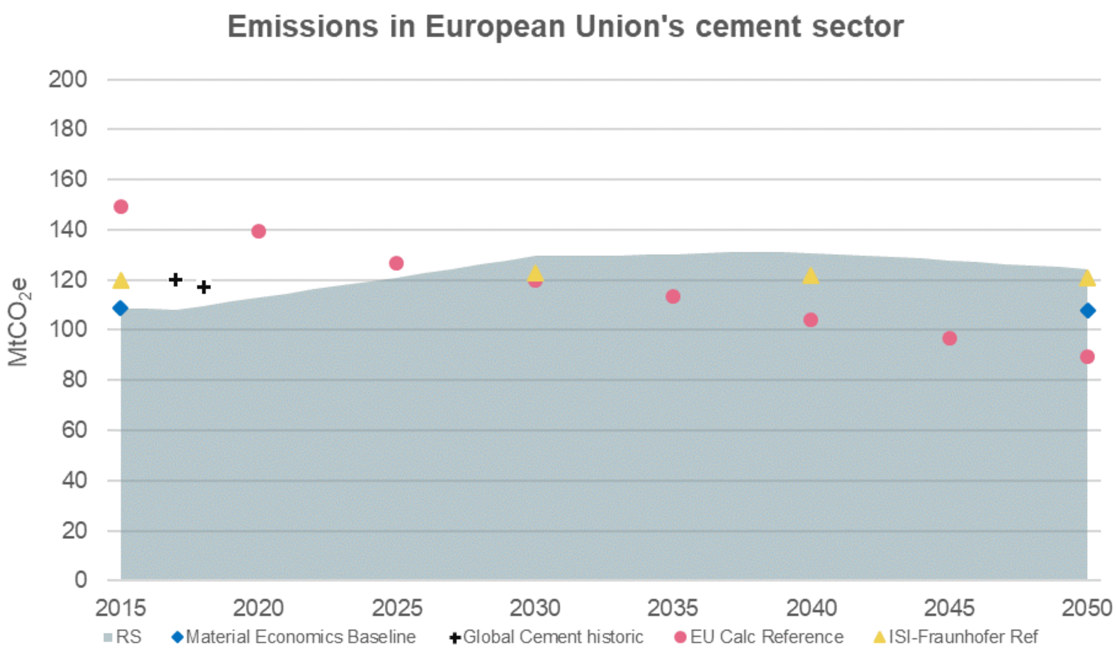

Figure 2: Cement sector emissions calculated in the EU CTI 2020 scenario evaluation tool under a Reference Scenario (R-S) for 2015-2050 before the outbreak of the COVID-19 pandemic (*pre-COVID-19*). Comparison with external data for validation. Note that projections from this analysis does not indirect emissions. Indirect emissions typically account for less then 10% of cement emissions and are not expected to affect the overall trend.

Validation with other literature indicates robustness of obtained results

To validate the results from the R-S modelling, we conduct a comparison with existing literature, using the *EU Calculator* (European Comission, 2016), *Industrial Transformation 2050* (Material Economics, 2019), ISI Fraunhofer *Industrial Innovation: Pathways to deep decarbonisation of Industry* (Fleiter *et al.*, 2019) and historic data from Global Cement (2019b). UNFCCC inventory data for historic emissions has not been used for comparison since the cement sector is not exclusively reported there. Cement emissions from the ISI-Fraunhofer study has been derived from aggregated emissions form the non-metallic mineral industry emission projections, assuming the current share from cement of 63% will remain constant. Corresponding reference scenarios from these studies are compared to the R-S of this study, including their underlying assumptions. Table 1 gives an overview of the major assumptions and characteristics behind the discussed scenarios.

Table 1. Overview of scenario descriptions and main assumptions behind the studies used for validation assessment of the R-S scenario.

Study	Scenario title	Scenario description
EU Calculator	EU Reference	Acts as a benchmark of current policy and market trends. Assumes that the legally binding GHG and RES targets for 2020 will be achieved and that the policies agreed at EU and Member State level until December 2014 will be implemented (developed in 2015-2016)
Material Economics	Baseline	Concrete is specified and used largely as it is today, without any dramatic changes to production. Improvements in cement production techniques.
ISI Fraunhofer	Scenario 1 Ref	Existing technologies and incremental improvements in energy efficiency and fuel switch towards natural gas and some biomass, driven by prices. Slow continuation of past trends regarding recycling. Slow reduction in clinker share. No CCS is considered.
This study	R-S	Energy efficiency improvements, including a 10% increase in efficiency for conventional dry kilns, while wet kilns are phased out by 2050. Modest decrease of the clinker-to-cement ratio and substitution to alternative fuels, including biomass and wastes.

Major inconsistencies are identified with the EU Calculator Reference Scenario, where an overall negative trend in emissions is observed. The inconsistency can be attributed to the underlying cement production projection shown in Figure 2, which is generally lower in the EU Calculator compared to that of this study. The EU Calculator projects cement production levels of 153 Mt in 2030 and 166 Mt in 2050 compared to 197 Mt and 182 Mt projected in this study. It should also be noted that the EU Calculator Reference scenario is somewhat outdated and does not fully capture the most recent trends. The Material Economics study finds a production rate consistent with ours, with production outputs reaching 184 Mt in 2050.

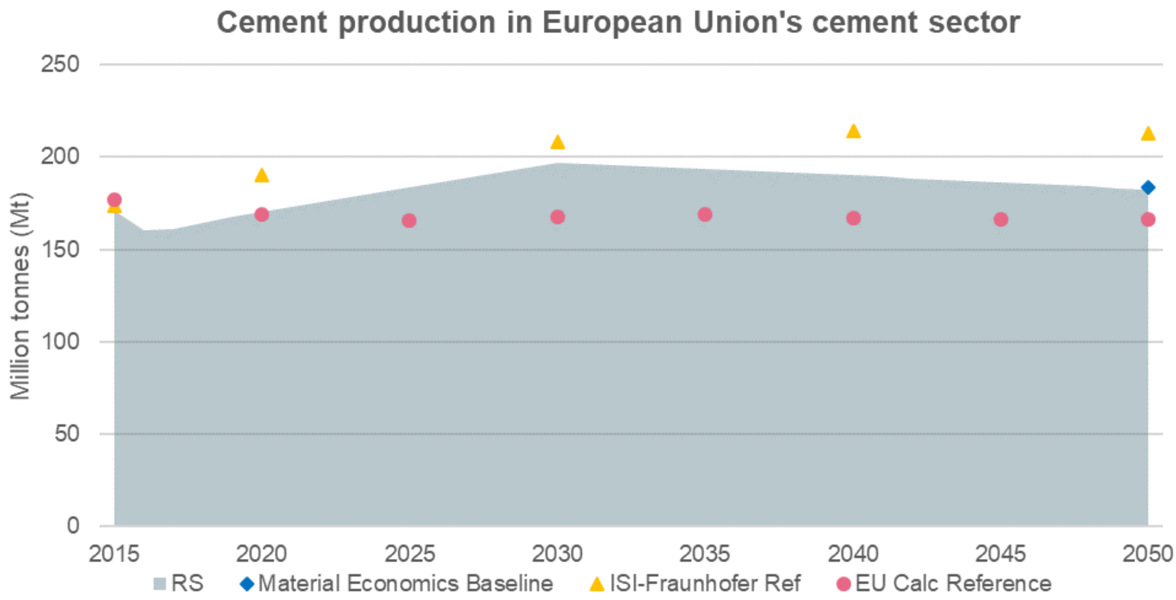

Figure 3. cement production in the European cement sector calculated in the CTI 2020 scenario evaluation tool under a reference scenario (RS) for 2015-2050 before the outbreak of the COVID-19 pandemic (pre-COVID-19). Comparison with external data for validation. Please note that projections from the ISI-Fraunhofer study includes material production from the complete non-metallic minerals industry.

In terms of emissions there is already a discrepancy with the historic data, where the EU Calculator indicates significantly higher values between 2015 and 2020, reasonably due to the exclusion of historic data in that period. Other sources, such as Material Economics and Global Cement, are aligned with the historical values used in this study. Looking forward, this study finds higher emission levels towards 2050 than those of the EU Calculator and Material Economics. Apart from cement production, one explanation behind this is likely the lack of inclusion of existing policies in this study's reference scenario.

The results from the ISI Fraunhofer study are more difficult to directly compare with as the study does not exclusively look at the cement sector but the complete non-metallic minerals sector. As can be expected, those projections are higher than other studies in terms of cement production. In any case, the overall trend is still useful for comparative analysis; the initial growth follows a similar trend as projected in this study. The ISI-Fraunhofer scenario projects a continuous stable production while this study assumes a slight negative growth after the peak toward 2050. In terms of emissions, the contribution from the cement industry has been derived using the current share of 63% of the non-metallic minerals industry, assuming it will stay constant until 2050. Similarly to this study, the ISI-Fraunhofer projections suggest an initial increase in emissions, albeit a more modest one in comparison. Toward 2050, both studies observe an overall comparable negative trend while overall emissions in the ISI-Fraunhofer projections remain slightly lower.

Further, the compared studies have generated scenarios through the application of different models. Variations in the set-up of these models is likely one contributing factor to minor discrepancies in the results.

2.3 The COVID-19 pandemic's impact on the EU's cement sector

Negative short-term impact of COVID-19 pandemic on cement sector with uncertain future ahead

The EU's construction and cement industry — as most sectors of the EU economy — has been negatively impacted by the outbreak of the COVID-19 pandemic in March 2020. The containment measures introduced by European governments in response to the pandemic led to a temporary drop in seasonally adjusted production from March 2020 onward (see Figure 3 below).

High uncertainty remains regarding the short- and medium-term effects of COVID-19 on the European Union's construction and cement sectors going forward. The lasting impact will be determined by the downturn's magnitude due to the ongoing COVID-19 pandemic and the duration of economic recovery influenced by economic stimulus measures to be implemented by European governments.

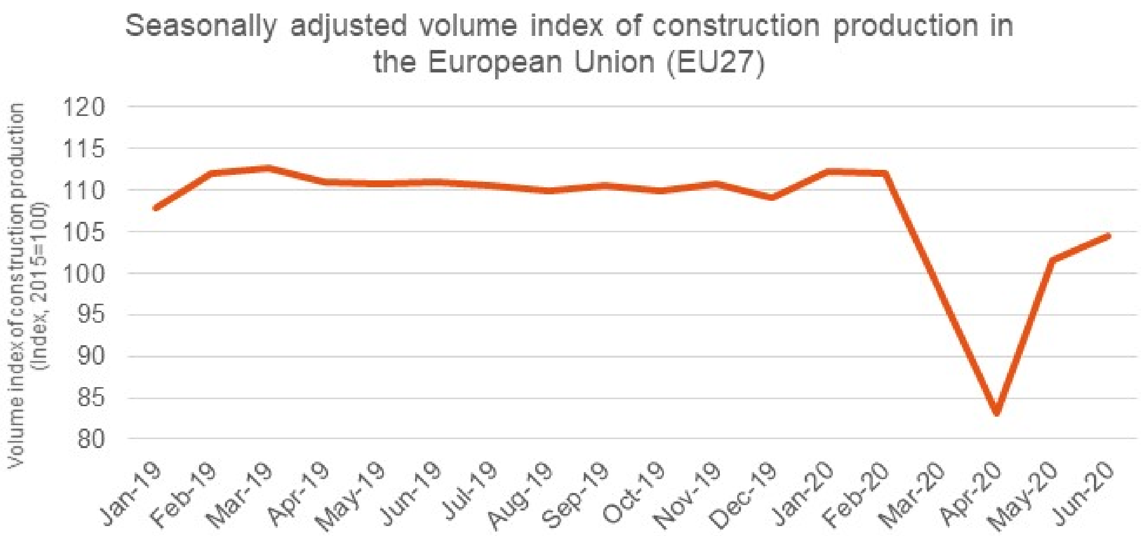

Figure 4: Seasonally adjusted production in the European Union (EU27) construction sector between January 2019 and May 2020 (Eurostat, 2020).

Economic recovery packages will determine longevity of crisis' impact on EU cement sector

Some EU Member States have already announced economic stimulus measures. The design and focus of these measures in construction, infrastructure investments, and R&D might provide incentives for research, development, and piloting in a hard-to-abate sector such as cement and trigger demand for green, low-carbon products and technologies. The overview of economic recovery packages both at the EU and Member State level remains incomplete as of September 2020 as more announcement will be made, hence only allowing for a more comprehensive assessment in the upcoming months.

The COVID-19 pandemic's impact on vital efforts to accelerate the sector's transition towards a low-carbon economy remains uncertain. A prolonged economic downturn might limit the cement industry's financial scope and planning reliability to invest in research and development, pilot testing, and application of new production technologies. At the same time, previous experience after the financial crisis of 2008-2009 shows that cement production and respective emissions can bounce back rapidly after an economic crisis (Peters *et al.*, 2012), thus potentially limiting the negative financial impact on the cement industry in case of a fast economic rebound.

3 Addressing the uncertainty: A framework for the cement sector's pathways analysis

The analytical framework for the long-term scenario analysis of the European Union's cement sector differentiates between an **Accelerating Current Technologies Scenario (ACT-S),** and two high innovation scenarios, namely the **High Innovation Capture Scenario (HIC-S)** and the **High Innovation Processes Scenario (HIP-S)**.

1. **Accelerating Current Technologies Scenario (ACT-S)**
   Ambitious roll-out of technologies, design options, and product specifications that do not require any highly complex or uncertain innovation for traditional cement making processes.
2. **High Innovation Capture Scenario (HIC-S)** with emphasis on **CCS/CCU** and **electrification**
   Highest plausible level of innovation and application of CCS/CCU technologies and electrification of thermal heating supply for traditional cement making processes, while novel cement and new clinker substitutes are only marginally introduced.
3. **High Innovation Processes Scenario (HIP-S)** with emphasis on **novel cement** and **new clinker substitutes**
   Highest plausible level of innovation and application of novel cement and new clinker substitutes for alternative cement making processes, while remaining traditional processes are partially equipped with CCS/CCU and electrified thermal heating supply.

This study differentiates between the HIC-S and the HIP-S to showcase abatement potentials of different technology routes towards 2050. No single technology route can achieve all the necessary emission reductions to realise a cement sector transition to (net) zero-emissions. For this reason, each scenario emphasises one technology route while assuming a smaller-scale uptake of other technology routes.

Further detailed analysis on (1) how the diffusion of different technology routes might interact with each other, (2) on demand-side effects due to changing preferences as part of *1.5°C compatible lifestyles* (for example lower m^2 per capita requirements), and (3) costs of different pathway choices remains outside the scope of this study.

3.1 Accelerating the known: The Accelerating Current Technologies Scenario (ACT-S)

The **Accelerating Current Technologies Scenario (ACT-S)** explores the cement sector's emissions pathway assuming an accelerated roll-out of abatement technologies considered technologically mature and economically feasible in the short to medium term. None of these technologies would require highly complex and uncertain innovation to the traditional cement making processes (e.g. novel cements or carbon capture technologies); however, further development of the different technology choices of this scenario will be necessary to adopt them at high levels throughout the sector. The scenario represents a starting point for the two *High Innovation* scenarios (HIC-S and HIP-S).

3.1.1 Technology options for ACT-S

Four technologies are considered in the ACT-S for which remaining room for improvement is expected:

i. Alternative fuels and sustainable near-zero biofuels
ii. Supplementary cementitious materials such as natural pozzolans and calcined clays
iii. Best Available Technology (BAT) for newly assembled energy efficient cement installations
iv. Material intensity reduction through (a) optimized or alternative design choices, (b) material substitution, and (c) advanced fillers and admixtures

The *Methodological annex* provides further detailed information on lever inputs and assumptions for the scenario modelling.

#1 - Alternative fuels and sustainable near-zero biofuels

Emissions related to the combustion of fuels for thermal energy generation account for about 40% of cement related emissions. By substituting conventionally used fossil fuels with more sustainable fuels such as waste and biomass those emissions can be considerably reduced. Technically, a clinker kiln could be fed with 100% alternative fuels, albeit with some efficiency losses related to heat transfer and increased energy demand for the drying of biomass. The EU cement sector is world leading in terms of alternative fuel substitution rates, with an average substitution rate of about 60%, reaching 95% for individual plants (ECRA, 2017). Current levels thus reveal modest room for improvement. Major barriers include the availability and competitiveness for sustainable biomass. Further, some waste materials commonly used are industrial wastes which contain carbon, meaning that their combustion emits CO_2. Therefore, biogenic wastes such as sewage sludge are preferable from a climate perspective.

In this study, the **European cement sector is assumed to achieve an average substitution rate of 70% by 2040**, with 50% biomass and 20% wastes.

#2 - Supplementary cementitious materials (SCMs) such as natural pozzolans and calcined clays

The current clinker-to-cement ratio in the EU averaged 77% in 2017 (GCCA, 2018). Along with the phase out of coal, traditional SCMs such as fly ash and granulated blast furnace slag, will decrease in supply. In order to maintain and further improve the clinker-to-cement ratio new SCMs should be considered. There are various promising alternatives with differing global and regional availability. Calcined clay and natural pozzolanas are examples of such. Calcined clay is particularly interesting as it is abundantly available and allows for substitution rates up to 50%. However, the level of substitution possible varies with different end-uses of the cement. Another barrier in the EU is the lack of comprehensive and updated standardisation. Standards need to be continuously updated for new SCMs to be efficiently introduced to the market.

In this study, an **average clinker-to-cement ratio of 60%** is expected in the EU cement sector by 2050.

#3 - Best Available Technology (BAT) for newly assembled energy efficient cement installations

The past three decades have seen significant improvement in energy efficiency of clinker kilns, leading to a near complete phase-out of wet kilns in the current EU technology stock. In 2018, almost 50% of the kiln in the EU were dry kilns of BAT standard and only a few percentage wet kilns. Small room is left for improvement, yet **another 12% of energy efficiency is assumed to be achievable by 2040** in this study. That is, based on the current EU average of 3680 MJ/t clinker (2018), which according to ECRA could be improved to 3150-3215 MJ/t clinker in the long term (ECRA, 2017; GCCA, 2018). With regards to the remaining wet kiln stock, that is assumed to be naturally phased-out.

#4 - Material intensity reduction through (1) optimized or alternative design choices, (2) cement and concrete recycling, and (3) advanced fillers and admixtures

Any avoided cement production is the cheapest and most efficient way of reducing emissions. Several demand-side measures are available to reduce the primary demand for cement; Firstly, cement can be substituted with alternative materials such as wood in buildings and recycled concrete in road infrastructure. Secondly, the material intensity can be improved through optimised design and increased use of fillers.

It is assumed that **30% of building materials and road infrastructure could be substituted** with alternative materials by 2050, while **10%-35% of demand could be reduced through smart design** and manufacturing (Scrivener, John and Gartner, 2016; Lehne and Preston, 2018; EU Calc, 2019; Cembureau, 2020).

3.1.2 Key findings of the Accelerating Current Technologies Scenario (ACT-S)

Cement sector emissions could be reduced up to 32% in 2050 compared to a reference baseline

The ACT-S assesses the **mitigation potential that already commercialised technologies and practiced techniques could bring if their full potential is taken advantage of**. As observed in Figure 4, when not considering any demand-side measures (ACT-min), an annual emission reduction of 25% is achieved in 2050, compared to the R-S. When also accounting for material efficiency and substitution potential (ACT-max), an additional 7% annual emission reduction is achieved, reaching 96 and 86 $MtCO_2e$/year respectively.

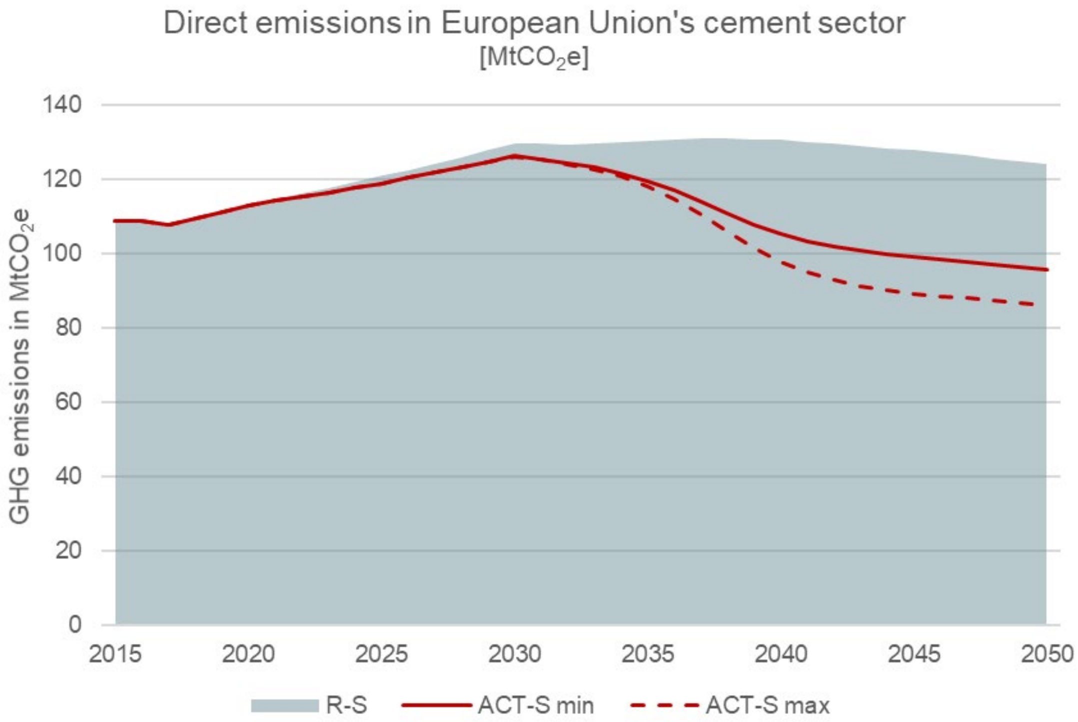

Figure 5: Cement sector emissions calculated in the EU CTI 2020 scenario evaluation tool under an Accelerating Current Technologies Scenario (ACT-S) for 2010-2050.

It is important to highlight that, even though the ACT-S scenario only considers mitigation options already commercially available, its follow-through requires significant efforts and the full roll-out of best available technologies. Further, it requires the remaining non-BAT kiln stock to be refurbished to BAT standards. A natural driver behind such upgrading could be cost savings as a result of less fuel consumption but could be further accelerated with updated energy efficiency standards.

Additionally, it requires improvements in the use of alternative fuels. The alternative fuel use in the EU is comparatively high today but could be further increased while maintaining the same level of production performance. When doing so, it is however important to ensure the sustainability of the alternative fuels used, in particular for biomass.

Several factors make the improvement of the clinker-to-cement ratio challenging. The availability of the traditionally most used supplementary cementitious materials fly ash and blast furnace slag, whose input into the cement-making process lowers the clinker inputs required, will decline along with a coal phase-out. New SCMs such as calcined clay is a promising alternative but comes with barriers. While clay is widely available, its geographic availability varies. Therefore, raw material supply chains must be ensured. In addition, clinker-to-cement ratio standards should be updated to allow cement producers to harness the full potential of new SCMs, which is limited by current standards.

The demand-side measures proposed in this study are not directly attributed to the cement industry itself. The achievement of suggested material efficiency improvements and substitution levels requires proper training of actors along the cement and concrete value chain, including architects, construction workers and infrastructure planners. The technical potential for the recycling of cement and the use of fillers in concrete is somewhat unclear. There is significant potential for improved filler content for certain end-uses of cement. As for recycling, further research should be directed towards the potential of using recycled processed cement in the clinker production process. More generally, the repercussions of any demand-side measures should not be underestimated as reduced production demand may lessen the pressure to pursue the more speculative solutions, which are discussed in the next section.

3.2 Exploring the unknown: The High Innovation Capture Scenario (HIC-S) and the High Innovation Processes Scenario (HIP-S)

The **High Innovation Capture Scenario (HIC-S)** and **High Innovation Processes Scenario (HIP-S)** investigate two diffusion routes of potentially high-impact technologies to reduce the cement sector's emissions by 2050 that are currently still considered technologically immature and economically unfeasible in the medium term.

Given these uncertainties, each of the two scenarios explores a distinct technology route with certain assumptions on the development and diffusion of technologies in the medium- to long-run towards 2050 found in recently published literature (Fleiter *et al.*, 2019; Material Economics, 2019; Cembureau, 2020). In this way, the scenarios transparently reflect a range of perspectives from advocacy, research, and industry representatives.

High Innovation Capture Scenario (HIC-S) **Carbon capture and electrification technologies as key enablers**	High Innovation Processes Scenario (HIP-S) **Novel cement and new clinker substitutes as key enablers**
✓ Scenario builds on the narrative that traditional clinker-based cement production process remains the predominant production technology in foreseeable future ✓ Scenario assumes highest plausible levels of CCS/CCU application to "traditional" cement making processes and comprehensive switch to an electrified thermal energy supply between 2030 and 2050 ✓ Novel cements and new clinker substitutes will be introduced to only a small extent	✓ Scenario builds on narrative that alternative cement production process using novel cements and new clinker substitutes become technologically and economically available for an accelerated deployment after 2030 ✓ Scenario assumes highest plausible levels of novel cements and new clinker substitutes introduced between 2030 and 2050 ✓ Remaining "traditional" cement making processes will be equipped with CCS/CCU and electrified thermal energy supply

3.2.1 Technology options for significant emission abatement in the long run

The HIC-S and HIP-S depend on four key technology options identified in the literature to have transformative potential to abate emissions in the long run towards mid-century:

v. Carbon Capture and Storage/Utilisation (CCS/U)
vi. Electrification and hydrogen for thermal energy supply
vii. Novel cements
viii. New clinker substitutes

Technology-specific overviews in the following provide an introduction to each of these options considering (1) their level of technological maturity, (2) their economic feasibility for wider market diffusion, (3) key barriers for accelerated roll-out, and (4) recent progress in R&D and pilot testing. Each overview further outlines the level of diffusion under each of the two scenarios. The *Methodological annex* provides further detailed information on lever inputs and assumptions for the scenario modelling.

Table 2: Overview of Carbon Capture and Storage/Utilisation (CCS/U) as a technology option, including scenario assumptions for High Innovation Capture Scenario (HIC-S) and High Innovation Processes Scenario (HIP-S)

1	Carbon Capture and Storage/Utilisation (CCS/U)
Technological maturity	• **Early demonstration stage** for CCS/CCU application in clinker and cement production (ECRA, 2017; Fleiter *et al.*, 2019) • **Near zero-emission option** considering that highest achieved capture rate of single applications has been around 90% as of 2020 (Jeffery et al., 2020)
Economic feasibility	• **High projected costs of capture process emissions at full scale** of 50-70 EUR/tonne CO_2 , without including any cost estimates for CO_2 transportation and storage (Hodges and Woods, 2020) • **Other estimates** assume CAPEX investments per tonne CO_2 of 150 EUR in 2030 and 111 EUR in 2050 for capturing processes, as well as 140 EUR in 2030 to 113 EUR in 2050 for transportation and storage (Fleiter *et al.*, 2019) • **Limited opportunity** for CCU due to disadvantageous combinations of product value, increased energy demand from the conversion process and market size of the product (Hodges and Woods, 2020)
Key barriers	• **Transportation and storage** of captured CO_2 critically important for applicability of CCS/CCU technology in cement making process (Jeffery et al., 2020; Cembureau, 2020), for example identification of storage sites in the proximity to cement sites. Further, permanence issues may appear related to the storage of captured CO_2. • **Cabon capturing requires high electricity demand** of 220 kWh/tonne CO_2 (Fleiter *et al.*, 2019), which makes decarbonisation of electricity supply crucial. In some cases, there will also be an increased thermal energy demand (Hodges and Woods, 2020).
Recent progress	• **Several demonstration projects** worldwide and in European Union ✓ Global CCS Institute database list lists seven completed or ongoing CCS pilot projects as of June 2020 worldwide (2x Norway, Belgium, 2x USA, India, China, Canada) (Global CCS Institute, 2020) ✓ Plans for additional plant in Norway with 400,000 tonnes CO_2 captured annually (HeidelbergCement, 2020) • **Several research programmes and consortiums** ongoing such as ✓ catch4climate by four major cement producers to investigate the *Oxyfuel Carbon Capture* technology in the cement production process (HeidelbergCement, 2019) ✓ Westküste100 to investigate the utilization of captured CO_2 form cement making process in Northern Germany to produce low-carbon aviation fuels (Westkueste100, 2020) ✓ CEMCAP project (completed, pilot plant in Norway) and LEILAC project (ongoing, pilot plant in Belgium) funded under Horizon 2020 programme (Jordal, 2015; Leilac, 2020)

High Innovation Capture Scenario (HIC-S) **Carbon capture and electrification technologies as key enablers**	High Innovation Processes Scenario (HIP-S) **Novel cement and new clinker substitutes as key enablers**
✓ Assumption of **76%-85%** of total emission of cement making process in conventional kilns captured for **by 2050** with a **s-curve shaped** phase-in starting **in 2030**	✓ Assumption of range of **33-42%** of total emission of cement making process in conventional kilns captured **by 2060** with a **s-curve shaped** phase-in starting **in 2030**

✓ Assumption of **20%-40%** of total emission of cement making process of novel cements captured **by 2050** with a **s-curve shaped** phase-in starting **in 2030** ✓ Indicator values follow narrative of *3a CCS Scenario* (Fleiter *et al.*, 2019) and the *CCS Scenario* (Material Economics, 2019)	✓ Assumption of **20%** of total emission of cement making process of novel cements captured **by 2060** with a **s-curve shaped** phase-in starting **in 2030** ✓ Indicator values follow narrative of *Unrealistic scenario* (ECRA, 2017) and the *Cementing the Green Deal Scenario* (Cembureau, 2020)

Table 3: Overview of electrification and hydrogen for thermal energy supply as a technology option, incl. scenario assumptions for High Innovation Capture Scenario (HIC-S) and High Innovation Processes Scenario (HIP-S)

2	**Electricity** and **hydrogen for thermal energy supply**
Technological maturity	• **Early demonstration stage** for plasma torches in clinker manufacture (Hodges and Woods, 2020) • **Several technological barriers** such as short operating life of the torch, difficulty with reproducing conditions and lack of reliability of electric power sources (Hodges and Woods, 2020)
Economic feasibility	• Future feasibility dependent on electricity/hydrogen prices • Current pilots show doubling of production costs for cement, although this ultimately entails only ~2% increase of finished infrastructure (Vattenfall, 2019)
Key barriers	• Use of plasma torches in clinker manufacture would require substantial refurbishment of existing kilns (Energy Transitions Commission, 2019) • Technical considerations of hydrogen's heating capabilities • Current cost of technology
Recent progress	• **Several demonstration projects** worldwide and in European Union ✓ Vattenfall/Cementa electrification pilot showed promise in 2017, resulting in investigations (started in January 2019) to build a pilot plant ✓ Solar Reactor in France showed promise and is moving to a demo-scale project for 1-5 ton/day with potential application for cement industry • **Several programmes and consortiums** continue to fund research and pilots, such as: ✓ SOLPART is looking to substitute fossil fuels with concentrated solar power, funded by Horizon 2020 program (SolPart, 2017) ✓ UK Department for Business, Energy and Industrial Strategy is providing GBP 90 million for Hydrogen and fuel-switching projects, including the Mineral Products Association pilots in the cement sector (UK Government, 2020)

High Innovation Capture Scenario (HIC-S)	High Innovation Processes Scenario (HIP-S)
Carbon capture and electrification technologies as key enablers	**Novel cement and new clinker substitutes as key enablers**

✓ Assumption of **9%** of thermal electrification **by 2060** with a **s-curve shaped** phase-in starting **in 2030** ✓ Assumption of **1%** of the thermal supply from hydrogen **by 2060** with a **s-curve shaped** phase-in starting **in 2030** ✓ Indicator values follow narrative of *Cementing the Green Deal Scenario* (Cembureau, 2020)	✓ Assumption of **17-26**% of thermal electrification **by 2050** with a **s-curve shaped** phase-in starting **in 2030** ✓ Assumption of **3-5**% of thermal supply from hydrogen **by 2050** with a **s-curve shaped** phase-in starting **in 2030** ✓ Indicator values follow narrative of the range of *Ambition Level 3* and *Ambition Level 4* in the EU Calculator (EUCALC, 2019)

Table 4: Overview of novel cement as a technology option, including scenario assumptions for High Innovation Capture Scenario (HIC-S) and High Innovation Processes Scenario (HIP-S)

3	Novel cement
Technological maturity	• **Few novel cements** have been commercialized despite significant R&D undertaken given barriers such as raw materials supply, cost-effectiveness, lack of customer demand for low-carbon cements and regulations that are unbeneficial for any cements that are competitive to traditional cements (Lehne and Preston, 2018) • **Small and medium-size producers** specialized in development novel cements (could) play a vital part in introducing new low-carbon techniques to major producers (Lehne and Preston, 2018)
Economic feasibility	• Fuel savings and be achieved, although material availability, scale and other barriers can also increase costs • Carbon prices can influence the overall feasibility of novel and low-carbon cements (Rootzén and Johnsson, 2017; Marco Kisic, Carole Ferguson, Christie Clarke, 2018) Economic perspectives from some novel cement types (Lehne and Preston, 2018): • Geopolymers and alkali-activated binders ✓ Cost competitive in some contexts • Belite-rich Portland cements (BPC) ✓ Retrofit costs ≈ EUR 0-12 Million ✓ Increased operational costs of EUR 2-3.8/ton of cement • Belitic clinkers containing ye'elimite (CSA) ✓ Increased material costs compared to traditional cement • Low-carbonate clinker with pre-hydrated calcium silicates and carbonatable calcium silicate clinkers ✓ Similar costs as for traditional cement • Magnesium-based cements ✓ No manufacturing process has yet been established. The cost aspect is too early to assess
Key barriers	• **Revision and standardization** of product standards by respective bodies (Lehne and Preston, 2018) • **Access to** raw materials (Scrivener, John and Gartner, 2016) • **Accelerating demand** for novel and low-carbon cements, for example through green public procurement such as the upcoming EU Sustainable Product Policy (The European Commission, 2018) • **Market acceptance,** as actual and/or perceived lack of performance and reliability might limit uptake for some applications (Harvey, 2018)
Recent progress	• **Several demonstration projects** worldwide and in European Union ✓ Pilot plant in Germany for new hydraulic binders as part of the Celitement collaboration between academia and industry (Joppig, 2020) ✓ Aether project conducted pilot tests ICiMB in Poland and two industrial trials in France with funding under Sustainable Industry Low Carbon Scheme (SILC) (the European Commission, 2014; Walenta, 2014) • **Several research programmes and consortiums** ongoing such as ✓ Nanocem research network by academia and industry initiatives such as ERICA project funded by Horizon 2020 (Nanocem, 2014; ERICA, 2019) ✓ ECO-Binder project funded under Horizon 2020 programme to develop Belite Ye'elimite-Ferrite (BYF) as a substitute for Portland cement (OPC) (EU Build up, 2015)

High Innovation Capture Scenario (HIC-S) **Carbon capture and electrification technologies as key enablers**	High Innovation Processes Scenario (HIP-S) **Novel cement and new clinker substitutes as key enablers**
✓ Assumption of **10%** of novel cements in total cement production **by 2060** with a **s-curve shaped** phase-in starting **in 2030** ✓ Indicator values follow narrative of *Ambition Level 3* in the EU Calculator (EUCALC, 2019)	✓ Assumption of **20-50%** of novel cements in total cement production **by 2050** with a **s-curve shaped** phase-in starting **in 2030** ✓ Indicator values follow narrative of *Ambition Level 4* in the EU Calculator (EUCALC, 2019) and *3b CleanGas* and the *3d Electric scenario* (Fleiter *et al.*, 2019)

Table 5: Overview of new clinker substitutes as a technology option, including scenario assumptions for High Innovation Capture Scenario (HIC-S) and High Innovation Processes Scenario (HIP-S)

4	New clinker substitutes, supplementary cementitious materials (SCMs)
Technological maturity	• Various SCMs available including natural pozzolanas, calcined clays, vegetable ashes and other reactive products • Requirement of thermal heat for activation, no supplementary equipment required • Ongoing research to reprocess recycled cement to be reused as an SCM
Economic feasibility	• Fuel saving costs through the reduced clinker demand replaced by SCMs • **Operational costs could decrease by EUR 3.1/t of cement** with calcined clays, while retrofit costs would range between EUR 8-12 Million – potentially higher with pre-processing of calcined clays and natural pozzolans (Lehne and Preston, 2018). • Transportation and extraction may lead to increased costs depending on resource accessibility and availability
Key barriers	• Low clinker-to-cement ratios may only be **applicable to some end-uses.** High blend cements commonly have low early strength, but superior durability in the longer term (Lehne and Preston, 2018) • **Seasonal and geographical** availability of raw materials • **Limited globally availability** of raw material, except for the case of clays • For some raw materials, the **presence of contaminants** can be an issue • Existence of **competitive uses**, particularly for vegetable ashes • **Cement standards** must be updated timely for new substitutes to be able to be used • Market acceptance
Recent progress	• **LC3 cement (calcined clays co-substituted with limestone)** ✓ First commercial production site put into operation in Colombia in 2020 (Edwards, 2020) ✓ Demonstration projects in Switzerland, India and Cuba (LC3, 2020) • **Several research programmes and consortiums** ongoing such as ✓ Ongoing research is looking at the potential of recycling cement and extract cementitious material based on electrodynamic fragmentation (TU Delft, 2013)

High Innovation Capture Scenario (HIC-S) **Carbon capture and electrification technologies as key enablers**	High Innovation Processes Scenario (HIP-S) **Novel cement and new clinker substitutes as key enablers**
✓ A modest increase in calcined clays production combined with other new supplementary materials results in a decreased clinker-to-cement ratio of **60%** on average **by 2050** with a **s-curve shaped** phase-in starting **in 2025** (*same as in Ambitious Development Scenario*). ✓ Indicator values follow narrative of assumptions/considerations by projections by ECRA (ECRA, 2017), Material Economics (2019) and UNEP (2016).	✓ Followed by successful calcined clay diffusion, a clinker-to-cement ration between **50-55**% is achieved **by 2050** with a **s-curve shaped** phase-in starting **in 2025**. ✓ Indicator values follow narrative of assumptions/considerations by projections by ECRA (ECRA, 2017)

3.2.2 Key findings of High Innovation scenarios (HIC-S and HIP-S)

Reduction potential of up to 92% below the R-S in 2050 emphasising carbon capturing

The High Innovation Capture Scenario (HIC-S) reveals the highest emission reduction potential of the three scenarios. Some 88-92% of emission reductions are achieved by 2050 compared to the R-S, which corresponds to emission levels of 10-16 $MtCO_2e$/year in 2050. Harnessing such potential would require unprecedented effort in terms of technology development, where all conventional clinker kilns are equipped with CCS.

The diffusion of CCS is not the only barrier attributed to the technology, there are also uncertainties with regard to its technical potential. The remaining emissions in 2050 in HIC-S is the result of a non-100% capture rate by the CCS technology. The relatively low CO_2 concentration in the clinker kiln exhaust gas makes it more challenging and expensive to capture. Ongoing research is being conducted looking at possibilities to use oxy-fuel technology to achieve a high CO_2 concentration in the exhaust gas.

For CCS to be successful, it also requires the development of an infrastructure network for the transportation of the captured CO_2, as well as the identification of CO_2 storage sites, which may be challenging in certain geographies. It is therefore necessary for the proper planning of such networks and the identification of potential storage sites to start sooner rather than later.

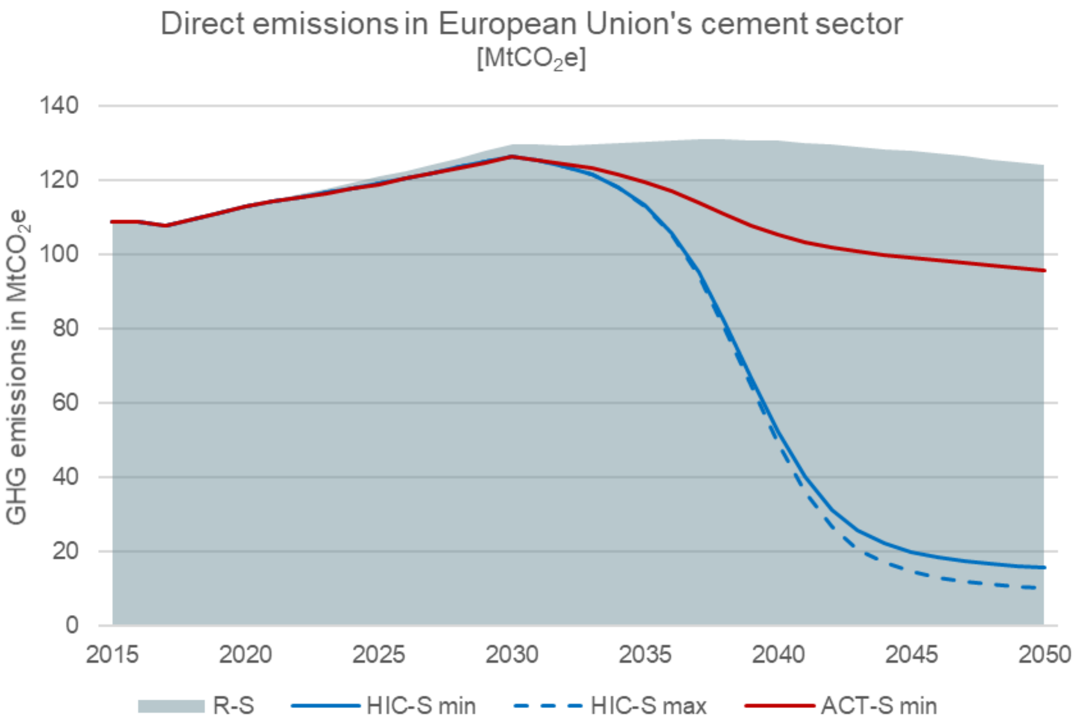

Figure 6: Cement sector direct emissions calculated in the EU CTI 2020 scenario evaluation tool under a High Innovation Capture Scenario (HIC-S) for 2010-2050 with carbon capture and electrification technologies as key enablers.

Reduction potential of up to 88% below the R-S in 2050 emphasising alternative processes

The High Innovation Processes Scenario (HIP-S) reaches the lower bound of the HIC-S under its most generous set of assumptions. Some 80-88% of emission reductions are achieved by 2050 compared to the R-S, corresponding to emission levels of 16-25 $MtCO_2e$/year in 2050. Due to the uncertainties in how much could be expected from novel cements in an optimistic scenario, in terms of technological potential as well as market enabling conditions, the min and max range differ quite significantly in HIP-S. In the more optimistic case, half of the conventional cement production is replaced by alternative binders while only 20% does so in the less optimistic case.

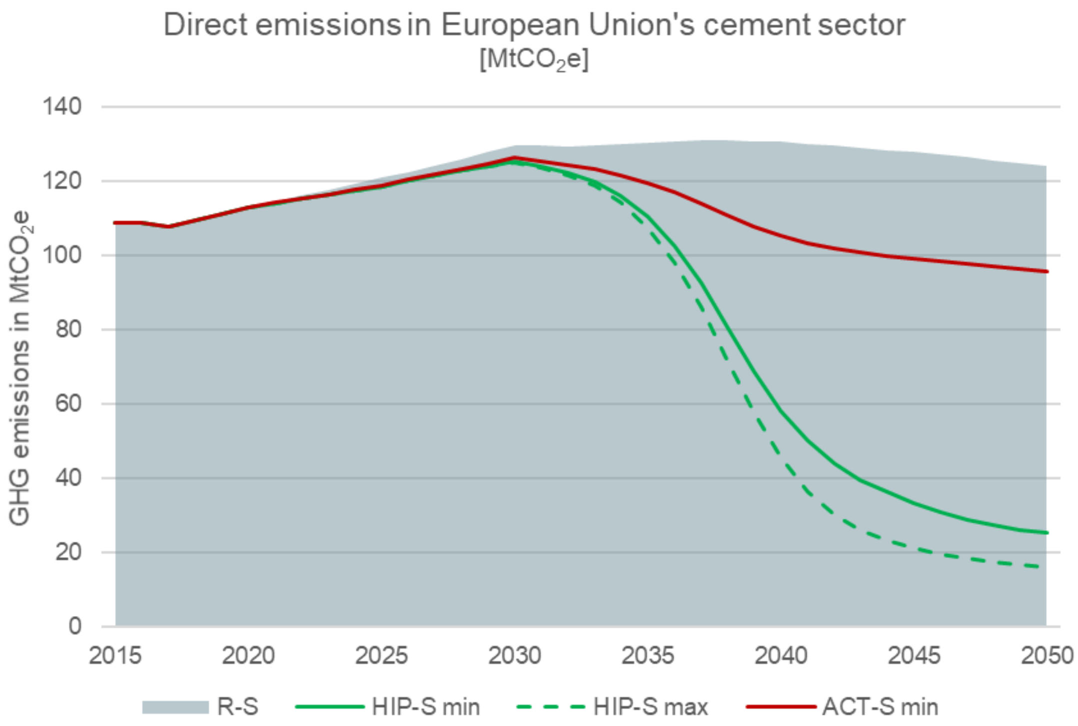

Figure 7: Cement sector direct emissions calculated in the EU CTI 2020 scenario evaluation tool under a High Innovation Processes Scenario (HIP-S) for 2010-2050 with novel cement and new clinker substitutes as key enablers.

From the wide range of alternative cements being researched, some are already close to commercialisation while others are in an early research phase. A major barrier for some of these is the availability of raw materials, which differs significantly depending on the location of the cement production. For a smooth market integration to take place it is vital to develop raw material supply chains for these. It is therefore important to assess raw material availability and standardisation at an early stage.

The electrification of the thermal energy mix is another speculative area in terms of market diffusion. The high temperature required for clinker production would put significant pressure on the clean electricity production in terms of rising demand, while being a relatively expensive technology. However, as novel cements production processes typically require lower temperatures, electrification could be a viable option. To reach carbon neutrality for conventional cement, any decarbonisation of the thermal energy mix would still need to be combined with CCS to target process emissions.

Cement and concrete are a low-value product which presents a challenge to make low-carbon cements competitive to conventional cements. A high price on carbon will therefore be a prerequisite to catalyse the roll-out of low-carbon technologies discussed in this study and to reach the penetration rates suggested in our pathways.

Exploring implications of prolonged implementation timeframe (2030-2060)

As discussed in the previous section, the proposed scenario pathways presented in this study are dependent on the successful development and market penetration of a set of key emerging technologies. Given the high uncertainty on the timing of such speculative technologies, which are subject to a wide set of external parameters, we conduct a simple sensitivity analysis to analyse the implications of a 10-year delay of the roll-out of our assumptions. Figure 7 demonstrates how such a delay could look like, leaving a notable emissions gap.

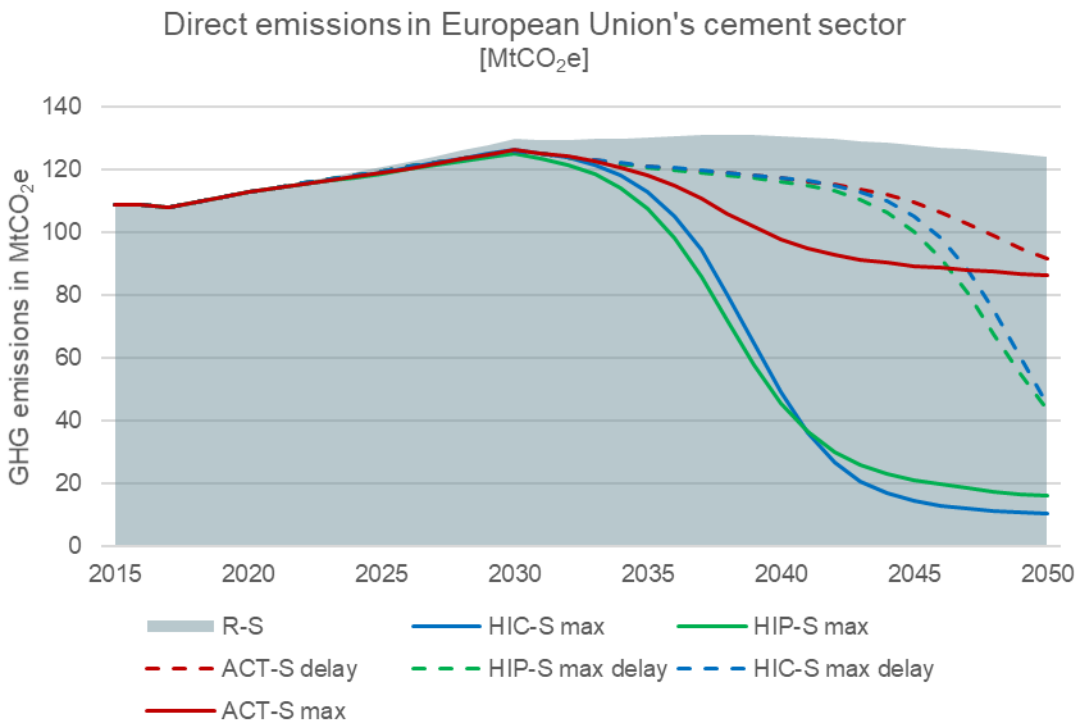

Figure 8: Sensitivity analysis on all scenarios with a 10-year time delay for the implementation of mitigation options (form 20-years between 2030-2050 to 30-years between 2030-2060).

One can think of various external disturbances which may affect the timing of the mitigation measures proposed in our pathways. The ongoing COVID-19 pandemic is one example of such. A severely slowed down economy could result in less investments available for research and development in a more cautious financial environment if economic rescue plans are not strategically planned.

A ten-year delay would still allow for substantial reductions in terms of annual emissions by 2050. However, in terms of aggregated emissions, such delay would lead to only modest emission reductions in the cement sector until 2045, eating into the already small remaining global GHG budget.

4 Discussion and the way forward

This section discusses the implications of the research findings from earlier sections. The results are validated, using other similar projections found in the literature. The Paris compatibility of the results is measured and discussed. Co-benefit aspects of the cement industry are brought up and discussed in light of key emerging technologies. In addition, some areas of future research are suggested.

Lastly, a way forward to set objectives in the short-, mid- and long-term is suggested. Given the limitations in emission reductions before 2030 proposed in this analysis, alternative ways to increase ambition and set objectives in that time frame are analysed; in particular related to NDC updating processes and Long-Term Strategy (LTS) planning.

4.1 Implications of the research findings

Given the different character and design of models used for projections, the results from this study are validated and compared with similar scenario analyses found in the literature. Each of our mitigation scenarios, ACT-S, HIC-S and HIP-S are compared in terms of aggregated emissions and cement production. Apart from the choice of model, variations in assumptions and scenario build-up lead to different results.

By deriving the emission intensity from the aggregated emissions and the cement production, the Paris compatibility of our high innovation scenarios is gauged by comparing results with Paris-compatible emission intensity benchmarks developed by the Climate Action Tracker (CAT) (Climate Action Tracker, 2020).

Realistic expectations from a decarbonisation route: Different perspectives

One outstanding observation from the comparative analysis is the introductory increase in emissions and cement production in the first 15-20 years of the scenarios in this analysis. In contrast, other scenarios in the literature show an immediate, more linear negative growth in Figure 8 and Figure 9.

The positive growth in the scenarios of this study can be explained by two main factors. Firstly, and as previously discussed, many of our mitigation measures and in particular those related to innovative technologies are introduced only in 2030, followed by an s-shaped market introduction. Several barriers are identified (section 3.1.4) for these mitigation measures to mature and reach commercialisation. Based on this, we find it more realistic to assume a slight delay in market introduction which explains the inconsistencies between the projections in this study and other studies in the 2030-2040 period. Once actually commercialised, it is however assumed that the expansion will ramp up rather intensively. The level of consensus in terms of 2050 emission levels is fairly high, in particular in the more ambitious scenarios.

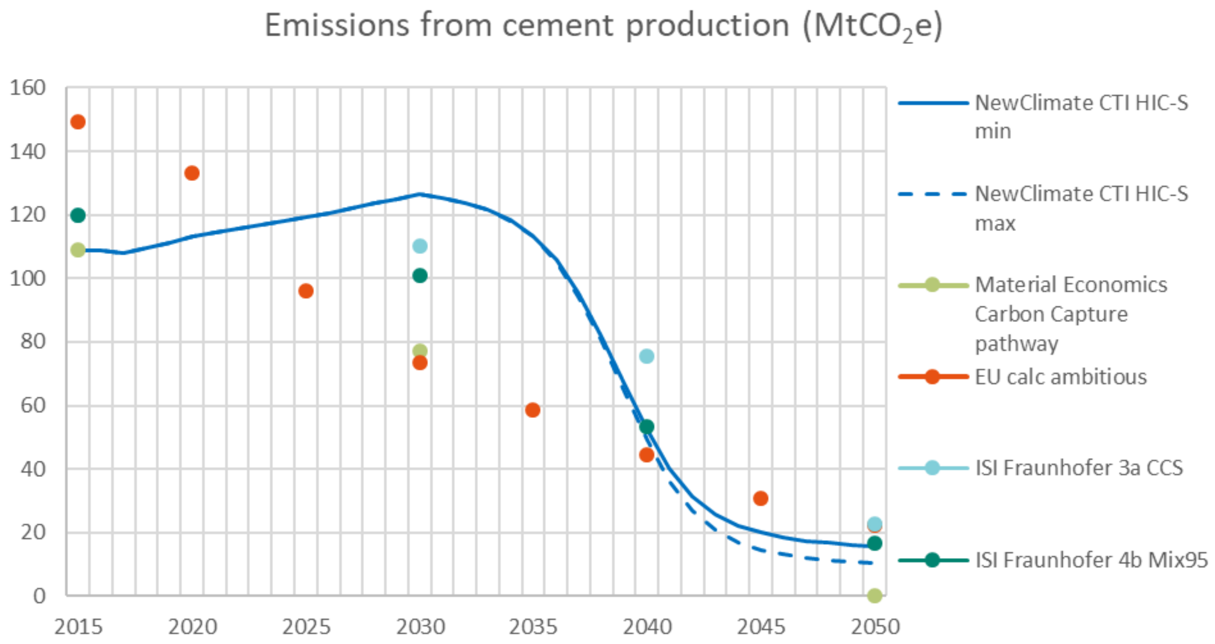

Figure 9. Comparison of the HIC-S with similar projections in the literature, in terms of emissions from cement production. Note that projections from the ISI-Fraunhofer study includes material production from the complete non-metallic minerals industry.

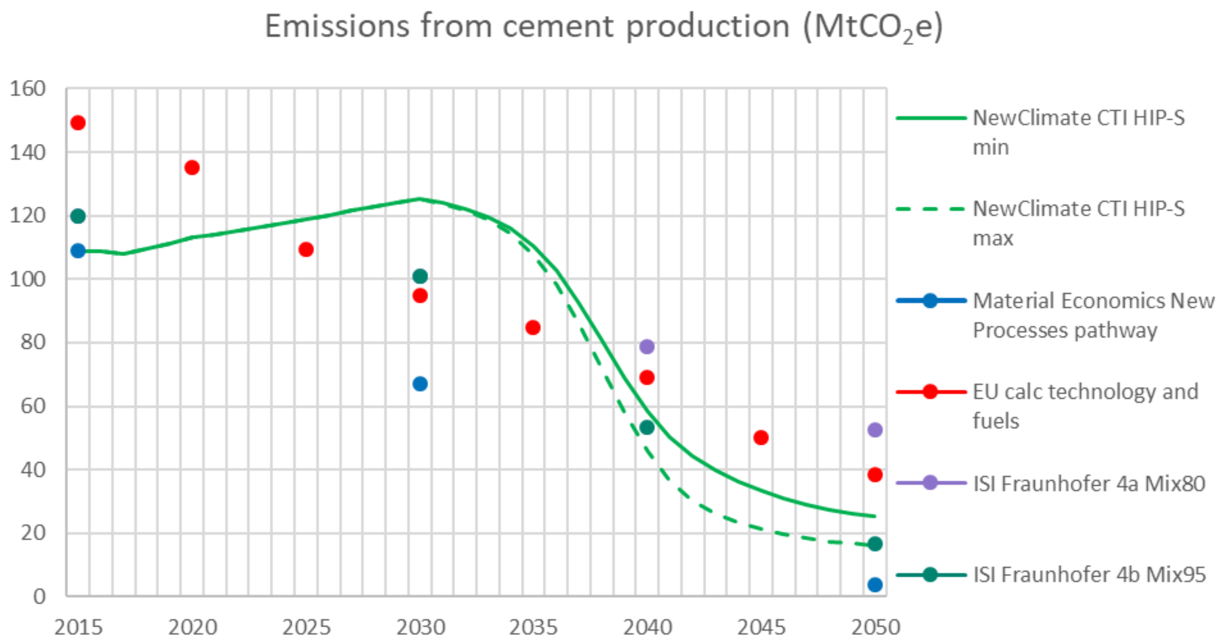

Figure 10. Comparison of the HIP-S with similar projections in the literature, in terms of emissions from cement production. Note that projections from the ISI-Fraunhofer study includes material production from the complete non-metallic minerals industry.

Secondly, the cement production is clearly a key driving factor behind the increase in aggregate emissions. An initial trend can be observed in this study regarding cement production, which is not aligned with other scenarios in the literature - despite demand-side measures introduced in mid-2020. Arguably, this is a result of variations in the model set-up of demand growth projections, which in CTI is strongly linked to GDP-growth. Looking at the larger picture, the overall negative trend followed by the implementation of demand-side measures towards 2050 seems to be aligned with other ambitious scenarios.

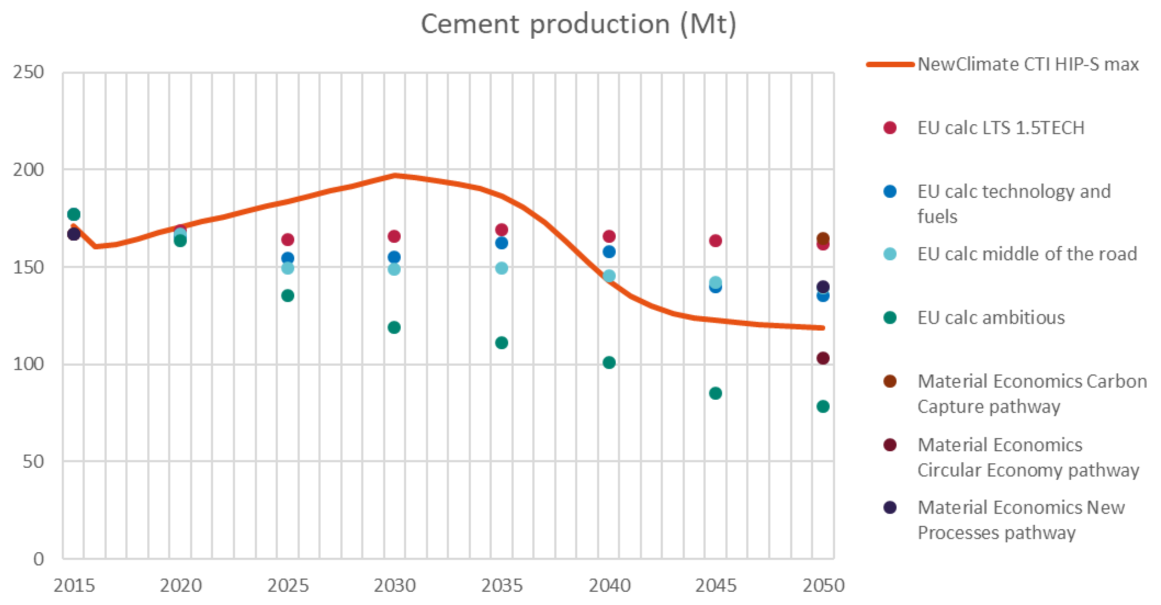

Figure 11. Comparison of the production of cement used in this study compared to other projections in the literature.

Taking stock of the Paris compatibility: Benchmark comparison

Lastly, the Paris compatibility of the high innovation scenarios is assessed by comparing the derived emission intensities with Paris-compatible benchmarks for 2030 and 2050. Given the delayed introduction of key innovation technologies suggested in this study, the high innovation scenarios do not achieve Paris compatibility by 2030. The comparative analysis (Figure 12) suggests an almost 10-year delay at this point in time, in contrast to the benchmarks and other scenarios used for comparison. We suggest careful consideration of the time required for planning, implementation of new regulations and infrastructure development to enable a rapid roll-out of innovative technologies at a later stage. That is, albeit technological readiness might be in place, aspects including market maturity and raw materials supply chains development are expected to require time and to delay the full deployment of innovative technologies. For these reasons, a large inconsistency with the 2030 benchmark is obtained, which to a larger extent have been based on technological maturity rather than the creation of an enabling environment. In the short term, ambition efforts should therefore be concentrated on the identification of an optimal technology route and the associated requirements in terms of development and regulative planning.

Despite differences in technology routes, our two high innovation scenarios show similar Paris compatibility in terms of emission levels by 2050 but may differ significantly in terms of execution. A CCS focused route could allow for production to remain similar to current techniques but would require massive infrastructure development. The HIP-S would mean a complete shift in how cement is being produced – both in terms of technologies and supply chains.

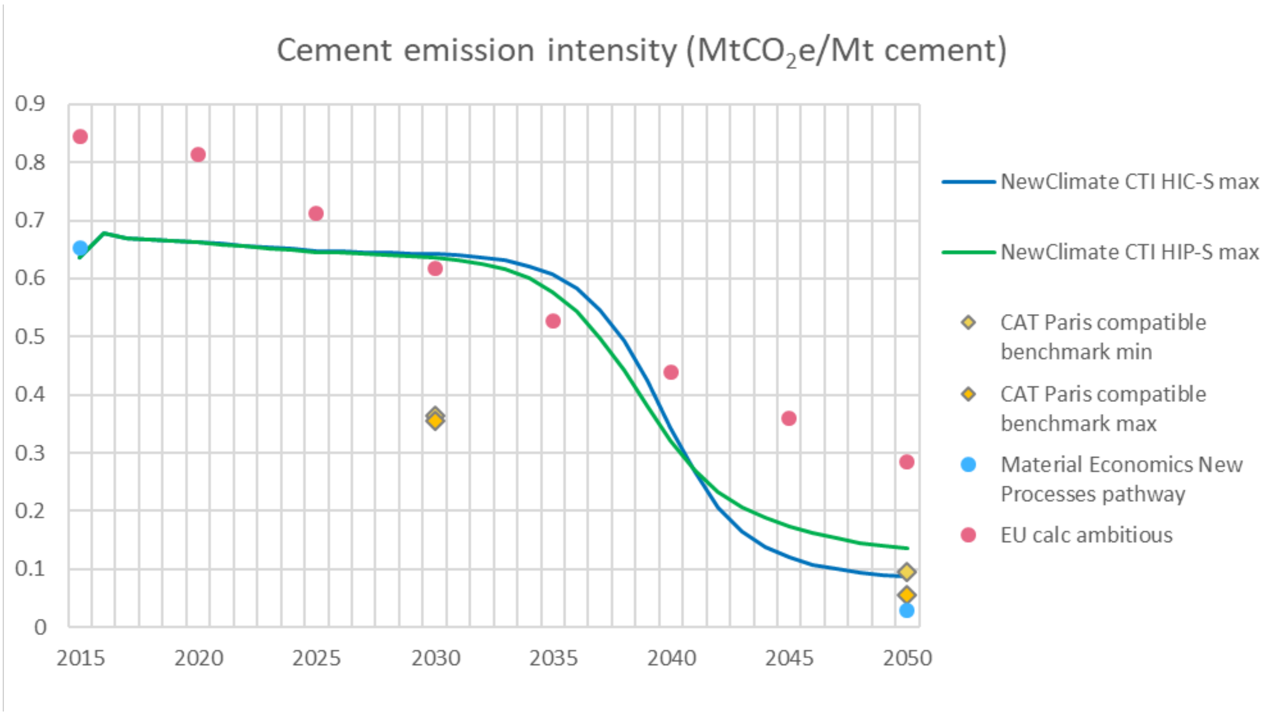

Figure 12. Validation of the Paris compatibility of the scenarios developed in this study, using Paris-compatible emission intensity benchmarks developed by the Climate Action Tracker (CAT). Despite differences in technology routes, our two high innovation scenarios propose how, similar different have comparable ability to achieve Paris compatibility in terms of emission levels by 2050 but may differ significantly in terms of execution.

The level of uncertainty related to the technological success of the key mitigation technologies proposed in this study, in particular CCS, alternative binders and electric/hydrogen clinker kilns, demonstrates the need for research and development and for the sufficient allocation and distribution of necessary resources. It is therefore important to carefully analyse the interaction between different technologies and their requirements in terms of regional context. Such requirements could be related to raw material supply and transportation needs, clean power demand and supply and the end-uses of cement in certain areas. By doing so, synergies and trade-offs can be identified to facilitate decision processes related to investments and regulations. It could also inform early policy planning to ensure rapid and smooth roll-out of technologies once mature. Looking beyond the cement industry, action from actors along the concrete value chain will be required to achieve improved material efficiency. Public procurement could also have a catalysing effect to drive demand for low-carbon cements.

The co-benefits aspect of the decarbonisation of the cement industry

In addition to the climate related benefits that would follow the implementation of the mitigation measures proposed in this study, a set of co-benefits related to the environmental and human health, as well as economic aspects could be achieved.

The conventional production of cement typically emits pollutants from thermal energy generation and indirectly from electricity generation and in the manufacturing process. The main air pollutants from these processes include nitrogen oxides (NO_X), sulphur dioxide (SO_2), carbon monoxide (CO) and particulate matters (PM_s). PM_s typically stem from manufacturing processes while other gases are generated in the thermal energy production process (Atamaleki *et al.*, 2019).

Direct emissions from the thermal energy generation would be reduced as a result of energy efficiency measures, which would lead to lower amounts of fossil fuels being combusted. Direct emissions could be further improved by switching to cleaner fuels - in particular to clean electricity and green hydrogen. While a switch to biomass and wastes indeed could have positive effects on the climate impact, the combustion of these would still generate polluting gases. Thus, a complete electrification of the thermal energy supply could theoretically eliminate direct emissions related to heating in the clinker production process. That is, from an air-quality perspective, electrification and green hydrogen use would be preferable to a fuel shift to biomass and wastes. As CCS/U technology application induces a rise in energy consumption, the widespread use of CCS/U could further encumber a complete fuel switch to clean fuels. As the production of novel cements typically requires lower temperatures compared to that of conventional clinker production, a complete fuel switch would be easier to achieve in an environment requiring a lower process temperatures and overall energy demand.

Pollutants from process emissions could be reduced through an improved clinker-to-cement ratio. In terms of process emissions, novel cements have a favourable characteristic as most novel cement types do not generate process emissions, albeit research in this area is scarce.

Pollution levels could be reduced through further energy efficiency improvements and fuel substitution. However, the combustion of biofuel and wastes do also generate polluting gases, indicating that a shift toward hydrogen and electricity would be preferable from an air-quality perspective. The application of CCS/U technology would induce a rise in energy consumption, both in terms of electricity and thermal energy. The sustainability of such increase would need to be considered to avoid impacts on air quality.

Apart from the air-quality aspect, economic benefits could be achieved, mainly through energy efficiency improvements leading to a reduced fuel demand.

Areas for future research – Knowledge gaps for further contextualisation

Based on the outcome of this study, we identify some **key areas for future research to better understand and define ways forward for the European cement sector**. Specifically, these could be directed toward the inter-linkages between key emerging technologies, but also their regional and context-specific barriers. Key research questions may include:

- What are local/regional barriers for the key innovation technologies identified in this report?
- What are the synergies and trade-offs considering the interaction between different innovative technologies?
- What is the level of uncertainty for the key innovative technologies?
- What are the enabling conditions to progress from technical maturity to market success, and which actors are involved in that process?
- How can policies facilitate such transition?

It is yet unclear how the COVID-19 pandemic may affect the cement industry on the mid and long term. Previous experience from the financial crisis in 2008-2009 indicates that cement production can recover relatively quickly in the aftermath of an economic crisis. For ongoing demonstration projects and pilot testing not to be left behind, the continuation of investments in R&D should be ensured. Recovery packages directed to this sector therefore remain vital and the impact of the COVID-19 crisis should be part of any future research.

A dialogue around these questions could serve as a starting point for the identification of next steps and determining the way forward for the EU cement sector. In the following section, options to improve and advance the decarbonisation of the EU cement sector is explored in the light of the Paris Agreement and its different time horizons.

4.2 A way forward to set objectives for 2030 and 2050

The Paris Agreement mandates all Parties to submit an updated Nationally Determined Contribution (NDC) and a Long-Term Strategy (LTS) for the first time in 2020. The 'ratchet mechanism' of the Paris Agreement, stipulated in Article 4, calls upon the European Union and other Parties to increase their mid-term mitigation objectives by 2030 in their updated NDCs. These revised targets for 2030 ought to be aligned with the long-term vision to achieve a climate-neutral EU by 2050 (Croatia and the European Commission, 2020).

Building upon the analysis in Chapter 3, the following sections propose options for the European Union to conceptualise, transparently communicate and advance the implementation of its cement sector's *mitigation ambition* towards 2025 (short term), 2030 (medium term), and 2050 (long term).

The short-term towards 2025: Getting started

Figure 13: A proposal for specific actions towards 2025 to decarbonise the EU's cement sector

The European Commission and EU Member States ought to initiate sector-level dialogues to determine a roadmap towards 2050 for the cement sector. This dialogue should reflect both the economy-wide objective of carbon neutrality in 2050 stipulated under the *Green Deal* announced in 2019 (European Commission, 2019), and the ongoing effort for economic recovery in response to the COVID-19 pandemic.

Planning for accelerated research, development, and piloting of highly innovative technologies and adjusting the sector's regulatory framework gains utmost importance. A range of *low-carbon* technologies is readily available for implementation before 2025 (Hodges and Woods, 2020), for example the application of preheaters and precalciners, heat recovery kilns and clinker coolers. Their combined impact — even if implemented to the maximum degree possible — would only result in relatively small emission reductions and not fundamentally shift the sector's production profile. A key challenge for policy makers and industry will be to stimulate economic well-being while taking the required next steps to prepare for the cement sector's long-term decarbonisation.

The medium-term towards 2030/2035: Setting the stage and creating the evidence base

The European Union intends to submit an updated NDC by the end of 2020 and plans to include an increase of the economy-wide GHG reduction commitment to a 55% reduction below 1990 levels by 2030, as proposed by the European Commission, a decision expected to be confirmed by the Parliament and Council (European Commission, 2020b). The previously submitted 2016 NDC currently commits to a GHG reduction of at least 40% below 1990 levels (Latvia and European Commission, 2015).

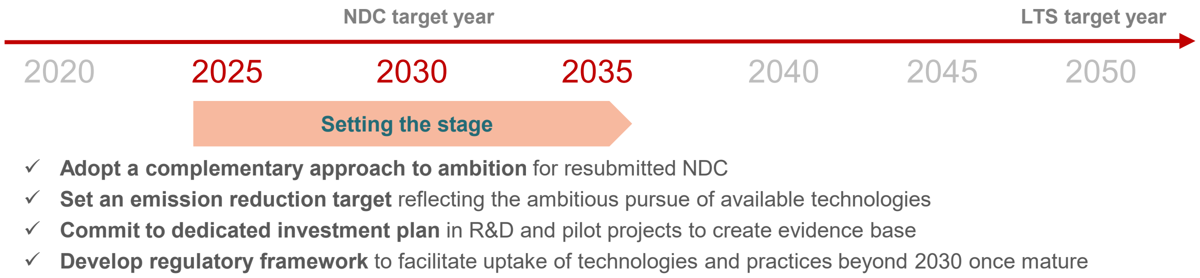

Figure 14: A proposal for specific actions towards 2030-35 to decarbonise the EU's cement sector

Setting an emission reduction target for the cement sector by 2030 provides transparency on the EU's *mitigation ambition* within the time frame of the updated NDC, even if the total emission reduction potential remains limited. This study's analysis indicates that the cement sector's contribution to the EU's economy wide GHG reduction target for 2030 may be limited. An ambitious and optimistic pursuit of available mitigation routes would only lead to a reduction of 18% below 1990 given the low availability of technologically mature and economically feasible technologies.

Beyond the NDC, single Member States can set respective national targets for the cement sector. For example, as previously described, Germany has already set a reduction target of 49-51% by 2030 and a permissible carbon budget of 140 $MtCO_2e$ for the industry sector (Government of Germany, 2019), while Sweden has committed to introduce carbon-neutral cements to the market by 2030. Such sectoral targets would require alignment with other national plans such as the National Energy and Climate Plans (NECPs).

The EU could further conceptualise their *level of ambition* until 2030 through a dedicated investment plan in R&D, pilot projects and regulatory adjustments in the cement sector. Such investment plan would complement a sector-level reduction target to build the evidence base for technologies and practices needed to unlock an accelerated low-carbon transition. For this purpose, the EU can utilize, extend and further align upcoming programmes and initiatives, namely the Horizon Europe research programme (2021-2027), the Innovation Fund (2020-2030) for supporting low-carbon demonstration projects, and the Modernisation Fund (2020-2030) for adopting decarbonisation technologies in lower income Member States.

This complementary approach to ambition setting towards 2030-2035 would account for the sector's starting point in 2020 and set a framework to facilitate uptake of technologies and practices once mature.

The long-term towards 2050: Transforming stringently

Figure 15: A proposal for specific actions towards 2050 to decarbonise the EU's cement sector

The EU would need to stringently transform the cement sector's production profile after 2030 to achieve substantial emission reduction towards mid-century in line with the economy wide GHG neutrality target. The successful transformation depends on the systematic introduction of novel technologies and practices available by the time, an adjusted regulatory framework (e.g. for carbon pricing or carbon storage regulation), and a commonly shared vision between public and private actors.

High uncertainty generally remains about the degree to which such technological development and the removal of other barriers will be accomplished by 2030. The analysis of this study indicates that a delay of ten years in introducing novel technologies and practices would result in emissions reduction of 70%-72% below 1990 level, compared to 89%-93% below 1990 levels without such delay.

Transparent updates of the EU's LTS and respective legislative and investment initiatives such as the *Green Deal* might ensure currency, inclusiveness and robustness of long-term planning. Continuous updates of long-term planning allow policy makers to reflect latest developments while planning for socio-economic consequences such as just transition consideration for affected workers and communities.

On a final note, the EU and its Member States can proactively foster solutions to achieve the Paris Agreement Goals in specific sectors through international cooperation on bi- and multilateral levels. An example of such is the bilateral agreement between China and France to promote the improvement of energy efficiency standards in the cooling sector and to phase out HFC gases in 2019 (Governments of France and China, 2019).

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6 Methodological annex

The methodological annex provides details on the methodological approach for the scenario development. It further explains the scope of the analysis, detailed scenario assumptions and their respective sources.

General introduction to analytical framework

The authors use the Climate Transparency Initiative's 2020 CTI Simulation Tool for the European Union developed by Climate Works Foundation and Climact for all scenario analyses to inform the above objectives (Pestiaux, J., Lalieu, S., Schobbens, Q., Monteith, S., Plechaty, D., Cronin, C. and Menon, 2020). The analytical framework assesses the following four stylized scenarios below building up on existing available literature and best practice case studies (Scrivener, John and Gartner, 2016; European Comission, 2016; ECRA, 2017; GCCA, 2018; Lehne and Preston, 2018; EU Calc, 2019; Fleiter *et al.*, 2019; Global Cement, 2019a; Material Economics, 2019; Cembureau, 2020; Climate Action Tracker, 2020). Figure 15 visualizes the analytical framework using the four scenarios.

The narrative behind each scenario is explained below. Figure 15 provides a stylized overview of the analytical framework used. The ACT-S serves as the starting point for both high innovation scenarios.

1. **Reference Scenario (R-S)** – The R-S presents the expected evolution of the European Union's cement sector assuming the continuation of sectoral trends before the outbreak of the COVID-19 pandemic (*pre-COVID*).
2. **Accelerating Current Technologies Scenario (ACT-S)** – The ACT-S assumes an ambitious roll-out of technologies, design options, and product specifications that do not require any complex and uncertain innovation for traditional cement making processes.
3. **High Innovation Capture Scenario (HIC-S)** – The HIC-S assumes the highest plausible level of innovation and application of CCS/CCU technologies and electrification of thermal heating supply for traditional cement making processes, while novel cement and new clinker substitutes are only marginally introduced.
4. **High Innovation Processes Scenario (HIP-S)** – The HIP-S assumes the highest plausible level of innovation and application of novel cement and new clinker substitutes for alternative cement making processes, while remaining traditional processes are partially equipped with CCS/CCU and electrified thermal heating supply

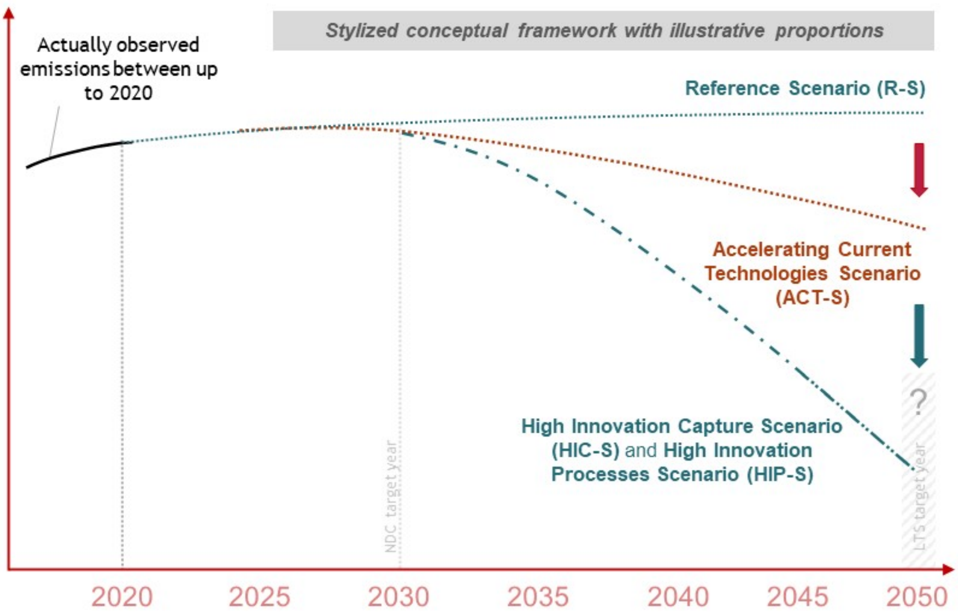

Figure 16: Stylized analytical framework to assess different technology routes in the cement sector considering the current development stage of key technologies and best practices. All proportions are illustrative.

2020 CTI Simulation Tool for the European Union

The CTI tool is an excel based bottom-up modelling tool. The evolution of the cement sector is built on a set of levers, including: activity demand, lifetime increase, share of product made in region, product switch to less intensive materials and product design improvements, material intensity reduction, recycled material, technology choice, energy efficiency, fuel switch (biomass, electricity, gas, hydrogen, syngas and synfuels), CCS. Target levels for each lever can be adjusted by the modeller, including start year, end year and extrapolation type.

Broadly, the levers can be categorised into three mitigation groups: avoid, shift and improve. The "avoid" group covers measures that aims to avoid production and subsequently emissions by affecting the demand side. The "shift" group covers mitigation measures that allows for production to be shifted to more efficient/less polluting techniques. Examples include materials shift and fuel shift. The "improve" group covers measures that aim to improve the production of the remaining demand. Examples include innovative technologies such as novel cements and CCS technology.

In this study, reduction of demand in terms of reduced consumption per capita has not been considered. Further, increased lifetime is also outside of the scope of this study. All shift and improve levers are covered in the modelling exercise, where a more detailed focus has been put on improve and technology specific levers.

Table 6: Overview of cement sector analysis inputs (Global Calculator, 2015; Material Economics 2019)

<table>
<tr><th></th><th>Lever group</th><th colspan="2">Fields of action</th><th colspan="2">Lever families</th><th>Covered in report</th></tr>
<tr><td>1</td><td>[Avoid]
Product demand</td><td colspan="2"></td><td>1</td><td>Reduce demand and increase lifetime</td><td>Not covered</td></tr>
<tr><td rowspan="4">2</td><td rowspan="4">[Shift]
Material demand per product</td><td rowspan="2">Materials efficiency and circular economy business models</td><td></td><td>2</td><td>Smart design</td><td>Covered</td></tr>
<tr><td rowspan="3">Material recirculation and substitution</td><td>3</td><td>Materials switch</td><td>Covered</td></tr>
<tr><td rowspan="2"></td><td>4</td><td>Materials recycling</td><td>Covered</td></tr>
<tr><td>5</td><td>Fuel switch</td><td>Covered in detail</td></tr>
<tr><td rowspan="3">3</td><td rowspan="3">[Improve]
Carbon intensity of material production</td><td colspan="2" rowspan="2">New and improved processes</td><td>6</td><td>Process change</td><td>Covered in detail</td></tr>
<tr><td>7</td><td>Energy efficiency</td><td>Covered in detail</td></tr>
<tr><td colspan="2">Carbon capture</td><td>8</td><td>CCS / CCU</td><td>Covered in detail</td></tr>
</table>

Scope definition scenario modelling

Given limitations in the CTI tool some aspects were not covered in the analysis and are explained in more detail below.

- In-direct emissions
  Any emissions related to electricity consumption are considered outside of the scope of this study and should be accounted for under the power sector. Such electricity consumption refers to thermal electrification, hydrogen production and other electricity consumption in the cement making process.

- Naturally occurring re-carbonation
  Studies show that about 23% of process emissions are naturally absorbed by cement over its lifetime, due to the reversible character of the chemical reaction of calcination (Stripple *et al.*, 2018). This is not accounted for in the scenario modelling of this study.

- Forced/improved re-carbonation
  The re-carbonation process can be accelerated and improved by applying certain grinding techniques while recycling concrete. That potential has not been included in this study due to lack of data on demolished product and recycling rates (Stripple *et al.*, 2018).

Overview of indicator inputs for R-S, ACT-S, HIC-S, and HIP-S

In this section detailed information on the assumptions made for each scenario is presented.

Table 7: Overview of indicator inputs for Reference Scenario (R-S)

Low	Ambitious Current Technologies Scenario (ACT-S)
High	High Innovation Scenarios (HIX-S)

			R-S					
Lever group	Unit	Ambition level	Target level min	Target level max	Start year	Duration	Curve type	Source
Product material switch	%	Low						
Material intensity	%	Low						
Industry - circularity - % of recycled material	%	Both	77%	#N/A	2020	25	L	(GCCA, 2018)
Process improvement - Technology changes, dry kiln	%	Low	100%	#N/A	2020	30	L	
Process improvement - Technology changes, wet kiln	%	Low	0%	#N/A	2020	30	L	
Process improvement - Technology changes, polymers	%	High						
Process improvement - Energy Efficiency, dry kiln	%	Low	10%	#N/A	2020	30	L	(ECRA, 2017)
Process improvement - Energy Efficiency, wet kiln	%	Low	0%	#N/A	2020	30	L	
Process improvement - Energy Efficiency, polymers	%	High						
Fuel switch towards alternative fuels	%	Low						
Fuel switch towards hydrogen and electricity	%	High						
CCS for Industry, dry kilns	%	High						
CCS for Industry, wet kilns	%	High						
CCS for Industry, polymers	%	High						

Table 8: Overview of indicator inputs for Ambitious Current Technologies Scenario (ACT-S)

Low	Ambitious Current Technologies Scenario (ACT-S)
High	High Innovation scenarios (HIC-S and HIP-S)

			ACT-S					
Lever group	**Unit**	**Ambition level**	**Target level min**	**Target level max**	**Start year**	**Duration**	**Curve type**	**Source**
Product material switch	%	Low	33%	33%	2027	23	S	(Lehne and Preston, 2018)
Material intensity	%	Low	90%	65%	2027	23	S	(Scrivener, John and Gartner, 2016; EU Calc, 2019)
Industry - circularity - % of recycled material	%	Both	40%	40%	2025	25	S	(ECRA, 2017)
Process improvement - Technology changes, dry kiln	%	Low	100%	100%	2020	30	S	
Process improvement - Technology changes, wet kiln	%	Low	0%	0%	2020	30	S	(GCCA, 2018)
Process improvement - Technology changes, polymers	%	High	0%	0%	2030	20	S	
Process improvement - Energy Efficiency, dry kiln	%	Low	12%	12%	2020	20	L	(ECRA, 2017)
Process improvement - Energy Efficiency, wet kiln	%	Low	0%	0%	2020	20	L	
Process improvement - Energy Efficiency, polymers	%	High	0%	0%	2020	20	L	
Fuel switch towards alternative fuels	%	Low	70%	70%	2020	20	L	(ECRA, 2017)
Fuel switch towards hydrogen and electricity	%	High	0%	0%	2030	20	S	
CCS for Industry, dry kilns	%	High	0%	0%	2030	20	S	
CCS for Industry, wet kilns	%	High	0%	0%	2030	20	S	
CCS for Industry, polymers	%	High	0%	0%	2030	20	S	

Table 9: Overview of indicator inputs for High Innovation Capture Scenario (HIC-S)

Low	Ambitious Current Technologies Scenario (ACT-S)
High	High Innovation Scenarios (HIX-S)

			HIC-S					
Lever group	Unit	Ambition level	Target level min	Target level max	Start year	Duration	Curve type	Source
Product material switch	%	Low	33%	33%	2027	23	S	(Lehne and Preston, 2018)
Material intensity	%	Low	65%	65%	2027	23	S	(Scrivener, John and Gartner, 2016; EU Calc, 2019)
Industry - circularity - % of recycled material	%	Both	40%	40%	2025	25	S	(ECRA, 2017)
Process improvement - Technology changes, dry kiln	%	Low	90%	90%	2030	30	S	
Process improvement - Technology changes, wet kiln	%	Low	0%	0%	2030	30	S	(GCCA, 2018)
Process improvement - Technology changes, polymers	%	High	10%	10%	2030	30	S	(EU Calc, 2019)
Process improvement - Energy Efficiency, dry kiln	%	Low	7%	7%	2020	20	L	(ECRA, 2017)
Process improvement - Energy Efficiency, wet kiln	%	Low	0%	0%	2020	20	L	
Process improvement - Energy Efficiency, polymers	%	High	0%	0%	2020	20	L	
Fuel switch towards alternative fuels	%	Low	70%	70%	2020	20	L	(ECRA, 2017)
Fuel switch towards hydrogen and electricity	%	High	10%	10%	2030	30	S	(Cembureau, 2020)
CCS for Industry, dry kilns	%	High	76%	85%	2030	20	S	(EU Calc, 2019)
CCS for Industry, wet kilns	%	High	0%	0%	2030	20	S	
CCS for Industry, polymers	%	High	20%	40%	2030	20	S	(EU Calc, 2019)

Table 10: Overview of indicator inputs for High Innovation Processes Scenario (HIP-S)

Low	Ambitious Current Technologies Scenario (ACT-S)
High	High Innovation Scenarios (HIX-S)

			HIP-S					
Lever group	Unit	Ambition level	Target level min	Target level max	Start year	Duration	Curve type	Source
Product material switch	%	Low	33%	33%	2027	23	S	(Lehne and Preston, 2018)
Material intensity	%	Low	65%	65%	2027	23	S	(Scrivener, John and Gartner, 2016; EU Calc, 2019)
Industry - circularity - % of recycled material	%	Both	45%	50%	2025	25	S	(Global Cement, 2019a)
Process improvement - Technology changes, dry kiln	%	Low	80%	50%	2025	25	S	
Process improvement - Technology changes, wet kiln	%	Low	0%	0%	2025	25	S	(GCCA, 2018)
Process improvement - Technology changes, polymers	%	High	20%	50%	2025	25	S	
Process improvement - Energy Efficiency, dry kiln	%	Low	12%	12%	2020	20	L	
Process improvement - Energy Efficiency, wet kiln	%	Low	0%	0%	2020	20	L	
Process improvement - Energy Efficiency, polymers	%	High				20	L	(EU Calc, 2019; Fleiter *et al.*, 2019)
Fuel switch towards alternative fuels	%	Low	70%	69%	2020	20	L	(ECRA, 2017)
Fuel switch towards hydrogen and electricity	%	High	20%	31%	2030	20	S	(EU Calc, 2019; Material Economics, 2019)
CCS for Industry, dry kilns	%	High	42%	42%	2030	30	S	(Cembureau, 2020)
CCS for Industry, wet kilns	%	High	0%	0%	2030	30	S	
CCS for Industry, polymers	%	High	20%	20%	2030	30	S	(EU Calc, 2019)