Clinker Substitution in the EU Cement Sector

Methodology report

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Abbreviations

BAU	Business as usual
CAT	Climate action tracker
CTI	Climate Transparency Initiative
ECRA	European cement and concrete association
EU	European Union
GCCA	Global cement and concrete association
GNR	Getting the number right
HCS	High clinker substitution
LCS	Low clinker substitution
MDS	Moderate clinker substitution
SCM	Supplementary cementitious material

1 Background and introduction

1.1 EU cement sector

Cement is one of the most important materials for the building and construction sector. It is a finely ground powder that - upon being mixed with water – forms the key binding ingredient of concrete and mortar. Consequently, cement is omnipresent in our modern day lives, being the world's most consumed material second to water only. This comes with a huge carbon footprint, as the manufacturing of cement currently accounts for 8% of global CO_2 emissions. Most of these emissions (>90%) can be attributed to the production of clinker in traditional cement making, which generates high levels of process emissions and requires significant amount of heat.

This picture is not different for the EU cement sector, being one of the most carbon-intensive sectors of our industries due to the high levels of traditional cements with high clinker content being produced. In 2019, the sector emitted 109 million tonnes (Mt) of CO_2 in the EU27, distributed over 202 production sites. This accounts for up to 8% of all verified emissions which are currently covered by the EU ETS trading system. Furthermore, recent years have witnessed all but a decline in emissions, as emissions increased by 4% between 2013 and 2021 (Marcu *et al.*, 2021; European Environment Agency, 2022).

A key lever for rapid decarbonisation is clinker substitution, referring to the use of cement types which require either much lower levels of clinker, or use different binding technologies altogether. The first set of solutions are currently most dominant and established and involve the use of supplementary cementitious materials (SCMs) and fillers in cement mixes to substitute large shares – but not all – traditional clinkers in cement mixes. The second set of solutions takes a different approach as they involve the development of different binder types, as such entirely substituting the use of traditional clinker. In doing so, they typically use very different production methods, requiring much lower or no heat, as well as raw material mix and feedstock (Lehne and Preston, 2018). Importantly, material innovations on both fronts are in full development, with an ever-growing number of working solutions being commercially available on the market, showing great potential for low-carbon cement and concrete making. Moreover, research shows that, of all regions, the EU is particularly well placed for achieving high levels of clinker substitution in the short-, medium-, and long-term (Miller, Jiang and Myers, 2022).

To maximize this potential for clinker substitution, it is important to remove barriers which hinder large-scale market uptake. Most notably in this regard are European cement and concrete standards which are highly prescriptive in nature, locking in high levels of clinker content in cement mixes. This limits the ability to develop and use novel low-carbon cement types, as such hampering innovation and decarbonisation in the EU cement industry (Frontier Economics, 2022). Therefore, it is widely acknowledged that the adoption of performance-based standards could serve as a key lever for further material innovations and the market uptake of already existing low carbon solutions. This because they are based on performance indicators such as strength, permeability, shrinkage, etc., without imposing restriction on the materials used to get there (Lehne and Preston, 2018; Scrivener, John and Gartner, 2018).

1.2 Objectives

The objective of this study is to estimate the CO_2 mitigation potential from the increased use of supplementary cementitious materials (SCMs) and alternative binders in the EU cement sector. The increased use of SCMs and alternative binders is enabled by the theoretical updating of the current recipe-based EU cement standards to performance-based approaches.

Three mitigation scenarios are developed to explore the mitigation potential of three different ambition levels. The mitigation potential is estimated by comparing each mitigation scenario to (a) the base year of 2015, and (b) a business as usual (BAU) scenario, representing the continuation of historical trends.

1.3 Introduction to the Climate Transparency Initiative (CTI) tool

The CO_2 emission scenarios are developed in the Climate Transparency Initiative's 2020 CTI simulation tool for the European Union developed by Climate Works Foundation and Climact. The CTI tool is spreadsheet-based and applies a bottom-up approach to scenario development, facilitated by a set of pre-defined levers.

The geographical scope of the analysis covers EU27 + the United Kingdom (i.e., EU28). The timeline of the scenarios is 2050. In terms of CO_2 emissions, the analysis considers scope 1 and scope 2 emissions, i.e., direct emissions from fuel combustion and processes emissions from the calcination of limestone, and indirect emissions from the use of electricity and heat. It does not include scope 3 emissions from up- and downstream operations and activities.

2 Methodology

2.1 Definition of scenarios

In total, the study considers four different scenarios: One business as usual (BAU) scenario which serves as a reference, and three mitigation scenarios with the purpose of estimating the mitigation potential of various clinker substitution levels using supplementary cementitious materials (SCMs), and the commercial-scale introduction of alternative binders. All scenarios and their definitions are summarised in Table 1.

Table 1. Definition of scenarios

Scenario name	Scenario description
Business as usual (BAU)	Represents the continuation of historical trends: Improvements across traditional mitigation options continue similar to the historical rate of change. Policies are not taken into account.
Low clinker substitution (LCS)	The clinker-to-cement ratio reaches 60% by 2050, and alternative binders make up 7% of the market by 2050.
Moderate clinker substitution (MDS)	The clinker-to-cement ratio reaches 50% by 2050, and alternative binders make up 7% of the market by 2050.
High clinker substitution (HCS)	The clinker-to-cement ratio reaches 50% by 2050, and alternative binders make up 7% of the market by 2050.

For the BAU scenario, all levers are enabled to allow for the parametrisation of various traditional mitigation measures including energy efficiency, the shift from wet to dry clinker kilns, the clinker-to-cement ratio, and the use of alternative fuels. In the mitigation scenarios, however, all levers except from the clinker-to-cement ratio and share of alterative binders remain the same as in the BAU scenario. By doing so, the unique mitigation contribution from an increased use of supplementary cementitious materials and alternative binders can be identified.

2.2 Scenario development

The development of the mitigation scenarios is largely based on the BAU scenario as a basis. In order to estimate the future evolution of the levers in the BAU scenario, historical data is collected which is then used to derive the historical rate of change for individual levers. Where historical data is not available, assumptions are made based on the available literature. The levers related to traditional mitigation measures and thus considered in the BAU scenario include:

- The clinker-to-cement ratio
- The share of biomass and alternative fuels and wastes[1] in the thermal energy supply mix
- The share of wet versus dry clinker kilns
- The thermal energy efficiency of the clinker kiln

Other, non-traditional mitigation levers including the electrification of clinker kilns and the adoption of carbon capture and storage (CCS) are not considered in the BAU scenario. That is based on the limited progress of those technologies in recent years, which is not expected to advance significantly in the theoretical BAU scenario.

In the BAU scenario, the increased use of SCMs is classified as a traditional mitigation measure as it is assumed that only traditional SCMs such as fly ash and blast furnace slag are continued to be used. More innovative SCMs, such as calcined clays, are only considered in the mitigation scenarios.

2.2.1 Development of projections for traditional mitigation levers

The historical clinker-to-cement ratio is retrieved from European industry associations (Cembureau, 2020), and share of biomass and alternative fuels and wastes are collected from the Getting the Numbers Right (GNR) database developed by the Global Cement and Concrete Association (GCCA) (GCCA, 2018). The average historical rate of change of the last 10-13 years of available historical data is then applied to estimate future improvements of those levers.

According to the historical data, the clinker-to-cement ratio in the EU28 has remained relatively stable at about 77-78% the last 8 years. Based on that, the clinker-to-cement ratio is assumed the remain constant at 78% in the BAU scenario. In terms of alternative binders, those are not expected to reach commercial scale in the BAU scenario.

Due to the historical rapid increases in the share of biomass and alternative fuels and wastes in the thermal energy mix (rising from 4% to 16% and 11% to 30% between 2005 and 2017, respectively), this lever increases significantly in the BAU scenario when based on the average annual historical rate of change. By 2030, the share of biomass and alternative fuels and wastes reaches to 32% and 50%, respectively, and to 56% and 44% by 2050. The thermal fuel mix is thus fully met by biomass and alternative fuels and wastes by 2050. Since applying the historical average rate of change to both indicators (biomass and alternative fuels and wastes) would result in a total rate above 100%, biomass is given priority because its higher sustainability potential. As a result, the share of alternative fuels and wastes decreases between 2030 and 2050.

The share of wet and semi wet kilns in the EU has decreased rapidly in recent years and represented about 9% of the EU technology stock in 2017, according to GNR data. If the historical average rate of change should continue, wet and semi wet kilns would be fully phased out by 2040 and forms the assumption for the BAU scenario.

[1] Alternative fuels and wastes include non-traditional fossil fuels such as residual oil, tyres and plastics.

In terms of the energy efficiency of clinker kilns, efficiency improvements are assumed to continue to be adopted incentivised by lower fuel costs for cement producers. According to data from the European Cement and Concrete Association, the energy efficiency of EU cement kilns could be improved by another 7%-12% (ECRA, 2017). In this study, it is assumed that the energy efficiency is improved by 10% which is achieved across the technology stock by 2050.

2.2.2 CO_2 emissions from biomass and alternative fuels and wastes

The combustion of biomass can only be considered carbon neutral if the biomass has been produced in a sustainable manner. When accounting for emissions from the combustion of biomass, several aspects must be taken into account, such as potential land use change caused by the harvesting of biomass and carbon absorption that would have taken place if the biomass was not harvested (Booth, 2018). Further, the production of biomass also competes with other products which require land, such as food production, or excessive biomass production could drive deforestation.

Due to uncertainties with regard to the sustainable biomass production potential in the future, and the future competitiveness for it across sectors, it is challenging to make quantitative estimates on the availability of sustainable biomass for use in the cement sector. Based on available literature, however, it does not seem realistic to assume that all biomass demand in the cement sector can be met sustainably. Based on that, it is assumed that 50% of the demand will be met from sustainable biomass, while the other 50% is assumed to be unsustainable and thus causing a net increase of the CO_2 concentration in the atmosphere.

In terms of CO_2 emissions from the combustion of alternative fuels and wastes, those are also assumed to have limited sustainability in this study. Since the composition of alternative fuels and wastes are commonly made up of residual oils, plastics, tyres and other materials containing fossil carbon (Zieri and Ismail, 2019), their combustion is considered to have a net negative climate impact.

2.2.3 Development of projections for the adoption of SCMs and alternative binders in the mitigation scenarios

Supplementary Cementitious Materials

In the BAU scenario, the clinker-to-cement ratio is assumed to change according to the historical average rate of change, as explained in section 2.2.1. In the mitigation scenarios, however, a top-down approach is used, where the clinker-to-cement ratio is set to reach a certain level by 2050. The clinker-to-cement ratio for all scenarios is presented in Figure 1. The pathway to reaching that target can take various forms. In order to reach clinker-to cement levels that are significantly lower than current levels, one needs to move from the more 'traditional' use of SCMs in binary blends – referring to cement mixes in which traditional Portland cement is mixed with one SCM – to much more complex and innovative mix designs - i.e. ternary and quaternary blends – in which traditional Portland cement is mixed with and substituted by a combination of SCMs, fillers and additives, often involving different griding techniques (Edwards, 2020; FLSmidth, 2022). Arguably, one of the most well-known and promising SCMs is calcined clays, which, in combination with other SCMs and fillers can achieve durable and strong cement types with low clinker content (Dixit *et al.*, 2021).

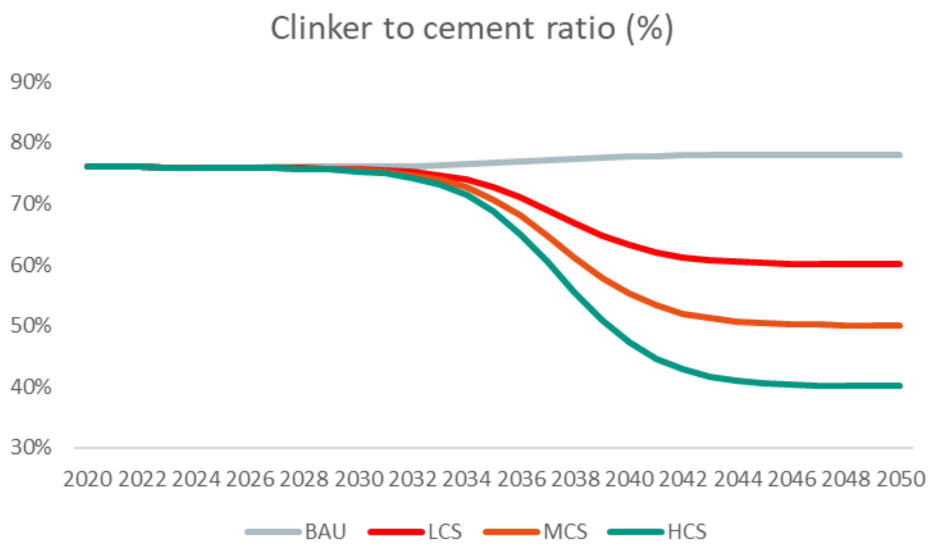

Figure 1. Clinker-to-cement ratio in the BAU, LCS, MCS, and HCS scenarios.

Based on that, the rate of the calcined SCMs in the SCM mix of the mitigation scenarios is assumed to reach 80% by 2050 (Figure 2). Because several of the new SCMS involve novel technologies (e.g. the calcination of clay), and because the development of new standards takes up a several years, market introduction is assumed to follow and s-shaped curve, starting in 2025. Traditional SCMs are assumed to gradually decline, reaching 10% in 2050. Their phase out is a result of the increased use of novel SCMS (e.g. calcined clays) as well as a decreasing supply of traditional SCMs resulting from the decarbonisation of power generation and steel production in a 1.5°C compatible scenario. It is further assumed that other SCMs such as those from the built environment (e.g., recycled concrete fines), and by-products of the mining sector will make up about 10% of the SCM mix.

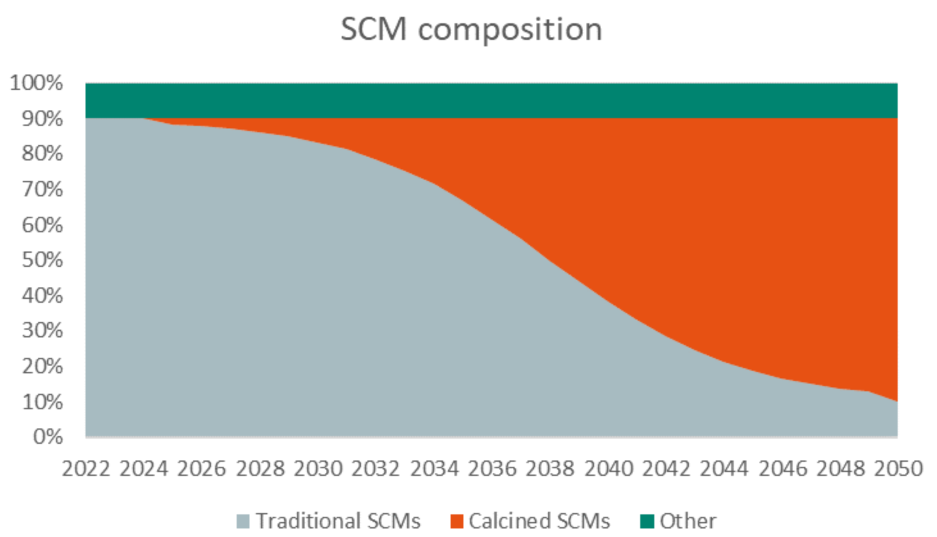

Figure 2. The composition of SCM types in the EU in the mitigation scenarios.

Alternative binders

There are a wide range of potential alternative binders in various stages of development (Lehne and Preston, 2018). So far, no alternative binders with deep mitigation potential have yet reached large scale commercialisation. Based on consultation with experts in the cement industry, as well as estimations put forward by the industry itself, it is assumed that alternative binders could reach about 7% of the market share in the EU by 2050, starting large scale commercialisation around 2030 and following an s-shaped growth (Figure 3). Such advancements are assumed to remain the same across all mitigation scenarios. In terms of the composition of the alternative binders mix, geopolymers and biocements are identified as the two most promising types and are the ones considered for the modelling exercise. Because geopolymers are further developed than biocements, their share is expected to be higher share – 70% geopolymers and 30% biocements.

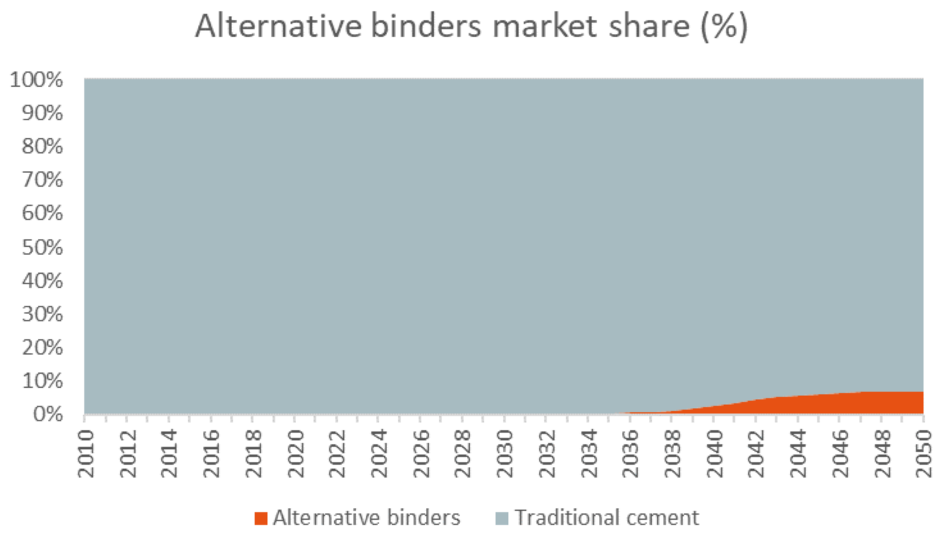

Figure 3. The projected introduction of alternative binders to the EU28 cement market.

2.2.4 Estimating CO_2 emissions from the production of SCMs and alternative binders

Supplementary Cementitious Materials

Even though SCMs do not generate process emissions, their production is subject to the generation of energy related emissions which need to be considered. In terms of traditional SCMs, they are the result of emissions intensive processes associated with the generation of electricity and the production of steel. However, since scope 3 emissions are outside of the scope of this analysis, their emissions are not considered.

For novel SCMs, calculations are based on the process emissions of the calcination of clay, motivated by the fact that this is the most studied novel SCM at present. It requires temperatures of about 750-850°C and could thus result in the generation of CO_2 emissions, depending on what fuels are used to generate the heat. The electrification of kilns for the calcination of clay is technically possible, but it is assumed that cement producers will initially use already existing assets (which are fed by solid fuels) to calcine clay, and that electric kilns will be gradually adopted. It is further assumed that cement producers initially will use the same fuel mix as is currently used in clinker kilns.

In terms of the indirect emissions resulting from the generation of electricity, those fall under scope 2 emissions and are thus accounted for in this analysis. It is assumed that the emissions intensity of electricity generation will follow a 1.5°C-compatible trajectory. 1.5°C -compatible benchmarks for 2030, 2040 and 2050 developed by the Climate Action Tracker (CAT) are applied, using linear interpolation to derive annual CO_2 intensities (Figure 4).

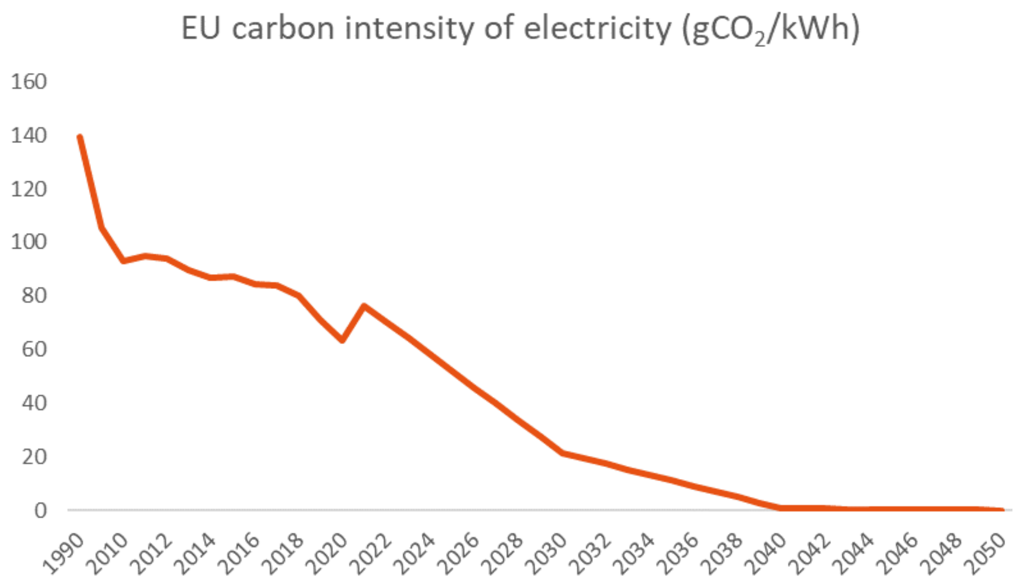

Figure 4. The carbon intensity of EU electricity generation derived from 1.5°C compatible benchmarks.

That results in CO_2 emissions from the production of novel SCMs reaching carbon neutrality by 2050 across all mitigation scenarios, peaking in 2041 (Figure 5). Because the SCM demand increases with the ambition level, the CO_2 emissions from SCM production is highest in the HCS scenario.

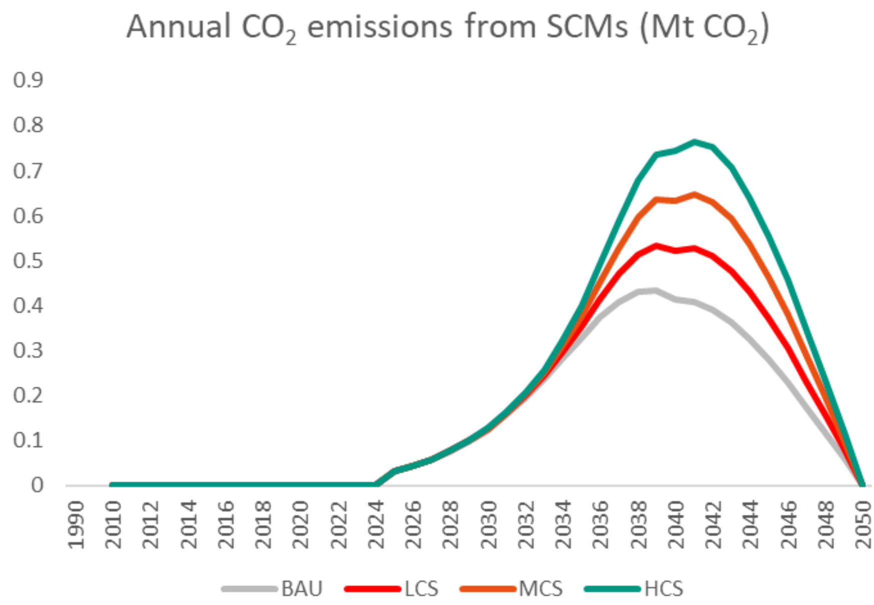

Figure 5. CO_2 emissions from the production of SCMs in the LCS, MCS, and HCS scenarios.

Alternative binders

The production of geopolymers and biocements does not generate any process emissions (Abiodun *et al.*, 2022). However, their production require energy which can result in direct or indirect CO_2 emissions from fuel combustion, depending on the type of fuels used. Geopolymer cements could mitigate about 80% of emissions compared to traditional cement making (Lehne and Preston, 2018; The Footprint Company, 2020), while emissions from biocement production currently reduces emissions by 90% (The Economist, 2022). Along with a decarbonisation of the energy supply – either through electrification coupled with a decarbonisation of the power supply or through the direct use of renewable heat (i.e., solar thermal or geothermal) – emissions from the production of alternative cements peaks in 2041 at about 0.4 Mt CO_2 and reaches carbon neutrality by 2050 (Figure 6).

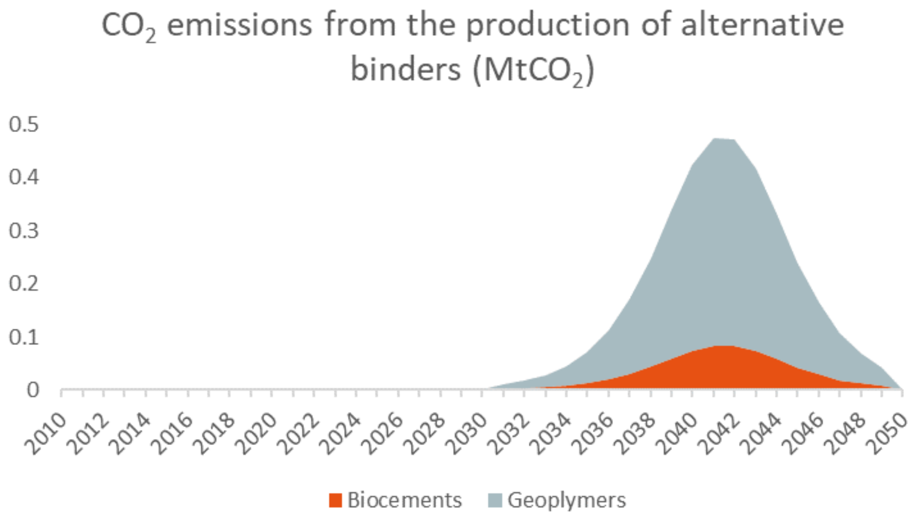

Figure 6. CO_2 emissions from the production of alternative binders across all mitigation scenarios.

3 Results

3.1 Cement production

In the absence of demand-side measures, the results suggest that EU cement production will continue to rise until 2030 when it peaks at 204 Mt of annual production. The cement production then decreases, reaching 187 Mt in 2050. Figure 7 shows the EU cement production pathway in the BAU scenario which remains the same across all scenarios.

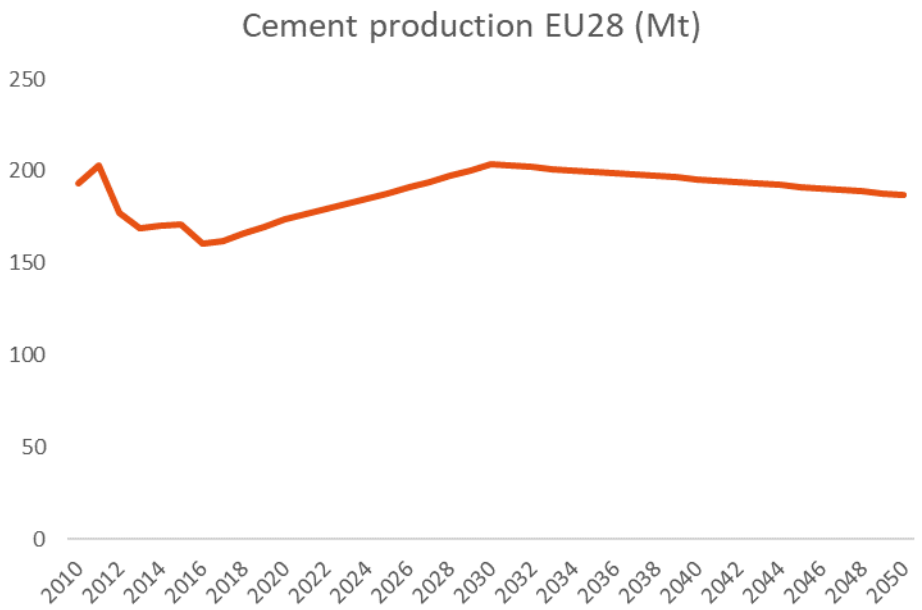

Figure 7. EU cement production in the BAU scenario.

3.2 CO_2 emissions

The results suggest a limited CO_2 mitigation potential from the improvement in the clinker-to-cement ratio and the introduction of alternative binders in the medium-term, and a significant potential in the long-term. We compare the mitigation potential of both to the latest year of historical data (2015), and to the BAU scenario (Table 2). Comparing to 2015 emission levels, annual emissions will increase by roughly a fifth until 2030, which is the result of two key parameters: (1) the continuous increase in cement production which offsets any reductions in the emissions intensity of cement production, and (2) the initially slow introduction of the mitigation measures (i.e., the new SCM standards assumed to start in 2025, and the increased deployment of alternative binders assumed to initiate in 2030)[2] which can be observed in Figure 8. The latter parameter is also the main reason to the limited mitigation potential observed in 2030 when compared to the BAU scenario: about 0.5%, 0.7%, and 0.9% in the LCS, MCS, and HCS scenarios, respectively.

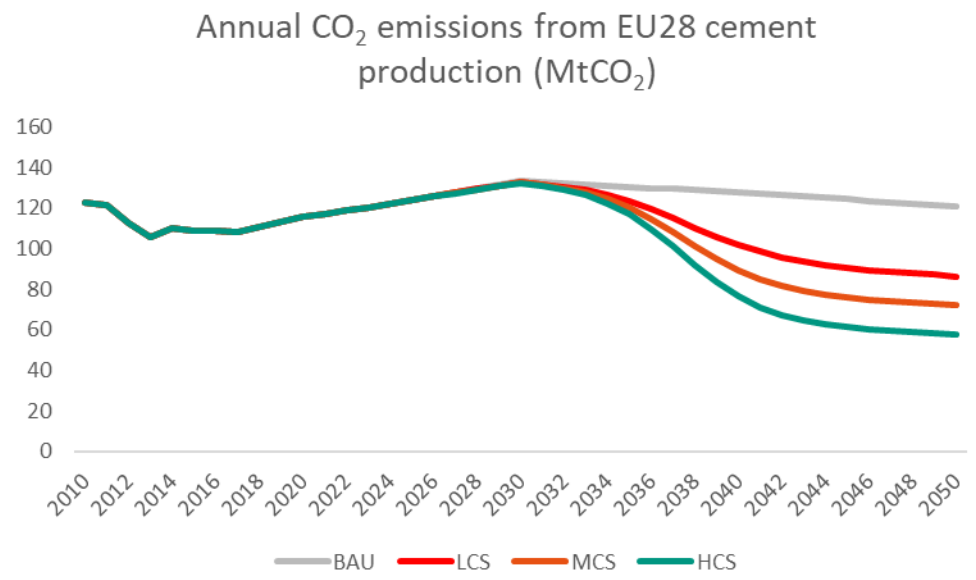

Figure 8. Annual CO_2 emissions from cement production in the EU28 in the BAU, LCS, MCS, and HCS scenarios.

In the long-term, however, annual emissions are significantly reduced, both when comparing to 2015 levels and the BAU scenario. As presented in Table 2, annual emissions can be almost halved in the HCS scenario when comparing to 2015 levels, and more than halved when comparing to the BAU scenario.

Table 2. CO_2 mitigation potential in 2030 and 2050 in terms of annual emissions from the EU28 cement sector.

		Mitigation potential compared to	
Scenario	**Year**	**Base year (2015)**	**BAU**
LCS	2030	22.2%	-0.5%
MCS	2030	22.0%	-0.7%
HCS	2030	21.8%	-0.9%

[2] The assumptions on the timing of the SCM and alternative binders introduction are motivated by two main factors: (1) Standards take time to develop and require a few years before they can be fully implemented, (2) The large-scale production alternative binders sector will require the development of new value chains, in particular for raw materials.

LCS	2050	-20.6%	-28%
MCS	2050	-33.8%	-40%
HCS	2050	-47.0%	-52%

4 Conclusions

The European cement industry is one of the most carbon intensive sectors, being responsible for 8% of all verified emissions covered by European ETS today. An often overlooked, but key lever for rapid decarbonisation is clinker substitution, referring to the use of cement types which much lower levels of clinker, or relying on different binding chemistries altogether. The objective of this study was to estimate the CO_2 mitigation potential from clinker substitution in Europe. In doing so, we assumed a situation whereby the current recipe-based European cement standards – which are widely considered as the key barrier for clinker substitution – were replaced by performance-based standards, as such allowing the large-scale market uptake of low carbon cements.

The different scenarios show a significant mitigation potential for Europe, up to cutting the industries' annual footprint in half by 2050. While this potential is limited in the short-term because of the time required to develop new standards, as well as develop new value chains; all scenarios show substantial cumulative mitigation potential by 2050. To achieve – and potentially even exceed - these deep emission cuts, it will be vital to decarbonise the energy supply (e.g., for the calcination of novel SCMs such as calcined clays) as well as continue to invest in material innovation (e.g., the use of captured CO_2 or bacteria as SCM and/or alternative binder).

In sum, it can be concluded that standards can play a key role in speeding up the decarbonisation of the European cement industry. Switching to performance-based approaches can bring the industry on a fast track to deep emission cuts, as such complementing other key levers for decarbonisation and Europe's ambitions to become the world's first climate neutral continent.

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