A SUSTAINABLE FUTURE FOR THE EUROPEAN CEMENT AND CONCRETE INDUSTRY

Technology assessment for full decarbonisation of the industry by 2050

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Foreword

This report summarises the practices and technologies that can be implemented to significantly reduce CO_2 emissions from the cement and concrete sector in Europe by 2050.

An important message communicated in this report is to show that reduction efforts must be supported along the complete value chain and not by a single stakeholder. In this way, the concrete construction sector can reduce up to 80% of these emissions (compared to 1990) without major changes in terms of standards and with moderate investments. Moreover, this approach would be a major step towards a more circular economy in the sector which is estimated to be a key element of a sustainable economy.

The possibility of achieving the objective of the Paris Agreement (temperature rise limited to 1.5°C in the long term) is also emphasised by analysing certain practices beyond current standards or by combining them with carbon capture and storage technologies showing that carbon neutrality is technologically feasible in the cement and concrete sector.

Finally, we propose measures and policies to overcome the limitations for the adoption of these technologies and practices targeting all stakeholders.

This one-year project was undertaken researchers from the Swiss Federal Institute of Technology (ETHZ), Zürich, and the Swiss Federal Institute of Technology (EPFL), Lausanne, and commissioned by the European Climate Foundation. The objective of the project was to assess the potential of technologies to reduce CO_2 emissions from the cement and concrete industry. Two consultation workshops with representatives from the construction industry, academic experts and European policy professionals in Brussels in January 2018 and May 2018 were held to verify the results.

We hope that the work presented in this report will bring attention to the needed policies to be put in place to transform the cement and concrete industry towards a more sustainable future.

Executive summary

This report examines different pathways to reduce CO_2 emissions associated with the use of cement in the construction sector.

Worldwide, cementitious materials make up more than half of all the materials we use. While cementitious materials are intrinsically materials with low embodied energy, these large volumes mean they account for approximately 8% of global emissions. The cement demand in Europe represents 5% of the global market and has been stable for nearly a decade. This demand is not likely to significantly increase in the future, unlike in emerging and developing countries, where the demand for cement will continue to rise to meet the demand of the growing population and urbanisation. In volume, construction is the biggest source of waste in Europe, but almost 90% can be revalorised highlighting an untapped potential for more efficient resource management in the sector.

The cement and concrete sector play an important role in the European economy and also in reaching the goals of the Paris Agreement which commits governments to keep global warming well below 2°C Celsius and to pursue efforts to keep it below 1.5°C. According to the Special Report on 1.5°C published by the Intergovernmental Panel on Climate Change (IPCC) (October 2018), limiting global warming to 1.5°C requires the economy to be carbon neutral globally by 2050.

Carbon neutrality is particularly challenging for the cement sector as less than 40% of emissions come from the energy used to produce cement. More than 60% of emissions come from the chemical breakdown of limestone – calcium carbonate ($CaCO_3$) – into CO_2; limestone is a calcium source that is used to produce the active component of cement - the clinker - which reacts with water at ambient temperature to produce a strong durable material. There is no practical alternative to the use of limestone due to its abundance and widespread distribution in the earth's crust. Therefore, total carbon neutrality can only be achieved by recapturing this "chemical" CO_2.

Technologies for carbon capture and storage are under development, although some technical challenges need still to be surmounted. These technologies are estimated to require large investments in terms of capital investment and in operating cost. They are also dependent on large quantities of renewable energy to be effective.

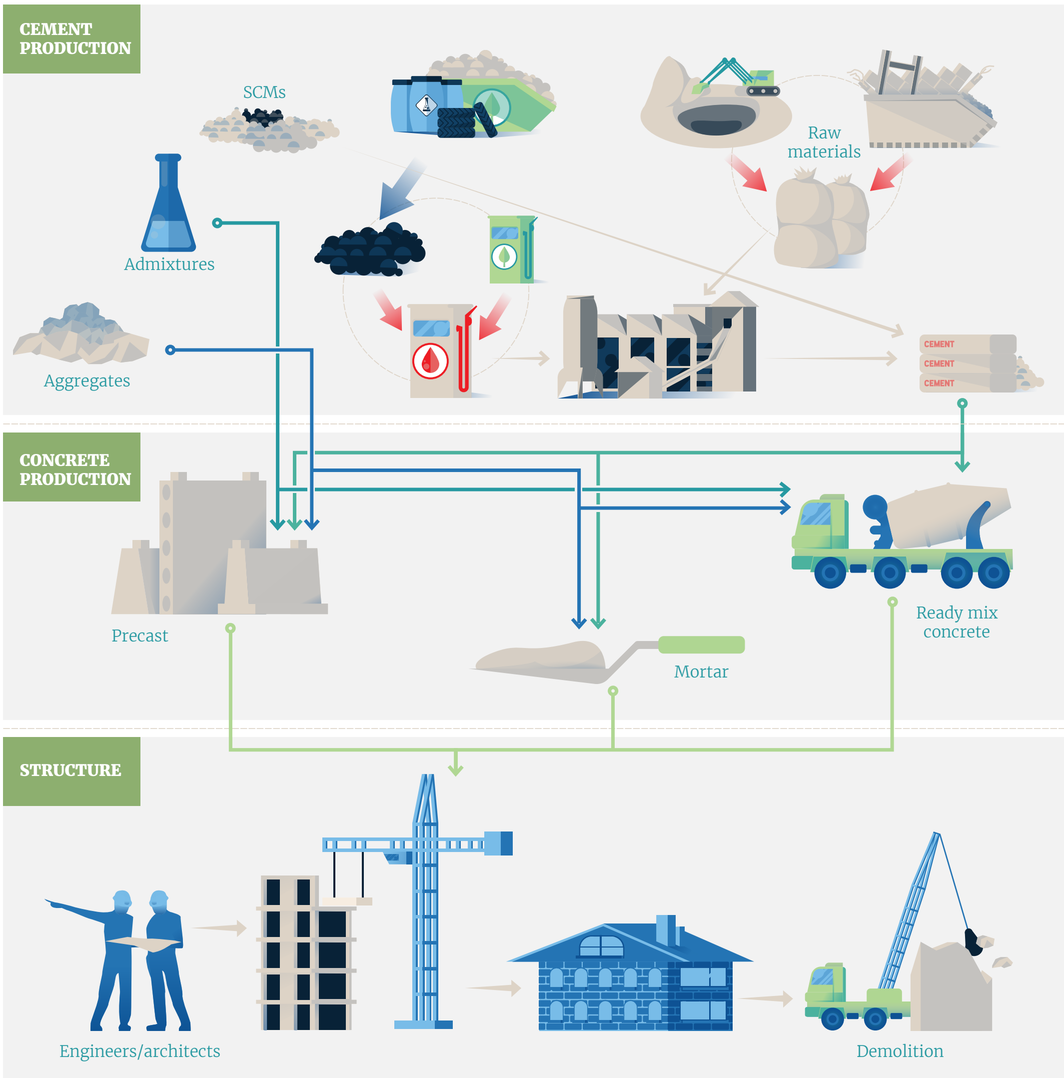
In this report, we examine different scenarios to reduce CO_2 emissions from cement production and minimise the cost of the remaining CO_2 that must be captured to achieve overall carbon neutrality.

We show that by considering all the stages in the value chain, reductions of up to 80% CO_2 emissions compared to the 1990 values is achievable by 2050 without using carbon capture and storage technologies. Achieving such reductions would require the different actors in the construction value chain to work together, and measures should be taken to incentivise this. However, these CO_2 savings could be achieved for a relatively low financial cost and even with financial savings in some cases.

Levers for CO_2 reduction along the construction value chain

The construction sector includes various players (figure below), and pressure for CO_2 reduction has, up to now, remained only at the level of the cement producers. Yet, cement production is highly efficient, and it is unlikely that further significant savings (more than 10%) can be made here due to the low growth perspective in Europe.

Representation of the cementitious construction value chain used in this report



We identify 10 technologies (kiln improvement, alternative fuels, recycling fines as raw materials, alternative binders, carbon capture and storage, concrete mix design, structure optimisation etc.) at different stages of the value chain and the corresponding CO_2 saving potential, focusing on actions that concrete producers, gravel producers, engineering offices, construction companies or demolition companies can make. All of the levers studied are based on proven technologies that can be quickly and massively implemented in practice. These levers are combined in different ways in three scenarios which are considered and compared to a reference, depending on the level of integration of the stakeholders and the different levels of the required investment.

Reference scenario is based on the IEA-CSI Roadmap 2018 reference scenario. It requires some investment by cement manufacturers to improve kiln technologies and some extension of the use of alternative fuels and clinker substitution.

Scenario 1: “Breakthrough technologies” will require massive investment by cement producers to equip their plants with carbon capture and storage technologies as well as increased market penetration of alternative clinkers.

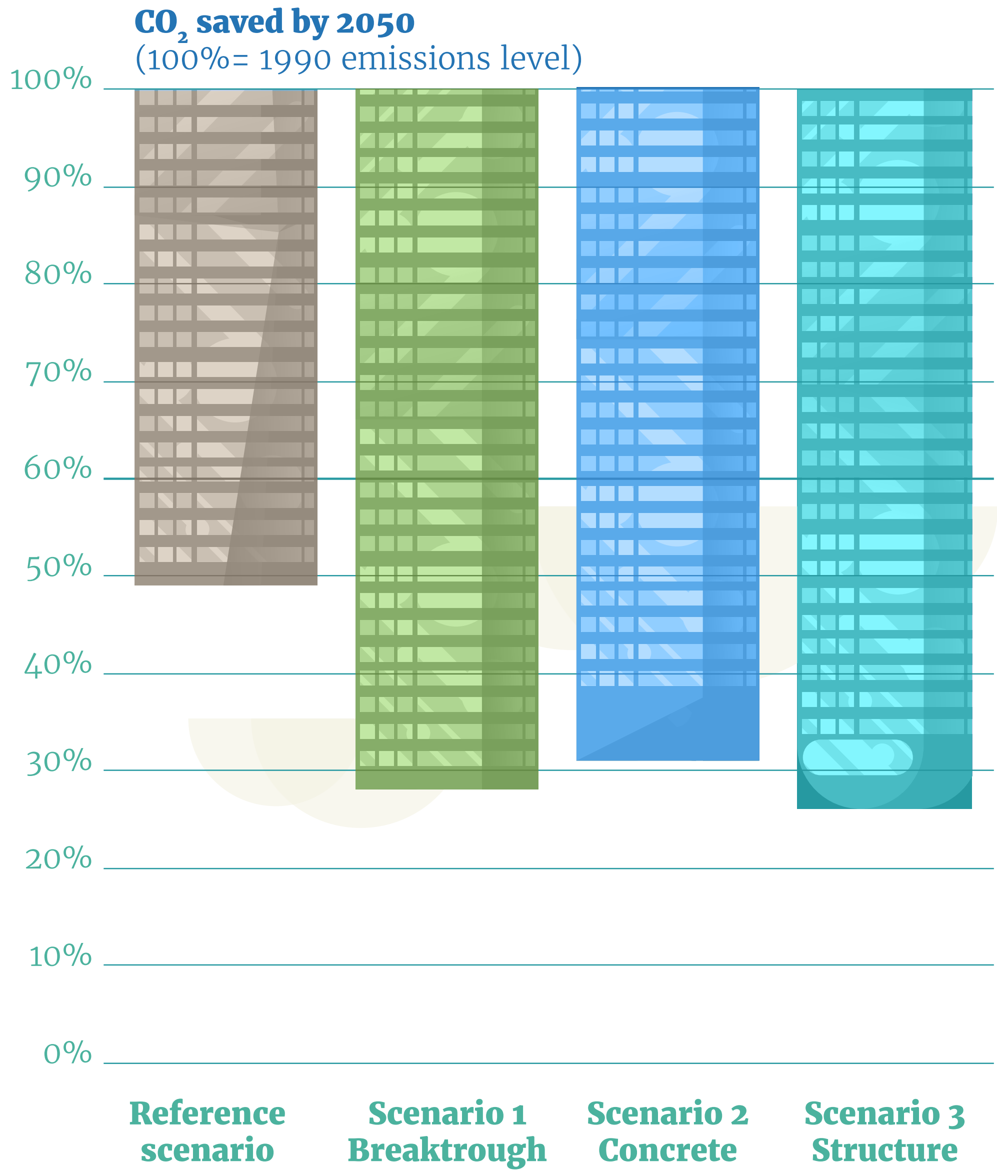
Scenario 2: “Efficient use and recycling” will require moderate investment distributed across the different actors; significant increase in the use of alternative fuels; recycling of concrete with fines reused as raw material for clinkers; optimisation of the concrete mix design via better aggregate packing and strictly **not** exceeding the requirements of codes and standards to avoid the over use of cement in concrete.

Scenario 3: “Structural optimisation and circular economy principles”, similar to scenario 2, will require slightly higher investment at the level of the structure (in particular the precast industry). In addition to concrete, the structure is also optimised, and consideration is given to reusing elements.

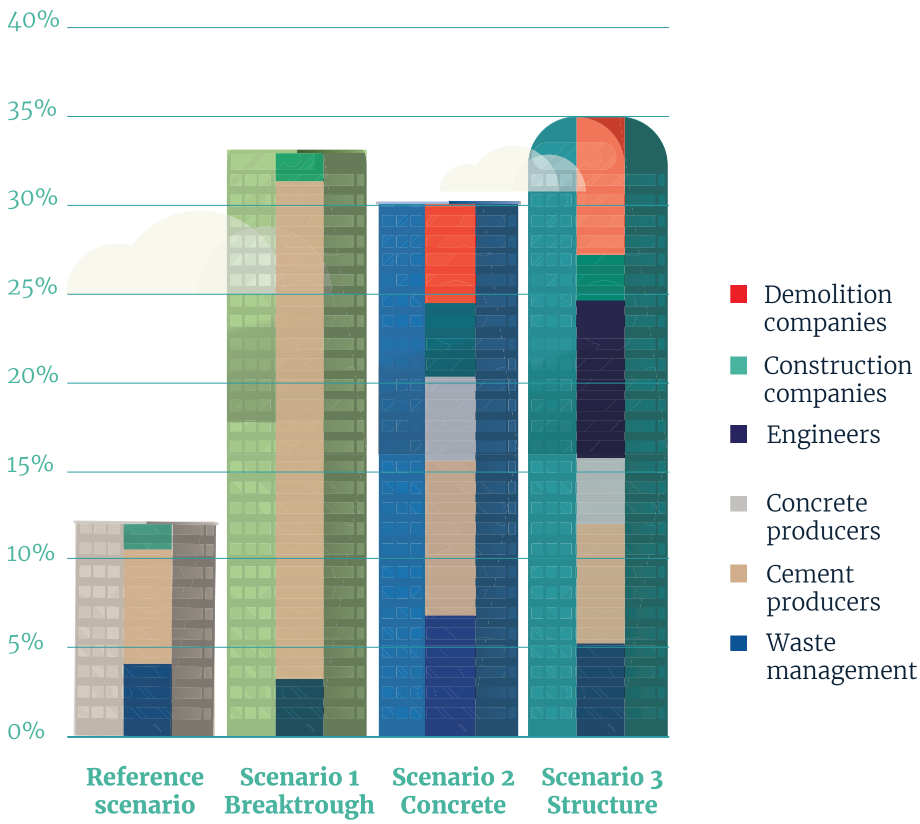
The figure below shows the final results for 2050 according to the scenario (figure a) and stakeholders (figure b from 2015 to 2050):

Figure 2 CO_2 savings by 2050 a) as a function of scenarios and b) as function of stakeholders

a)



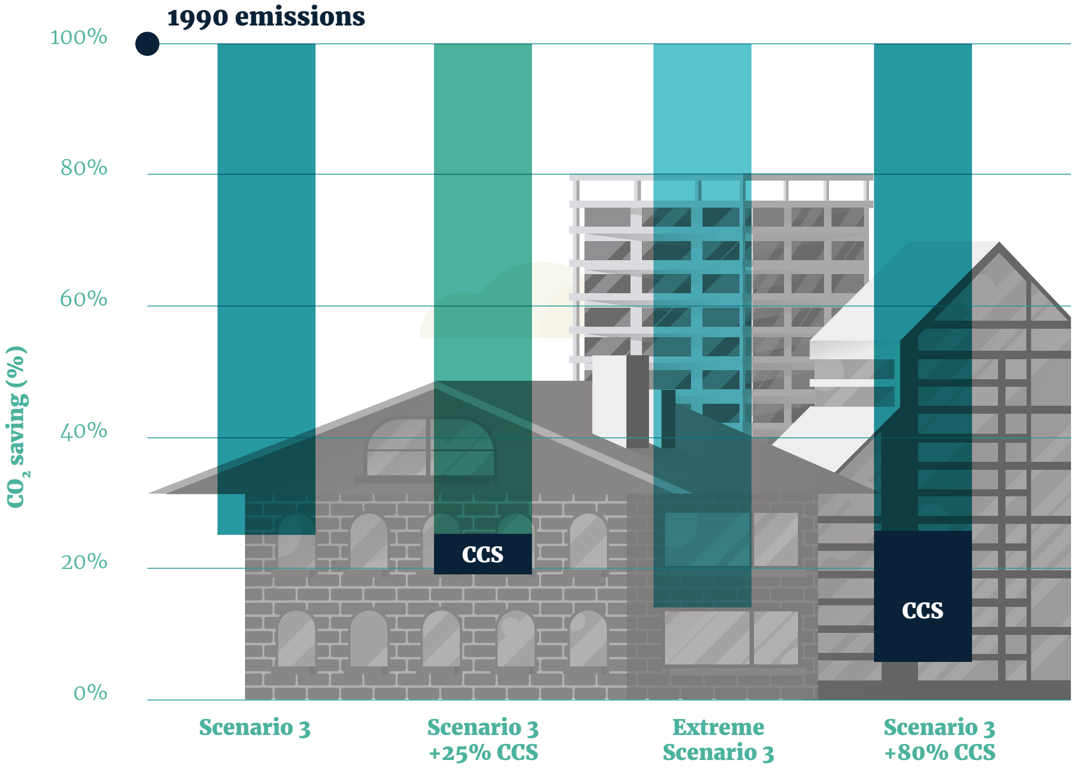
b) CO_2 emission reduction



Under the proposed scenarios, the pressure to reduce CO_2 emissions is based on different stakeholders. It is clear that to achieve the same reduction, the overall investment required in scenario 3 is very much lower than that required in 1, and the effort is distributed more evenly (figure 2b). The challenge will be to find incentives that can push this cooperation and integration. The reduction measures used in scenario 3 are mostly well known, and there are no major technical issues to their implementations. With this scenario, the reduction is close to a 2°C scenario. However, we think that the reduction measures in this scenario could be pushed even further if standards and norms are adapted. Moreover, net-zero emissions would be possible to reach if combined with the use of carbon capture and storage technologies.

Figure 3 shows that a 2°C target (80% emission reduction) can be achieved by combining extreme scenario 3 with 25% CCS or by "pushing" the savings in scenario 3 and 95% CO_2 reduction can be achieved compared to 1990 levels using 80% CCS. Net zero emissions are technically possible, but will require very large investments in the cement industry. The objective of carbon neutrality in the cement industry could also be achieved in combination with other sectors using less costly technologies, but this has not been assessed in-depth in this work.

Figure 3 How to achieve the 1.5°C and well-below 2°C target?



Summary of the key recommendations

To enforce the applicability of the structural optimisation and circular economy scenario, we propose incentives for policy makers. The main incentives are as follows:

At the clinker scale

Stakeholders	Suggestion
Cement producers	Introduce financial incentives to close old plants and implementation of stringent landfill regulations to increase the use of alternative fuels.

At the cement scale

Stakeholders	Suggestion
Cement and concrete producers	Incentive to invest in better grinders and clay calciners.

At the concrete and structure scale

Stakeholders	Suggestion
Concrete producers, engineering offices, demolition and construction companies	Encourage communication between all actors by: • Defining sustainable concrete and sustainable structures as criteria for awarding contracts; • Rewarding the use of low carbon concrete; and • Limiting total demolition via taxes and severe landfill regulations.

Finally, we propose to the stakeholders and policy makers the use of indicators at each level of the concrete value chain to directly involve the concerned stakeholder.

- For cement producers: a clinker with less than 0.7 t CO_2/tclinker
- For concrete producers: a standard concrete containing less than 3.5 kg clinker/m3/MPa
- For structural engineers: a structure containing less than 250 kg CO_2/ m2 of building
- For construction companies: a building containing less than 500 kg CO_2/m2

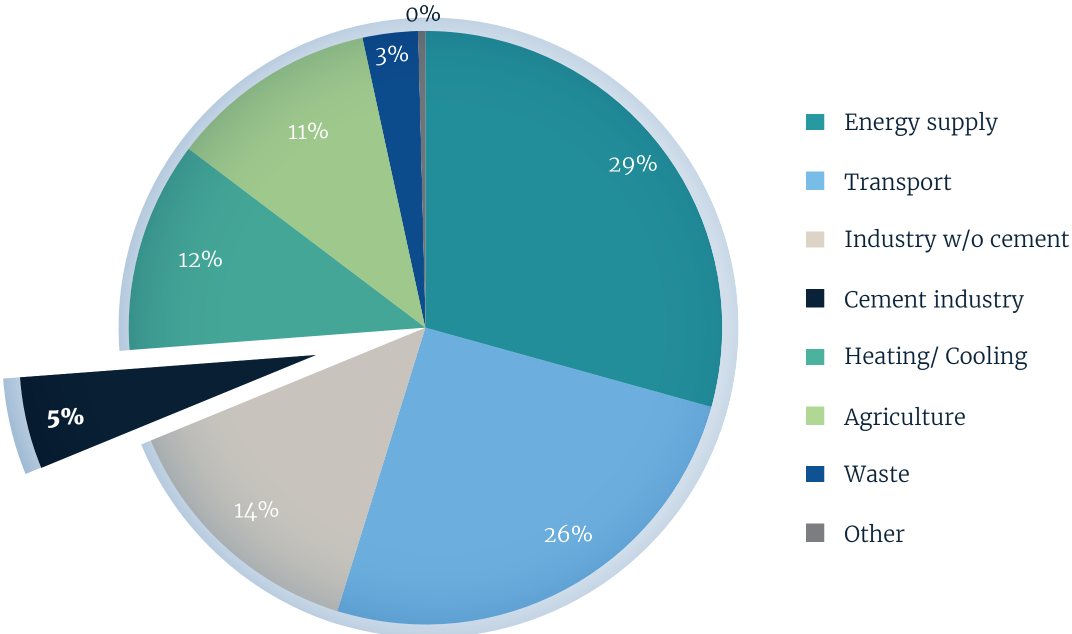
The upstream indicators and constraints for cement producers already exist considering the energy intensive EU regulations. Downstream targets also exist for construction companies considering sustainable building labels, but only on a voluntary basis. The middle stream indicators are lacking, and their enforcement would allow the involvement of concrete producers and engineering offices and the integration of the complete value chain into the common objective of fulfilling the Paris Agreement. These indicators are targeted for 2030 and should be regularly reviewed in line with latest scientific and technological developments at sectoral level.

Contents

1. Introduction

The construction sector provides 18 million direct jobs and constitutes approximately 9% of EU's GDP. However, the construction sector represents a major share of European greenhouse gas emissions (GHG). The two main construction materials represent approximately 10% of the total European CO_2 emissions. Cement production is responsible for 5% of CO_2 emissions, and the steel used in construction represents a similar amount [1].

Figure 1 EU OECD countries' CO2 emissions by sector (source:[2])



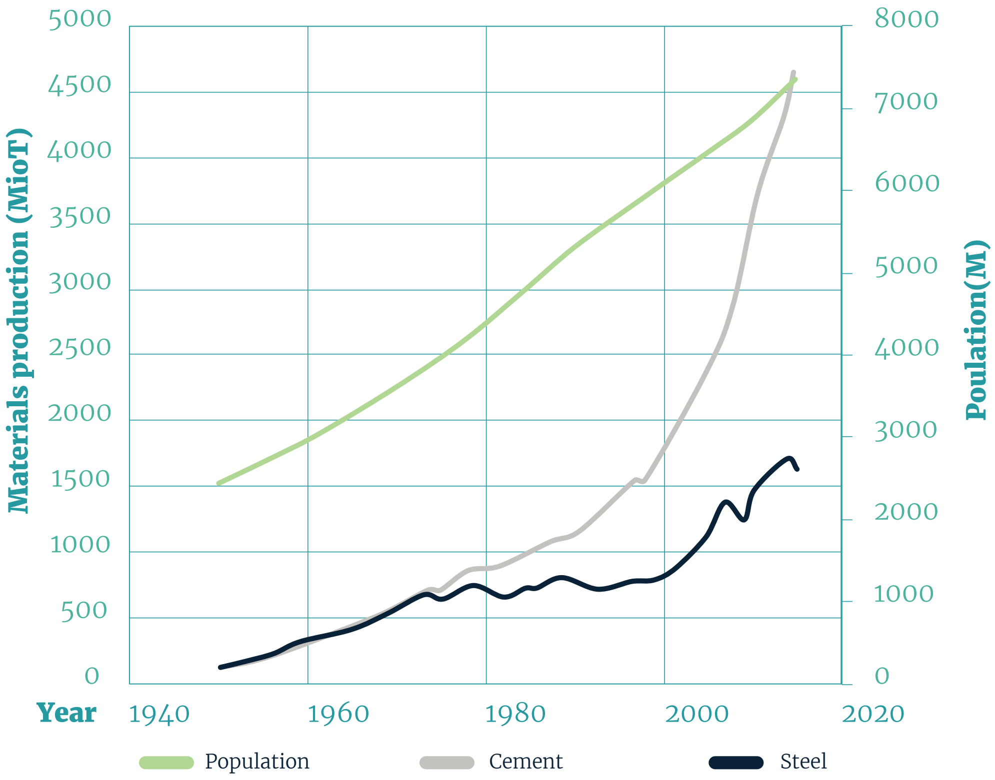
These materials are then incorporated into a multitude of construction products. Regarding cement, it is used in mortars and tile adhesives, concrete blocks and reinforced concrete. To date, the main efforts to reduce CO_2 emissions have focussed on the cement level; however, further savings can be achieved by considering the entire value chain, from cement production to its final use in the construction site in mortars and concrete. Furthermore, Europe is a very specific context for the construction industry: most of the building stock and infrastructure required by 2050 already exists. The population is expected to be relatively stable (although aging) and economic growth is expected to be moderate, which is in strong contrast to the rest of world, where the construction industry is booming due to economic and population growth. The objective of this report is therefore to identify the low carbon technologies for cement as well as for downstream products in the European context. To do so, we define scenarios and calculate the CO_2 saving potentials for the construction industry. We then provide recommendations for their implementation.

2. The European cement and construction sector

2.1. World situation and UNEP report

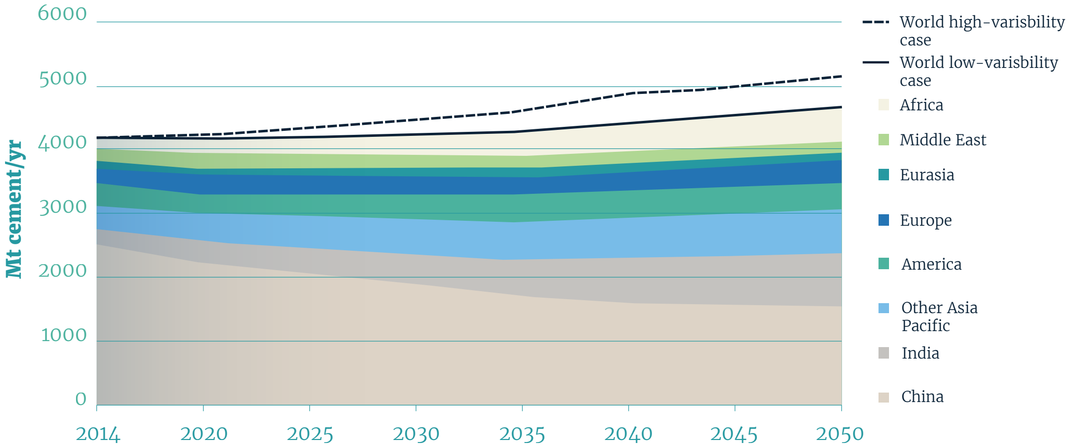
Between today and 2050, the world's population will increase from 7 to 9 billion [3], mainly in urban regions (Figure 2). The need for infrastructure and housing will increase, leading to an increase in demand for energy and materials. This increase will take place in a context in which resources are already limited and the effects on climate are extremely difficult to mitigate.

Figure 2 Production of cement and crude steel with population [4]



In 2015, a group mandated by UN Environment published the report "Eco-Efficient Cements" [4]. This report explains the central role cementitious materials play in our modern societies, as these materials constitute more than half of all manufactured materials. This report stresses that the majority of the growth in cement demand will happen in emerging countries. As an example, the demand will increase by 2 or 3 times in India during the next few decades (Figure 3). This increase in cement demand would have drastic consequences in term of CO_2 emissions and resource depletion if the current industrial trend continues.

Figure 3 Projection of cement demand from the IEA-CSI report[5]



The report argues that action at the level of cementitious materials has the potential to deliver a major contribution to climate change mitigation. The report shows that there are low cost solutions available and usable everywhere by low skilled workers and should be pushed forward by all governments and industry representatives.

The UN report "Eco-efficient Cement" identifies two main routes that can fulfil the demand and deliver CO_2 reductions in the relatively short term, which are as follows:

- increasing the substitution of clinker by supplementary cementitious materials and
- making more efficient the use of cement in downstream products (mortars, concrete).

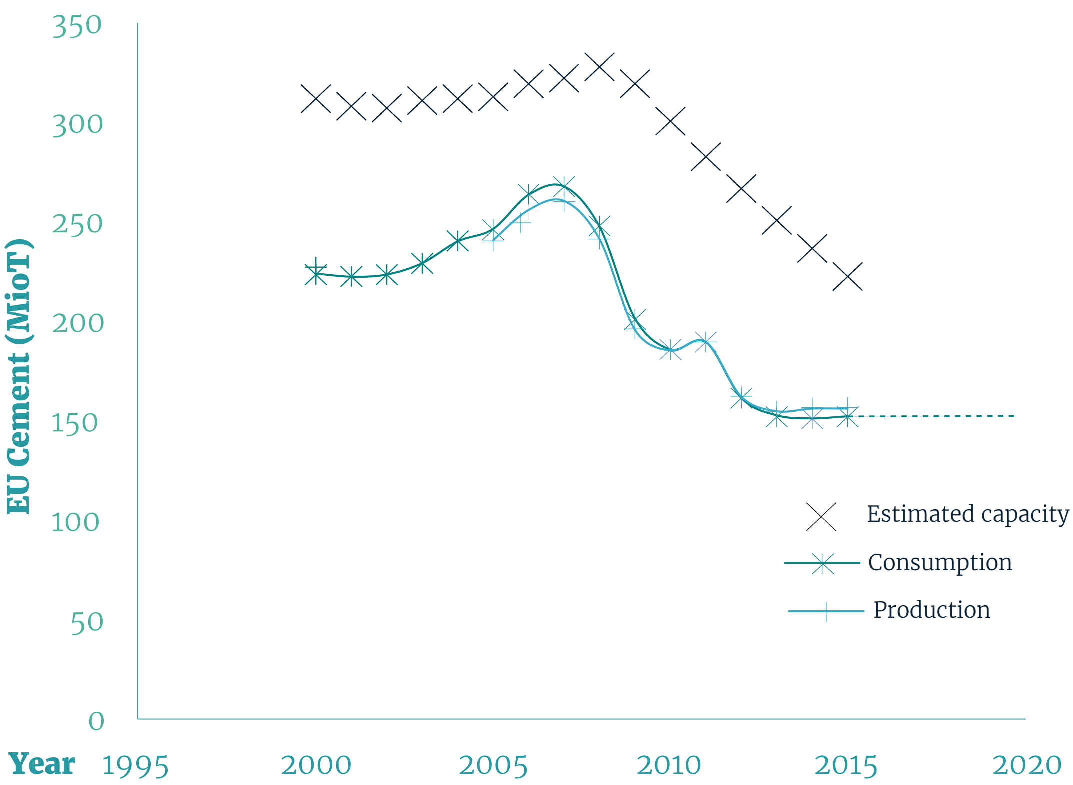
In the long term, breakthrough technologies such as carbon capture storage will have to contribute to fully decarbonise the sector, but within the short time gap between now and 2050, and considering that most of the construction growth will happen during this period, these technologies cannot be implemented at the required pace and will play a significant role in the long term, while the low carbon solutions identified in the UN report can already be implemented at the required scale.

2.2. The European situation

In Europe, one can expect a very moderate growth in cement demand. Eurostat's projections indicate that the EU-28's population will grow overall by 3.7 % by 2045 [6] and economic activity, if sustained at the current rate, will stabilise between 1 and 2% per year [7]. As a consequence, the cement demand, which has been stable (even decreasing) over the last 20 years, is projected to remain stable for the coming decades [8]. Finally, as the production of cement has been decreasing since 2007 (Figure 4) and despite efforts to reduce the production capacity, there remains an overcapacity in the cement sector.

Considering Europe's slow economic growth, stable population, the existing over production capacity and the focus of the European Commission to reduce public deficit, it is likely that large capital investment from private or public institutions in the cement infrastructure will not occur in Europe, even if the cement demand in the rest of the world is increasing.

Figure 4 Projection of cement demand from the IEA-CSI report[5]



In 2011, the European Commission [10] redefined its commitment to reduce GHG emissions by 40% by 2030 and 80-95% by 2050 compared to 1990. These objectives and strategies are currently under revision to fully align the European Union's climate action efforts of the Paris Agreement (2015). To meet a 1.5°C target, all sectors must fully cut their emissions, especially the energy, building and industry sectors. Although it is a mature market in Europe, the construction sector is an important player to meet the commitments to GHG reduction in the Paris Agreement. With this perspective, many associations and stakeholders have analysed potential solutions to reduce GHGs in the construction industry, notably the European association of cement producers, CEMBUREAU. In 2013, CEMBUREAU [11] proposed five routes for cement and concrete industries that would lead to a significant reduction of the carbon footprint: resource efficiency, energy efficiency, carbon sequestration, reuse, product efficiency and downstream applications. However, breakthrough technologies, such as carbon capture and storage, would have a major impact on the cost of cement production. One can question the feasibility of this scenario considering the previous assessment of the European economic situation and the likelihood of limited investment.

Therefore, carbon storage ambitions need to be pursued, but with the objective of being effective for post 2050 targets (2100), and we urgently need solutions that can be implemented massively within the next ten to twenty years to fulfil the Paris Agreement to stay within a 1.5°C scenario.

3. Levels of intervention for CO_2 reduction

Four strategies can be identified to reduce CO_2 emissions in the concrete industry, as follows:

- Reduce CO_2 emissions from **clinker** production by improving the energy efficiency of cement plants. This strategy includes improving the thermal efficiency of the kilns and increasing the use of alternative fuels.
- Reduce CO_2 emissions from **cement** by reducing the clinker content. This strategy mainly consists of substituting a part of the clinker with supplementary cementitious materials at the cement production level but also at the concrete production level.
- Reduce CO_2 emissions from **concrete** by reducing the cement content. This strategy looks at the mix design of concrete and the quantity of the binder phase as well as the quantity and quality of the aggregates.
- Reduce CO_2 emissions from **structures** by adapting the concrete mix design and the element shape to the final application. Two aspects are taken into account, i.e., reducing the quantity of concrete to manufacture a structural element or a standard residential building in the first place and reducing the amount of concrete if the shape of an element is optimised to meet the same structural load requirements.

All of these strategies can be combined as follows: the use of less fossil fuel for clinker production combined with the use of less clinker in cement and less cement in concrete and, finally, the use of less concrete per structure or m^2. The result is that the same level of services is provided to society but with much less CO_2 emissions due to the lower clinker use.

4. Technologies applicable at the different levels

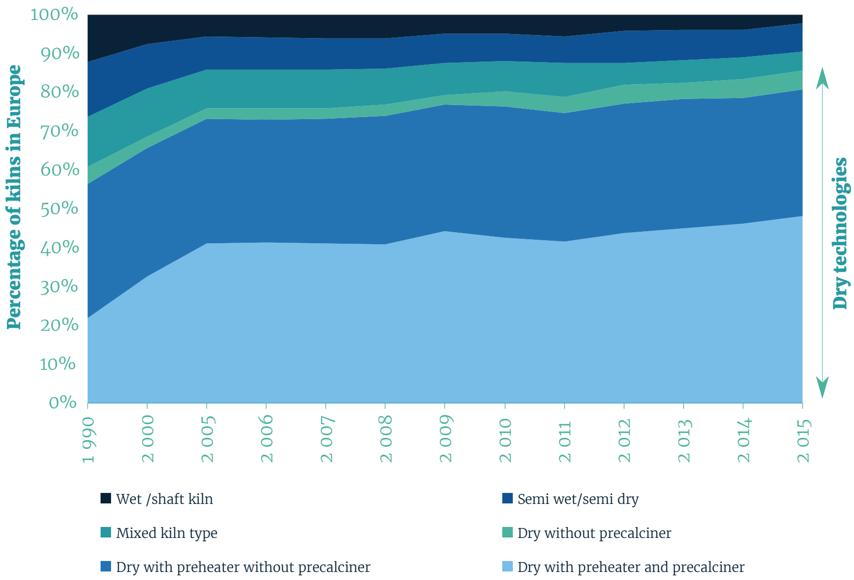
4.1. Clinker level

Clinker is the active component of cement and is produced by calcining limestone and clay at 1500°C. The cement industry has been active in the past decades in improving the efficiency of clinker production. Clinker production is an energy intensive process and produces approximately 875 kgCO_2eq/t clinker. 30%- 40% of CO_2 emissions are coming from the energy required to heat limestone and clay at 1500°C, while 60%-70% of the emissions are linked with the chemical reaction of the decarbonisation of limestone. The first level of action has been to reduce the CO_2 contribution from energy.

Energy efficiency

The energy required for clinker production has been significantly reduced over the time, especially since the energy crisis in the 70's[12]. Technologies where raw materials are introduced in a dry stage are more energy efficient than wet processes. Therefore, wet kilns have been gradually replaced in EU by the dry kiln process combined with heat recovery technologies that allow for preheating and precalcining of the raw material before entering in the kiln (Figure 5). As old kilns have already been replaced, improvement in kiln technologies are reduced and the new IEA CSI roadmap estimates that a 10% improvement can be made by 2050 in the best case scenario at the global level.

Figure 5 Evolution of cement kiln technologies [13]

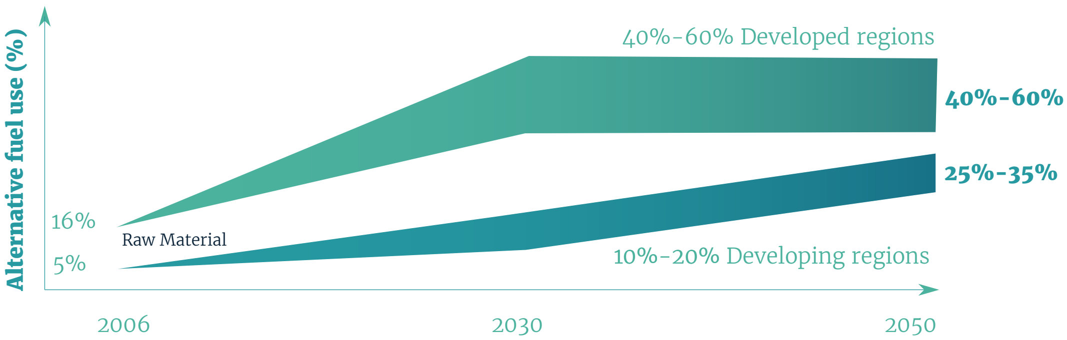


The best available technologies in modern cement plants are based on dry kilns with pre heaters and precalciners that require 3000 MJ/t clinker. The energy efficiency of an EU cement plant is currently approximately 3300 MJ/t clinker. Finally, it has to be noted that waste heat recovery is a technology where there is room for progress. In Europe, plants may be retrofitted with this technology. The cost of the initial investment and the dependence on local electricity costs are barriers to the more widespread uptake of this technology.

Alternative fuels

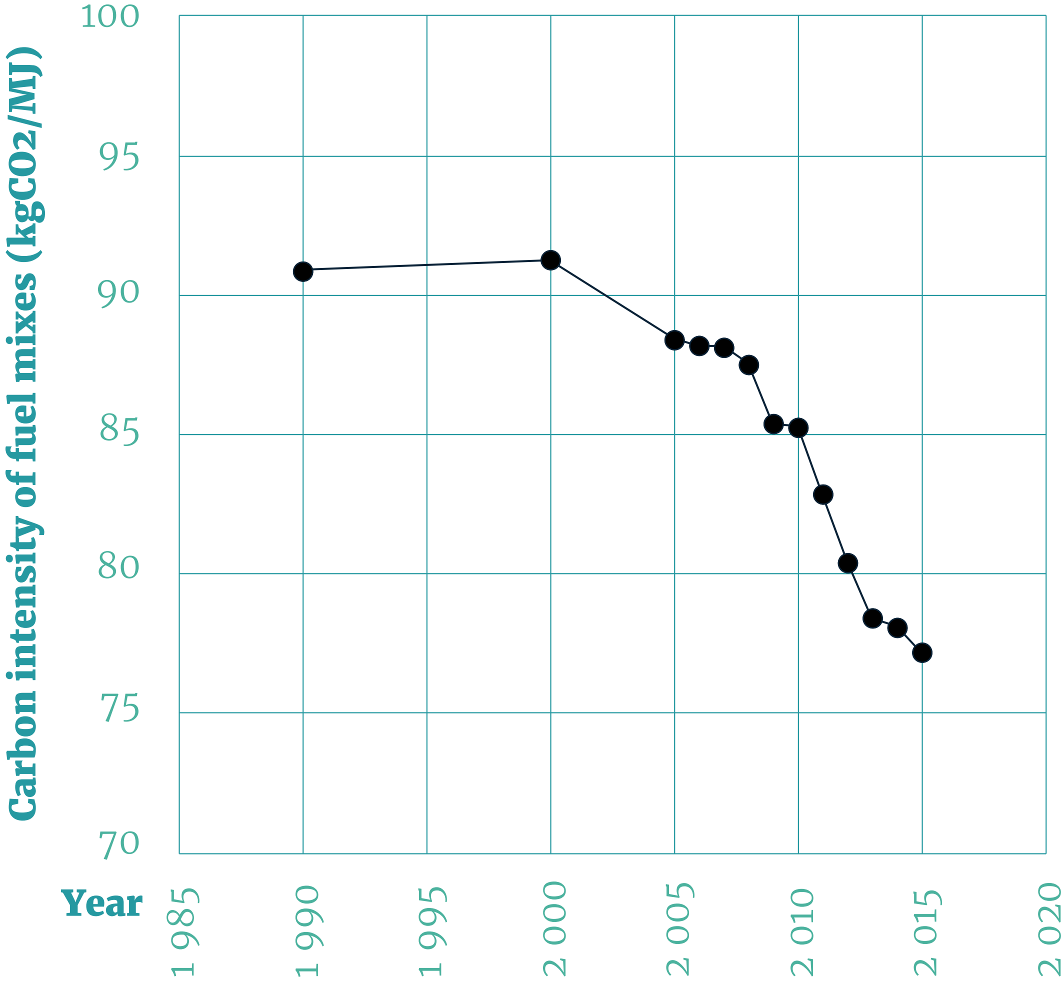
The use of alternative fuels and raw materials for cement clinker production is of major importance. Currently, the fuel source is a mix of coal, pet coke, biomass and waste materials. In Europe, the cement industry has replaced a part of its traditional fuel sources with biomass, which involves a significant reduction of CO_2. The cement industry was using three times more biomass in 2010 than in 2000.

Figure 6 Forecast of alternative fuel use in cement technology by region. Europe is part of the developed region in the forecast for alternative fuel use by 2050 (Source: [5,14,15])



Further improvement can be made [11]. Actually, much higher substitution rates are technically possible, but several factors limit the use of alternative fuels. First, the calorific value of most organic materials is relatively low, and additional treatment may be needed. Second, the availability of waste is dependent on the local waste legislation. Third, an important limiting factor is the potential impact on clinker chemistry, e.g., increase in phosphate by use of sewage sludge, increase in chlorides when waste plastics (PVC) are used, etc. Finally, a higher CO_2 price may increase the global demand for biomass, for which cement companies will then compete with heat and electricity producers.

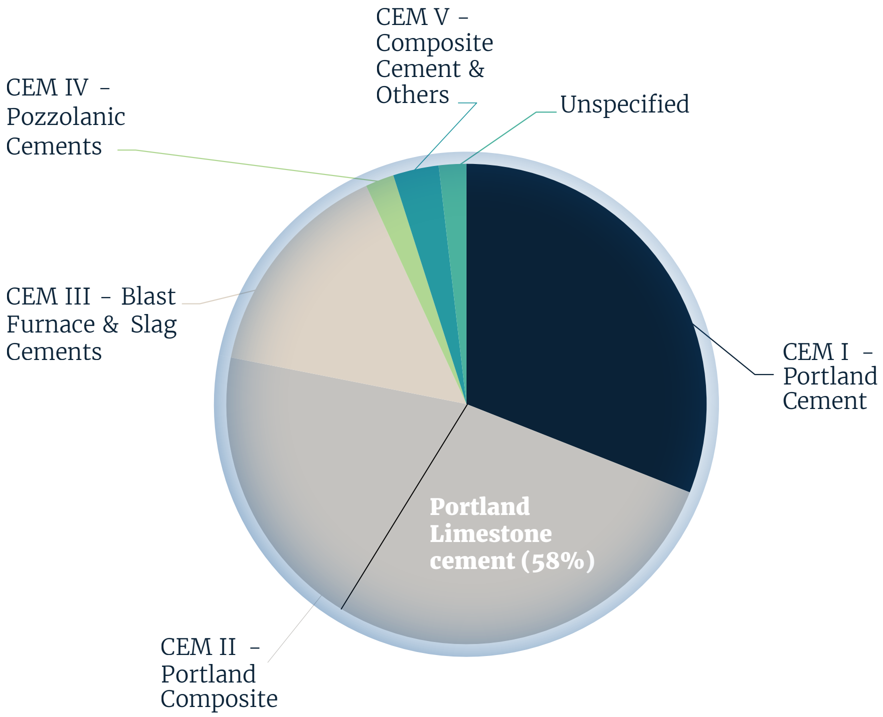
Figure 7 Carbon intensity of the fuel mix in Europe - Data from WBCSD GNR [16]



4.2. Cement level

The so called CEM I (ordinary Portland cement) contains 95 % clinker. European standards EN197-1 allow other cement types with a clinker to cement ratio varying from 5% to 95%. In the other cement types (Figure 8), a part of the clinker has been substituted by a product that does not require the same energy intensive production process. These products can be waste or by-products from other industries, such as fly ash from coal power plants or blast furnace slag from the iron industry. These products can also be natural materials, such as natural pozzolans or even just ground limestone. These substitutions drastically reduce the energy required to produce the cement and therefore the CO_2 emissions. Today in Europe, the average clinker to cement ratio (also called clinker factor) over all cement types is equal to 0.73. The most sold cement type is CEM II-A, where clinker is substituted with limestone up to a maximum substitution of 20%. 47% of the cements sold in Europe are CEMII Portland composite cements mostly substituted with limestone.

Figure 8 Cement type sold in Europe in 2015 (Source: Cembureau)



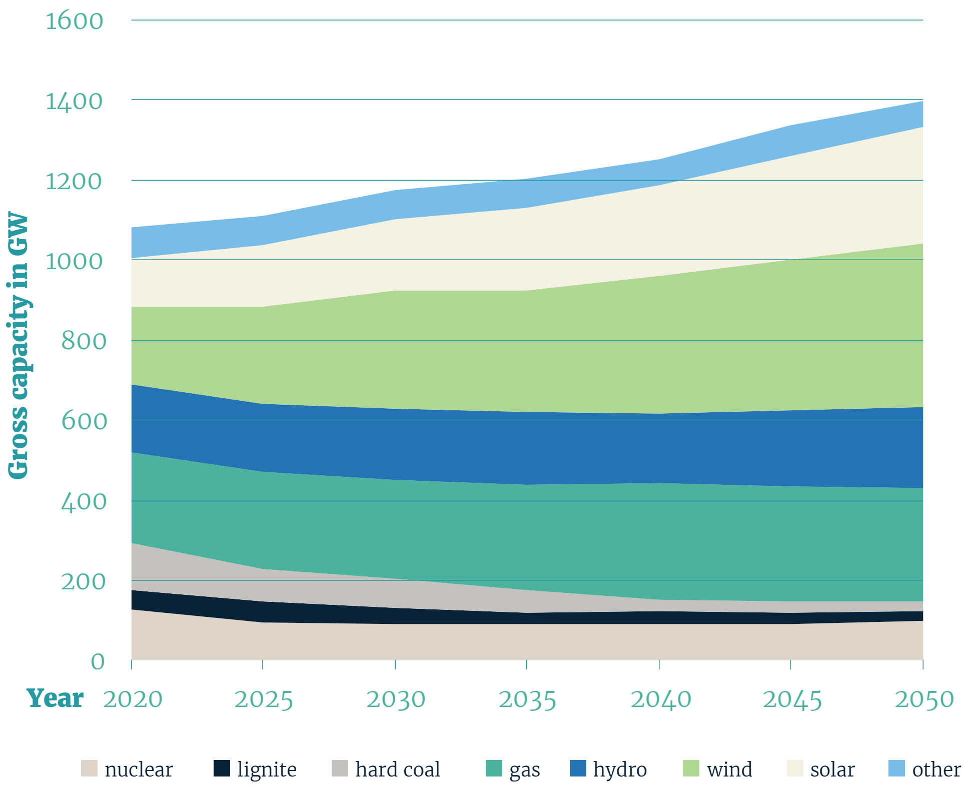
Variations in the clinker content influence the type of applications the cement can be used for. Different supplementary cementitious materials (SCMs) can give particular properties. Part of the substitution may also take place at the concrete production stage. In ready-mix concrete, the cement factor is currently approximately 0.8 and the main additions are slag, fly ash, limestone and silica fume.

Availability of SCMs

We can consider six classes of alternative materials to substitute for clinker. These are discussed below according to the level of their current use as substitute materials:

- **Limestone** is the most widely used SCM, currently, in Europe and worldwide. Limestone is simply ground without heating, is abundant and is easily accessible to most cement plants. However, the substitution potential of limestone is relatively low as only small amounts react, due to the limited availability of alumina in cement. Nonetheless, the potential of limestone increases significantly when it is used in ternary blends with other aluminium rich additions, such as calcined clay, burnt oil shale, and fly ash.
- **Fly ash** is used in significant amounts in concrete worldwide to replace clinker and thereby lower CO_2 emissions. Fly ash comes from the coal power industry and represents the mineral residue once the organic material has been burned. Fly ash may be siliceous or calcareous, showing different reactivity in cement. Approximately 34 Mio tons of fly ash were produced in Europe in 2013 and 4.7 Mio tons of bottom ash (source: ECOBA[1]), which correspond to 74 % of the total of coal combustion products (CCP). Almost 90 % of CCP has already been valorised by the construction industries and their availability is planned to decrease with the closing of coal power plants. Figure 9 represents the electricity energy mix, including the share from hard coal and from lignite. Both sources were already low in the energy mix and will be reduced by 2050 [17]. In 2050, a production of approximately 23 Mio tons of fly ash can be expected, which is insufficient to increase the substitution of clinker by fly ash.

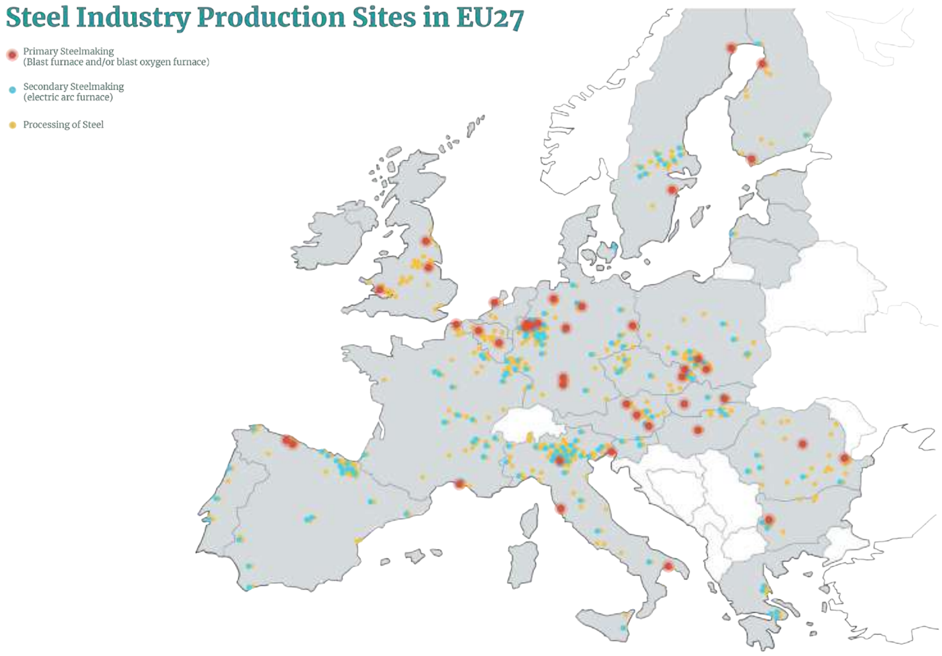
Figure 9 Fuel mix forecast in Europe from Energy Brainpool [17]



[1] ECOBA : European Coal Combustion Products Association

- The production of **blast furnace slag (BFS)** was equal to 24.6 Mio tons in Europe in 2016. More than 80% is already used in cement or concrete (Source: Euroslag[2]). In 2016, we used in total 25.8 Mio tons (5% coming from interim storage), which is already more than the European production (implying import of slag from other regions). The availability of BFS is linked to the steel industry and production in Europe is not forecast to increase. Moreover, Figure 10 shows a map of blast furnaces in Europe (red dots). It is observed that these furnaces are not homogeneously distributed in Europe. A future increase in use of BFS would require significant imports, but possibilities are still limited, as the worldwide level of BFS production covers only 8% of the cement demand and the proportion already used in cement and concrete in Europe is close to 80%.

Figure 10 Map of the steel production sites in EU 27. Red dots correspond to the production sites of blast furnace slag [18]

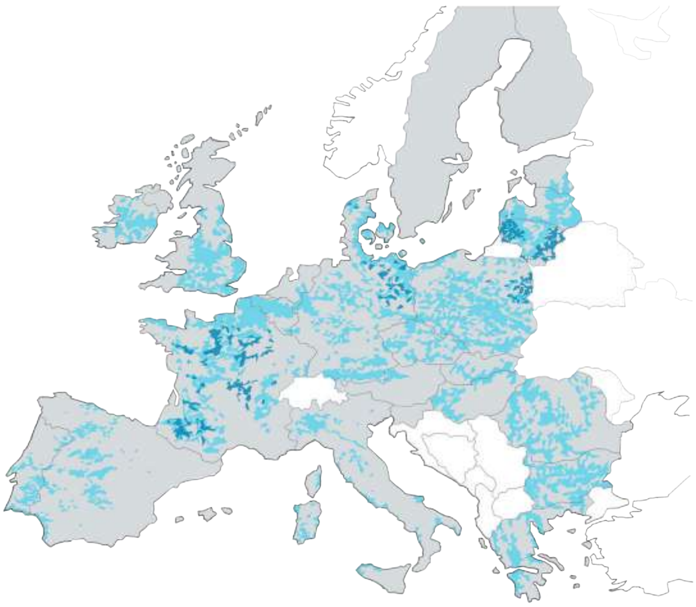


- **Natural pozzolans** (**called P** in EN 197-1) are mainly volcanic ashes, and their use is relatively common in some areas of Europe, where they are available, i.e., mainly southern regions, such as Italy, Greece, and Slovenia. According to the European standard EN 197-1, various cement types may contain natural pozzolans from 6 to 55 mass%; however the proportion of pozzolans is usually in a range of 15 to 35 mass%. In 2003, only approximately 150 Mio tons were used worldwide in cement and concrete industries [19]. The reserves are not known, but only a slight increase is assumed. Further increased use of pozzolans for cement manufacturing will also imply larger transport distances.

[2] Euroslag : European association of organisations and companies concerned with all aspects of manufacturing and utilisation of ferrous slag products

- **Burnt shale (T)** is also used in Europe, and the availability is estimated to be important. According to the European standard EN 197-1, the production of various cement types containing natural pozzolans from 6 to 35 mass% is possible. However, it is the by-product of the shale gas industry, whose exploitation raises important unresolved questions in Europe in term of social acceptance.
- **Calcined pozzolans (Q)**, such as calcined clays, require an "activation" treatment (thermal or mechanical). This means there are some CO_2 emissions associated with their production, but this may be offset by their high reactivity, which allows high levels of substitution. Today their use is limited in Europe as they have not been economically competitive compared to slag and fly ash. However, this situation is likely to change in the future due to the limited availability of slag and fly ash and the discovery that higher levels of clinker substitution are possible with a coupled substitution of calcined clay with limestone. It is now widely accepted that a ternary blend (clinker, limestone, calcined clay) allows for 50% substitution with strength comparable to CEM I [20,21]. Furthermore, low-purity clays that cannot be used by other industries (ceramic, gravel…) can be used in these ternary blends. Recently, Scrivener and co-workers demonstrated the real potential of low quality or overburden clays as artificial pozzolans in ternary blend Limestone Calcined Cements LC^3 [22–24]. However, even if the clay availability in Europe is important, as shown on the map of clay soils suitable for SCM in Europe (Figure 11), the size of the quarries and the logistics for the supply of large cement plants can be difficult.

Figure 11 Repartition of argilitic soils in EU 27 from Portail Européen des Sols. The areas in blue are clayey soils except soils containing smectites (called albeluvisol, luvisols and acrisols). The blue areas are suitable for SCM use.



Dredging sediments are also a potential resource, as Europe generates approximately 300 Mton/yr of dredging sediments (expressed on dry base). Finally, other by-products from industries can also be used as substitute materials, such as vegetable ash and wood ash, but the availability is low, and the quality is variable. It is crucial to understand that a viable SCM source is ideally a product available in large quantities and with a constant composition. Deviation from this ideal case requires higher costs in supply chain management and quality control.

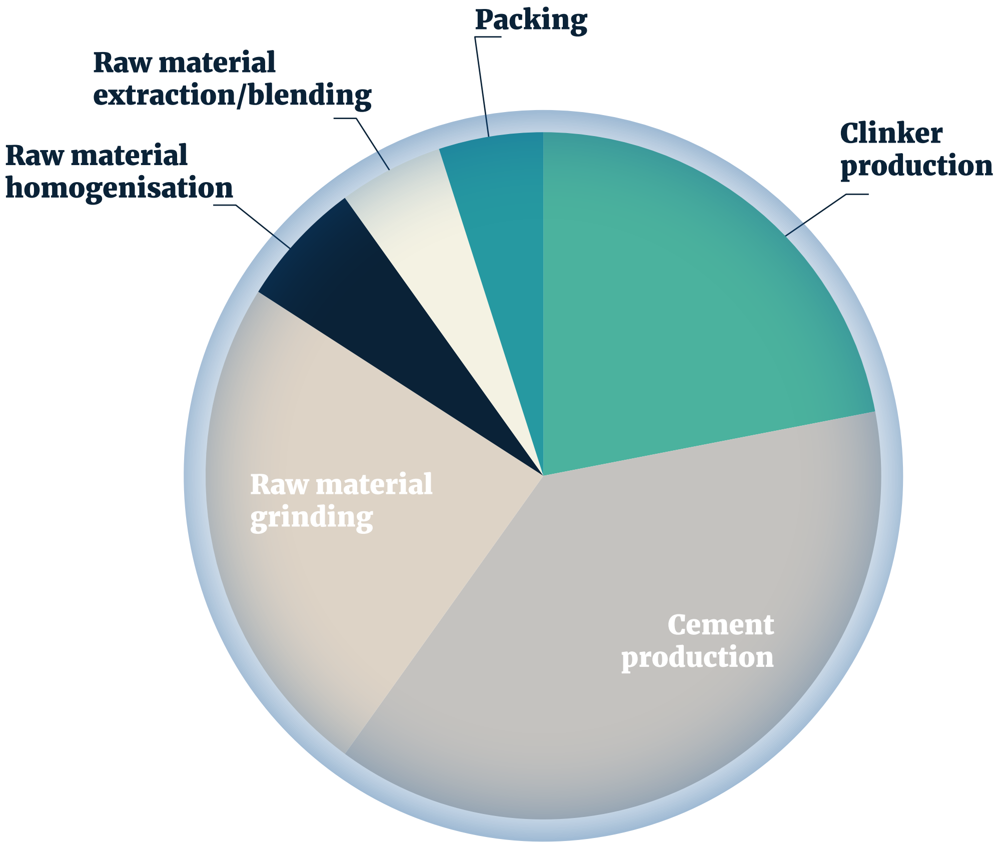
Improving reactivity with efficient grinding and separated grinding/blending of blended cements

The main hurdle of clinker substitution of SCM is the low early strength development of the blended cements. Finer grinding can help to improve this early strength development, but a compromise needs to be found to avoid detrimental effects on workability. Nevertheless, there is room for considerable improvement in the performance of blended cements by optimising the particle size distributions of the different components, which will require high performance grinders and separate grinding of each component.

Ball mills are the traditional grinding technology. They have been improved by adding a separator in the closed circuit [25]. Furthermore, high pressure comminution systems, such as vertical rolls mills (VRMs) or high pressure grinding rolls (HPGRs), are slowly replacing grinding by ball mills and could be further implemented. Separate grinding allows a better-controlled particle size distribution, giving the best compromise between workability (water demand) and strength development. The limitation in using separate grinding or improving the actual technology is the investment cost. VRMs and HPGRs cost approximately 30 Mio€ for a new installation and approximately 6 Mio € for a retrofitted technology [14].

Grinding remains the biggest source for electric energy consumption in a cement plant, which means that additional grinding has a direct impact on the electricity costs of the cement plant. Considering the CO_2 emissions, the impact of energy is negligible compared to the impact of calcination[26], but considering the economic costs, extra grinding has a consequence on the operational costs.

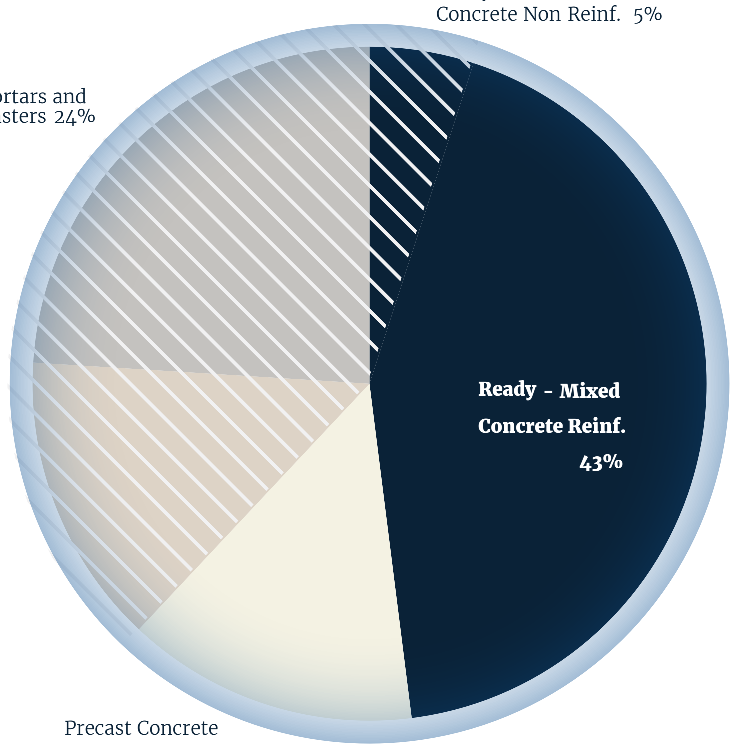
Figure 12 Electrical energy demand for cement production [11]



4.3 Concrete level

Concrete has a low embodied carbon coefficient compared to other common construction materials, with, on average, 200 $kgCO_2eq$ /t of concrete. For example, in contrast, recycled steel emits 1100 $kgCO_2eq$ by tonne of steel produced. However, for the same purpose, you will need more concrete than steel. The question of improving the environmental performance is more a question of improving the efficient use of cement in concrete. It is important to look at the whole life cycle to understand how cement is used in concrete. In Europe, half of the cement is used in non-reinforced structures where there is a higher potential of substitution without risk of serious durability problems. On the contrary, improving the mix design of reinforced concrete needs to be more carefully considered due to safety and durability concerns. The mix design of reinforced concrete is also more sensitive to a reliable supply of aggregates, admixtures, cement and additions.

Figure 13 Use of cement in downstream products in Europe (2015). The hatched area corresponds to unreinforced applications (Source: Cembureau, ERMCO[3], and BIBM[4]).



It is observed that in ready mix concrete, on average, 20 % of the cement (CEM I or CEM II) is substituted by additional materials, including mainly fly ash, slag, silica fume and inert fillers. The limitations are similar to those at the cement scale, as follows: low early strength development slows down the construction process and creates productivity losses; and lower workability may involve an increase in admixtures (and therefore costs) or water on the construction site (and therefore strength loss). As a consequence, the use of blended cements is excluded in parts of Europe for certain concrete exposure classes because of the lack of building experience within the scope of the respective national annexes to concrete standard EN 206-1 and because there have been no scientific investigations into the use of these cements. Müller et al. [27] combined national specifications, as shown in Table 1. For example, Denmark allows a low cement content of 150 kg cement/m3 of concrete but has a high restriction concerning the cement type. It is therefore difficult to have a common European rule in terms of the amount of clinker that can be substituted.

[3] ERMCO : European Ready Mix Concrete Organisation

[4] BIBM : European Precast Association

Table 1 National annexes to the norm EN 206-1 for the choice of cement as a function of the exposure class[27]

Country	Exposure class	min f_c	max $(w/c)_{eq}$	min c	CEM I	CEM II																		CEM III			CEM IV		CEM V	
				kg/m³		S		D	P/Q		V		W		T		LL		L		M									
						A	B	A	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	C	A	B	A	B
Austria	XC1+XF1	--	0.55	300	x	x	x	x			x	x	(x) 2)						x	(x) 2)		(x) 2)	x	(x) 2)					
Belgium	EE3 (XC4+XF1)	C30/37	0.50	320	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				
Czech Republic	XC1 to XC4 or XF1	C30/37	0.50 or 0.55	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x					
Denmark	(XC2, XC3, XC4, XF1, XA1)	C25/30	0.55	150 3)	(x) 4)						(x) 4)	(x) 4)					(x) 4)			(x) 4)									
Finland	XC3 or XC4, XF1	C25/30	0.60	250 5)	x	x	(x) 6)	x			x	(x) 6)					x 6)				x	(x) 6)							
Germany	XC4 + XF1	C25/30	0.60	280	x	x	x	x	x	x	x	x	O	O	x	x	x	O	O	O	(x) 7)	(x) 7)	x	x	O	O	(x) 8)	(x) 9)	(x 9)
Ireland	XC2 or XC4 + XF1	C30/37 if XC4 + XF1	0.55	320	x												x		x										
Italy	XC1	C25/30	0.60	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	XC2 + XF1	C32/40	0.50	320	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Luxembourg	XC4 + XF1	C25/30	0.60	280	x	x	x	x		x					x		x				(x) 10)		x	x					
Netherlands	XC3	--	0.55	280	x	x	x				x	x			x	x							x	x					
	XC4 + XF1	--	0.50	300	x	x	x				x	x			x	x							x	x					
Norway	XC4 + XF1	--	0.60	250	x	x		x			x						x		x										
Portugal	XC4 + XF1 11)	C30/37	0.60	280	x	x		x	x		x		x		x		x		x		x								
			0.55	300	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	(x) 12)			(x) 12)	(x) 12)	(x) 12)	
Sweden	XC4, XF1	--	0.55	300	x 4)	x 4)		x 4)			x 4)						x 4)				(x) 4)		x 3)	x 3)					
Switzerland	XC4 + XF1	--	0.50	300	x	x		x									x				(x) 4, 13)								
United Kingdom	XC3/4 + XF1	C28/35	0.60	280	x	x	x	x		x	x						x	x	x	x			x	x					

x allowed
(x) allowed with restrictions
not mentioned
O not allowed

Sources: [2, 9, 10]

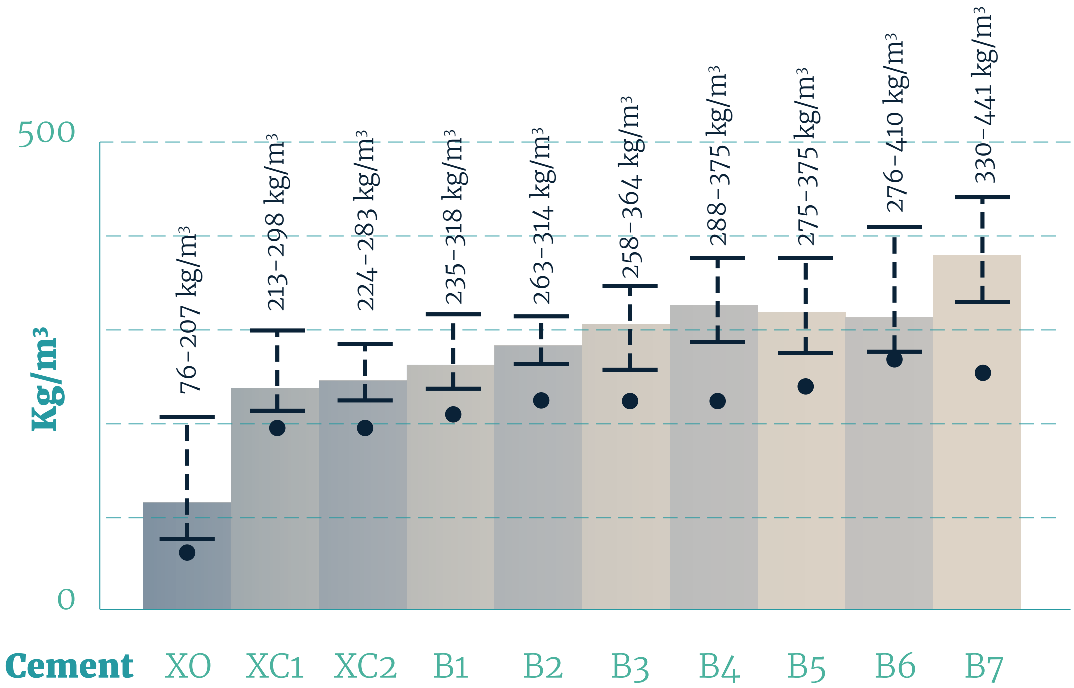
1) Due to the complexity of the national annexes, this compilation is not exhaustive and the accurate repetition of all specifications cannot be guaranteed.
2) Cements need testing
3) min filler: 375 kg/m³
4) Minimum strength class 42,5
5) min c = 270 kg/m³ for XC4
6) Cement not approved for XC4)
7) Only CEM II/A-M (S-D; S-T; S-LL; D-T; D-LL; T-LL; S-P; S-V; D-P; D-V; P-V; P-T; P-LL; V-T; V-LL) and CEM II/B-M (S-D; S-T; D-T; S-P; D-P; P-T; S-V; D-V P-V; V-T)
8) Only CEM IV/B (P) and valid only for trass according to DIN 51043, used as a main constituent up to a maximum content of 40 % (m/m)
9) Only CEM V/A (S-P) and CEM V/B (S-P) and valid only for trass according to DIN 51043
10) Only CEM II/A-M (S-D; S-T; S-LL; S-V)
11) Assumption
12) Not less than 50 mass% clinker
13) Only CEM II/A-M (D-LL)

However, it seems that the construction community agrees that it is possible to achieve savings by better respecting these norms, which can be done at two levels.

The first level is the difference between the field reality and what is required in the standards concerning the amount of cement per cubic metre. There is often 20% more cement in the concrete mix than what is required by the standard. The study performed by Passer and co-authors [28] confirms this statement for concrete produced in Austria

(Figure 14). Mix designs systematically contain too much cement, which can be explained by the fact that concrete producers want to reduce the risk and have an error margin (of 20%) or want to be sure that the concrete still has the appropriate strength even with the addition of uncontrolled extra water to the construction site.

Figure 14 Quantity of cement per cubic meter of concrete as a function of the exposure class in Austria. Black dots represent the quantity of cement specified in the Austrian national standards. The bar charts with uncertainties represent the effective mix design produced in Austria.



The second level of saving is on the choice of the exposure class. Actually, the engineers and designers working on a project will often specify only one single concrete exposure class, which will then be the most conservative. However, for a house, the exterior concrete and the interior concrete are not subject to the same constraints. As an example, if a house is built with a distinction between indoor concrete, where exposure class XC1 C16/20 would be sufficient, and concrete exposed to external weather, which could be consist of XC4 C25/30, 20 kg of cement per cubic meter can be saved compared to the current classic solution in which all of the concrete will be specified as XC4 C25/30.

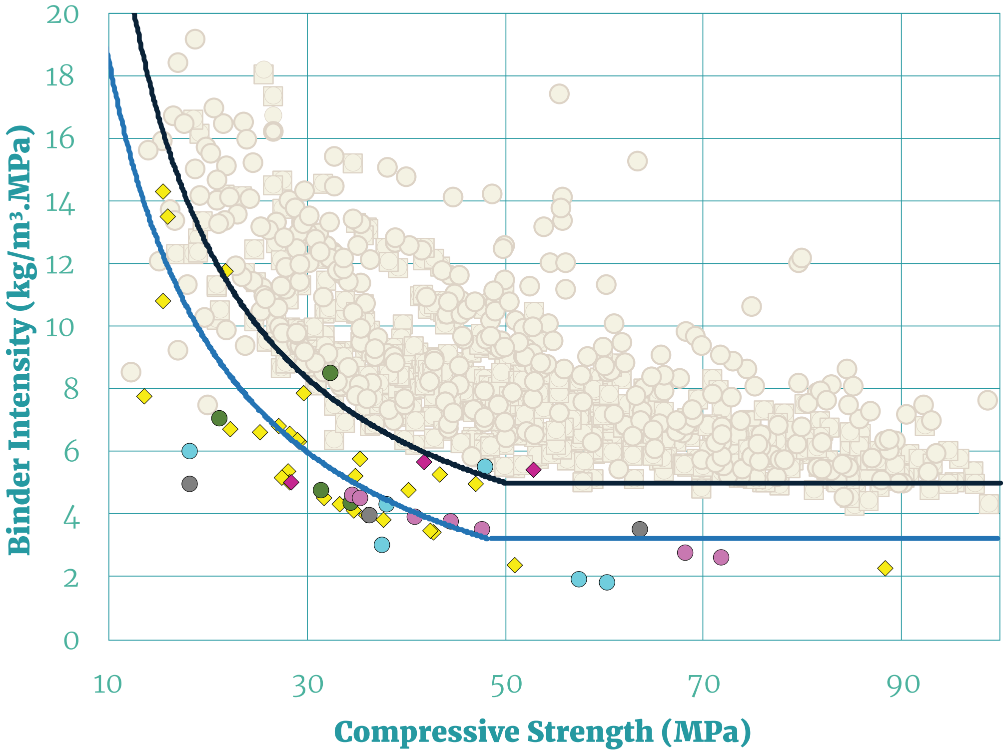
The role of civil engineering and engineering offices is therefore very important because they often choose the simplest and safest option and comply with the standard. Optimization of the concrete formulation, particularly of the granular skeleton, by continuous distribution of aggregates and thus reducing the final porosity of the granular skeleton. It is this final porosity that is filled by the cement paste. Therefore, optimizing the granular lining reduces the amount of cement required for a given compressive strength [29] but is also essential for the workability and the robustness of the mix. On average, we will then find 300 kg cement/m3, even though the standards could allow for much less [27]. It is possible to replace a part of this cement by fines fillers and keep a similar volume of paste for workability reasons, but the concrete producer will usually go for easy and robust mixes and prefer to have just one fine particle to weight and mix, the cement. The second reason that creates difficulty in optimising the mix the supply of good quality aggregates is not always easy. Aggregates are local materials. Therefore, if the local quarry is not able to provide a good variety of aggregates, it will not be possible to design an optimised granular skeleton and more cement will be required to achieve the necessary strength and workability criteria.

Granular optimisation through a better aggregate quality can significantly reduce the cement demand. Granular optimisation is estimated to be able to save 10% of cement in a concrete mix.

Another way to reduce of cement is through the use of admixtures. These admixtures will reduce the water demand and therefore allow the amount of cement to be reduced while achieving similar workability and strength [30,31]. Today in Europe, 80% of ready mix and precast concrete is modified with admixtures. Although the savings are small, Cembureau estimated that the improvement in admixture use could reduce global warming potential of concrete by 10 to 20%.

To assess the efficiency of cement use, an indicator of binder intensity has recently been developed. This indicator calculates the amount of cement needed for 1 m3 of concrete to generate 1 MPa of strength. This factor was discussed in many papers [29,32–34] and the UNEP report [4]. Table 1 shows the results presented in the study by Müller et al (2014) [29], where a binder with approximately 110 kg of CEMI by cubic metre of concrete can be designed to reach 40 MPa and a good durability, compared to the classic 250 to 300 kg cement/m3. They also showed in their study that the use of microcement (Portland cement; Blaine value 6900 cm2/g) can allow a compressive strength of 60 MPa with 110 kg of microcement by cubic meter of concrete due to the optimised packing of microcement within the full granular skeleton of the concrete.

Figure 15 Binder intensity related to the compressive strength in fcm of a 7d cube of mixtures with varying cement contents and particle size distributions (fit parameter n) compared to the literature results of Fennis and Daminelli [33] (all of the literature values are given in 28-days strength). The black line is the lowest amount currently used, and the blue line represents the trend of low carbon cement that can be produced.



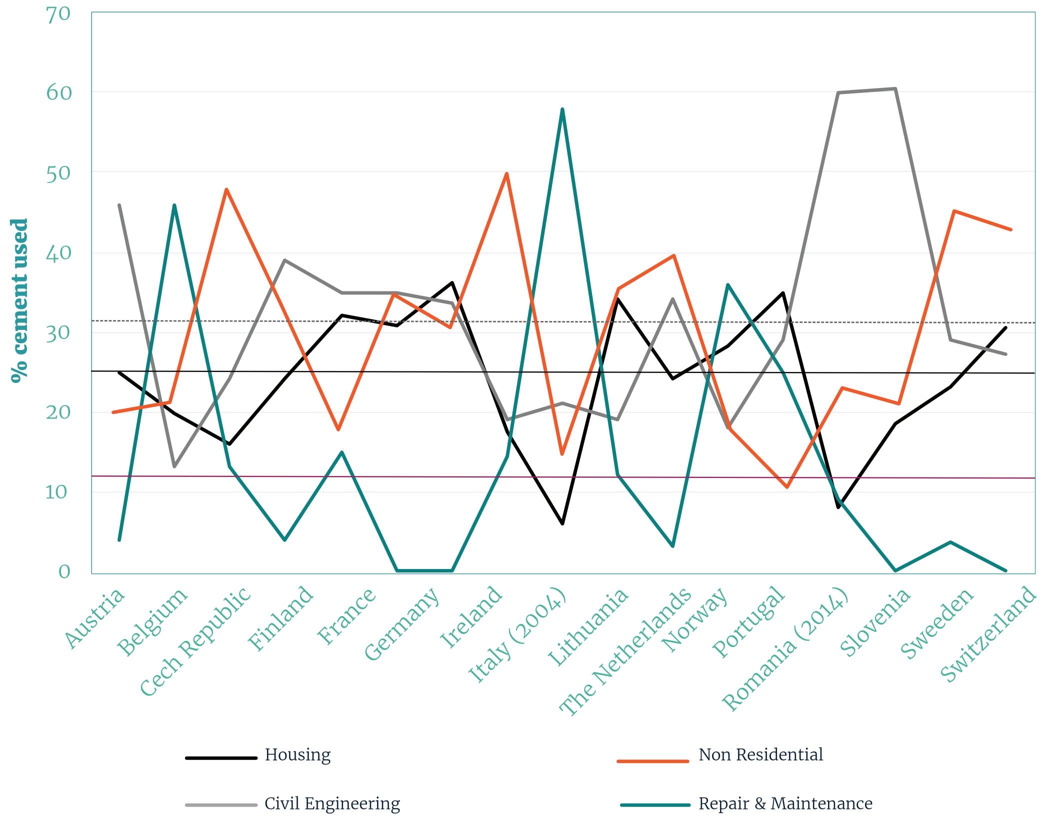
4.4. Structural level

Cement is not used by itself, but in cementitious materials, such as concrete or mortar, and concrete is used for architectural structures, walls, foundations, dams, bridges etc. Therefore, the main objective is to provide society with housing and infrastructure, if the same service is provided, the amount of cement or clinker in these elements is not of primary importance.

In this section, discuss the possibility of reducing the amount of concrete required while still providing the same level of service of the structure. On average, 50% of the cement is used for building construction, 30% for civil engineering structures and the rest in maintenance work, even if this repartition is not homogeneous across Europe (Figure 16). Civil engineering structures are often carefully designed, and the form is controlled by the load. So, the amount of concrete is fairly well optimised. This is different from buildings where engineering offices are take less time to optimise the design and where habits in term of repetitive structures lead to the overuse of materials. A concrete slab has 20 cm, as does a concrete wall, and the spacing between columns is often close to

6 metres. These dimensions are used regardless of the height and dimensions of the building, and these sizes are more controlled by practical reasons on the construction site, the size of the truck used to transport the element or acoustic purposes than by structural reasons. Looking at the concrete used in buildings from a structural perspective shows great savings potential.

Figure 16 Use of cement in different construction types at the national scale (2015). The straight lines show the averages for Europe.



Overestimation of concrete in structures

The strategy to reduce CO_2 emissions from structures is to optimise the quantity of concrete needed [31]. The quantity is often overestimated to "be on the safe side" but also sometimes for practical reasons, such as the quantity in a router truck, etc. In the short term, savings could be made by insisting that only the quantities specified in the codes are used and not more. In their survey (MEICON Project)[36], researchers from Cambridge University and Bath University highlight that there are no requirements for designers to be efficient in the use of embodied energy. Examining steel beams in the UK, Moynihan and Allwood [37] shows that the average use of the material is 50% below its capacity. In addition, Dunant and co-authors [38] note that 35-45%wt of steel is not structurally necessary. A large part of the embodied energy could be saved within the framework of existing European design codes. Concerning concrete, Orr and co-authors [39] show that the use of concrete structural elements suffers like steel from a lack of design optimisation.

In the long term, there is almost certainly scope for further savings, but this would require the difficult and time consuming process of revaluation of the safety criteria as defined in Eurocode: the generalised normative construction framework in Europe. Some researchers have used algorithms or other systems to optimize the cost and embodied energy. Paya and co-authors [40] provide a methodology to help structural engineers to improve their design in term of cost, constructability and environmental impact simultaneously. Yeo and co-authors [41] conclude from their study that approximately 10% of embodied energy can be reduced for an increase of 5% in the cost for the same simple reinforced concrete structural element. Although difficult to quantify, the works of De Wolf [42], Shank and co-authors [43] show that a reduction of 10%-20% can be made today without design changes. By combining low carbon cement and reducing the amount of cement and concrete in a structure, a reduction of more than 50% is possible.

Improving structural elements

Some shapes can be optimised to provide the required performance with much lower amounts of concrete, such as beams. It is well known that the most optimised shape to distribute forces is the arch shape. Up to now, this was difficult to realise on site, as optimised elements need high control in the concrete mix design and the reinforcement's structure and specific frameworks. However, through the development of digital fabrication, the development of these elements can be envisaged in the precast industry, where a good control of all parameters is possible. The work of Block and co-workers [44] (Figure 17) shows drastic savings of more than 50% of the cement for a similar service as a normal concrete slab that would be a solid 20 cm thick.

Figure 17 Rib-stiffened funicular floor system. Block research group https://block.arch.ethz.ch/brg/research/rib-stiffened-funicular-floor-system Photo credit: Nick Krouwel

4.5. Recycling, circular economy

The philosophy of the circular economy is linked to the promotion of resource efficiency, taking into account the full lifecycle of buildings, from initial planning and manufacturing of construction products to final demolition and waste treatment and disposal. Improving the resource efficiency throughout the lifecycle of buildings will make the construction sector more competitive as well as reduce material use and the environmental impact associated with our built environment. In 2015, the EU Commission adopted the Circular Economy package and LIFE Programme[45] to stimulate and support the transition towards a circular economy. The construction and demolition waste sector was defined as one of five priority sectors for a more circular economy. In volume, construction is the biggest source of waste in Europe and almost 90% can be revalorised but is largely downgraded in low-value applications.

Recycling concrete

Recycled concrete can be reused as aggregates; however, the quality varies greatly according to the origin and treatment. Recycled aggregates often have lower intrinsic strength than virgin aggregates. It is often necessary to increase the quantity of cement in the new concrete to achieve the same strength as a concrete with natural aggregates. However, CO_2 savings are still possible if the use of recycled aggregates reduces the transport distance compared to natural aggregates. Studies show that if distances as above 50 km are saved it starts to be an environmentally viable solution [46]. The quantity that can be incorporated varies according to national restrictions from 10% to 25% and often the recycling of fines is not considered. A large part of recycled aggregate is already used as road base (where it saves use of virgin aggregates), so there may not be large amounts of recycled aggregate available. The fine material can most effectively be used as a raw material for clinker production as a zero fossil CO_2 source of calcium. Studies have shown the feasibility[47–49]. The main difficulty is the quality of the source. To encourage the waste provider to give a source of pure concrete fines to the cement plant (without a mix of plaster or brick), some partnerships between cement producers and demolition companies have been proved efficient. The demolition companies that also have a construction business gets the cement back at a lower cost with its own concrete waste incorporated, which works for. Therefore, the waste provider has a direct interest to provide good quality waste, as he will beneficiate from a good quality cement at a lower price. More efficient recycling treatments with better fine separation can still be developed, but it is also clearly a change in the construction culture that is needed, where the waste at the end of life is no longer considered to be an end product, but is considered to be a valuable resource that, if well sorted, can be economically interesting to trade.

Recycling element

Increasingly, concrete recycling after deconstruction is not only about being recycled into aggregates but also about reusing certain elements in their original form [50]. An example in Belgium is give below:

Figure 18 Circular Retrofit Lab, Vrije Universiteit Brussel, Van Der Meeren (1973), Brussels[42]

In this case, they re-used original elements in a new construction, which significantly reduces the cost of construction, and the potential for reducing the embodied CO_2 is very important. In this case, the only energy cost is due to transport if the elements are not available nearby. Unfortunately, some of the drawbacks seem higher than the advantages currently, e.g., availability of elements, as elements are integrated into structures designed for 50-100 years, changing connections between elements will reduce other properties, which will need extra material to compensate, and elements available today can be outdated in 10 years. To counterbalance, designing flexible structures to allow new functions of the building by rearranging walls, for example, should be promoted.

5. Breakthrough technologies: The reality behind the hype

5.1. Alternative clinkers

Alternative binders were studied in detail in the UNEP report[4] and in two supporting white papers written by Gartner and Sui [51] and John Provis [52]. Here, we resume the basics as they apply to Europe.

These cements have not been proven, and their potential for CO_2 saving is limited by questions regarding resources and technical application difficulties, which means that they are only likely to find niche applications. Such applications usually require a high level of technical support, which, along with the loss of economies of scale, means that the products will have a cost often several times higher than conventional cements to be economically viable. It is not realistic to imagine that such materials will be able to meet more than approximately 5% of the demand for cementitious materials. It should be noted that the CO_2 savings are expressed compared to plain Portland cement, CEM I. Given that the average level of clinker substitution in Europe is currently 0.73, the average CO_2 saving of the cements we already use compared to CEMI are already approximately 25%.

5.1.1. Belitic clinkers

The technology is very similar to Portland cement, but the calcination to form belitic phases is performed at a slightly lower temperature. There is typically only a 10% CO_2 reduction (much less than in current CEM II). Moreover, the lower performance cancels out this marginal savings. These cements can be made in existing plants, so there are negligible investment costs. The main drawbacks are the lower reactivity, the low savings potential and a lower heat recovery potential at the cement plant. Overall, this technology is of interest for mass concrete, where the lower heat of hydration is an advantage, but the potential for CO_2 savings is negligible.

5.1.2. Calcium sulfo aluminate cements

Calcium sulfo aluminate cements (CSAs) have been produced commercially in China for more than 40 years and there is now some production in Europe. They can be produced with the same technology as Portland cement. The reduction in CO_2 mainly comes from the change in the chemical composition. The main reactive phase (ye'elimite: C4A3$) contains a lower proportion of calcium, so there are lower process emissions from the decarbonisation of limestone. In addition, the clinkering temperature is lower, and they are more easily ground. The CO2 saving potential is approximately 20-30% (+/- 5% compared to CEMII), depending on the content of the reactive phases: ye'elimite. The fast and variable setting time of these cements poses some barriers to their use and favours development in precast applications. Their long term durability in different environments is also not yet well established. However, the main issue is the expense and availability of the high alumina raw materials needed for their production. In the UN Environment report "Eco efficient cement", the extreme situation was considered in which all bauxite currently mined for production of aluminium would be switched to the production of CSAs. Even in this extreme situation, only approximately 15% of the current cement demand could by met. It has been shown that some waste materials can also be used for production but supplies of these are also limited. In China, after many years of promotion of this technology, the amount of CSAs produced is only approximately 0.1%. Therefore, even in the long term (2050), an upper level of substitution of 10% is considered, but it is likely to be much lower as a niche product.

5.1.3. Energetically modified cement (EMC) [53]

Energetically modified cement (EMC) technology is based on blended cement (see discussion above, section 4.2), which is finely ground to improve its reactivity by changing the atomic structure. The CO_2 savings potential is linked to the potential to obtain higher levels of clinker substitution with reasonable performance, but this is offset by the higher energy required. As such, we do not consider an independent contribution for this technology, but it could contribute to an overall reduction of the clinker factor in blended cements.

5.1.4. Alkali activated binders

Alkali activated binders are also well known, and residential infrastructures were built in the 60's in Ukraine with alkali activated slag. However, it was performed in the specific context of Portland cement scarcity and high availability of slag, which is not representative of the context in Europe today. Some products are still produced around the world and they are partially standardised. The savings potential of CO_2 (compared to CEM I) is estimated to be between 40 and 80 %; however, the emissions of the activator are often not taken into consideration. Different solid precursors can be used. These are basically the same as the SCMs used in blended cements, with the same limitations in their availability as discussed previously. In particular, slag and/or high calcium fly ash are always used in formulations that can set and harden at ambient temperature; other formulations require heat curing to develop significant strength. In addition, there are many other technical issues, such as the safety issues associated with the use of strong alkalis, fast and variable setting and hardening, lack of admixtures able to improve workability, high shrinkage and questions regarding the durability in different environments. In view of these constraints, their use is likely to be limited to precast factories and niche applications.

5.1.5. Supersulfated slag cements

Supersulfated slag cements are estimated to have the potential to reduce CO_2 emissions by up to 80% compared to CEMI, but the production is linked to the availability of slag, which is decreasing and is already used in blended cement. In addition, their setting and hardening is highly variable, so it is difficult to deliver a consistent product on site.

5.1.6. Carbonatable calcium silicate cements

These are cements based on Wollastonite ($CaSiO_3$) and dicalcium silicate (Ca_2SiO_4), which hardens by reaction with CO_2 rather than water. The saving potential in CO_2 is up to 60% (eventually higher if waste derived calcium silicates are used (e.g., steel slag)). These materials have potential applications in precast products, such as blocks, tiles and pavers, but there are several limitations to their more extensive use, which are as follows:

- The elements need to be thin enough for the CO_2 to be able to penetrate;
- The carbonation needs to be carried out in a specially adapted curing chamber with a supply of concentrated CO_2; and
- The alkalinity of the materials is greatly reduced and will not protect conventional steel reinforcement from corrosion.

For these reasons, the UN Environment report estimated the maximum market penetration at 10%.

5.1.7. Hydrothermal reactive belite cements (incl. celitement)[54]

The production of these materials consists of the two following steps, before mixing with water:

- Production of α-C2SH by a hydrothermal process, generally from lime and silica; and
- Activation of α-C2SH to produce reactive belite (x-C2S), either by mechanical action (Celitement) [37] or heat treatment [56].

Such a manufacturing process is complex due to the need for more processing steps than required for Portland cement and, at present, has only been proven at laboratory scale. Due to the lack of a commercially viable process, it is difficult to estimate their energy and CO_2 efficiencies at this stage. However, simple thermodynamic arguments indicate that the manufacture of the reactive belite cannot be more energy or CO_2 efficient than the production of belite in PC or the high belite cements discussed above. The technology seems to make no sense if processed lime (with very high process CO_2)

is used as a precursor, but could be interesting if waste materials were used. Due to the early stages of the technology and CO_2 savings, which are unclear compared to existing blended cements, we do not think the contribution of this technology can be significant in the period of study.

5.1.8. Magnesium cements

Magnesium based cements, which harden by carbonation, have been proposed. The CO_2 saving potential is critically dependent on the source of the raw materials. If the more common magnesium carbonate is used, the CO_2 emissions are higher than for Portland cement due to the lower atomic weight of magnesium. Therefore, the focus has been on preparation from magnesium silicates. This has proven to be possible on a small scale but requires high amounts of energy and several steps involving high pressure. Despite considerable effort, it has not proven possible to find a process that can be scaled up (Novacem [57] went out of business in 2012). Furthermore, even though magnesium silicate minerals are abundant, they are much more localised than limestone and occur deeper in the earth's crust, so wide spread use would require significant efforts in mining and transportation. Even if all these technical problems were surmounted, the properties of these cements seem quite limited, and the hardening by carbonation means that they would suffer from the same limitations identified for the carbonatable calcium silicates cements described above.

5.1.9. Summary of potential from alternative binders

As a summary of the sections above, we consider that only calcium sulfo aluminate cements (incl. BYF) and carbonatable calcium silicates cement (CCSC) have any significant potential to contribute to CO_2 reduction in the period of study. The penetration in the market will be limited due to the level of investment required, the lack of standards and available resources. We estimate that no more than 5% of cement can be replaced by these alternatives by 2030 and 10% by 2050.

5.2. Carbon capture, storage and use

Carbon capture and storage (CCS) of use (CCU) is being studied in many industries. Carbon capture and storage, or CCS, is the term used when captured CO_2 is transported to an underground facility and stored permanently. There are technical and social issues to be solved if this is to be deployed on a large scale. Carbon capture and use or CCU envisages use of the captured carbon as a precursor for the production of other chemicals. Apart from the technical issues, there is a major issue here that the requirements for such chemicals are several orders of magnitude less than the amount of CO_2 that would have to be captured. CCS/CCU has been identified in the IEA/CSI roadmaps of 2009 and 2018 as an important technology to reduce CO_2 emissions from the cement industry. There are several on-going pilot programmes. Precombustion capture technologies have limited mitigation potential in cement production, as only energy-related CO_2 emissions, which represent approximately 35% of the total cement carbon emissions, would be affected. **Oxyfuel combustion technology** is considered promising to give higher concentrations of CO_2 in the output gases, which allows more efficient capture. In this technology, pure oxygen is used to burn fuel and, as nitrogen is not heated, fuel consumption is reduced, and higher flame temperatures are possible. The main problem has been separating oxygen from the air. This process requires a large amount of energy, and the additional electricity needs can increase by 2 or 3. The investment cost is estimated to be 300 Mio€ and the CO_2 saving potential can be between 50 and 800 kg CO_2 per t clinker (10 to 100% CO_2 saving).

The non-exhaustive list below presents some of the CCS technologies under development, including the post combustion process, combustion process and storage process. The investment costs are current estimations and can be reduced with further research and development. The information mainly comes from the technical report written by CSI[5] and ECRA[6] [14].

- **CCS by adsorption** refers to the uptake of CO_2 molecules onto the surface of another material. The investment cost is estimated to be between 200 and 300 Mio€, inducing a possible increase between 10 and 50 € per ton of cement. The direct CO_2 saving can be between 0 to 740 kgCO_2 /t clinker, but the high energy demand will increase the indirect CO_2 emissions.
- **CCS by membrane process** leads to a potential CO_2 saving of approximately 720 kg CO_2/tCK and a lower investment of approximately 50 Mio€. However, the process requires a high electrical energy demand that induces a higher cost of producing of cement.
- **CCS by Calcium looping** is a second generation carbon capture technology. This process is not a post combustion capture, but the cement production is perfectly designed to reuse the CaO sorbent needed in the Ca-looping process with no additional CO_2 emissions during the clinkerisation. However, a low temperature calcination is needed to form the sorbent, which leads to an increase in the thermal energy demand. The potential CO_2 saving is approximately 800 kg CO_2/tCk (without taking into account the CO_2 emitted in the production of the CaO sorbent), and the investment is approximately 200 Mio€, increasing the price by 36€ per tonne of clinker.
- **CCS by mineral carbonation** involves the reaction of CO_2 with a mineral compound such wollastonite or olivine to form stable mineral carbonates and SiO_2. This technology needs expensive additives for the direct carbonation of minerals. The cost is estimated to be higher than geological storage due to an important increase in the thermal and electrical energy requirement. The cost is approximately 100€ per tonne of captured CO_2. Moreover, the carbonated minerals would then have to be used or disposed of somehow.

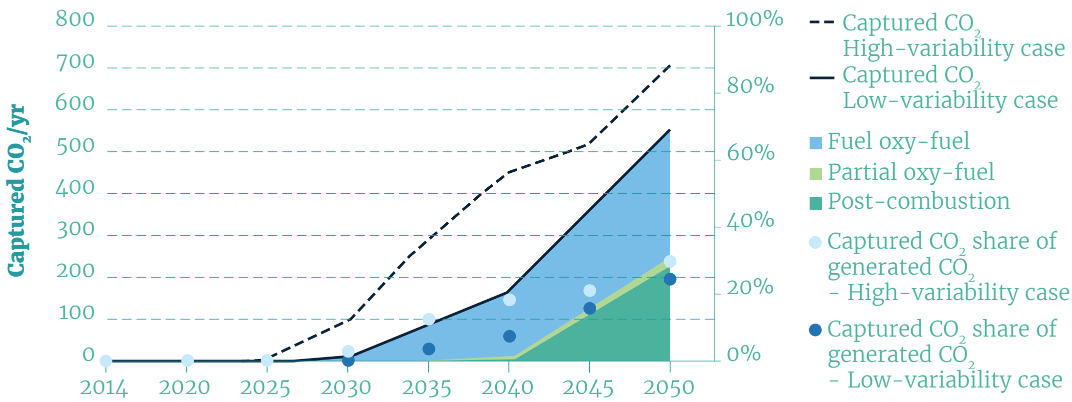
[5] CSI : Cement Sustainability Initiative – From the World Business Council on Sustainable Development

[6] ECRA : European Cement Research Academy

- With exactly the same savings potential of 750 kg CO_2/t CK as the previous technology, the **CCS by algae capture** involves the consumption of CO_2 for the growth of algae, which can be used as biomass fuel. The cost is projected to be competitive with other CCS processes at approximately 30 -50€ per tonne of CO_2 capture. The main limitation is the need for large amounts of land to grow the algae.

Figure 19, from the roadmap from IEA CSI, shows the projected deployment of these technologies by 2050 in the cement sector worldwide.

Figure 19 Global deployment of CO_2 capture for permanent storage in the cement sector worldwide.



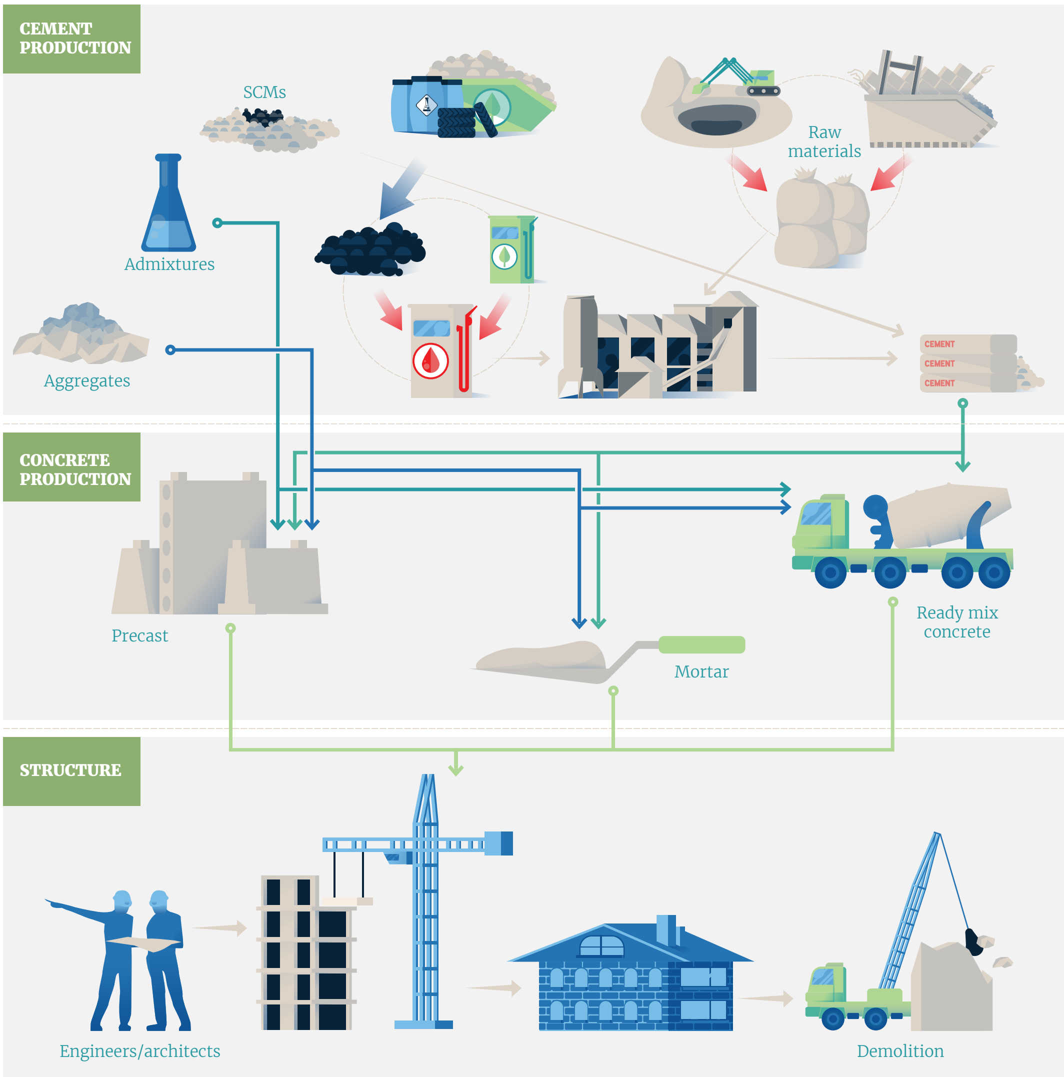
The main limitation of the implementation of CCS is its very high cost. The cost of investment is 2 times higher than that of a new cement plant (approx. 150 Mio € for 1 million tonne annual capacity). If these technologies are to be applied at a large scale, the power consumption would increase drastically. The requirement for high amounts of electrical energy also has implications for both the cost and CO_2 mitigation potential as it heavily depends on the decarbonisation of electricity.

6. Strategies for CO_2 reduction in the cementitious value chain

6.1. Introduction

This section focuses on the assessment of CO_2 reduction achieved under different scenarios. We considered the whole cement and concrete value chain, as represented below.

Figure 20 Representation of the cementitious construction value chain used in this report



Interviews with cement producers, European associations, and constructors showed us that for those different actors of the construction:

- maintaining the productivity on the construction site is considered very important.
- maintaining the low cost of cement production and low cost of building construction are also very important.
- the availability of resources is a critical question, as often it is not easy to obtain access to the desired resource in the right amounts.
- performance based standards would solve many problems but are currently not in place. National Standards on cement choice and kg of cement per m^3 of concrete are too restrictive and do not allow the CO_2 reductions that would otherwise be possible..

Moreover, the construction sector is a capital intensive industry with long returns on investment and little incentive to invest due to the current production overcapacity. This sector is also fragmented between many players [57]. Few constructive partnerships have been observed, and they are mainly based on client-supplier relationships with no interactions. Furthermore, a recent study from McKinsey reported in 2015 that construction is among the least digitised the sectors, resulting in typical delays in completion of 20%, budget overruns of 80% and finally a very low financial return for the constructor [58]. Based on different discussions (workshops taking place in January and May at ECF Brussels) and reports published so far, future developments in the construction sector with a view to reducing their GHG emissions appear to be as follows:

- An increase in the digitalisation of the sector will occur, leading to more prefabrication and the use of building information modelling.
- Resource conservation and the circular economy approach are gaining traction in economic and political circles. The construction industry will have to position itself in the conversation [45,59].
- Breakthrough technologies all require very high investment costs and the industry is not willing to invest so much in the current situation.

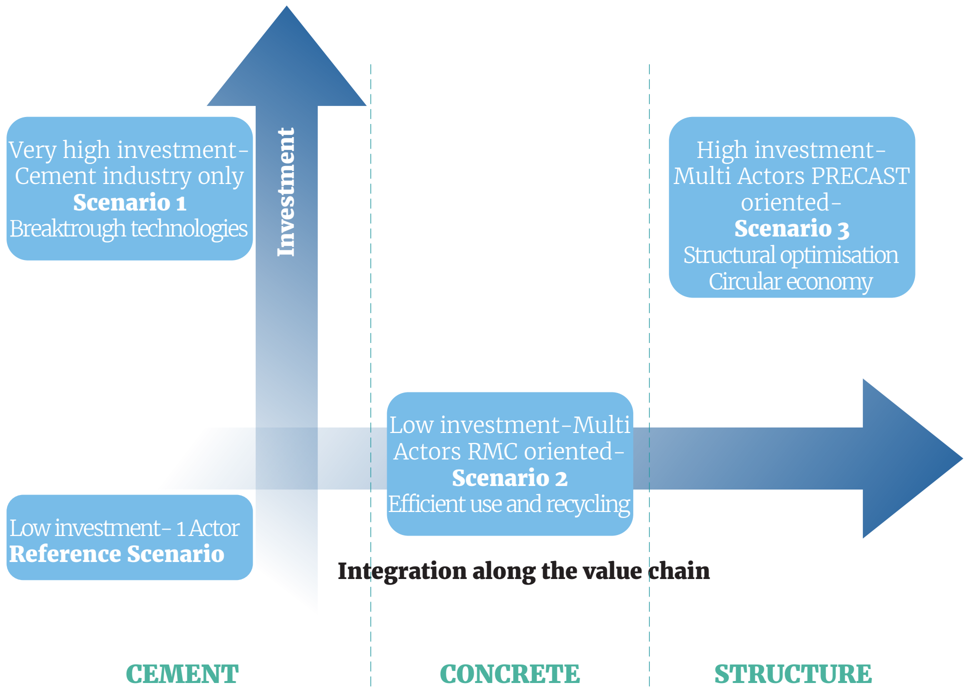
The sector will need to evolve on two fronts, as follows:

- Continuous improvement of old technologies and aggregating different good practices to systematically reduce emissions and
- Using new technologies.

Following these findings, the construction sector faces two limitations, as follows: the need for investment on the one hand and the lack of interaction between the various stakeholders along the fragmented value chain on the other. As an example, increasing the use of blended cements needs research and development from cement plants, but these cements need to be bought by concrete companies and allowed by construction companies to be implemented largely.

Based on these two bottlenecks for innovation in the construction sector, four scenarios covering the potential future evolution of the sector are proposed (Figure 21). The CO_2 reduction potential for each potential future are then assessed.

Figure 21 Four scenarios covering the potential future evolution of the sector



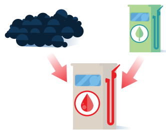
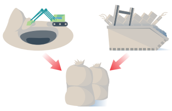
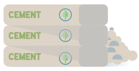
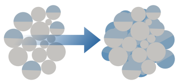
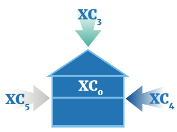
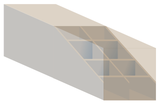
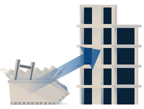
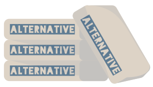
As will be explained, these scenarios are not mutually exclusive and cannot simply be added to each other.

6.2. Background data

All scenarios combine different abatement levers and involve one or many actors in the value chain. For these calculations, our hypothesis is to maintain the same required properties of concrete (strength, durability, etc.) and the same standards. In the model (Annex 1), the parameter "quantity of cement" is consider to be stable in Europe [5] from 2015 to 2050; however, scenario 2 and scenario 3 will involve a decrease in cement demand in the medium and long term, but a constant supply in terms of final service.

It is commonly accepted to refer to 1990 emissions as 100% of total CO_2 emissions, but our scenarios will start in 2015. It is important to note that the 40% observed reduction between 1990 and 2015 is mainly (30%) due to the reduction in cement demand that followed the 2008 economic crisis. The roadmap of the European Commission defines the objective of reducing greenhouse gas emissions by 80-95% compared to 1990 levels, [60] but in a Paris Agreement compatible scenario, the sector will most likely have to reduce to almost zero CO_2 emissions.

The ten levers evaluated in the possible scenarios are the following:

	TECHNOLOGIES	DESCRIPTION
	**Efficiency of clinker production**	Reduce the thermal energy during clinker production by upgrading old kilns to dry kilns with preheaters and precalciners.
	**Alternative fuels**	Increase the quantity of waste and biomass as the main fuels for clinker production.
	**Recycling the fines from concrete**	Use alternative raw materials (with no fossil CO_2) in the clinker process, including the fines from concrete demolition.
	**Clinker substitution**	Decrease the clinker factor in cement to 0.6 using supplementary cementitious materials.
	**Improving the concrete mix design**	Improve the packing of aggregates and optimise the mix design.
	**Strict respect of exposure classes**	Reduce the cement in concrete by following the standards. Engineering offices specifying different concrete classes and concrete producers providing concrete with just the necessary cement content.
	**Reducing the concrete content in structures**	Optimise the structural design of the elements to reduce concrete needs.
	**Favouring reuse and recycling**	Reuse of concrete elements- designing flexible buildings.
	**Alternative binders**	Different alternatives can be used as previously described. (See Annex 1) The CO_2 emissions will be averaged to 520 kg CO_2 /t alternative binders in 2030 and 495 kg CO_2 /t alternative binders in 2050.
	**Carbon capture and storage**	Equip cement plants with carbon capture technology and reinject the cement in storage facilities.

6.3. Reference scenario

Characteristics:

- Low investment capacities.
- No collaboration between actors: only cement producers can act.

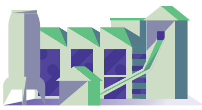
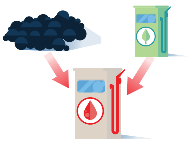
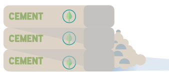
Most promising actions in this context:

- Kiln technologies improvement.
- Small increase in clinker substitution and alternatives fuels.

6.3.1. Description

The scenario is based on and is an extension of the Reference Technology Scenario named RTS in the IEA-CSI Roadmap 2018 (see Blue Box). The low investment envisaged in this scenario is mainly confined to improving the thermal efficiency of clinker kilns. A small increase in the use of alternative fuels as well as an increase in the use of SCMs are the other reduction levers.

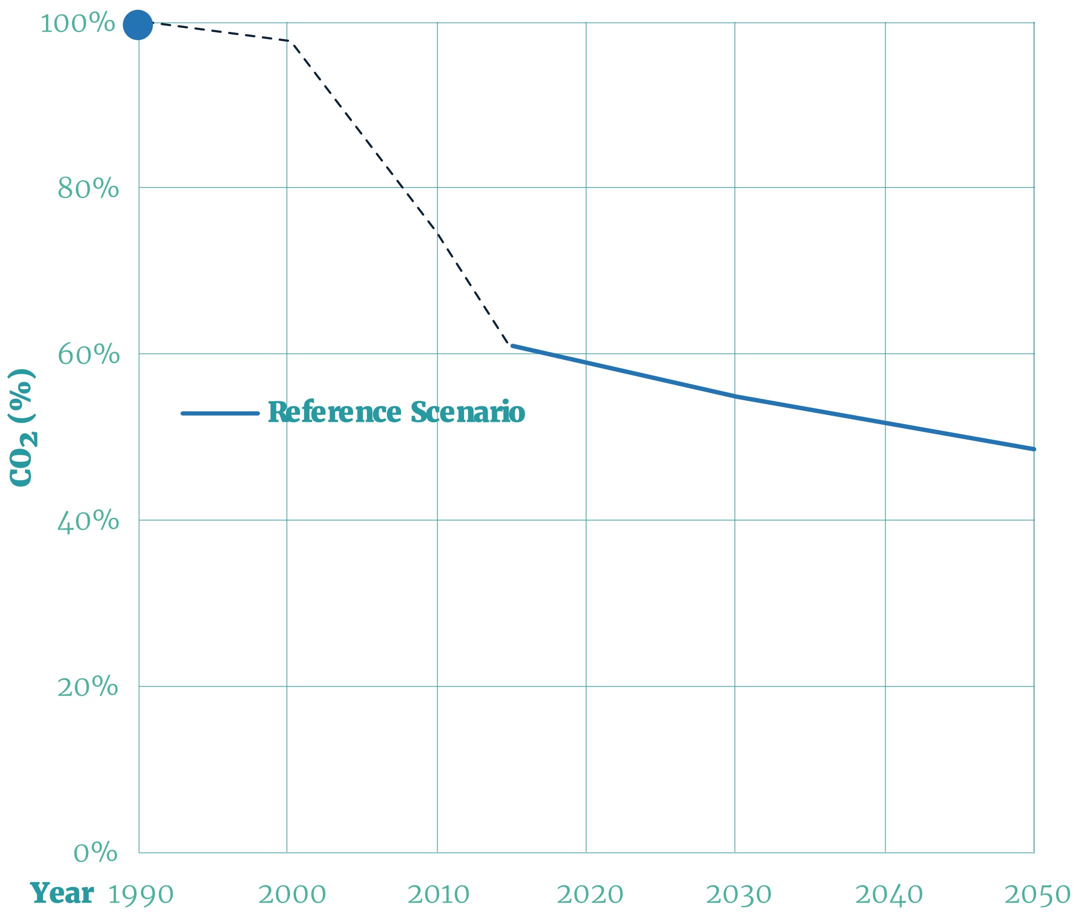
Table 2 Summary of the potential savings by technologies for the reference case scenario

REFERENCE SCENARIO	DEGREE OF IMPLEMENTATION			
	2015	2030	2050	SCALE
Efficiency of clinker production 	80%	83%	84%	Clinker scale
Alternative fuels 	33%	40%	60% (No data IEA-CSI at EU level –global 17.5%in RTS- 30% in 2DS)	Clinker scale
Clinker substitution 	23%	30%	35% (No data IEA-CSI at EU level –global 34% in RTS and 40% in 2DS)	Cement Scale
CO_2 savings compared to 1990	40%	45%	55%	

6.3.2. Results

Compared to the actual emissions (2015), this scenario will lead to a reduction of nearly 15% by 2050. Indeed, the improvement of kiln technologies is marginal and at its maximum can allow a reduction of only 4%. Further development discussed by CSI-ECRA Technology papers[14] indicates that with more investment, it is possible that 10% can be achieved on thermal efficiency.

Figure 22 CO_2 evolution by 2050 for the reference case scenario



BOX: IEA-CSI Roadmap 2018

The International Energy Agency and Cement Sustainable Initiative (part of World Business Council for Sustainable Development) developed a Roadmap to consider the reduction of CO2 emissions of the cement sector up to 2050 at a world scale. Global cement demand is set to grow by 12-23% by 2050, under the Reference Technology Scenario (RTS), the direct CO_2 emissions are expected to increase by 4% by 2050. To realise the 2 degree scenario (2DS), direct emissions from cement manufacture must be cut by 24 % compared to the current level by 2050. Improving energy efficiency, switching to alternative fuels, reducing clinker content, alternative clinkers and Carbon Capture and Storage (CCS) are the mitigation levers supported by the cement sector to realise 7.7 $GtCO_2$ reduction by 2050. Realising the RTS scenario will represent an investment of 107-127 billion USD by 2050 and the 2DS will require an investment of 176-244 billion USD by 2050.

6.4. Scenario 1: breakthrough technologies

Characteristics:

- High investment capacities coming either from public or private investors.
- No collaboration between actors: only cement producers can act.

Most promising actions in this context:

- Carbon capture and storage
- Alternative clinkers

6.4.1. Description

In this scenario, very high investment is required. This investment must be made by a single actor, i.e., the cement producer, which would probably be done through public/private investment to finance a carbon storage infrastructure and subsidise the installation of carbon capture technologies. Cement companies would invest only if there is a high tax on CO_2; otherwise, they would prefer public support. Two types of investments are then considered. First, cement producers adapt their clinker kilns with carbon capture post-combustion systems and develop CO_2 storage facilities. Second, alternative cements such as calcium sulfoaluminates cement and carbonatable calcium silicate cements with a CO_2 saving potential of 40-50% become more common and available at a larger scale in 2050. As explained in section 5, alkali activated binders are severely limited by resources and pose technical difficulties, particularly for use on site. The other issue is the market penetration; in the case of calcium sulfo aluminates, the lack of high alumina raw materials means that the there is a substitution limit of approximately 5%. These technologies are added to the one that would be favoured in the reference scenario.

Table 3 Summary of the potential savings by technologies for scenario 1

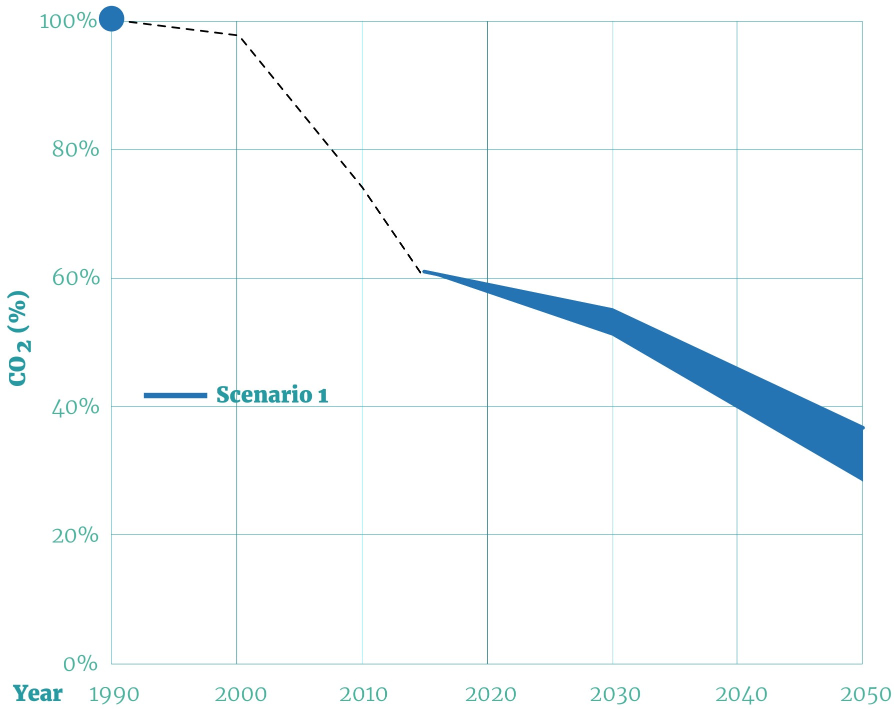
SCENARIO 1: BREAKTHROUGH TECHNOLOGY	DEGREE OF IMPLEMENTATION 2015	2030	2050	SCALE
Efficiency of clinker production	80%	83%	84%	Clinker scale
Alternative fuels	33%	40%	60%	Clinker scale
Clinker substitution	23%	30%	35%	Cement
Carbon capture and storage	0%	0-5%	25-50%	Clinker scale
Alternative binders	0%	0-12%	10-25%	Cement
CO_2 savings compared to 1990	40%	50%	65-75%	

6.4.2. Results

With 25 % CCS and 10% alternative binders, a reduction of 25% is possible, and in case of higher investment, 35% can be achieved compared to 2015. A major difficulty in this scenario is to access the real numbers for implementation of CCS and alternative binders.

CCS is not a proven technology at large scale and its deployment is estimated to be expensive. Its potential is extremely interesting. In our calculations, this technology allows all the CO_2 emitted during production to be "reabsorbed". However, our calculation neglects the CO_2 coming from the electricity sector and the capacity of this sector to provide the necessary low carbon energy for the installation of CCS technology. In addition, transport to a use or storage site for the captured carbon is not considered.

Figure 23 CO_2 savings by 2050 for scenario 1



6.5. Scenario 2 Efficient use and recycling

Characteristics:

- Moderate investment capacities distributed among different actors.
- Integration of the value chain from cement to concrete and collaboration between actors.

Most promising actions in this context:

- Good waste management practices: increase in alternative fuels and concrete recycling.
- High increase in clinker substitution.

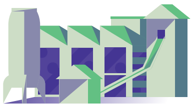
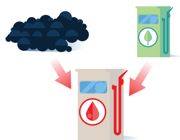
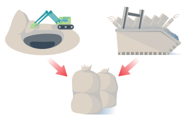
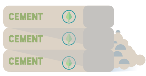
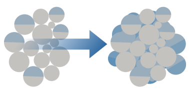
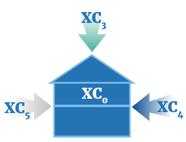
6.5.1. Description

Scenario 2 follows a different path than scenario 1 by involving the whole value chain. In this scenario, there is no strong investment in carbon capture and storage.

The use of waste as energy as a raw material in the manufacture of clinker or as SCM in cement and concrete production is emphasised. The good integration of actors in one territory favours good waste management practices and efficient collection of waste and biomass for alternative fuels as well as sorting construction demolition waste. If well sorted, the fine part of concrete demolition waste can be used as a raw material in the manufacture of clinker and the rest can be used as recycled aggregates in concrete. Waste from other industries, such as calcined overburden clays, wood ashes, agricultural ashes etc., are implemented as supplementary cementitious materials.

The availability of local resources is no longer limited, and the clinker factor can reach 0.5-0.6 if the required properties are reached. Moreover, there is an important contribution at the concrete scale; the quantity of cement needed is optimised by the better packing of aggregates and by respecting the various exposure classes of concrete in the building, which can be achieved through the active involvement of sand and gravel producers that can invest in crushers and sieves to produce diverse aggregate sizes. Optimisation of the quantity of cement needed also involves the engineering offices, which are currently specifying the use of a single type of concrete that meets the highest exposure class and therefore contains the most cement, and would change their practice in scenario 2 and specify the appropriate exposure class for each part of the project. The only risk would be not to have the right concrete at the right place due to confusion on the construction site, but new technologies, such as tracking concrete trucks with RFID technologies and Building information modelling [61,62], can easily be implemented at low costs.

Table 4 Summary of the potential savings by technologies for scenario 2

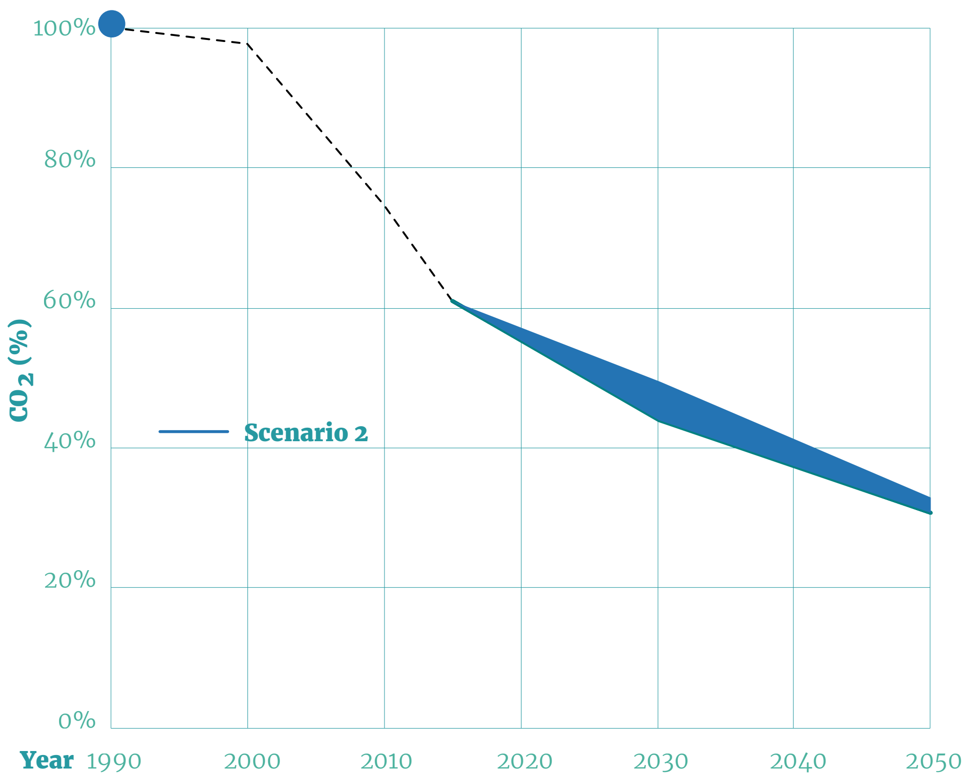
SCENARIO 2: EFFICIENT USE AND RECYCLING	**DEGREE OF IMPLEMENTATION**									
	2015			**2030**			**2050**			**SCALE**
	RMC	PRECAST	MORTAR	RMC	PRECAST	MORTAR	RMC	PRECAST	MORTAR	
Efficiency of clinker production 	80%			83%			84%			Clinker
Alternative fuels 	33%			40/ 60%			80%			Cement
Alternative raw materials including recycling fines 	3-4%			10%			20%			Clinker
Clinker substitution 	23%			30%	30%	30%	40%	40%	40%	Cement
Binder per m³ of concrete per MPa 	8 kg/ m³/ MPa			5 kg/m3/ MPa	5 kg/m3/ MPa	-	5 kg/m3/ MPa	5 kg/m3/ MPa	-	Concrete
Appropriate use of standards 	300 kg/m3			287-292 kg/m3	–	–	275-285 kg/m3	–	–	Concrete
CO_2 savings compared to 1990	**40%**			**50%**			**65%**			

6.5.2. Results

In this scenario, emissions are reduced by approximately 25% compared to 2015 (65% compared to 1990). The recycling of concrete fines and the reuse of waste as fuel are limited by the availability and commitment of demolition and waste companies to co-process.

The other limitation in this scenario is the reduction of the amount of cement in the concrete while meeting the standards in place. The values represent a European average, with some countries allowing larger reductions. Homogenisation of standards on a European scale as well as better thought-out requirements in terms of durability constraints would ultimately lead to greater emission reductions.

Figure 24 CO_2 savings by 2050 for scenario 2



6.6. Scenario 3 Structural optimisation and circular economy principles

Characteristics:

- Moderate to high investment by all actors.
- Integration of the value chain from cement to structure (involving the precast industries).

Most promising actions in this context:

- In addition to scenario 2, higher use of prefabrication.
- Structural optimisation and reuse of building elements.

6.6.1. Description

Scenario 3 adds levers to scenario 2 at the structure scale.

In this scenario, the involvement of construction companies and concrete producers is dominant. The technologies developed in the previous scenarios are the same and an additional effort is made in terms of structures. The structural element will be optimised, an example is the use of partially hollow structures that reduce concrete usage by 50 to 70% while maintaining the same performance.

Regardless of the chosen routes, i.e., using less cement or less concrete, the mix design of the concrete must be perfectly controlled as well as its placement and curing, which can be achieved more easily in a controlled environment, such as ready mix plants for the concrete mix design and the precast industry for the structural design. To properly control the quantity of concrete for the structure, the precast industry will have to develop skills in cement substitution; today, the use of CEM I is preferred to ensure rapid demoulding. This scenario will therefore favour the development of precast elements, more complex shapes can be used and only the performance of the finished element counts for its future use. The market share between ready mix concrete and precast industries could be changed to obtain higher impact.

Table 5 Market share in scenario 3

	2015			2030			2050		
	RMC	PRECAST	MORTAR	RMC	PRECAST	MORTAR	RMC	PRECAST	MORTAR
MARKET SHARE	50%	25%	25%	40-45%	30-40%	25%	30-40%	35-45%	25%

Table 6 Summary of the potential savings by technology for scenario 3

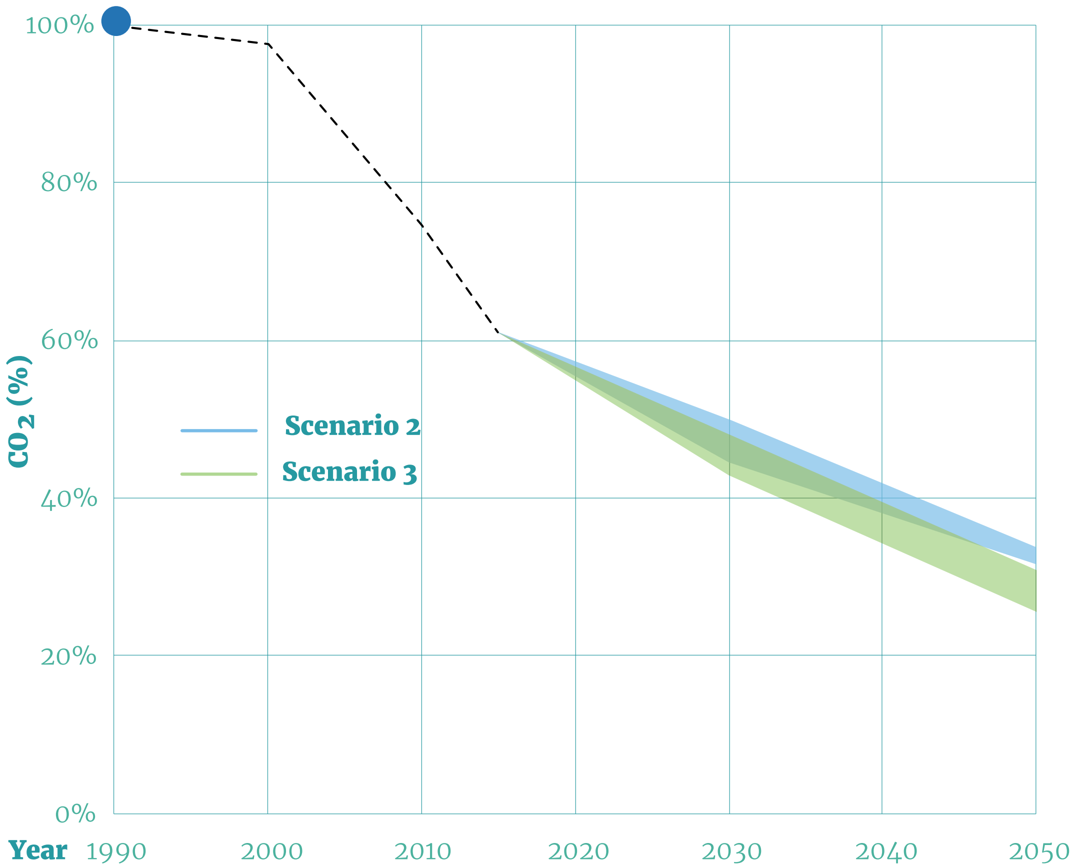
SCENARIO 3: STRUCTURAL OPTIMISATION	DEGREE OF IMPLEMENTATION									
	2015			2030			2050			SCALE
	RMC	PRECAST	MORTAR	RMC	PRECAST	MORTAR	RMC	PRECAST	MORTAR	
Efficiency of clinker production	80%			83%			84%			Clinker
Alternative fuels	33%			40-60%			80%			Cement
Alternative raw materials including recycling fines	3-4%			10%			20%			Clinker
Clinker substitution	23%			30%	30%	30%	40%	40%	40%	Cement
Binder per m³ of concrete per MPa	8 kg/m3/ MPa			5 kg/m3/ MPa	5 kg/m3/ MPa	–	5 kg/m3/ MPa	5 kg/m3/ MPa	–	Concrete
Appropriate use of standards	300 kg/m3			292 kg/m3	–	–	285 kg/m3	–	–	Concrete
Re-use of cement	N/A			–	0-10%	–	–	10-20%	–	Structure
Optimization	N/A				10-20%			20-40%		Structure
CO_2 savings compared to 1990	40%			55%			75%			

6.6.2. Results

This scenario is the most promising to reduce CO_2 emissions while integrating all construction actors and reducing investment compared to scenario 1. A reduction between 30 and 35% is possible compared to 2015. An additional reduction is, however, possible because the reduction of concrete in a structure and the reuse of elements present a large potential. Although difficult to quantify, the work of De Wolf et al.[42] and Shank et al.[43] show that a reduction of 10%-20% can be made today without design changes. By combining low carbon cement and reducing the amount of cement and concrete in a structure, a more than 50% reduction is possible.

This scenario involves a controlled production chain as in precast and to achieve a reduction in CO_2 emissions, a change in the market share was considered; it was assumed that 5% to 10% of the cement (all types) previously used in the ready mix industry was now used in precast. This assumption does not upset the economic balance of the two sectors, but a more marked change in market share can be envisaged and would allow an even greater reduction.

Figure 25 CO_2 savings by 2050 for scenario 3



6.7. Towards the well-below 2°C and 1.5°C target

To sum up, Scenario 1 and Scenario 3 are the most promising scenarios to reduce CO_2 emissions. Scenario 3 can be considered more interesting as it integrates the full value chain in the CO_2 reduction strategies and considerably lowers the investment needed compared to Scenario 1. However, none of the scenarios achieve the reduction required to reach the 2 degree target. In this section, we tested combined scenarios using costly and integrative technologies to reach the EU recommendations.

It is actually possible either to make more constraining efforts in the sector with better quality control, allowing, for instance, changing the standards or to combining scenario 3 and 1 and to include carbon storage for a good value chain integration.

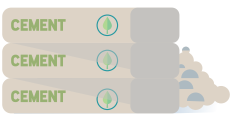
6.7.1 Extreme scenario 3 beyond the standards

Characteristics:

In addition to moderate investment and good integration of all actors:

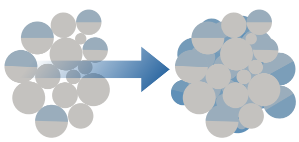
- Change in standards can be required.
- Strong effort to optimise concrete and structures.

Clinker substitution



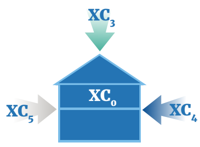
50%

Improved packing



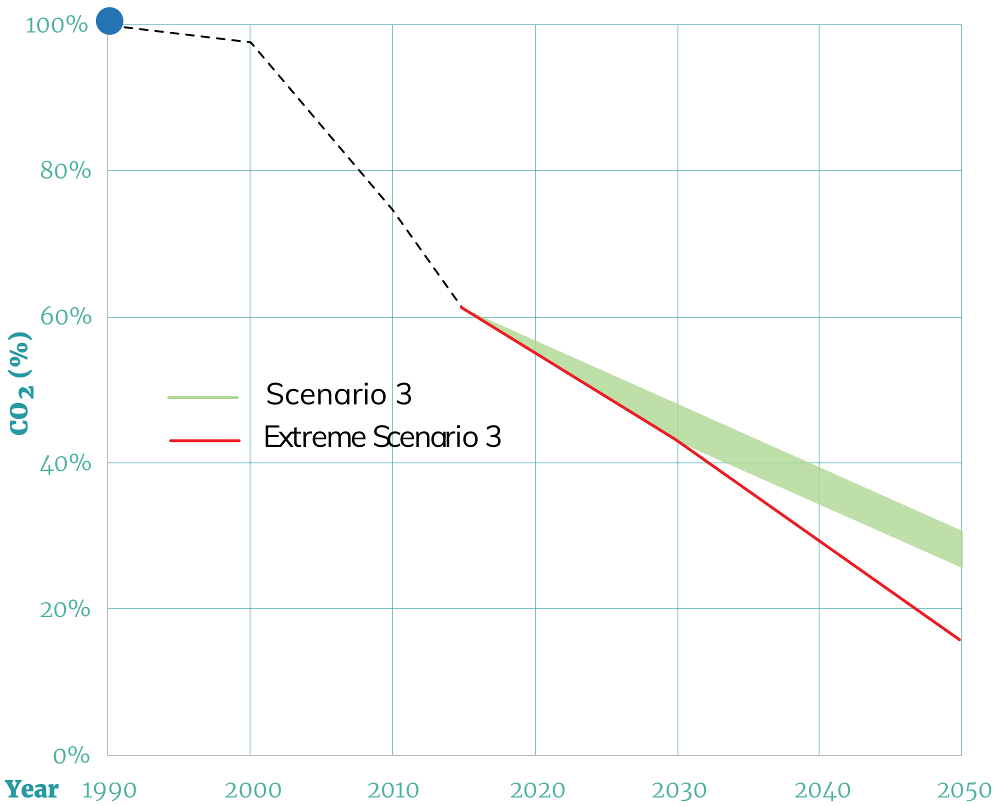
4kg/m³/MPa

Exposure class



200kg/m³

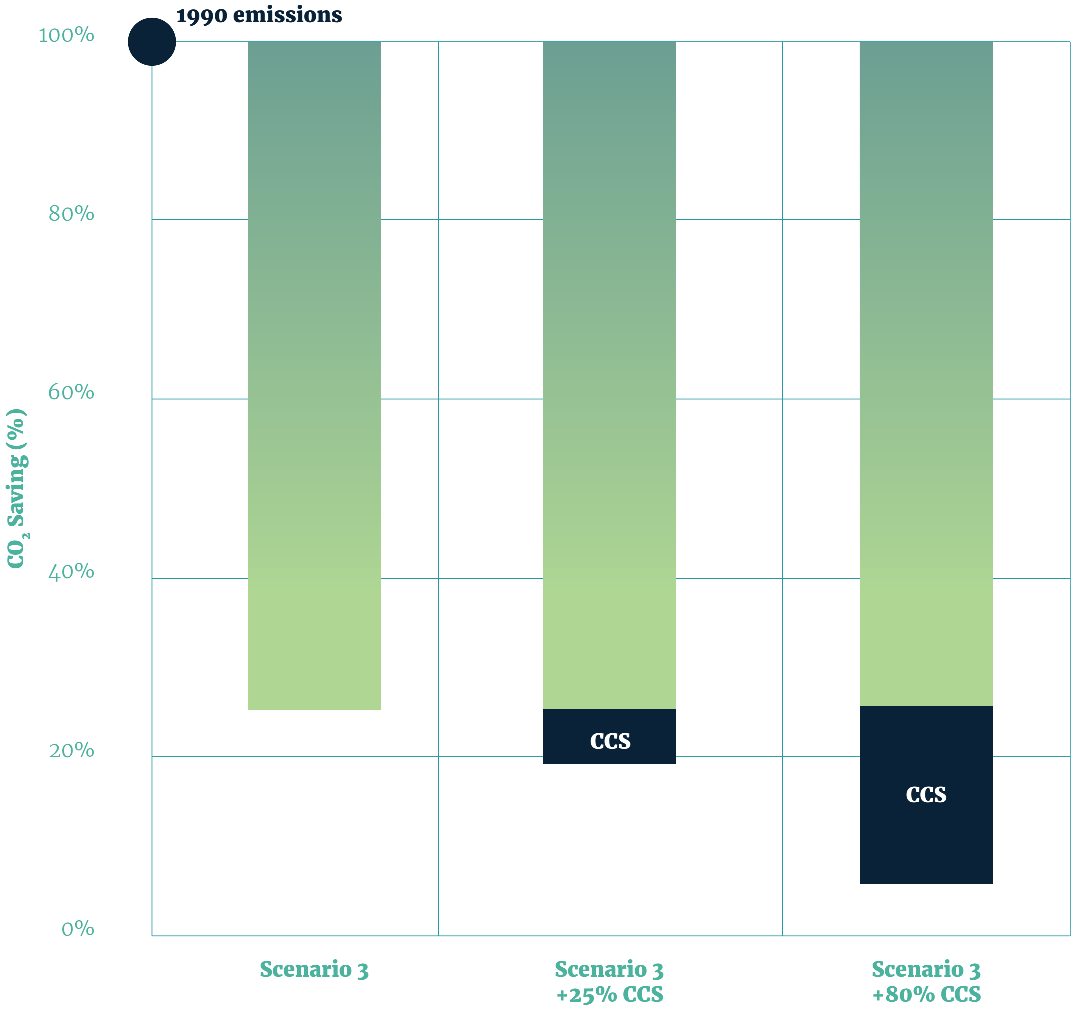
Figure 26 Extreme Scenario 3 towards a 1.5 °C target



6.7.2 Scenario 3 with additional Carbon Capture and Storage

The second option is to keep efforts along the value chain as in scenario 3 and add capturing emissions during the manufacturing process by CCS (Carbon Capture and Storage). Figure 27 shows that the 2°C target can be achieved by combining scenario 3 with 25% CCS and that a 95% reduction can be achieved compared to 1990 through the use of 80% CCS.

Figure 27 CO_2 savings by integrating carbon capture and storage (CCS) for scenario 3



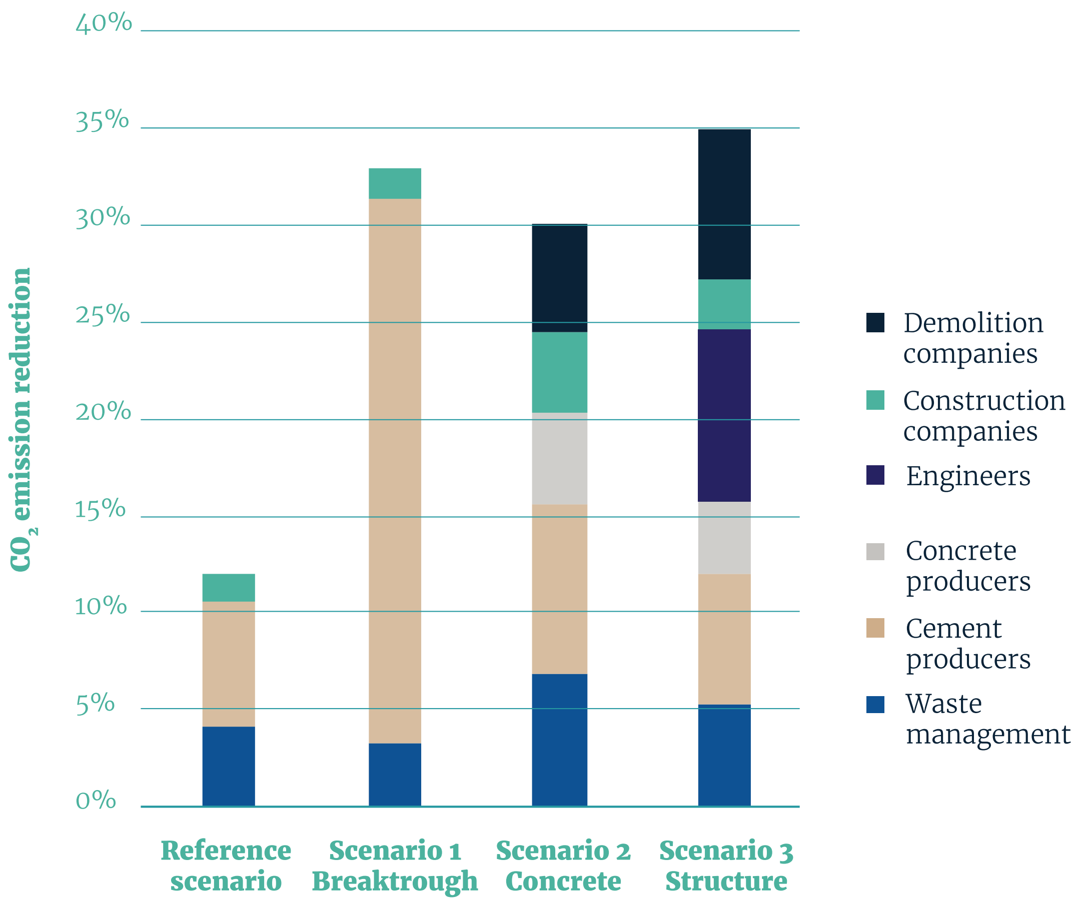
These scenarios will imply the investment of scenario 3 and an additional investment of 12 billion euros to equip 1 million ton/year plants for the 25% CCS scenario. Net zero emissions would technically be possible, but only with extremely large investments. We introduce this net zero carbon vision to highlight the choices available.

7. Policy recommendations

7.1. Introduction

Under the proposed scenarios, the pressure to reduce CO_2 emissions is based on different stakeholders. Figure 28 shows the distribution of "forces". It is clear that to achieve the same reduction objective (Scenario 1: Breakthrough technologies vs Scenario 3: Structural optimisation), the effort is distributed more evenly in the cases of Scenario 2 and Scenario 3. Consequently, the incentives will also have act on to the entire value chain. In Scenario 1, the effort to reduce CO_2 emissions relies heavily only on the cement producers and the capacity to finance their investment.

Figure 28 Savings along the concrete value chain from the scenarios between 2015 and 2050

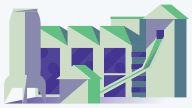
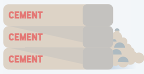
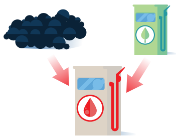
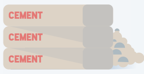
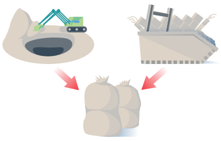


7.2. Enabling lowering of CO_2 in the clinker

To enable a reduction of CO_2 in the clinker, the following four processes need to be incentivised through policy: kiln optimisation, alternative fuels, use of fines from demolished concrete as raw materials and carbon capture and storage.

1. Dry technologies implementation is limited in term of savings, as the cement industry is already optimised. Some kilns are underused or not used anymore, some financial incitation can force cement producers to close old kilns and update some other kilns. As an example, a cement producer could keep the CO_2 ETS from an old kiln for some years after its closure.
2. The use of alternative fuel to improve energy efficiency is highly linked to the waste supply chain. Without a policy to favour co-processing and a legislation against landfill of waste, no CO_2 can be saved. Incentives or taxes should prioritise waste managers. Adopting this policy will also support a shift in waste heat recovery and renewable energy, such as Energy Efficient Certificates available in some EU countries (e.g., Italy).
3. The third method to reduce CO_2 at the clinker scale is to replace the main component of clinker and the main emitter of CO_2 during calcination, i.e., the limestone. One of the most interesting ways to do this is to replace part of the limestone with concrete fines from demolition, which implies a good demolition process that is able to separate the coarse aggregates, sand and cement matrix properly. Fostering local business models between cement and demolition/recycling companies in a circular economy approach should be performed. In a sense, what the cement industry has been able to do very efficiently with the waste collection for alternative fuels needs to be applied to the end of life concrete demolition to provide a continuous and quality-controlled supply of fines from recycling that mainly contains a zero fossil CO_2 calcium source for clinker. Furthermore, focusing on recycling fines allows the continued use of coarse recycling concrete to be valorised as aggregates or as road base (main reuse of demolished concrete today).
4. The last technology, i.e., carbon capture and storage as post combustion, is a real innovation that offers great potential but is not proven at large scale. Deployment of these technologies before 2040 should be ensured. Several projects are underway in Norway in particular, where SINTEF is currently studying the full-scale use of CCS in power generation industries (Horizon 2020 project CEMCAP https://www.sintef.no/cemcap). CCS can only be useful if a complete chain is available, including transport infrastructures and suitable storage facilities. A legal framework for CO_2 transport and public acceptance will be the key for application.

Table 7 Summary of policy suggestions at the clinker level

TECHNOLOGIES	RELEVANT STAKEHOLDERS	BARRIERS	POLICY SUGGESTIONS
Kiln improvement 	**Cement producers** 	High Investment	Financial incentive to close old plants (keep CO_2 credits temporarily)
Alternative fuels 	**Waste managers** 	Waste supply chain inefficient	• Foster co processing • Landfill regulations (taxes)
Carbon capture and storage 	**Cement producers** 	• Very high investment-not proven at scale • Societal acceptance	Public-private financial support
Alternative raw materials 	**Demolition company** 	Need a good demolition technique (time & cost)	• Incentivise local partnerships between cement and waste producers (circular economy) • Landfill regulations (taxes, legislation)

7.3. Enabling the reduction of CO_2 in cement

Another lever consists of replacing a part of the clinker in cement by substitutes, such as fly ash, ground blast furnace slag and limestone. To date, clinker substitution has contributed a 20-30% decrease in CO_2 emissions compared to the 1980's[63]. Unfortunately, further increases in substitution are limited by the reactivity and the availability of classic SCMs; therefore, it will involve introducing new types of SCMs, such as ternary blends with calcined clays and limestone. Increasing the use of calcined clay requires an investment in clay calciners. Improving the reactivity will also involve investments in grinder, separation, homogenisation technologies. Moreover, under the current situation of overcapacity, there is no motivation to increase the amount of cement that can be produced from a given quantity of clinker, which would be a consequence of increased substitution levels.

As discussed in section 5, it is not realistic to imagine that alternative binders, such as alkali activated materials or cements based on magnesium silicates, can make a significant contribution before 2050. Most importantly, these technologies are limited by lack of available resources in the EU, lack of technologies for large scale production, as well as uncertainties about long term performance.

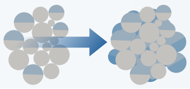
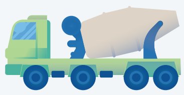
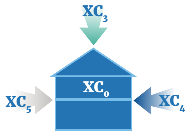
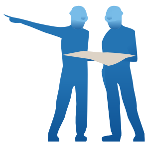
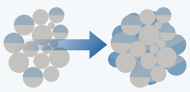
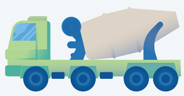
Table 8 Summary of policy suggestions at the cement level

TECHNOLOGIES	RELEVANT STAKEHOLDERS	BARRIERS	POLICY SUGGESTIONS
Alternative binders	**Cement producers**	Low market penetration	
Supplementary cementitious materials	**Cement producers** **Concrete producers**	● Lower Reactivity = Lower production speed ● Scarcity of resources = need for new sources (calcined clay = investment in calciner for clay)	● Compensation for loss of productivity ● Incentives to optimise reactivity by better grinding/blending ● Financial incitation to invest in clay calciners

7.4. Enabling the efficient use of cement in concrete

An improvement in the design of the concrete by optimizing the choice of aggregates and with the help of admixtures would reduce the quantity of cement and, consequently, CO_2 emissions. On the other hand, the exposure classes of concrete determine the minimum quantity of cement; this quantity varies from one country to another for the same class. Moreover, it is usual practice to choose the simplest solution, which is to use a single concrete for all the elements of a building that meets the most restrictive exposure class and therefore contains the most cement. This practice requires several incentives targeting different actors. Quarries should be encouraged to provide several granular classes of aggregates. Initially, without changing standards, we would recommend promoting the know-how in the ready-mix sector to establish a basis in mix design and by taking into account the full carbon life cycle, including the choice of materials. To make a real change, it would be necessary to increase the demand for low carbon concrete by construction companies by making it interesting for engineering firms to propose low carbon solutions (e.g., through the gain of points in tenders). In a second step, the homogenisation of standards towards the most competitive national standards in terms of sustainable construction as well as a more efficient approach to sustainability could allow a more significant reduction.

Table 9 Summary of policy suggestions at the concrete level

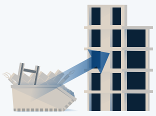
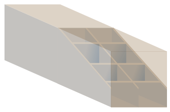
TECHNOLOGIES	RELEVANT STAKEHOLDERS	BARRIERS	POLICY SUGGESTIONS
Concrete mix design: Packing 	**Concrete producers** 	● Scarcity of aggregates ● Need space to have different grades on site	Require quarries located close to urban areas to provide more than one granular class
Concrete mix design: Exposure class 	**Engineering office** 	● More time for design ● Need tracking on site ● Engineering offices need to assume risk	Include as a criterion for awarding contracts
Overestimation of concrete 	**Concrete producers** 	Perceived risk of loss of robustness	● Enforce respect of standard (e.g., tax on additional cement) ● Increase demand for low carbon concrete by incentivising construction companies (e.g., lower VAT)

7.5. Enabling the efficient use of concrete in structures

Reducing CO_2 emissions at the scale of the structure would mean reducing the quantity of concrete. It is known that the quantity of concrete is often overestimated (by approximately 20%), and part of the concrete is even unused and ends up as waste. Moreover, part of the concrete does not necessarily contribute to the structural strength of an element. Block et al.'s work[44], for example, perfectly illustrates that for an element, a part of the material can be removed without compromising its integrity. The contribution of concrete and the potential of CO_2 emissions can be difficult to quantify because it is necessary to take into account all materials in the elements; however, the reduction in CO_2 can represent several tens of percent. It is obvious for an engineering firm to perform this structural optimisation move, and either their client has to ask, or it must be part of the tender. In addition to progressive digitisation, the increasing use of planning tools (BIM, Integrated Project Delivery) should be encouraged.

There is an increasing trend to recycle after demolition whereby entire concrete elements are reused in their original form. Designing flexible building elements, an increase in taxes for complete demolition and good deconstruction practices should be promoted.

Table 10 Summary of policy suggestions at the structure level

TECHNOLOGIES	RELEVANT STAKEHOLDERS	BARRIERS	POLICY SUGGESTIONS
Reuse of elements 	**Demolition company** 	Need a deconstruction technique (time & cost)	• Promote deconstruction-carbon credits for reusing elements • Tax for complete demolition • Landfill regulations
Optimisation of structure 	**Engineering office** 	• More time for design • Engineering offices need to assume risks	• Include as a criterion for awarding contracts • Foster the development of Integrated Project Delivery practices

7.6. How to track good practices and sustainable concrete?

In recent decades, the reduction of the ecological impact of buildings has received increased attention from researchers, decision-makers and businesses.

It focused on two strategies. The first one, which was taken with an industrial efficiency point of view, targeted the main industry and tried to reduce their energy consumption. As cement is an energy intensive industry, these first actions were dedicated to improving the cement production and the cement plants. The second strategy was dedicated to the building sector, which, from a political point of view, does not involve cement producers, but rather real estate developers. For buildings, the main problem (or cost) is the energy consumed during the use of the building. Therefore, this strategy focused on the improvement of building energy efficiency through better insulation, changing the energy technical systems from fuel to heat pump, etc.

These two approaches have fundamentally disconnected cement improvement, which was directed by an industry efficiency approach, and building improvement, which focused on operation energy. Over the last 10 years, with the development of sustainable labels for buildings [64], the embodied energy associated with building material production has been considered in combination with the operation energy but also in combination with many other sustainability criteria. DGNB, the German sustainability standard has, for instance, more than 200 indicators, one of them being the embodied energy in building materials. Recently, some countries have been tempted to reduce the number of indicators and specifically focus on the combination of embodied and operation energy to optimise both together, which is typically the approach developed in the Swiss 2000W society labels, where a total CO_2 budget per m^2 built is given and has to be allocated between embodied energy, operation energy and the energy used to commute to work. This is also the approach developed very recently in France with the new label E+C- (energy positive carbon negative buildings), where embodied and operation energy are considered together and compared to a global carbon budget.

However, due to this heritage of the two visions, one industry focused, the other real estate developer focused, the different stakeholders along the complete value chain are still not involved together along one project.

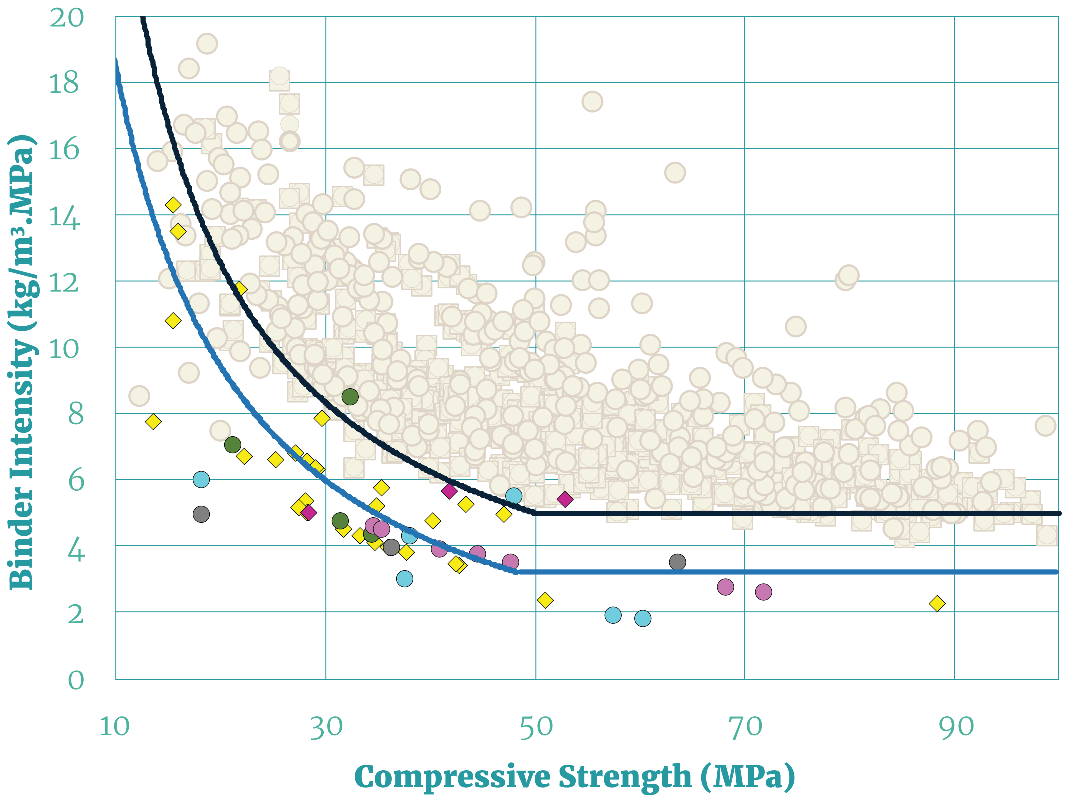
Cement producers are still focused on reducing CO_2 emissions per ton of cement, while developers will achieve a reduction of CO_2/m^2 by looking at all of the materials involved in the construction, not only the concrete, and surely not by looking at which exposition class the engineering office has specified. This reduction is currently the main barrier, i.e., determining to involve the stakeholders that are positioned in the middle (or on the side) of the value chain instead of those at the two opposite ends.

We propose defining specific indicators for the different stakeholders.

For the cement producer, it is important to focus on kg CO_2 per ton of clinker, which is the indicator that is directly related to the energy efficiency of the industrial process. As mentioned, this indicator is already quite good in Europe, but small improvements are still possible and need to be pursued. A value of 0.7 tCO_2/tclinker could be achieved.

For the concrete producer, the kg cement/m^3 is an obvious parameter but depends too much on the performance of the concrete to be used as such. However, the work compiled in the UN Environment report on Eco efficient cements [4] shows that we can use the kg cement/m^3/MPa for a given strength of concrete as a good indicator of the environmental efficiency of the concrete. For instance, for 30 MPa concrete, Figure 29 shows that most of standard concretes are above 8 kg Cement/m^3/MPa (240 kg cement/m^3), while it is possible to reach 5 kg cement/m3/MPa for environmentally efficient concrete. This indicator is appropriate for the concrete producer as it relies on parameters that the concrete producer knows, i.e., the amount of cement and the strength. This indicator is not related to upstream processes, such as the energy efficiency of the cement plant, nor to downstream processes, such as the final use of the concrete in the building. For a given concrete strength, it is easy to see for the concrete producer if he is producing a good or a normal concrete.

Figure 29 Estimated binder intensity versus the 28-day compressive strength. The lines represent concretes with the same amount of total cement. The black line is the lowest amount currently used, and the blue line represents the trend of low carbon cement that can be produced [33].



At the structural scale, the final material is the amount of concrete we use per square metre. One can consider the kg concrete/m², but this does not consider the strength of the concrete. It is better to use the carbon footprint of the structure and consider the kg CO_2/m^2 considering only the structure or all building materials involved. Looking at the quantity of CO_2/m^2 in concrete (independent of the limit value) can favour a change of materials (steel instead of concrete) and thus increase the risk of weakening the demand for cement and increasing the CO^2 output. The second indicator, kg CO_2/m^2 of structure, reduces the risk of changing materials, but the target value is dfficult to define in the case of integrated structural elements such as facades. Finally, the quantity of CO_2 per m² of building allows a complete assessment. In this case, concrete is one of the components, and there is less pressure on engineering offices and concrete companies. The literature also gives us target values for the amount of CO_2 emitted by materials (steel and concrete) in the building and maintaining a building at less than 255 kg CO_2/ m² is possible [65,66] and will be facilitated by the use of BIM (Building Information Modelling) to do a direct assessment and extract the bill of quantities.

In summary, we need different indicators that are simple to measure and are targeted for the different stakeholders to involve the complete value chain. These indicators are targeted for 2030 and should be regularly reviewed in line with latest scientific and technological developments at sectoral level.

- For cement producers: $t_{CO2}/t_{clinker}$ < 0.7-0.75 (*Scenario 2 by 2030 – IEA-CSI roadmap by* 2030), which is the direct thermal energy efficiency measure.
- For concrete producers: achieve less than 3.5 kg clinker/m^3/MPa< 3.5. for a standard concrete (30-50 MPa).
- For engineering offices: (kg $CO_2/m^2)_{structure}$ < 250 kg [66],
- For construction companies: $(kgCO_2/m^2)_{building}$ < 500 kg at the building scale [67]

8. Final remarks

This work has drawn on the following reports:

- IEA-CSI Technology Roadmap, 2018
- The role of cement in the 2050 LOW CARBON ECONOMY by CEMBUREAU, 2013
- The Circular Economy a Powerful Force for Climate Mitigation by Materials Economics, 2018
- Making Concrete Change: Innovation in Low-carbon Cement and Concrete by Chatham house, 2018

The main efforts of these reports focus on the cement scale by pushing the development of breakthrough technologies, such as carbon capture and storage and alternative clinkers. It is clear that these technologies will lead to very high investments and uncertainties regarding scale up and societal acceptance. Moreover, this strategy focuses on only one actor, i.e., the cement producers, and requires huge engagement from public institutions (European and national) to invest in carbon storage and capture infrastructure.

In our report, we highlight the necessity of involving the complete concrete construction value chain to spread the pressure along the stakeholder's chain and reduce investment. We investigated four technological levers, as follows:

- Reducing the CO_2 emissions at the clinker scale by optimising the process;
- Reducing the CO_2 emissions at the cement scale by reducing the clinker content in cement;
- Reducing the CO_2 emissions at the concrete scale by reducing the cement in concrete with a better mix design (including recycling and circularity strategies); and
- Reducing the CO_2 emissions at the structural scale by optimising the structure (less concrete by element) (including recycling and circularity strategies).

Four scenarios have been considered to effectively combine these technologies to reduce CO_2 emissions depending on the investment required and the integration of different stakeholders.

- A **reference scenario**: little investment in cement manufacturers to improve kiln technologies and slightly develop the use of alternative fuels and clinker substitution.
- The **Scenario 1**: very strong investment for cement producers to equip their plants with carbon capture and storage technologies as well as the market penetration of alternative clinkers.

- The **Scenario 2**: a moderate investment distributed among the different actors allows a significant increase of the use of alternative fuels and recycling of concrete, in particular, the fines in the clinkerisation process. In addition, optimisation of the concrete design mix with a better packing of aggregates and better respecting the standards in force on the quantity of cement in concrete.
- The **Scenario 3**: identical to scenario 2 with a slightly higher investment at the level of the structure (in particular the precast industry). In addition to concrete, the structure is also optimised, and consideration is given to reusing elements.

Scenario 3 gives a CO_2 emission reduction of approximately 70% since 1990 by improving cement production and optimizing concrete and the structure. In this strategy, two main approaches are highlighted. First, waste management that allows the following:

- the reuse of concrete fines as raw materials for cement manufacture,
- the increase in waste and biomass as fuel sources, and
- recycling concrete as aggregates or elements as such.

The second approach is compliance with good practices, including the following:

- strictly respecting the standards to reduce the amount of cement used and
- optimizing the mix design of concrete and the structure.

However, as discussed in the Chatham House report, pushing technologies at the concrete scale, such as concrete mix design optimisation, structural optimisation and recycling/reuse, will potentially have the effect of reducing the cement demand, which should be taken into consideration by public authorities and avoids significant competition for the supply of alternative fuels between industrial sectors.

Finally, in order to further reduce CO_2 emissions, the use of breakthrough technologies, such as carbon capture and storage, will be unavoidable. However, the necessary investment can be considerable reduced if the proposed efforts in scenario 3 are implemented. In addition, a further reduction of CO_2 emissions in this scenario is possible. The main difficulty is to propose relevant initiatives that will allow better communication throughout the stakeholder chain.

9. Acknowledgement

Thank you for the support of the European Climate Foundation, in particular Rannveig van Iterson and Simon Wolf for their involvement in the finalisation of this report.

The participants of the two workshops, the reviewers as well as the panel of experts of the Low-Carbon Cement based materials Initiative (LCCI under UN Environment- http://www.oneplanetnetwork.org/initiative/low-carbon-cement-based-materials-initiative-lcci) are warmly thanked for their contribution to this project through their support and comments. Finally, we would also like to thank the European companies and associations for sharing their information and helping to shed light on the complexity of the sector.

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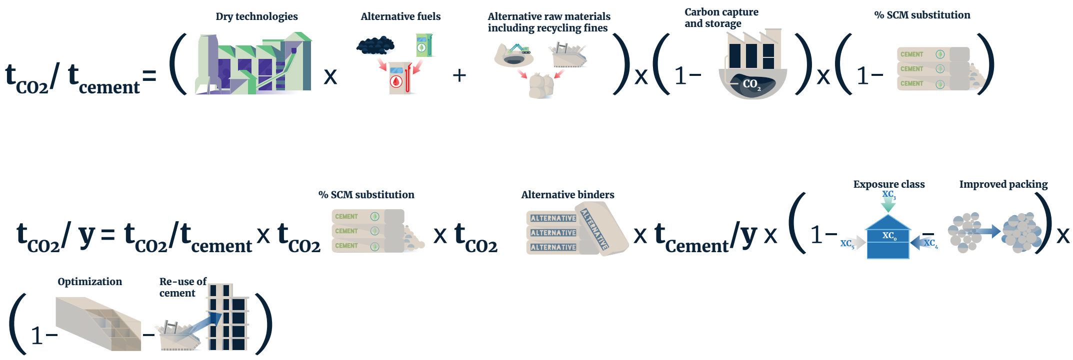
11. ANNEX 1: Model

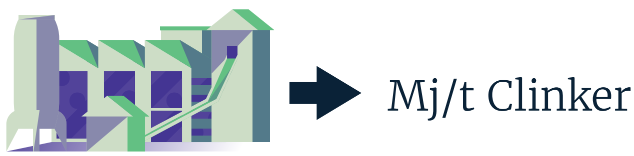
The equation to calculate the tonne of CO_2 per year is as follows:

$$\frac{t_{CO_2}}{y} = \left\{\left\{\left[\left[\left(\frac{MJ}{t_{CK}}\times\frac{t_{CO_2}}{MJ}+\frac{t_{CO_2RAW}}{t_{CK}}\right)\times(1-\%CCS)\times(1-\%SCM)\right]+\left(\frac{t_{CO_2SCM}}{t_{SCM}}\times\%SCM\right)\right]\times(1-\%AltBin)+\left(\frac{t_{CO_2AlBin}}{t_{AlBin}}\times\%AltBin\right)\right\}\times\frac{t_{cement}}{y}\right\}\times(1-\%Saving\ CO_{2\,Concrete})\times(1-\%Saving\ CO_{2\,Structure})$$

This can be translated with technologies, as follows:



With:

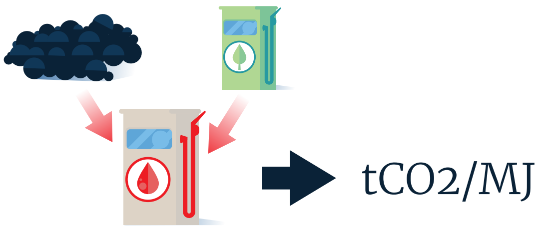


Data from CSI-GNR: 25aAGK and 8TGK% for EU 28

KILN TECHNOLOGIES	VALUE MJ/tCk	AVERAGE 1990	AV. 2015	MAX.AV. 2015
Dry with preheater and precalciner	3541	3960.26	3702.77	3565.6
Dry with preheater without precalciner	3664			
Dry without preheater (long dry kiln)	3831			
Mixed	4000			
Semi wet	4176			
Wet kiln	5505			

Further development of these technologies described in the CSI-ECRA technologies papers[14] can potentially reach 3200 MJ/tCk.

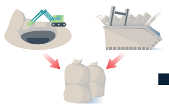
Alternative fuels



Data from Habert et al.[57].

KILN TECHNOLOGIES	VALUE tCO_2/MJ	AVERAGE 1990	AV. 2015	MAX.AV. 2015
Coal	9.60E-05	9.40E-05	7.60E-05	4.71E-05
Petcoke	1.01E-04			
Natural gas	5.40E-05			
Waste + Biomass	3.50E-05			

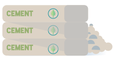
Alternative raw materials including recycling fines



Data from Habert et al.[57].

Limestone	Recycling fines
0.53 tCO_2/t	0 tCO2/t

% SCM substitution



Data (from Thyssen Krupp [68]).

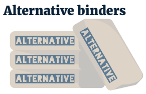
Calcined clay	Other SCM
0.25 tCO2/t c	0 tCO2/t

Hypotheses: Market penetration of calcined clay =18% (adapted for EU from IEA-CSI roadmap[5])

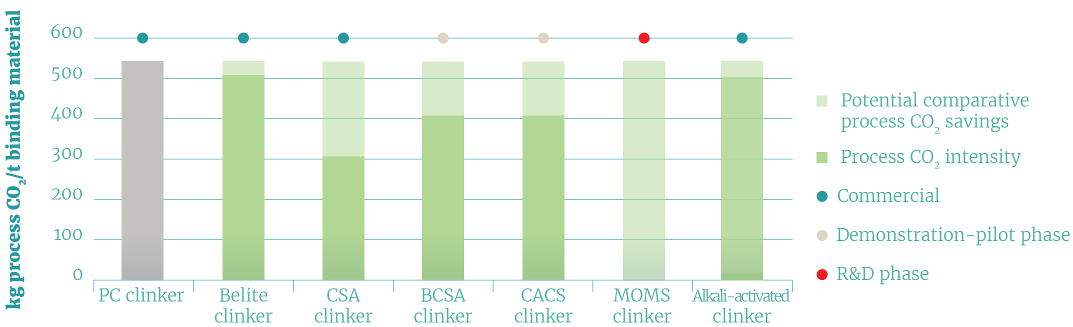
Demand in cement – Data from CSI-GNR EU 28 : 21TGWcm.

1990	2015	2050
222000000 t	157000000 t	157000000 t

Alternative binders



KILN TECHNOLOGIES	MARKET PENETRATION		POTENTIAL VALUE TO REDUCE EMISSIONS COMPARED TO PORTLAND CLINKER
	2030	2050	
Calcium sulfo aluminates	5%	10%	20%
Carbonatable calcium silicate clinker	5%	10%	70%
Alkali activated binders	1%	2%	50%
Magnesium silicate clinkers	0%	0%	100%
Hydrothermal calcium silicate clinkers	1%	3%	15%

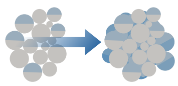


AVERAGE	520 kgCO2/t alt binders	490 kgCO2/t alt binders

Figure 30 Process CO_2 emissions generation intensity for selected cement binding materials

Average potential value based on the IEA-CSI roadmap [5] (Figure 30) and UN Environment report.

Improved packing

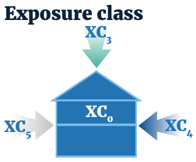


Data from Damineli et al.[33] and the UNEP Report[4]

2015	2050
8 $kg_{cement}/m^3/MPa$	4 $kg_{cement}/m^3/MPa$

Hypotheses: concerned 50 % of total concrete in a building and concerned 50 % of market penetration.

Exposure class



Data from national annexes of EN 206-1.

2015	2050
8 $kg_{cement}/m^3/MPa$	4 $kg_{cement}/m^3/MPa$

Hypotheses: concerned 50 % of total concrete in a building and concerned 50 % of market penetration.

12. Definition and glossary

Clinker is a component of cement, which is produced by calcining a mixture of about 80% limestone (which provides calcium) and 20% aluminosilicates.

Cement is a hydraulic binder (which hardens under the action of water), which is nowadays most often used in the manufacture of blocks, reinforced concrete, paving, plasters and mortars. Cements are currently classified under the name “CEM” followed by a Roman numeral from I to VI followed by a capital letter according to their clinker content and other components (lime, silica fumes, pozzolan, blast furnace slag, etc.).

Concrete is a composite material composed of fine and coarse aggregate bonded together with a fluid cement (cement paste) that hardens over time.

AAB Alkali activated binders

BIBM European Federation for Precast Concrete

BFS Blast furnace slag

BYF Belite ye’elimite ferrite

CCS Carbon capture and storage

CCSC Carbonatable calcium silicate clinker

CEMBUREAU European Association of cement industries

CSI Cement Sustainable Initiative

ECOBA European Coal Combustion Products Association

ECRA European Cement Research Academy

ERMCO European ready mix concrete organisation

EUROSLAG European association of ferrous slag products

FA Fly ash

GNR Getting the number right (database of CSI)

IEA International Energy Agency

IPCC International Panel of Climate Change

LCA Life Cycle Analysis

MOMS Magnesium oxides derived from magnesium silicates

OECD Organisation for Economic Co-operation and Development

PC Portland cement

SCM Supplementary cementitious material

UN Environment United Nations Environmental Programme

WBCSD World Business Council for Sustainable Development

ETH zürich

EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE