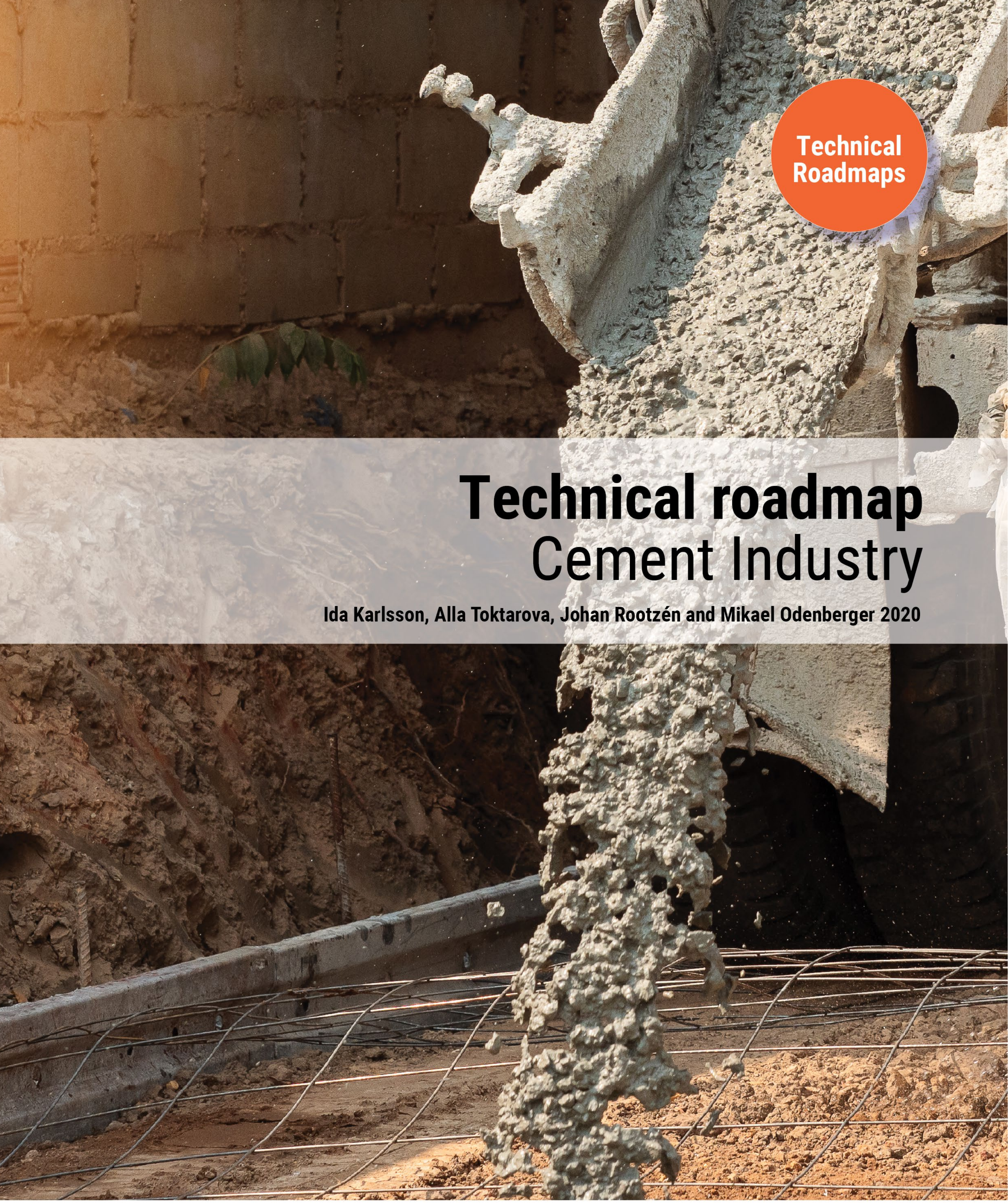

Technical Roadmaps

Technical roadmap
Cement Industry

Ida Karlsson, Alla Toktarova, Johan Rootzén and Mikael Odenberger 2020

MISTRA CARBON EXIT

About the authors

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Abstract

This report explores different possible trajectories of technological developments in the primary production of cement. By linking short-term and long-term goals with specific technology options, the Mistra Carbon Exit roadmaps describe key decision points and potential synergies, competing goals and lock-in effects. The analysis combines quantitative analytical methods, i.e. scenarios and stylized models, with participatory processes involving relevant stakeholders in the roadmap assessment process. The roadmaps outline material and energy flows along with costs associated with different technical and strategical choices and explore interlinkages and interactions across sectors. The results show how strategic choices with respect to process technologies, energy carriers and the availability of biofuels, carbon capture, transport and storage (CCS) and carbon neutral electricity may have very different implications on energy use and CO_2 emissions over time.

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The three reports: Technical roadmap Steel Industry, Technical roadmap Cement Industry and Technical roadmap Buildings and transport infrastructure.

Mistra Carbon Exit – Technical roadmaps

Introduction

Sweden has, in line with the Paris agreement, committed to reducing GHG emissions to net-zero by 2045 and to pursue negative emissions thereafter. The overarching goal of the Mistra Carbon Exit (MCE) research program is to identify and analyse the technical, economic and political opportunities and challenges involved in this undertaking.

With a time horizon of several decades, any notions as to the future development of the complex economic, social, and technical dynamics that govern demand for energy and materials, and the associated greenhouse gas emissions, are likely to be speculative. Nevertheless, decisions as to how to best manage the transition must be made taking the future into account.

In Mistra Carbon Exit we work with a set of Scenarios and Roadmaps as tools to assess interlinkages and interactions across sectors and to communicate internally between the project partners and externally to inform and engage relevant stakeholders. The MCE Roadmaps are aimed at exploring different future trajectories of technological developments in the supply chains for buildings and transportation infrastructure. By matching short-term and long-term goals with specific technology solutions, the MCE Roadmaps make it possible to identify key decision points and potential synergies, competing goals and lock-in effects.

Mistra Carbon Exit research investigates External scenarios (described in WP1, related to global development in “Shared Socioeconomic Pathways”, SSPs), Internal scenarios (described in WP1, referring to the development of the Swedish energy system meeting national targets) and Roadmaps that explore different technological pathways for the supply chains for buildings and transportation infrastructure (cf. Figure 1). The latter, i.e. the Roadmaps, will be used in an iterative approach to be included in the narratives for the internal scenarios, which means that there for example should be consistency between the development of the Swedish demand for electricity and the development of transforming Swedish steel industry to using hydrogen as reduction agent in the reduction of iron ore. Thus, Roadmaps are an important part of describing drivers that give rise to new demand that need to be included in the Internal scenarios. The aim is to find clear timelines for scenarios and roadmaps and finding combinations of roadmaps that fit a certain scenario narrative. Thus, it may take iterations to find both coherence in terms of timing of measures and which measures that fit what scenario.

Roadmap description

This report describes the initial work with the Mistra Carbon Exit roadmap for the Cement industry. The following subsections are described for each of the Mistra Carbon Exit roadmaps:

- Technological options
- Alternative pathways (Key decision points and investments, technological specifications, assumed activity levels, energy carriers)
- Timeline (Describing production mix/ market shares, resulting energy mix and CO_2-emissions)
- Description of risks, barriers and enablers linked to the respective roadmap

To find all the roadmap reports, please visit www.mistracarbonexit.com.

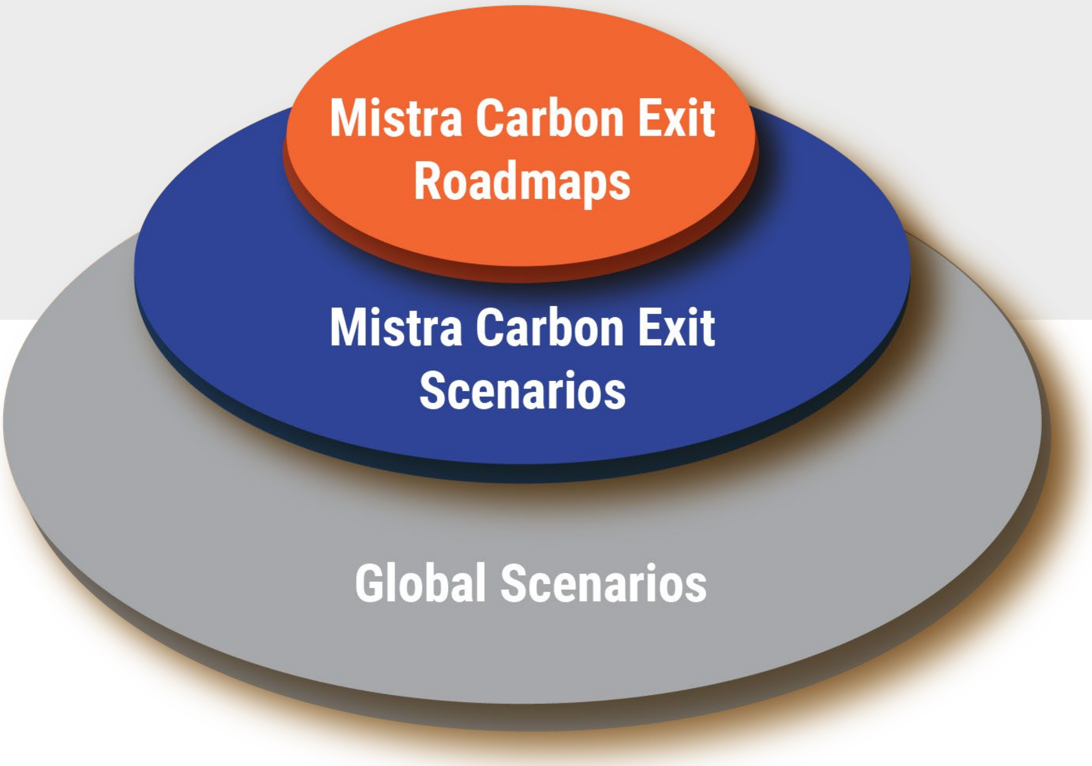

Figure 1. Mistra Carbon Exit use External scenarios to describe global development to meet a low carbon future, Internal scenarios to describe the development of that Swedish energy system and Roadmaps to describe how different technology options may impact the Internal scenarios.

Mistra Carbon Exit Roadmap

Cement Industry

Current status

Cementa, which is part of the Heidelberg Cement group, owns the two cement plants currently in operation in Sweden. The plants, which are located in Slite and Skövde, together have a capacity of approximately 3 Mt cement per year with the Slite plant accounting for around 80% of Swedish cement production. The Swedish cement industry is responsible for around 2.5 Mt CO_2 emissions annually, equivalent to around 15% of the total industrial CO_2 emissions.

Technological options

The cement clinker production is responsible for the majority of GHG emissions related to concrete use with around 60-65% of the CO_2 emissions stemming from the calcination process and 35-40% emanating from the fuels used in the cement ovens, the so-called kilns. The main current emission abatement options comprise of replacing fuels in the cement kilns with waste- or bio-based fuels along with reducing the amount of cement clinker by either using alternative binders (i.e. waste-based or natural supplementary cementitious materials, SCMs) and/or by optimising the concrete recipes to use less cement (Karlsson, Rootzén, and Johnsson 2020). Cementa is a frontrunner when it comes to alternative fuels with biofuels and waste-based alternative fossil fuels (e.g. plastic waste, tyres and solvents) together making up around 70% of the fuels for its kilns in 2017 (Kungliga Ingenjörsvetenskapsakademien 2019).

In contrast Sweden is behind the rest of Europe in using alternative binders. While the average share of clinker in cement in Europe is 73% (Favier et al. 2018), Swedish cement production has an average clinker content of 86% (Cementa and Fossilfritt Sverige 2018). Partly explained by regulations, national standards and norms historically being more restrictive, adoption of concrete with cement clinker substitutes is a key measure requiring further attention. However, as the main alternative binders used at current, i.e. fly ash from coal power production and blast furnace slag from steel production, are both set to reduce as coal power production is phased out and primary steel production is converted, the use of alternative SCMs, such as agricultural ashes and calcined clays will need to upscaled.

Regarding optimisation of concrete recipes, there is often 20-30% more cement in the concrete mix today than what is required by standards, which occurs for two reasons: over-specification of cement by concrete producers, and higher exposure classes for the concrete than the situation demands (Favier et al. 2018). In Sweden, we are also facing an additional issue in that faster construction processes have led to highly set drying requirements, for example for slabs covered with plastic or parquet flooring.

To meet these requirements, concrete with very high cement content are used. In regards to overall use of concrete in both the building and civil engineering sector, there are indeed indications that the average cement content in concrete in Sweden have increased over recent years, from about 400 kg cement per cubic metre in 2012 to now being at least 420 kg cement per cubic metre (Naturvårdsverket and Boverket 2019; ERMCO 2014).

There is thus a large potential for the cement demand to be reduced by changing construction production planning to suit new cement types, adjust concrete recipes depending on the specified flooring and add a screed layers or apply floating flooring solutions to create a buffer zone between concrete and flooring (Adnerfall 2018).

The cement demand can be also reduced by modifying the concrete production to achieve the same strength of concrete with a much lower cement content. This implies reducing the so-called binder intensity by better aggregate quality and adopting more advanced techniques in the blending and processing of concrete to enable granular optimisation.

Even if current abatement options are combined to its full potential, transformative technologies are still required to reach the goal of close to or net zero emissions in the cement industry by 2045. Carbon capture technologies (CCS) with or without electrification of the cement kilns are key deep decarbonisation alternatives, as specified in Table 1.

The Swedish cement industry roadmap is targeting climate neutrality by 2030, with the main focus being on biofuels together with CCS. However, Cementa is also pursuing electrification together with Vattenfall through its CemZero project, with a pre-feasibility study released in 2018 (Wilhelmsson et al. 2018). Even with electrification or using biomass to abate the energy related emissions, process emissions remain, and CCS still needs to be applied. However, the electrification serves to purify the flue gas streams which eases CO_2 capture.

In terms of CCS there are two main options, where CO_2 can be either captured after being generated in the cement kiln (post combustion capture technologies) or purified from kiln flue gases by applying combustion with oxygen instead of in air (oxy-fuel capture technologies). Post-combustion capture technologies do not require fundamental modifications of cement kilns and could be applied to existing facilities provided there is enough physical space available on the site. These technologies include scrubbing of CO_2 in flue gases using solvents such as amine solutions or capturing CO_2 via a calcium looping cycle using lime-based sorbents. Oxyfuel combustion requires more or less a new plant as well as an air separation unit (ASU) for the production of oxygen.

Applying carbon capture only in the precalciner has a higher technical maturity than applying carbon capture in the cement kiln. While the capture rate is lower, at about 60%, it provides an important early capture opportunity and has the potential of reducing the energy penalty associated with the captured due to use of waste heat recovery. Implementing carbon capture technologies in both the precalciner and the kiln could typically achieve 85-90% avoidance of onsite CO_2 emissions.

Oxy-fuel capture technologies require process modifications but are in general expected to have lower energy consumption and costs than post combustion capture using scrubbing technologies. However, while some pilot plant projects for post combustion capture with amine scrubbing are underway, for example in Norway, both calcium looping and oxyfuel technologies are still at the early development stage when it comes to cement application (while oxyfuel has been tested at pilot scale in power plant application).

Table 1. Specifications of conventional and low CO_2 production processes for cement production in greenfield production facilities

Technology	GHG emission	Costs	References
Cement production processes			
Dry kilns	0.80 t CO_2/ t clinker	Investment costs: 231 €/t cement €53/t cement	(Cementa and Fossilfritt Sverige 2018; Wilhelmsson et al. 2018)
Electrification (plasma heating) + CCS	0 t CO_2/ t clinker	Investment costs: 304 €/t cement Total production costs: €95-120/t cement	(Lechtenböhmer et al. 2016; Wilhelmsson et al. 2018)
Post-combustion carbon capture via amine scrubbing	0.06-0.13 t CO_2/ t clinker	Investment costs: 374 €/t cement Total production costs: €107-127/t cement €76/ tCO_2 avoided	(Leeson et al. 2017; Wilhelmsson et al. 2018; Cormos, Cormos, and Petrescu 2017; Rootzén and Johnsson 2016)
Post-combustion carbon capture via calcium looping	0.01-0.06 t CO_2/ t clinker	€37 /tCO_2 avoided	(Cormos, Cormos, and Petrescu 2017; Rodríguez, Murillo, and Abanades 2012; Leeson et al. 2017; Kuramochi et al. 2012; Favier et al. 2018)
Carbon capture via oxy-fuel technology	0-0.32 t CO_2/ t clinker	Investment costs: 332 €/t cement Total production costs: €82-93/t cement €42 /tCO_2 avoided	(Kuramochi et al. 2012; Rootzén and Johnsson 2016; IEA and CSI 2018; Hasanbeigi, Price, and Lin 2012; Garðarsdóttir et al. 2018)
Carbon transport and storage		Transport via ship: €10-35/ tCO_2 Storage in offshore saline aquifers: €7-24/ tCO_2 Storage in depleted oil & gas fields: €3-14 /tCO_2	(Jakobsen, Roussanaly, and Anantharaman 2017; IOGP 2019; Grant et al. 2018; Banks, Boersma, and Goldthorpe 2017)
Alternative binders			
Fly ash and blast furnace slag	0 t CO_2/ t fly ash 0.06-0.07 t CO_2 / t blast furnace slag	€30-95/t	(Lehne and Preston 2018; Şanal 2017)
Limestone and calcined clays	0.07 t CO_2/ t calcined clay 0.08 t CO_2/ t limestone	€3/t limestone €11/t common clay €125/t kaolin €510-600/t metakaolin	(Lehne and Preston 2018; Zhou et al. 2017; Shanks et al. 2019; Rootzén and Johnsson 2017; Samad and Shah 2017; Scrivener, John, and Gartner 2016)
Material efficiency			
Optimised concrete recipe	8-30% CO_2 reduction	Reduced binder intensity via appropriate use of standards and granular optimisation Investment costs for new grinders: 30 M€ for new installation; 6 M€ for retrofit implying ~1-5€/t concrete	(Shanks et al. 2019; Energy Transition Commission 2018; Favier et al. 2018)

Alternative cement production pathways

Four pathways were designed for the cement roadmap, in which all calculations relate to a constant cement production as a baseline assumption. The first pathway, Pathway 0, can be seen as a reference scenario based on conventional production technology with dry kilns where the share of biofuels is expanded over time while the current cement clinker substitution rate of 14% remaining.

The next two pathways, Pathways 1 and 2, are also based on expanded use of biofuels together with carbon capture and progressive cement clinker substitution. The first one of these adopts post-combustion capture with amine scrubbing, which is the technology tested by Norcem in Breivik in Norway, while the second one infers implementation of oxy-fuel technology, which is another test project of Heidelberg Cement within the EU-funded CEMCAP project.

Pathway 3 describes a development of electrification with CCS. As with Pathways 1 and 2, a progressive realisation of cement clinker substitution towards 30% replacement in 2045 is assumed.

A constant cement demand has been assumed in these pathways. A sensitivity analysis is used for the amine CCS and electrification pathways to explore the impact of a consumption increase in line with estimates on cement consumption increase at the European level (23% to 2050; Fleiter *et al.*, 2019) along with a potential cement demand reduction from optimisation of concrete recipes in closer alignment with current standards together with additional cement clinker substitution.

Details of the timelines for the pathways are described in Figure 2.

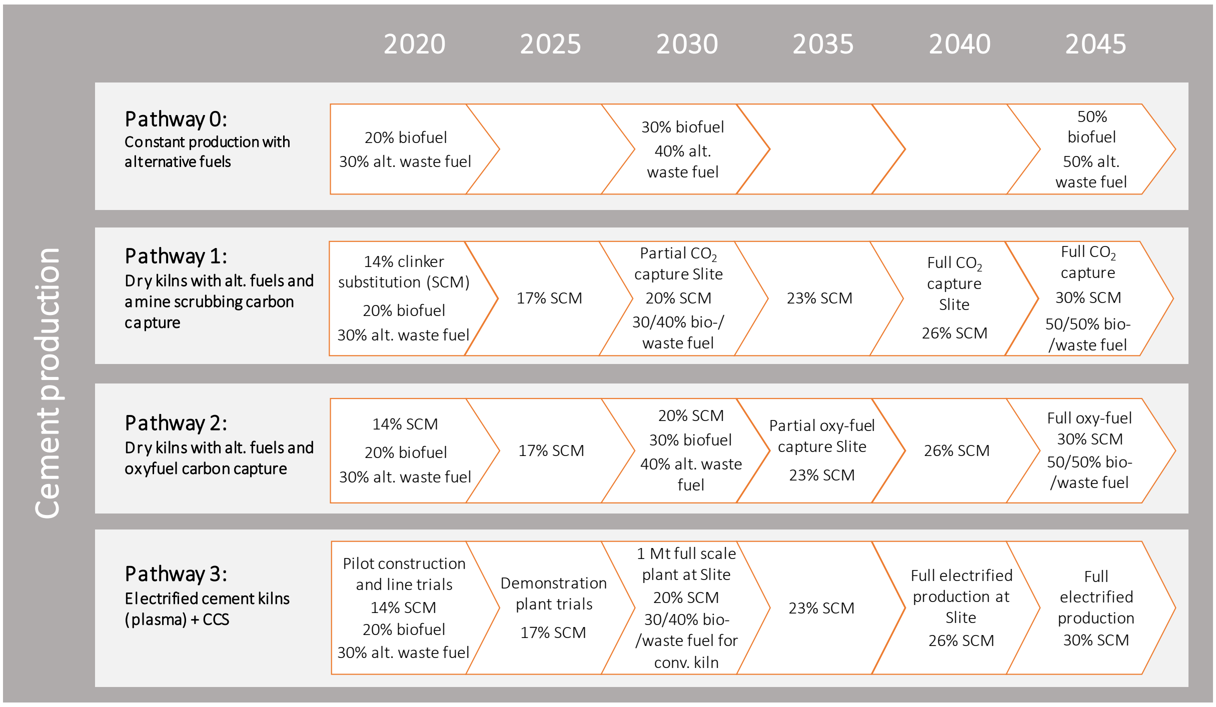

Figure 2. Key time-line decision points and investments for the cement industry roadmap pathways

Results

The resulting share of production technology, reduction in carbon emissions and captured emissions together with the developing share of energy carriers over time for the five pathways considered are depicted in Figure 3, 4 and 5.

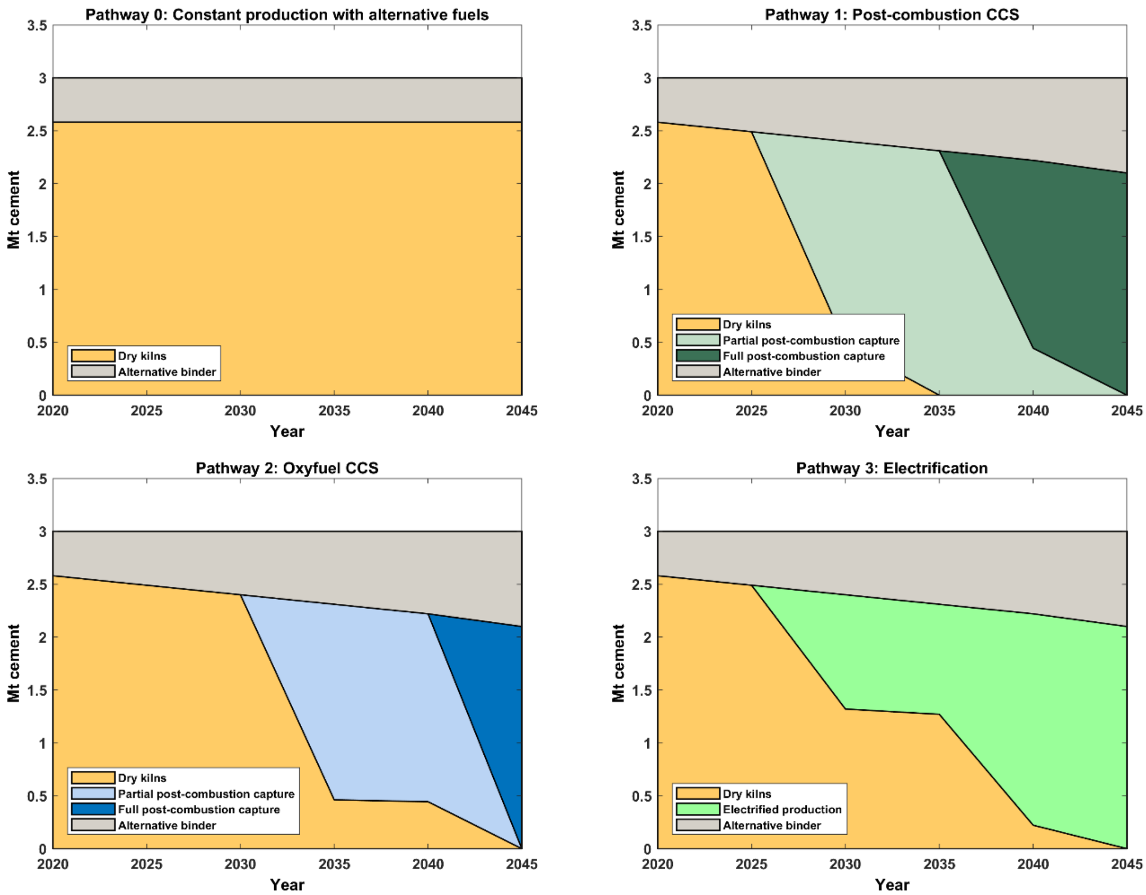

Figure 3. Production mix/market shares for the Sweden cement industry by process from 2020 to 2045

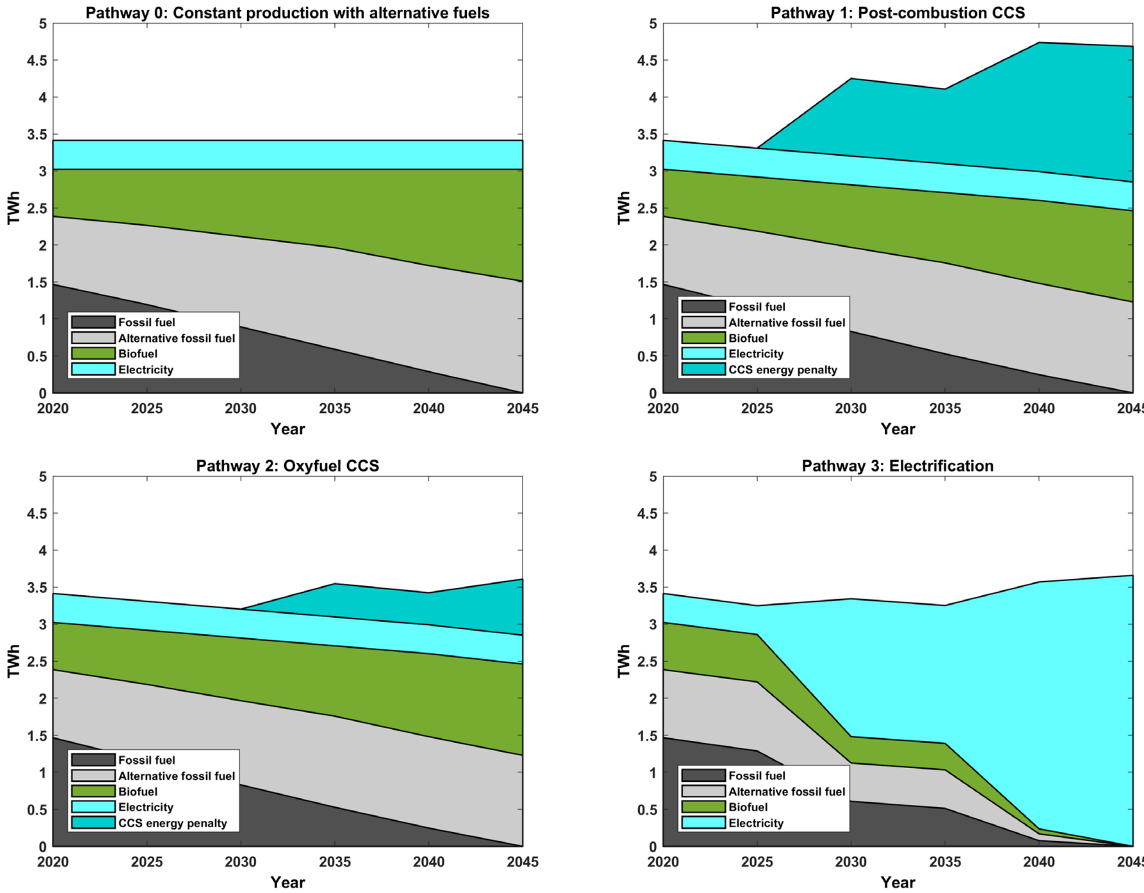

Figure 4. Energy use per energy carrier over time for the alternative pathways devised within the cement roadmap

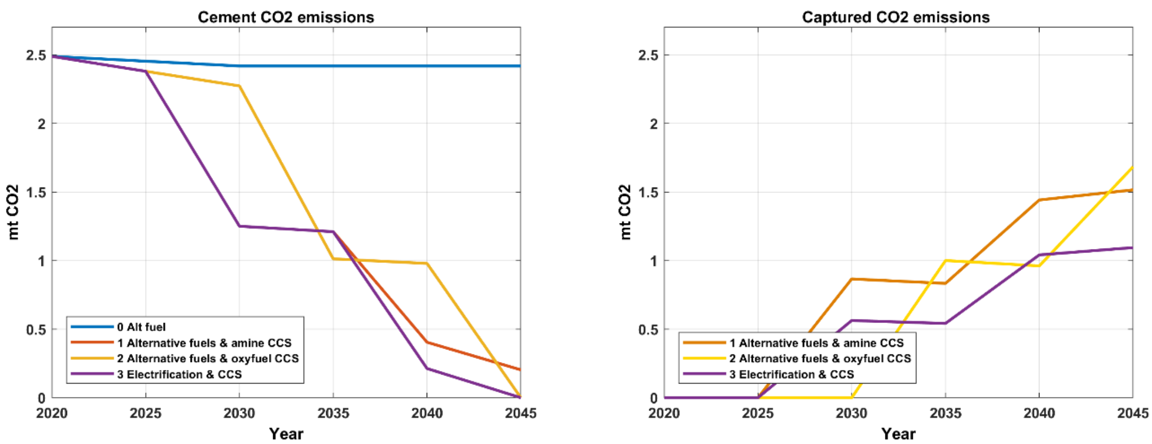

Figure 5. Results on emissions and captured CO_2 for the cement roadmap pathways

Although all decarbonisation pathways exhibit a potential for close to zero emissions, Figure 5 shows that the emissions in the alternative fuels and post combustion capture pathway do not reach zero emissions in 2045. Although depending on the share of biofuels and the capture rate, it might be possible to account for a certain share of negative emissions resulting from the capture of bio-based emissions, noting that there are no incentives for such negative emissions today (Å.-B. Karlsson et al. 2020).

The carbon capture process is associated with an energy penalty that can either be satisfied with thermal energy or electricity. The energy penalty is particularly prominent with the post combustion carbon capture in Pathway 1. If this energy penalty is covered by thermal energy, and in the form of bioenergy, the requirement for biofuels could reach 2.0 TWh in 2030 and up to 3.1 TWh in 2045. If the fuel demand would be 100% covered by biofuels (substituting also waste-based fossil fuels), this would mean a requirement for biofuels of around 4.3 TWh for Pathway 1 and 3.2 TWh for Pathway 2 in 2045. Biofuel use (without the carbon capture energy penalty) correspond to around 0.9 TWh in 2030 and 1.2 TWh in 2045 for both Pathways 1 and 2.

In the electrification pathway (Pathway 3), the electricity use increases gradually towards full electrification, implying electricity needs of around 3.7 TWh per year in 2045. The electrification eases the carbon capture process, however, leading to a potential for zero carbon emissions by 2045. Even so, the magnitude of captured emissions is lower than in the other pathways, as the electrification eliminates the carbon emissions from fuels, with only process emissions remaining.

Economic analysis

The parameters employed to evaluate the economic performance of cement production for the different decarbonisation pathways are the cost of cement production and the CO_2 avoidance cost. Although the cost figures given here are rather exact (as obtained from the calculations) it should be noted that they are associated with uncertainty.

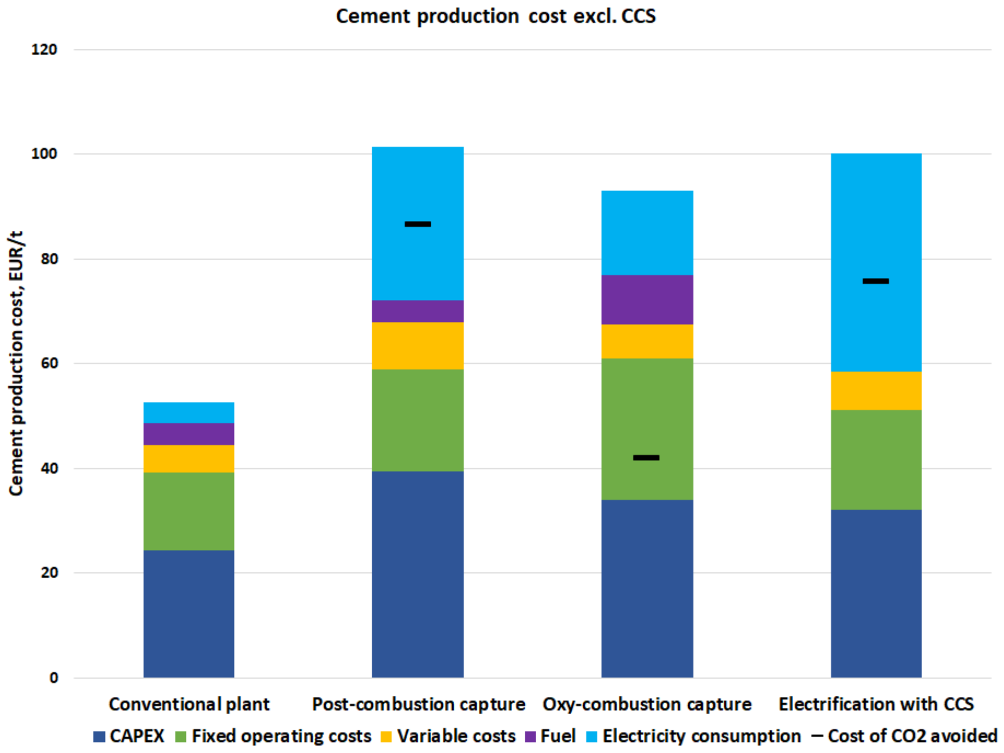

Figure 6. Comparison of cement production costs for the investigated technical options, assuming the use electricity to cover the energy penalty for post-combustion carbon capture and a combination of electricity and fuel for oxy-fuel carbon capture

The cost of cement in the alternative production pathways increases with 77-93% from the conventional production cost of €53 EUR/t. The CO_2 abatement cost ranges from €42/t CO_2 for the oxyfuel technology to €87/t CO_2 for the post-combustion technology.

The most important contributions to the carbon abatement cost differ among the technologies and illustrate the fundamental differences between technologies. In the case of the electrification pathway, electricity contributes 41% to the cost of CO_2 avoided, while for oxy-combustion technology, fixed operating costs provide the highest share of the abatement costs.

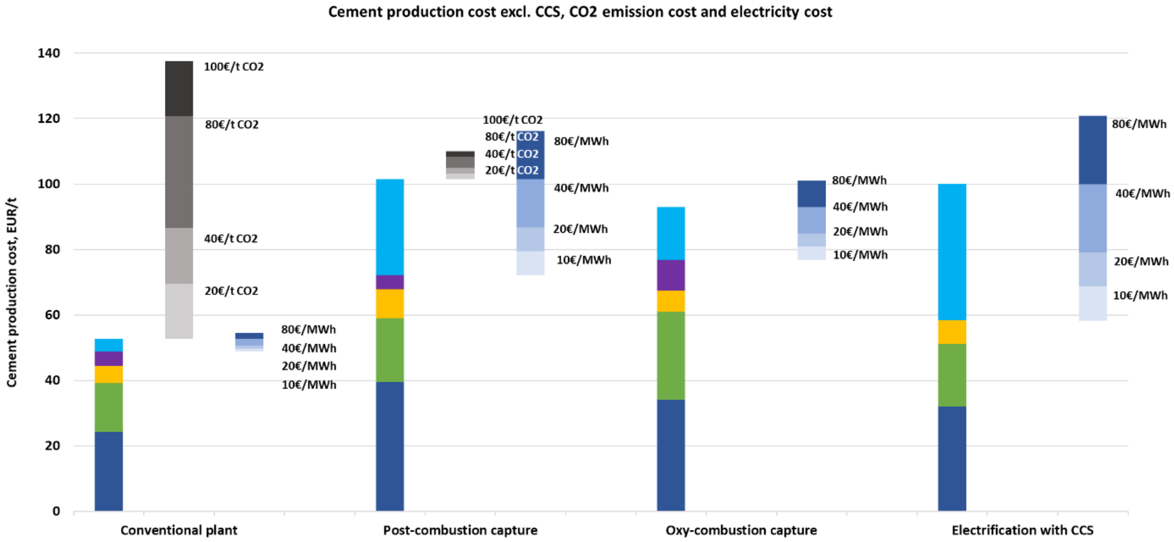

Figure 7. Comparison of cement production cost depending on differences in carbon price (grey bars), and electricity cost (blue bars). The left-most coloured bars show production costs without carbon pricing based on electricity prices of €40/MWh

As demonstrated by Figure 7, the conventional cement production process is most sensitive to the cost of CO_2, where a carbon price of €65/tCO_2 is needed to make post-combustion capture competitive to the conventional process. This figure is slightly less for the oxy-fuel combustion capture pathway (€48/tCO_2) and for the electrification pathway (€55/tCO_2), assuming an electricity price of €40/MWh.

Comparing the different decarbonisation pathways based on the electricity prices demonstrate that the electrified cement production pathway is the most cost-beneficial pathway for electricity prices up to €29/MWh. For electricity prices of €30/MWh and above, cement production with oxyfuel capture technology becomes the lowest cost option among the decarbonisation pathways.

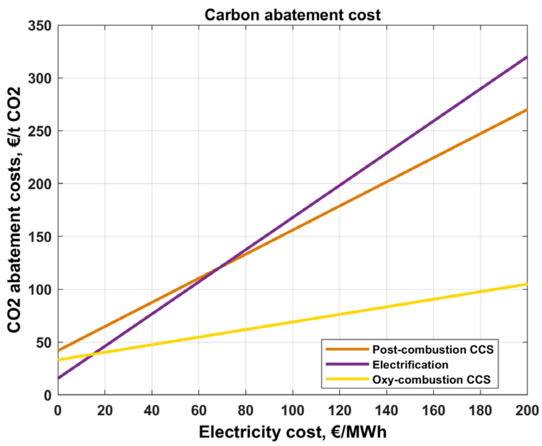

Figure 8. CO_2 abatement costs in 2045 (excluding carbon transport and storage costs) for the alternative pathways devised within the cement roadmap

The sensitivity of carbon abatement costs to electricity prices is shown in Figure 8. Post-combustion capture technology using electricity to produce the steam required for the capture process outcompetes the CO_2 avoidance cost for electrification only at electricity costs of €70/MWh and above.

It is worth noting here that if we include CO_2 transport and storage costs the picture will shift, as the captured emissions are 32-40% lower in the electrification pathway compared to the post-combustion and oxy-fuel combustion capture options due to the elimination of fuel emissions. The estimates for carbon transport and storage vary greatly depending on transport distance and type of storage (cf. Table 3). Whilst observing the large degree of uncertainty, taking account of carbon transport and storage costs mean that the point at the where electrified cement production achieves the lowest CO_2 avoidance costs is shifted upwards towards electricity costs of €20-38/MWh.

Sensitivity analysis

The sensitivity of the analysis to changes in production levels is presented in Figure 9 and figure 10. In terms of emissions, the main difference occurs in the medium term where a gap of 0.4 mt CO_2 in 2025 and 2030 is exhibited between the scenarios of consumption increase versus optimisation. Optimisation and clinker substitution also reduce captured emissions, by 28% for the post-combustion amine CCS pathway and by 12% for the electrification pathway, respectively.

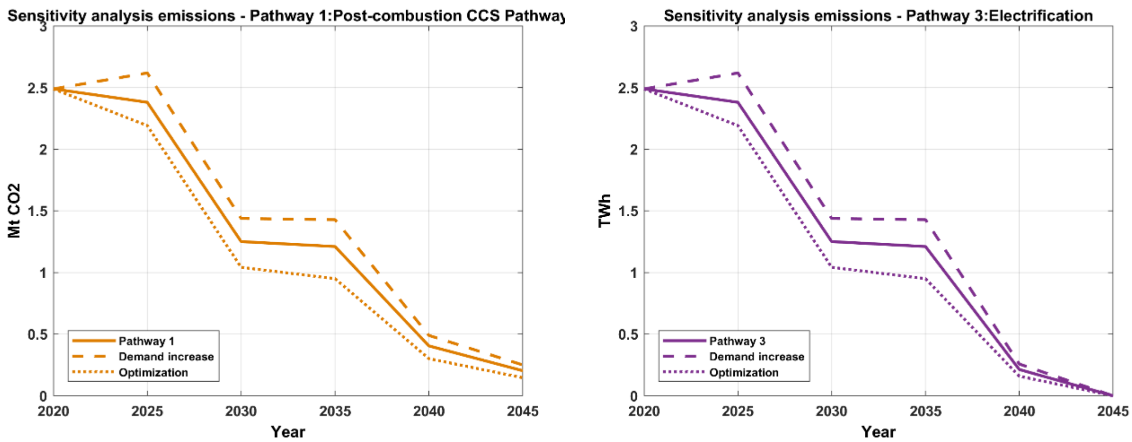

Figure 9. Changes in emissions from the sensitivity analysis exploring the impact of a consumption along with a potential cement demand reduction from optimisation for the amine CCS and electrification pathways

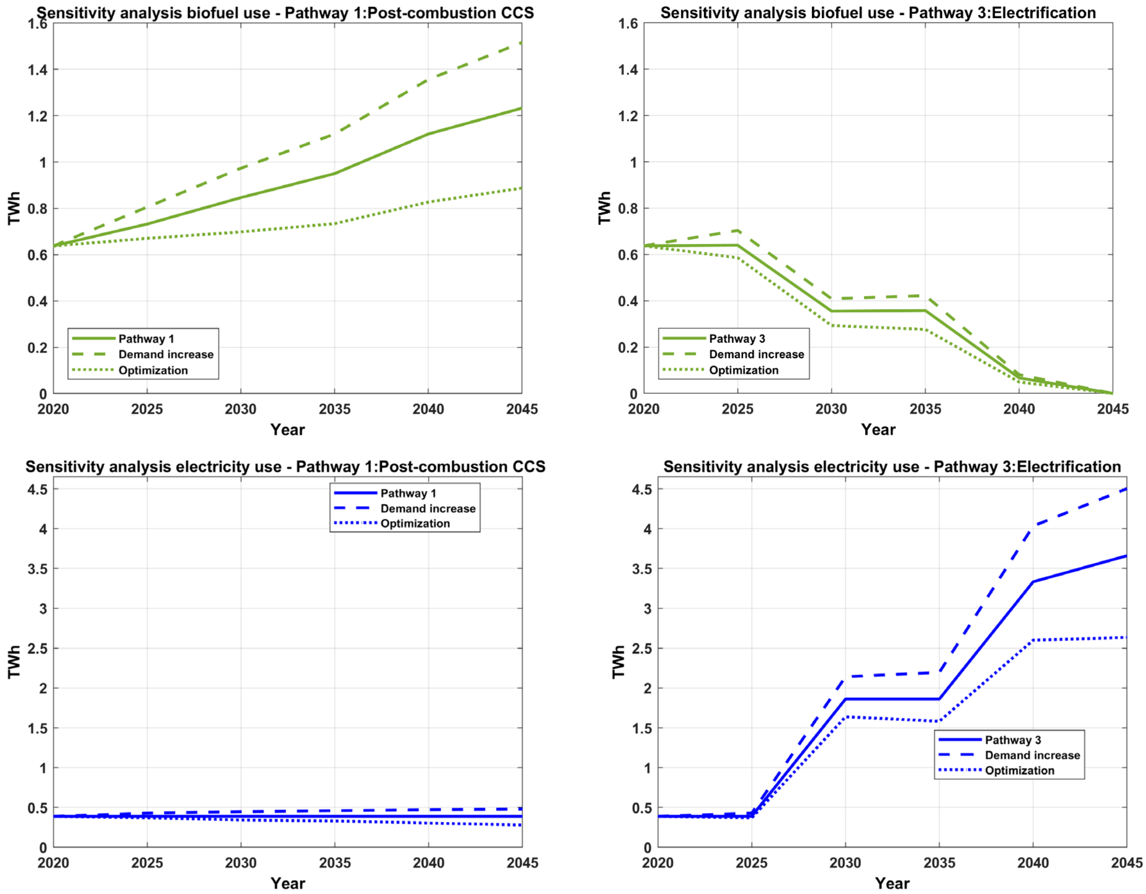

Figure 10. Changes in biofuel (top graphs) and electricity use (bottom graphs) for consumption increase versus optimisation

The sensitivity analysis shows notable impacts in terms of energy use for increases in cement consumption versus demand reductions from optimisation, particularly in regards to electricity. While a consumption increase would imply an increase to 4.5 TWh electricity for the electrification pathway, optimisation has the potential to reduce total energy needs by around 30%.

Risks, enablers & barriers

Details of some of the key risks and uncertainties together with potential enablers to realise the different technological pathways and its associated prerequisites are described in Table 4. The input is drawn from the industries' own roadmaps developed within the "Fossil-free" Sweden initiative, stakeholder input and feedback gathered from workshops and conferences within Mistra Carbon Exit together with inspiration from other relevant national and international literature (see Appendix 1).

Table 2. Risks, enablers and potential barriers for low carbon cement production

Technological development and diffusion	Risks and uncertainties	Enablers
Deployment of cement clinker substitutes	Restrictive regulation, standards and norms - Conservatism and 'belts and braces'; Technical challenges around production control; Economic concerns on process adjustments; Concerns around concrete properties and guaranteeing durability; Limited market demand reinforcing existing business models;	Ease of testing and project-to-project approvals regime; Apply learnings and experiences from Swedish pilot projects and international adoption of cement clinker substitutes; Introduce requirements and incentives in public and private procurements based on function and carbon footprint; Establish "Policylabs" for industry regulations; Move from word to action around increased supply chain collaboration - unified product development and risk sharing; Education and engagement of the entire construction value chain of the potential and possibilities with cement clinker substitutes;
	Limited availability of raw material - Phase-out of coal power and conversion of blast furnaces	Support research, development and deployment of unconventional cement clinker substitutes
Reduced binder intensity	Risk distribution along the value chain; Longer hardening times for certain applications; Requires changes to industry practices and more flexibility in the production planning and operations	Measurement and reporting of cement/binder use per application; Digitalisation to follow the cement trail; Introduce requirements and incentives in public procurement based on function and carbon footprint; Develop construction production planning processes allowing optimisation towards climate impact as well as cost and time; Controlled production chain, e.g. precasting; Ensure exposure and strength classes are optimised per individual application - right concrete in the right place; Education and engagement of the entire construction value chain of the potential and possibilities of optimised concrete recipes;
Alternative waste-based fuels	Slow permitting processes	Clarify authorities' mandate in supporting the low carbon transition
	Limited availability of waste feedstocks	Develop policy instruments to support a faster transition to biofuels in industrial production
Biobased fuels	Accessibility and pricing of biomass feedstocks; Consequences for other environmental targets; Focus on biomass as carbon storage and provider of biodiversity - limiting biomass use to certain sectors; Requires specific biofuels adapted for each process; Additional costs for pre-treatment	Develop a national bioenergy strategy and action plan for access to and distribution of sustainable biofuels; Establish a regulatory cross-sectoral framework for biomass use; Develop tightly defined sustainability standards for biofuels; Establish and secure a well-functioning market for biofuels; Potential of bioenergy combined with CCS to provide negative emissions;

Carbon capture and storage	Lack of national CCS strategy; Availability and accessibility of CO_2 storage and transport infrastructure; Financing and public acceptance	Commission an authority with responsibility for developing and implementing a national CCS strategy; Develop financing structure including risk sharing, e.g. consumption-based fee to support deployment; Public support for research and development - Particularly for moving from pilot to development scale; Supplementary and supportive instruments to the EU emissions trading scheme;
Electrification	Large upfront investments; Lack of coordinated electrification strategy allowing for increased electrification in both industry and transport; Demand for sufficient power generation/ transmission/ distribution; Electricity price uncertainty	Develop a national electrification strategy and action plan for access to and distribution of low/zero CO_2 electricity; Create conditions for transformation of the basic industry through financing, risk sharing, innovation support and policy instruments; Political engagement to secure grid stability, access to and availability of zero-carbon electricity; Active public policy coordination; Secure a well-functioning electricity market

Summary and discussions – Cement

The ambition with this Roadmap is to explore how different choices, with respect to technological development in the Swedish cement industry, affect material flows, energy use, CO_2 emissions and cost over time. However, it is important to note that the cement production pathways assessed in this roadmap are explorative and not intended as projections. The analysis effectively illustrates how different technological choices (i.e. increased biofuel use, electrified cement kilns and CCS) will have very different impacts on the surrounding energy system. The results also give an indication of the rate and scale at which support infrastructure would need to be rolled out (renewable electricity supply, electricity grid expansion, CCS infrastructure, sustainable biofuel supply).
Successful decarbonisation of the cement industry will involve the pursuit - in parallel - of measures to reduce cement and concrete use and complementary policy interventions and/or private initiatives to secure financing and lessen the risk in investments in zero emission production processes.

Since more than half of the emissions from cement production arise from the calcination of limestone, carbon capture is more or less inevitable to decarbonise the production of cement clinker. Important lessons may come from Cementa's Norwegian sister company Norcem that has performed a series of pilot-tests of different CO_2 capture technologies. Norcem is now awaiting financing decisions which, if approved, can make it possible to launch the first industrial-sized project for CCS in Europe. Since the lead times related to planning, permitting and construction of both support infrastructure (CO_2 transportation and storage infrastructure) and piloting and upscaling to commercial scale of the actual production units are long, initiation of strategic planning will need to be take place as early as possible.

The technological options considered in this work belong to the options that tends to be most widely discussed (and possibly most technologically mature) but other options, at different stages of development, are also being explored. Examples of innovative processes that are being investigated, which have not been part of this study, include new production technologies to produce cement and construction materials based on magnesium oxide, geopolymer cement, calcium looping technology for CO_2 capture and methods to separate unhydrated cement from concrete demolition waste (see e.g. Hasanbeigi, Price and Lin, (2012) and Allwood et al., (2019) for a more thorough review).

In practice, however, the hurdles for new innovations and new entrants are high (Karltorp et al. 2019; Rootzén and Johnsson 2017). Cementa is, as a subsidiary to the Heidelberg Cement Group, vertically integrated into the concrete manufacturing industry. Similarly, several of Sweden's largest contractors, through subsidiaries, are major actors in the market for concrete. Thus, aside from a few of independent concrete manufacturers, a dozen building materials and contractor firms together enjoy strong positions in the Nordic markets for both cement and concrete.

Further, the versatility, relatively low cost and relatively abundant access to raw materials means that cement and concrete sets high standards for competing materials. That said, technical improvements and environmental benefits (if managed properly) means that structural wood components have made inroads on markets traditionally dominated by concrete. The interest in building multi-storey buildings and bridges with wooden structural frames is growing both in Sweden and abroad. It is likely that this trend will continue and that the use of structural wood will increase, and thus, contribute to lowering the demand for cement and concrete, especially in building construction.

Whereas the emphasis of this report is on options to reduce the direct on-site energy- and process-related CO_2 emissions from cement plants, it is also important to increase efforts on the demand side to curb and reduce the consumption of cement and concrete, yet, not necessarily at the expense of the profitability of concrete products. Since most of the cement and concrete produced in Sweden is used within the country, there is a clear link between measures to reduce the use of cement and concrete and the possibility to reduce emissions from domestic cement production. Here public procurers in governmental agencies, municipalities and county councils, by virtue of their significant purchasing power, play an important role in lowering the risks in material innovation and incentivizing circular practices and material efficiency. In addition, private actors can help to increase the volume of demand and to legitimize public strategies.

Although the findings reported in this report draw primarily on Swedish experiences and while some of the conclusions are contextual, many of the challenges and opportunities are global. Concrete is already today, second to water, the most consumed material in the world and there is a lot to suggest that the appetite for cement and concrete will continue to be high as the demand for basic infrastructure and good quality housing grows in developing economies (IEA 2019; IRP and UN Environment 2019).

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Appendices

Appendix 1: Overview of relevant roadmap studies and reports

	Description	Geographical scope	Reference(s)
Basic industry			
The "Fossil Free Sweden" initiative development of "Roadmaps for fossil free competitiveness"	Initiative in which Swedish business sectors (including cement, concrete, steel and building and construction) have developed roadmaps towards zero GHG emissions. Roadmaps have been developed for: the Aggregates Industry, the Aviation Industry, the Cement Industry, the Concrete Industry, the Construction and Civil Engineering Sector, the Digitalisation Consultancy Industry, the Food Retail Sector, the Forest Sector, the Heating Sector, the Heavy Haulage Industry, the Maritime Industry, the Mining and Minerals Industry, and the Steel Industry.	Sweden	(Fossil Free Sweden Initiative 2018)
Klimatneutral konkurrenskraft - Kvantifiering av åtgärder i klimatfärdplan	Quantifies the increased requirements for electricity and bioenergy in 2045 resulting from the combined measures of the industry roadmaps developed within the Fossilfree Sweden initiative, together with other parts of the Transport sector and the Chemical industry.	Sweden	(SWECO 2019)
Så klarar svensk industri klimatmålen	Survey of technological and process abatement options in the Swedish industry sector up until 2045. Coverage: Iron and steel, Cement, Petrochemicals/Chemicals, Non-Ferrous metals, Forestry, Oil Refining, Mining and minerals.	Sweden	(Kungliga IngenjörsVetenskaps Akademien 2019a)
Hinder för klimatomställning i processindustrin	A report within the government assignment *Innovation-promoting efforts to reduce greenhouse gas emissions in the process industry*. Details technical, market, regulatory, resource and infrastructure barrier to a low-carbon transition for the Swedish process industries: Iron and steel, non-ferrous metal, Cement, Petrochemicals/Chemicals and Oil Refining.	Sweden	(Swedish Energy Agency 2019)
Statens roll för klimatomställning i processindustrin	Provides an overview of the role of the government and other public and private actors in facilitating a climate transition in the Swedish process industry. Coverage: Iron and steel, Cement, Petrochemicals/Chemicals and Oil Refining	Sweden	(Karltorp et al. 2019)
A Steel Roadmap for a Low Carbon Europe	Industry association assessment of abatement options for the steel industry and conditions required for its realisation. Also details the role of steel for low carbon solutions in other societal sectors.	Europe	(Eurofer 2013)
Cements for a low-carbon Europe	Industry association report focusing on the diverse solutions applied by the cement industry across Europe to reduce the carbon footprint of its products through the production of low clinker cements.	Europe	(Cembureau 2013)
A sustainable future for the European cement and concrete industry	Summarises the practices and technologies that can be implemented to significantly reduce CO2 emissions from the cement and concrete sector in Europe by 2050. Details the potential and need for reduction efforts along the complete value chain.	Europe	(Favier et al. 2018)

Towards A Flemish Industrial Transition Framework	Puts forth a proposal on the possible scope and blueprint of a future facilitative framework towards a Flemish low-carbon economy taking into account the interactions and possible synergies between energy intensive industries and the rest of the economy.	Flanders and Belgium	(Wyns et al. 2019)
Decarbonising Europe's energy intensive industries	Sketches the blueprint of an industrial strategy towards climate neutrality in the EU. The study provides an integrated structure that scrutinizes a broad set of policy instruments and provides ideas for making the whole policy set as tangible as possible.	Europe	(Wyns et al. 2019; Wyns and Axelson 2016)
Building Blocks for a Climate-Neutral European Industrial Sector	Outline an integrated industrial climate strategy for the EU and describes five policy options to facilitate decarbonisation of the basic materials industry by 2050.	Europe	(Neuhoff et al. 2019)
Industrial Innovation: Pathways to deep decarbonisation of Industry	Investigates the extent to which key EU industrial sectors can benefit and contribute to a climate-neutral future. The project takes a perspective to 2050 and beyond and analyses the technologies, pathways to 2050 and the policy mix needed for implementation.	Europe	(Fleiter et al. 2019; Chan et al. 2019)
Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry	Characterises how net zero emissions can be achieved by 2050 from the largest sources of 'hard to abate' emissions: Steel, Plastics, Ammonia, and Cement. Starts from a broad mapping of options to eliminate fossil CO2-emissions from production and integrates these with the potential for a more circular economy.	Europe	(Material Economics 2019)
Mission Possible - Reaching Net Zero Carbon Emissions from Harder-to-abate sectors by Mid-century	Outlines the possible routes to fully decarbonize Cement, Steel, Plastics, Trucking, Shipping and Aviation. Combines technical abatement options with materials efficiency, recycling, logistics efficiency and modal shifts.	World	(Energy Transition Commission 2018)
Construction			
Roadmap for a carbon neutral and competitive construction and civil engineering sector	Ongoing initiative, with the ambition to increase the awareness of the building sector's climate impact and highlight trends, motivations, barriers and business opportunities; and ultimately establishing a common view of responsibilities and actions required to achieve a carbon neutral and competitive building sector.	Sweden	(Fossilfritt Sverige 2018)
The Property Sector's Roadmap Towards 2050	Recommendation to Norwegian owners and commercial building managers regarding their short and long-term choices in ensuring that the property sector contributes to a sustainable society by 2050.	Norway	(Grønn Byggallianse and Norsk Eiendom 2016)
Finnish Ministry of Environment's Low Carbon Construction Roadmap	Plan for how to reduce GHG emissions related to building materials and the construction industry in general, with the goal of regulating buildings' emissions via legislation by mid 2020s.	Finland	(Finnish Ministry of Environment 2019; WGBC 2019)
Low Carbon Routemap for the UK Built Environment	A project exploring options to reduce GHG emissions from the user phase, supply chain and construction activities for the UK built environment. Covers operational as well as embodied carbon emission from both the buildings and infrastructure sectors.	UK	(Green Construction Board 2013; Steele, Hurst, and Giesekam 2015)
Bringing embodied carbon upfront	Call for coordinated action for the building and construction sector to tackle embodied carbon.	World	(WGBC 2019)

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