Using LCA/TEA to Characterize Technological Transitions in Integrated Models: The Case of Cement

A Thesis

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By

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To my family….

Abstract

Cement manufacturing is responsible for 8% of global anthropogenic CO_2 emissions and the industry lacks clear paths toward decarbonization. A number of emergent technologies could cut the emissions from feedstock calcination or process heat but the role of these various approaches on global scale decarbonization efforts remain unclear. Here, life-cycle analysis was paired with a technoeconomic analysis to characterize the performance of a range of emergent cement technologies, and these were then input into the Global Change Analysis Model, a US-based IPCC-class integrated model. The six technologies modeled here are: a high efficiency kiln system (HEKS); fuel switching (FS); the use of supplemental cementitious materials (SCMs); alternative cements limestone calcined clay cement (LC3) and carbonateable calcium silicate cements (CCSC); and the adoption of carbon capture and storage (CCS) on the cement plant. LCA/TEA results suggest that CCS offers emissions reductions of 572 kg CO_2 but at substantial costs increases to the industry of $46.02 per t-cement. In contrast, alternative formulations like LC3 cut emissions by a more modest 250 kg CO_2 per t-cement but are already cost-competitive with conventional cements. Incorporating all these findings into GCAM enables a projection of cement industry composition over the coming years. With alternative cements LC3 and CCSC available, there is near term reduction of emissions, but the emission plateau and the industry remains a major source of emissions, responsible for 200-300 $MtCO_2$/year by end of century. CCS is not nearly as important of an enabling technology as existing integrated modeling runs would suggest but these results are very sensitive to price. These results suggest that the cement industry needs significant innovation over the coming decades, or it needs the prices of CCS to drop considerably in order for the industry to meet decarbonization goals.

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1. Introduction:

Limiting global warming levels to below 2°C will require widespread transformation of our power, transportation and industrial systems [1]. While the power and transportation sectors have a clear, if challenging, path toward decarbonization, there remain a number of unanswered questions about how to decarbonize the industrial sector. These challenges stem from the carbon-intensive feedstocks involved in many industrial processes and the high temperatures used in processing them, which cannot yet be delivered economically without fossil fuels. Taken together, industry accounts for >21% of global CO_2 emissions, with most of those emissions concentrated in a few high-volume, high-emissions sectors namely iron/steel and cement [2]. Cement manufacturing alone generates 7-8% of global CO_2 emissions each year [3]. The most common cement is Ordinary Portland Cement (OPC), which is made predominantly of limestone, that must be calcined at temperatures exceeding 1450ºC to produce calcium oxide. The CO_2 emitted during calcination represents over 50% of the emissions from cement production and the emissions from the coal or natural gas burned to generate the temperatures constitutes most of the rest [3]. Alternatives to OPC are emerging slowly but given its importance in building infrastructure of all kinds, and a surge in demand from Asia and expected demand from Africa and other developing regions of the world the emissions from the sector are expected to continue to increase, which would undermine global efforts to limit warming [4][5]. Figure 1 shows how some of these recent trends and expected growth over the coming decade and how different pathways might influence global emissions from the global cement sector.

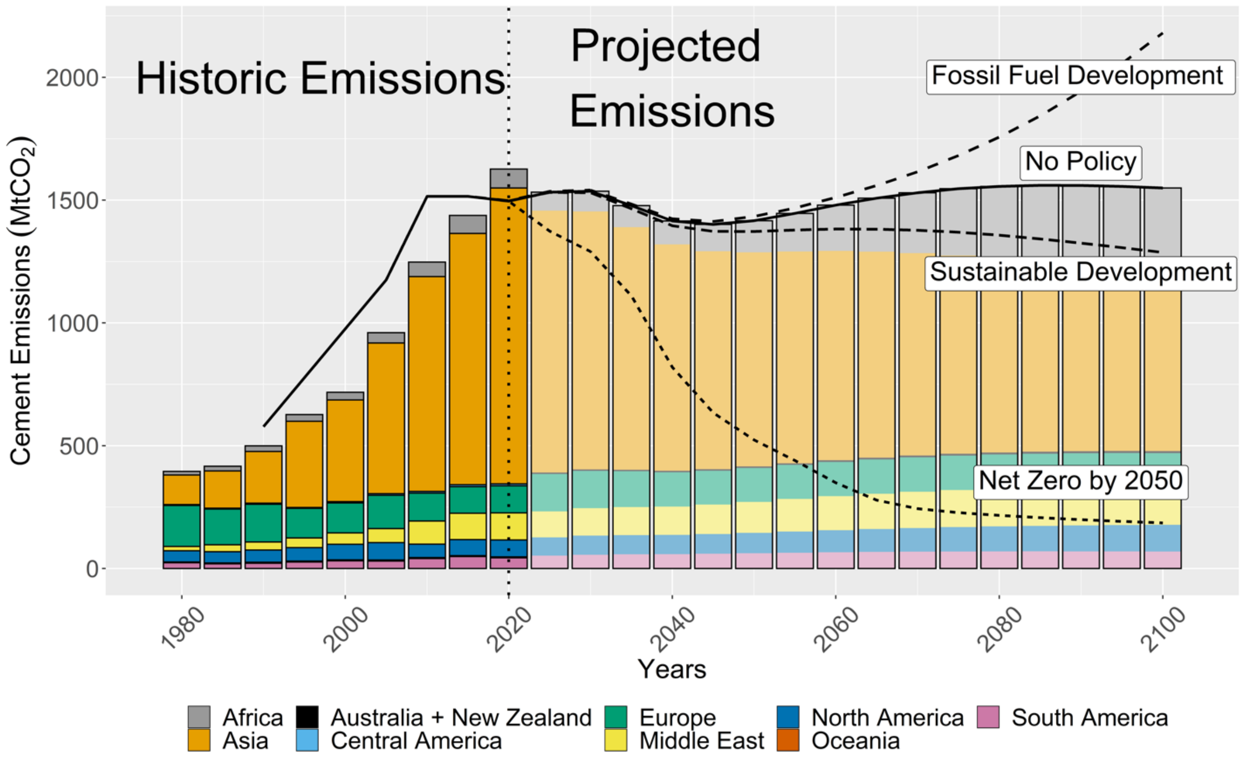

Figure 1. The historic emissions from cement production are represented by the bar plot starting in 1980 and continuing to 2020. The projected emissions are represented by the dotted black lines from the years 2025 to 2100. These emission projections are obtained using the Global Change Assessment Model. The Fossil Fuel Development and Sustainable Development scenario are projected scenarios where different socio-economic parameters are varied.

A growing body of academic and industrial research is focused on alternative chemistries and/or processing steps for decarbonizing cement. Many of these chemistries have been evaluated using life-cycle assessment (LCA) and technoeconomic analysis (TEA) to assess their environmental and economic prospects [6,7,8,9,10,3]. Bosech et al. studied the potential of using fuel switching and incorporating clinker substitution with supplemental cementitious materials (SCMs) and found reductions of 9 and 18% for the US and Europe respectively [6]. Miller et al. assessed the use of non-calcined limestone, fly ash, and blast furnace slag as supplemental cementitious materials finding there to be reductions of over 20% in CO_2 emissions with no change of technology or manufacturing [7]. Boesch et al. studied how different types of cement kilns impact emissions and found that the long-wet kiln is the most energy intensive while the precalciner paired with a suspension preheater is the most efficient on a GJ/t-clinker basis [8]. Huang et al. compared the life cycle impacts of alternative cements in concrete and their potential to uptake CO_2 when using alternative cement binders like Wollastonite, Portland Cement, Calcium Silicate Cements in concrete, particularly when considering steam curing, demonstrating that alternative chemistries based on wollastonite and calcium silicate can have the biggest reductions in overall CO_2 emissions [9]. Pillai et al. researched an emerging cement mixture discussed in the industry called LC3 finding that this novel product can produce significant emissions reductions in comparison to OPC [10]. A non-hydraulic pathway that has gained increasing interest is based on carbonateable calcium silicate cements (CCSC) which must be cured in a CO_2 environment in order to fully harden. Another alternative chemistry is based on belite ye'elimite ferrite formulations, which has slight reductions in CO_2 emissions. In all cases, material availability plays a large role in the deployment of the alternative binders [3]. Scrivener et al. concluded that the most conventional form of cement, ordinary Portland cement (OPC), will dominate the near term, while the use of SCMs and more optimum use of OPC can reduce CO_2 emissions [5]. Voldsund et al. conduct an LCA of cement manufacturing with different carbon capture and storage technologies placed on the cement kiln concluding that there should be multiple CCS technologies used if CCS is adopted by the cement industry [11]. Gardarsdottier et al. look at the technologies presented in the Voldsund et al. paper and perform a cost analysis on the CCS technologies finding that to conclude which CCS technology is best suited to be used at a cement plant, there should be plant specific analysis done [12].

A number of roadmap studies have been conducted in recent years. In California, a report by the Global Efficiency Intelligence found that clinker substitution and CCUS have the most potential for high emissions reductions in cement production. Like the California Report, the

International Energy Agency (IEA) issued a cement technology roadmap discussing the low carbon transition of the cement industry. The IEA roadmap looked at five different ways to reduce emissions from cement production: electricity intensity, thermal energy efficiency, fuel switching, reducing the clinker to cement ratio and innovative technologies like CCS, concluding that innovative technologies have the highest potential to create avoided emissions. Climateworks published a study on ways to decarbonize the production of concrete and looked at the life-cycle stages during concrete production. They specifically looked at the life cycle stages of cement manufacturing, aggregate production, concrete manufacturing, construction, use, and end of life. They concluded that the greatest reductions of emissions occur from material substitution and CCS [13]. A main conclusion from these roadmaps is that CCS has the highest potential to cut emissions in the cement industry.

Modeling cement decarbonization at the level of materials or manufacturing provides only a limited under[14]standing of global projections for industry emissions. Decarbonization pathways in other sectors have been explored using integrated assessment model (IAM), but the treatment of cement in these models has been limited to process heat fuel switching and carbon capture and storage (CCS) [15] . Zhang et al. studied the CO_2 emissions deriving from the process heat used in cement production around the world under different socioeconomic pathways, suggesting that most emissions will come from countries expected to build the most infrastructure in the coming decades including India, China, Nigeria, the US, and Pakistan [16]. Le et al. used the stock-based model Markal and the China-TIMES model to study how fuel switching, CCS, and energy efficiency measures might be adopted between 2010-2050 in China .The authors conclude in the near term, energy efficient measures and fuel switching will dominate decarbonization activity, but the paper did not include a full suite of alternative chemistries [14]. Kermeli et al. used the IMAGE model to model kiln retrofitting and clinker-to-cement ratio to reduce emissions finding that the reducing the clinker-to-cement ratio reduces great CO_2 emissions from the cement sector [17].We et al. used the Asian Pacific Integrated Model to model China's cement sector finding that structural adjustment and technological promotion would be the most direct paths for decarbonizing China's cement industry [18].

The goal of this paper was to combine a harmonized assessment of the state-of-the-art in alternative cement chemistry and processes as reflected in the LCA and TEA literature, and incorporate that understanding in a technology-rich IAM to help understand how the industry might decarbonize over the coming decades, and how that will impact global-scale decarbonization pathways. Using published estimates in an LCA-TEA metanalysis context, we characterized the cost and energy inputs of seven pathways: high efficiency kiln system (HEKS); use of fuel switching in cement production (FS); use of supplemental cementitious materials (SCMs): fly ash (FA), granulated blast furnace slag (GBFS), and limestone; carbon capture and storage (CCS); and alternative cement chemistries, particularly CCSC and LC3 cement [13], [19]–[22]. We then used the outputs from this LCA-TEA to parameterize input assumptions for cement production in GCAM (The Global Change Analysis Model). GCAM is an open-source IAM with detailed treatment of global energy, water, and land systems [23]. The scenarios run in GCAM allowed us to gain insight into the role each of these technologies might play under ambitious economy-wide CO_2 emissions constraints consistent with limiting warming to well-below 2C. We added detailed resolution to the cement sector to enable a better understanding of decarbonization pathways for the industry as part of broader climate strategy. In GCAM, we model six different scenarios: a no policy scenario with the remainder of scenarios under a carbon policy where we vary the availability of emerging technologies and the price of CCS to understand how these factors affect the associated deployment of these technologies.

2. Materials and Methods

An LCA-TEA meta-model was developed using cradle-to-gate boundaries and a functional unit of 1 tonne-cement (t-cement). The production of cement is modeled via the following steps: (1) the mining of raw materials, (2) the transportation of raw materials to the cement plant, (3) the crushing of raw meal, (4) the feeding of raw meal into a kiln system where the raw meal is heated at 1450ºC to form clinker, and (5) the blending and grinding of the cement with gypsum and SCMs to form cement. Emissions derive from raw material processing and transportation, the process heat used in the kiln system, limestone calcination, indirect electricity and emissions caused by the use of other materials. The costs associated with cement production are the feedstock, raw materials extraction, fuel, variable operating, fixed operating, plant capital, and CCS thermal energy costs.

Lifecycle Assessment

Lifecycle inputs were determined as follows: the raw material processing and transportation emissions were calculated based on raw material extraction emissions and transportation of raw materials to the cement plant emissions with low values obtained from Feiz et al. and high values obtained from Nisbet et al. [24]. The emissions from the process heat are dependent on the kiln system as well as the fuel type. Values for the kiln system's total thermal energy demand are obtained from Boesch et al. In this analysis, the two kiln systems considered are a precaclicner kiln system with a thermal energy demand of 3.20 GJ/t-clinker and a high efficiency kiln system with a thermal energy demand that is 10% less than the precacliner kiln [8]. The fuels considered in the model bituminous coal, petroleum coke, natural gas, and biomass with the associated emissions intensities provided by the US Energy Information Association (EIA). The emissions related to limestone calcination are calculated based on the stochiometric ratio of limestone ($CaCO_3$) to CO_2 in the calcination reaction ($CaCO_3$ - > $CaO + CO_2$). The limestone content varies with different cements/clinkers so the limestone inputs modeled in this analysis are obtained from Huntzinger and Eatman, the IPCC, Rodriguez et al., Benhelal et al., and Miller and Myers [3], [25], [26] [27], [28]. The indirect electricity emissions modeled in this analysis are based on Boesch et al.'s system low, central, and high electricity requirements [8]. The emissions based on the electricity load are modeled off the USA's low, 50th percentile, and high values from De Chalendar et al. The electricity is used to crush and blend the raw meal, which results in indirect CO_2 emissions. The clinker to cement ratio is the fraction of clinker used to create cement. The clinker ratio depends on the use of SCMs, and the amount of gypsum blended with clinker. The clinker factor is modeled based off values from Huntzinger et al., Rodriguez et al., and Diaz et al. Huntzinger et al. and Rodriguez et al. modeled OPC as having a clinker to cement ratio of .95, where Diaz et al. modeled the clinker to cement ratio as being 0.75 when SCMs are blended in the cement. Post combustion CCS technologies allow a cement kiln to be retrofitted without large modifications [19].The CCS technology in this work is modeled as a monoethanolamine (MEA) adsorption process, which is a post combustion process [29].The capture rate of MEA is obtained from Jakobsen et al. with a base case of 42% and a max of 85% [30].

Each one of the emerging technologies results in an emission change due to the variation of certain model inputs. To simplify the model, the transportation, raw material extraction, and electricity emissions remain constant for each emerging technology due to the emissions being negligible in comparison to other emissions. But for each emerging technology, the other inputs are varied and therefore, the emissions are reduced. Figure 2 shows the different inputs in the model, and the different outputs.

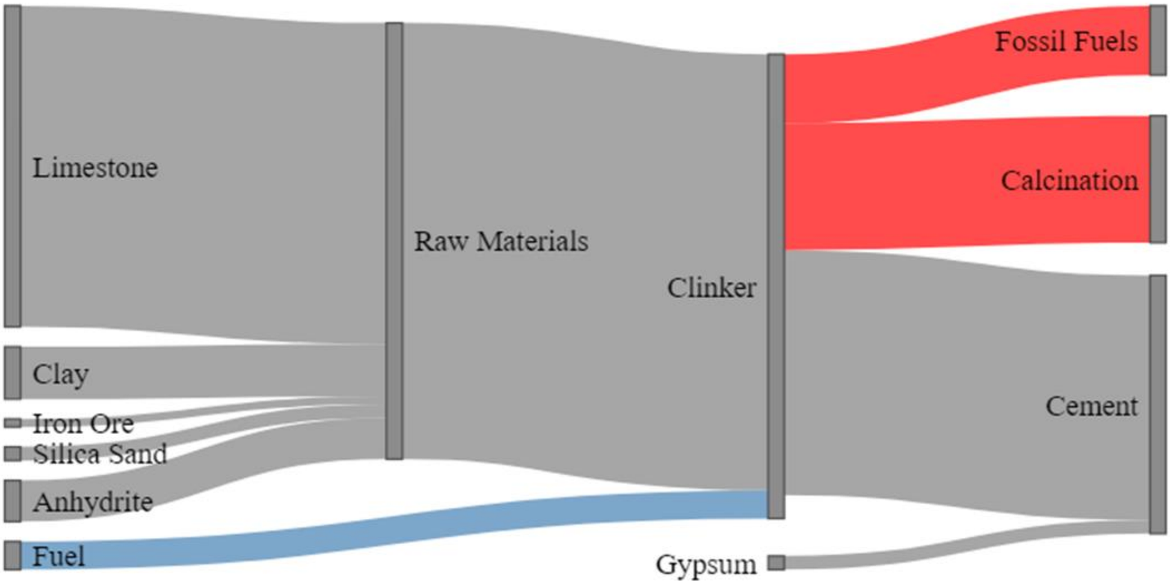

Figure 2. Material and energy flows that go into making cement and the associated emissions with that production. The material flows are in grey, the energy flows are in blue, and emissions are represented in red. Not every process in cement manufacturing is represented in this figure, however, this diagram represents the main contributors to emissions and where emission reductions can occur. Each flow is in terms of t-cement, where the raw materials are in terms of t-material, process heat is in terms of GJ, and emissions are in terms of kg CO_2.

Technoeconomic Assessment

The LCA model feeds directly into the TEA analysis. The raw material extraction costs are based off the raw material extraction and transportation emissions modeled in the LCA. Assuming that raw material extraction and transportation use trucks that run on diesel fuel, the amount of diesel fuel required is calculated for the related emissions, and then the price of the total diesel consumed is found [24]. The cost of fuel used in cement production was found by totaling the amount of fuel needed to produce 1 t-cement and finding the associated cost of the fuel. Feedstock costs are calculated based off the raw material compositions obtained from Miller and Myers [3]. To obtain economic values for the cement plant, the CEMCAP model is used. The CEMCAP model is an economic module created by Milano Politecnico and SINTEF laboratory which looks at the economics of a cement plant with and without CCS. The reference plant used in the CEMCAP model assumes clinker production of 3000 tonnes per day with a clinker to cement ratio of 0.737. The raw meal to clinker factor was 1.6 [31]. These parameters can be changed in the model, for which we changed the clinker-to-cement ratio to our OPC assumptions of 0.95. In the CEMCAP model, cement manufacturing process is modeled as a dry kiln process with a five-stage cyclone preheater, a precalciner, rotary kiln and a grate cooler [11]. This process is considered the Best Available Technique plant according to the European Cement Research Academy. The CEMCAP model is an interactive spreadsheet that allows the user to input different process heat values in GJ/t-clinker, raw meal costs in euro/t-raw meal, electricity costs in euro/MWhe, and electricity demand values in MWh/t-clinker, allowing the five decarbonization pathways to be modeled [31]. The technoeconomic numbers obtained from the CEMCAP model are the plant capital, variable operating, fixed operating, and CCS thermal energy costs.

Sensitivity Analysis

The software Crystal Ball by Oracle is used to conduct a sensitivity analysis on the LCA-TEA. The sensitivity analysis for the OPC pathway is presented in Figure 5 where each input parameter is varied by ± 10% while the rest are held constant [32].

Decarbonization Pathways

Supplementary Cementitious Materials (SCMs)

The blending of clinker with SCMs has been practiced for many decades. At the moment, countries like China and India use a large amount of SCM's in cement, with the clinker to cement ratio's in 2017 being 0.79 and 0.69 respectively, compared to the United States, which had a clinker to cement ratio of 0.9 [33]. The SCMs blended in the cement is highly dependent on the regional availability of materials [13]. Ground granulated blast-furnace slag (GBFS) is a by-product of the iron and steel industry, specifically from a Basic Oxygen Furnace (BF-BOF). However, as the steel and iron industry are taking steps to decarbonize, they are adopting the use of an electric arc furnace, which does not produce GBFS. The predominant furnace used in the US use an EAF process while 70% of the world use a BF-BOF process. Due to decarbonization, the BF-BOF process is expected to phase out, decreasing the supply of GBFS [22]. Another widely used SCM is Fly Ash (FA) which is a byproduct of coal power plants. There is expected to be a decrease in FA as decarbonization measures are adopted globally, due to the phase out of coal power plants. Currently, the cost of FA is lower than the price of OPC, but the cost of FA could rise due to the phasing out of the coal industry [5]. In this analysis, SCMs are modeled as one pathway in the LCA, but in the TEA, we model three different SCMs, FA, GBFS and limestone.

Limestone Calcined Clay Cements (LC3)

LC3 is mixture of 15% limestone, 50% clinker, 5% gypsum, and 30% calcined clay [34]. LC3 has been gaining traction in the cement industry in the past decade even though it has not been used at a large scale and lacks commercial adoption [34]. We model LC3 with a clinker to cement ratio of 0.5 and the emissions from calcined clay and limestone as "other emissions".

High Efficiency Kiln System (HEKS)

The HEKS has limited potential for decarbonization due to the maturity of the technology. However, most plants are already equipped with a precalciner and a multistage preheater: all the cement plants in California are currently equipped with a precacliner and multistage preheater systems [22]. Likewise, over the past two decades, the percentage of European kilns adopting a dry kiln with a preheater and a precacliner has grown from 20 percent in 1990 to around 40 percent in 2015 [20]. Therefore, in this analysis, we model the HEKS as having a decrease in thermal energy demand of 10% and an increase in total costs of %.

Fuel Switching

Fuel switching is a relatively mature cement decarbonization pathway that has been practiced for a couple decades. Over the past decade, China has been adopting the use of waste fuels, the United States has increased the share of waste fuels, natural gas and biomass and India has slowly increased the use of waste fuels and oil to produce cement [13]. Retrofitting a cement kiln that runs on coal to run on natural gas will require certain kiln adjustments due to the increase in flame temperature of natural gas in addition to an increase in cost for natural gas pipeline construction to deliver the gas to the plant. However, once the kiln is retrofitted to use natural gas as a fuel, Suhail et al. predict that the clinker production rate will increase and there will be less fuel used by the cement kiln [35]. We model fuel switching as switching from bituminous coal to natural gas.

Carbonatable Calcium Silicate Cement (CCSC)

CCSC cement is a relatively new technology and has yet to be used on a large commercial scale. A large factor that goes into the deployment of this cement technology is the raw material availability. The main ingredient in CCSC cement is wollastonite ($CaSiO3$), but is not mined in many countries present day [5]. We model CCSC as 0.922 kg of limestone per kg of cement, and 0.518 kg of silica sand per kg of cement, based off modeling assumptions from Miller and Meyers [3].

Carbon Capture and Storage (CCS)

The use of CCS in cement manufacturing has potential to capture up to 85% of CO_2 emissions produced from calcination and the process heat [36]. Currently, CCS technologies have not been implemented at cement plants at a large scale. There are two CCS plants that have been built in the past decade, a mobile capture unit in Brevik, Norway and a plant in Texas which used the CO_2 captured to produce sodium bicarbonate bleach [19]. Due to the small commercial implementation of CCS in the cement industry this pathway is not proven to be an economically viable option at this point in time. The viability of this technology has potential to change if carbon policies are put in place to reduce the costs of CCS. We model CCS as capturing 85% of emissions from the calcination and process heat.

Integrated Modeling

The Global Change Analysis Model (GCAM) (version 5.4) was used to evaluate how the cement industry might evolve in the coming decades in light of emergent cement formulations. The existing cement module in GCAM was developed over 20 years ago and it includes two technologies: cement and cement CCS. Cement represents conventional cement production while cement CCS represents conventional cement with CCS added to the technology capturing 90% of the overall emissions. The inputs for these technologies are a process heat input (EJ/t-cement), electricity input (kWh/t-cement), limestone input (t-limestone/t-cement), and cost (1975$/t-cement) [23]. The process heat input is amount of thermal energy required in to produce cement the kiln. The fuel used to fire the kiln can be coal, refined liquids, gas, or biomass [23]. The electricity input represents the electricity needed to blend and grind the raw materials. The limestone input is the amount of raw limestone used to create the cement. For cement CCS, there is an additional input, the amount of CO_2 captured. Although GCAM only represents two cement technologies, the multiple inputs allow for easy addition to of new technologies. We use the outputs from the LCA-TEA to parametrize the emerging technologies in GCAM's cement sector. The emerging technologies built into GCAM are alternative cements, SCM cements, and the adoption of a HEKS. The input parameters for these technologies are shown in table 3.

Table 3. Parameter inputs in GCAM.

Cement Technology	Process Heat Input (GJ/kg-cement)	Electricity Input (kWh/t-cement)	Limestone Input (t-limestone/t-cement)	Cost ($/2020)
cement	4.0	34	1.18	0.079
cement HEKS	2.7	34	1.18	0.083
cement CCS	4.0	34	1.18	0.125
cement CCSC	2.2	34	0.92	0.09
cement SCMFA	2.4	27	0.88	0.077
cement SCMGBFS	2.4	27	0.88	0.071
cement SCMLL	2.4	27	0.88	0.062
cement LC3	2.0	25	0.59	0.069

We used six scenarios to evaluate the conditions under which these emerging cement technologies might be deployed. The first assumes no carbon policy in the modeling exercise to analyze the cement industry at a baseline. The rest of the scenarios assume global policy that constrains CO_2 emissions to decline to net-zero by 2050. GCAM calculates the carbon price required to meet this constraint. The carbon policy scenarios are designed to understand the tradeoffs between the availability, the price of and the associated deployment and emission profile of the emerging technologies. There is an all-tech scenario that was designed to understand when every emerging technology is available, what will the future of the cement industry look like. However, this scenario has high uncertainty because alternative cements and

CCS have yet to be implemented on a large scale. Because alternative cement chemistries like CCSC and LC3 have not been used on a large commercial scale, there is a scenario that includes all technologies besides alternative chemistries. Because a carbon policy forces emission reductions, if available, GCAM uses CCS at a large scale. To understand what effects the deployment of CCS, there are three scenarios designed dealing with changing parameters of cement CCS because there have only been a few CCS plants deployed at a large scale currently. To study this, we run three different scenarios where we vary the price of CCS by +- 50% and vary the availability of CCS, making the technology unavailable in one scenario.

3. Results

CO_2 Emissions from Emerging Cement Technologies

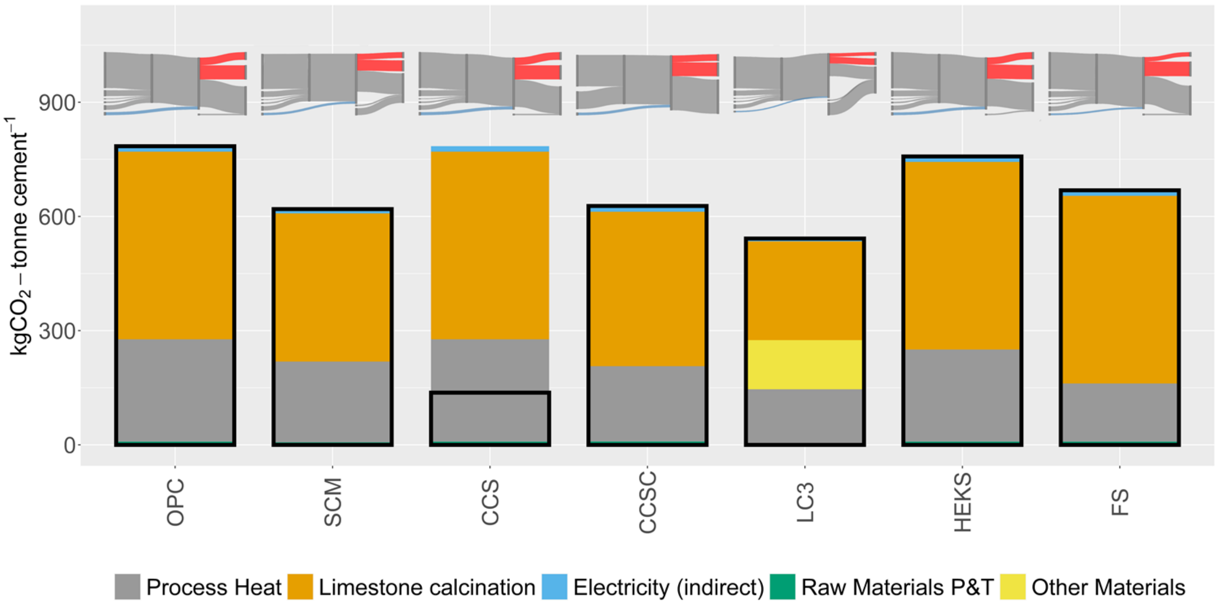

Figure 3. Emissions deriving from the production of emerging cement technologies compared to OPC cement. The functional unit of this analysis is 1 t-cement. Each pathway has the associated flow diagram above. The flow diagram is the flow diagram from figure 2 with no labels. The unlabeled flow diagram shows the changing inputs and the resulting emissions.

Of the various technologies evaluated here, OPC has the largest CO_2 footprint emitting 786 kg CO_2 per t-cement. Our analysis concludes that 34% of OPC CO_2 emissions are from fossil fuel burning and 62% are from calcination. The SCM pathway cuts emissions by around 21% because of the change in the clinker to cement ratio switching from 0.95 to 0.75. Another pathway that reduces the clinker to cement ratio is LC3, where LC3's clinker to cement ratio drops to 0.5. With the clinker to cement ratio drop, there are significant reductions in cement emissions from this materials production. Overall, the emissions would be cut in half by halving the clinker to cement ratio, but due to other materials used in the cement like calcined clay and limestone, there are additional emissions with the calcined clay and limestone accounting for around a fifth of the emissions associated with the production of LC3 resulting in an overall emission reduction of 68%. The fuel switching pathway cuts emissions solely from the process heat by changing the fuel from coal to natural gas. Fuel switching from coal to natural gas has a reduction of emissions of 10%, with the process heat emissions having reductions of 32%. The adoption of alternative cements like CCSC cuts CO_2 emissions from process heat and calcination due to the change in chemical composition. There is around a 18% reduction in calcination emissions and a 26% reduction in process heat emissions. Further emissions reductions can be seen by curing the cement with CO_2 when the cement is used as concrete in a precast application, but this is outside the scope of this analysis. The HEKS reduces the CO_2 emissions deriving solely from the burning of fossil fuel due to a decrease in thermal energy demand resulting in a net emission reduction of around 10%. The HEKS pathway should be applied to cement plants with a long dry kiln which has a higher energy demand. CCS provides the highest reduction in

CO_2 emissions cutting emissions by 73%, with 85% of the calcination and process heat emissions being captured.

Costs of emerging technologies.

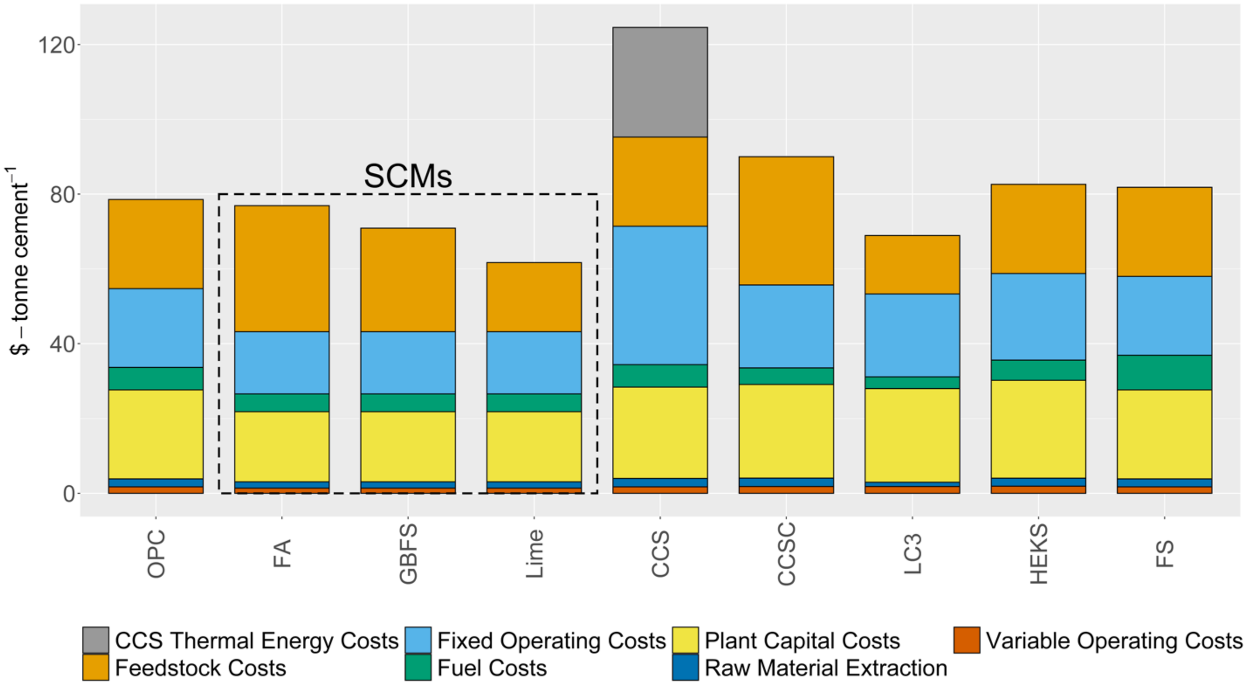

Figure 4. The technoeconomic analysis of cement with a functional unit of 1 t-cement. The prices of cement are in $2020. The SCM pathway is represented by the dashed box with the labels representing the associated SCM used in the production of cement.

As expected, the pathways with the lowest emissions profiles required interventions that increase the cost of the material. But the cost of emissions reductions is not linear. Many of the comparatively inexpensive retrofits, such as fuel switching, provide relatively modest emissions reductions $ 0.03 per kg CO_2 avoided whereas alternative cements, such as CCSC materials, produce much more reduction per dollar invested $ .07 /kg CO_2 avoided. The lowest emitting pathway, CCS, has heavy additional costs resulting from the variable operating costs and the CCS thermal energy demand. CCS has an increase in cost of 59% compared to with the thermal energy demand accounting for 23% the cost and the additional increase of 76% in the fixed operating cost in comparison to OPC. Fuel switching, a low emitting pathway has a slight increase in costs due to the use of natural gas. Natural gas is currently more expensive than coal in terms of dollars per GJ of fuel, but this price is dependent on the region. According to future markets, the price of natural gas is expected to rise, with the cost of coal staying constant. But as carbon policies are put in place, the price of using coal will increase due to the larger emission factor. Overall, CCSC has higher material costs due to the different chemical composition. CCSC is made of 0.922 kg of limestone per kg of cement, and 0.518 kg of silica sand per kg of cement, based off modeling from Miller and Meyers [3]. A decrease in limestone in comparison to OPC leads to a reduction in limestone cost, but due to the high cost of silica sand, the total raw material cost increases. Although there is an increase in costs for the materials, an advantage of the chemical composition of CCSC is that it takes less heat to produce clinker and cement, leading to a reduction in the amount of fuel used, decreasing the fuel cost for this pathway. The high efficiency kiln system has a decrease in price in the fuel used, but this is only a slight reduction, compared to the increase in price of the capital costs. Blending clinker with SCMs reduces the overall price of the production of clinker in all three cases with different SCMSs. The price of producing SCM cement is highly dependent on the region and the access to SCM materials. In our analysis we see the FA SCM cement is the most expensive, followed by the GBFS, and the cheapest option is the limestone SCM cement. In addition, as previously stated the prices of FA and GBFS are likely to increase due to the phase out of coal power plants and blast furnaces, making limestone an attractive SCM to use, especially due to the availability. There will be additional costs and emissions for the use of SCM due to transportation of the

SCMs to the cement plant [37].Currently, the cost of FA is lower than the price of OPC, but the cost of FA could rise due to the phasing out of the coal industry [5].

Sensitivity Analysis.

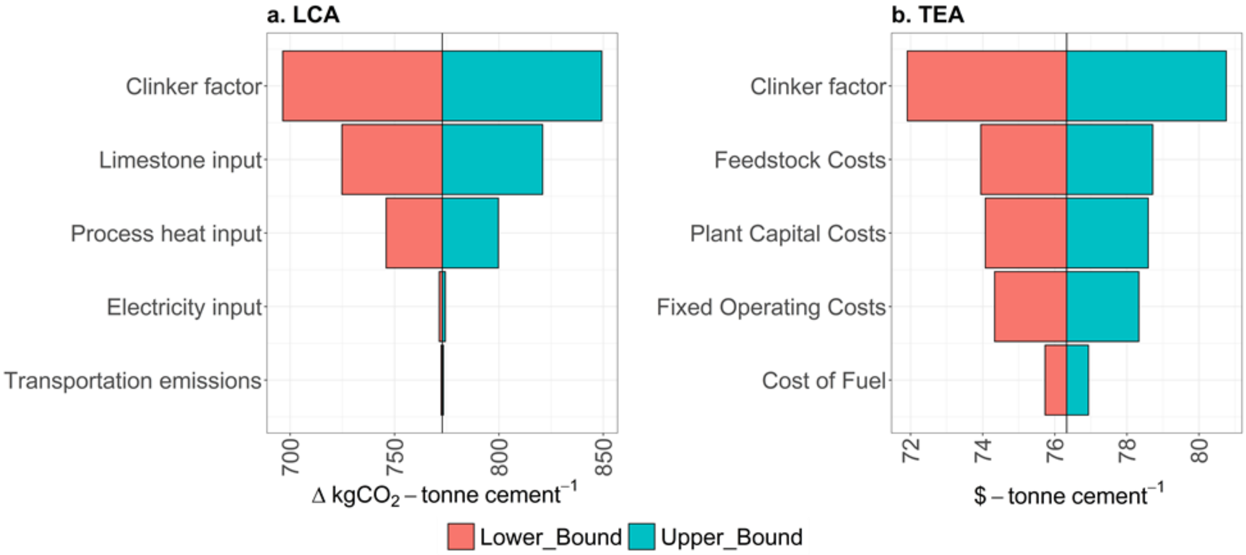

Figure 5. Sensitivity analysis of the a) The LCA b) the TEA. The inputs of the input parameters are varied by +- 10% in addition to the costs of certain prices of the technologies.

A variation in the clinker to cement ratio creates huge variations in cement emissions around 153 kg-CO2 per cement. Varying the limestone creates substantial changes in emissions, with a change in emissions of around 100 kg/CO2 per t-cement. When changing the process heat input, the resulting change in emissions around 50 kg/CO2 per t-cement. However, when the inputs like the electricity input and the transportation and raw materials are varied, there is not great variations. The parameters sensitive in our analysis are the parameters that control the bulk of the CO2 emissions. Each emerging technology has a change in one of the following the sensitive variables, limestone input, process heat input, and the clinker-to-cement ratio, which results in reductions of emissions. Not shown in figure 5 is the sensitivity analysis for the CCS pathway, which the most sensitive variable is the capture rate. The capture rate has a range in emission of 127 kg CO2, which alone is larger than the number of emissions produced from the CCS pathway. Overall, in each emerging technology sensitivity analysis, the most sensitive variable is the clinker to cement ratio. This variable is also the most sensitive in the TEA analysis.

Emerging cement technology deployment and associated emissions

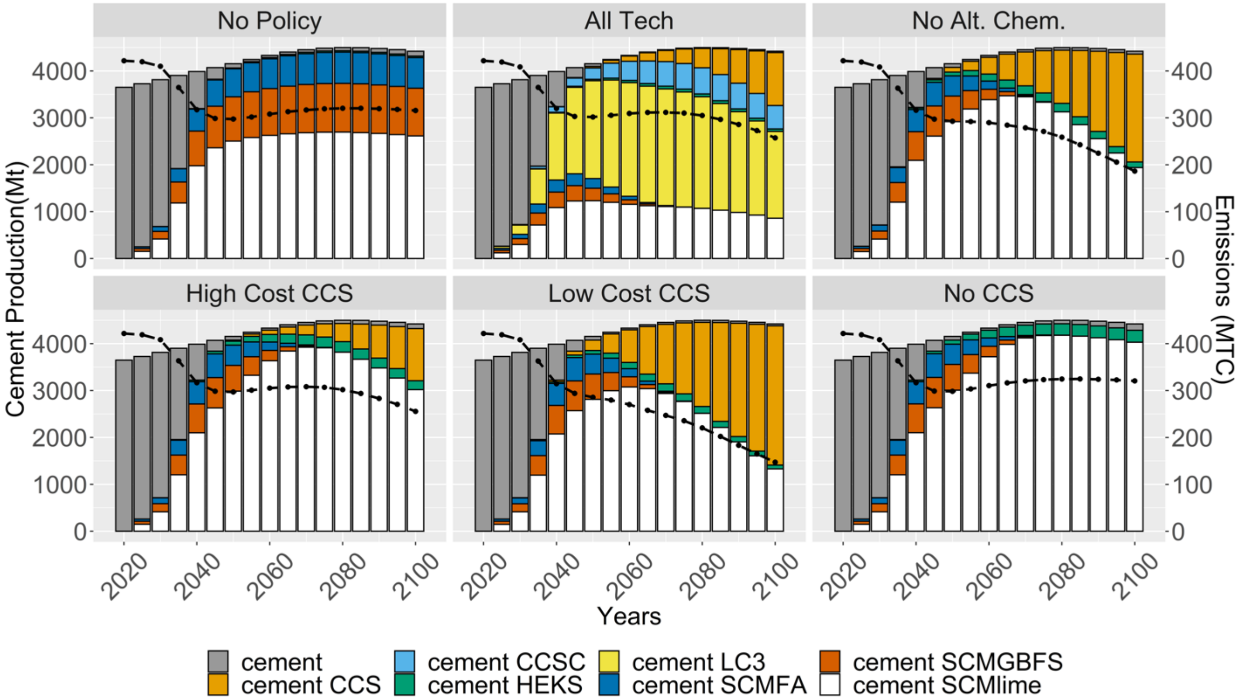

Figure 6. Emerging cement technology deployment from 2020 to 2100 under a no policy, all tech, all tech no alternative chemistries, high-cost CCS, low-cost CCS, and no CCS scenarios. The bar plots represent the production technologies in terms of MT of cement. The dashed line represents the emissions profile in the production of cement.

The base case sees reductions in cement production emissions due to the deployment of the three cement SCMs. Once the technologies are available, there is rapid adoption of all three technologies, with cement SCMlime having the greatest deployment, and cement SCMFA and cementGBFS having the similar deployment. The market penetration of these technologies stops around the year 2050, and there is stagnant emissions till the year 2100. While cementSCMFA and cementSCMGBFS provide emission reductions, with a carbon policy in place, we assume there to be a phase out of coal power plants and bast-furnaces, so cement SCMFA and SCMGBFS are expected to be unavailable in the year 2050. However, with all technologies available under a carbon policy, cement LC3 dominates the cement market. Cement LC3 has rapid deployment once available in 2025 and becomes the dominant form of cement in the year 2040 and continues to dominate the market, outcompeting cement SCMlime and cement CCSC till 2100. The other emerging technology being deployed at a large scale is cement CCS. When cement CCS is available in 2050, there is an exponential increase in deployment of this technology the following years, creating an inflection point in the emissions profile, further decreasing cement emissions. The alternative chemistries are shown to assist in providing near term emission reductions, but other forms of cement like cement SCMlime dominate the industry when alternative chemistries are not available. In addition, we see the availability of alternative chemistries reduce the deployment of cement CCS, for in the case where no alternative chemistries are available, the industry shifts to rely on cement CCS to provide emission reductions. In the case with all technology available besides alternative chemistries, there is near term reductions in CO_2 emissions due to the production of cement SCMlime creating an inflection point in emissions as the material gets produced at a larger scale. But when cement CCS becomes available, the industry shifts to cement CCS, and as this emerging technology gets deployed at a higher rate, there is an additional inflection point in the emissions profile. By 2100 in the no alternative chemistry scenario, the market is split between cement CCS and cement SCMlime, seeing a 41% reduction in CO2 emissions from the base case scenario. A main reason there is such a huge reduction is because the industry is around half cement CCS.

The deployment of CCS is very uncertain at the moment, there is not a fixed price, and the use of this technology is not well known at the moment. When the price of cement CCS is high, we see minimal deployment, with cement CCS only making up 25% in 2100 compared to the no alternative chemistry scenario where CCS makes up around half the market. With less cement CCS deployment there is less emission reductions with a reduction of only 19% by 2100. However, there is great emissions reductions when cement CCS has a low cost. When cement CCS has a low cost, the cement industry goes all in on cement CCS, with 68% of production coming from cement CCS. Because cement CCS is the lowest emitting pathway, this scenario sees the highest emission reductions by 2100. This behavior shows that the deployment of cement CCS is highly dependent on the price, and if CCS becomes more economical, there is potential for great emission reductions. Yet, without cement CCS available, there is similar behavior to the base case scenario, with a similar emissions profile. Yet, the fuels used are quite different without CCS available.

Fuel Switching.

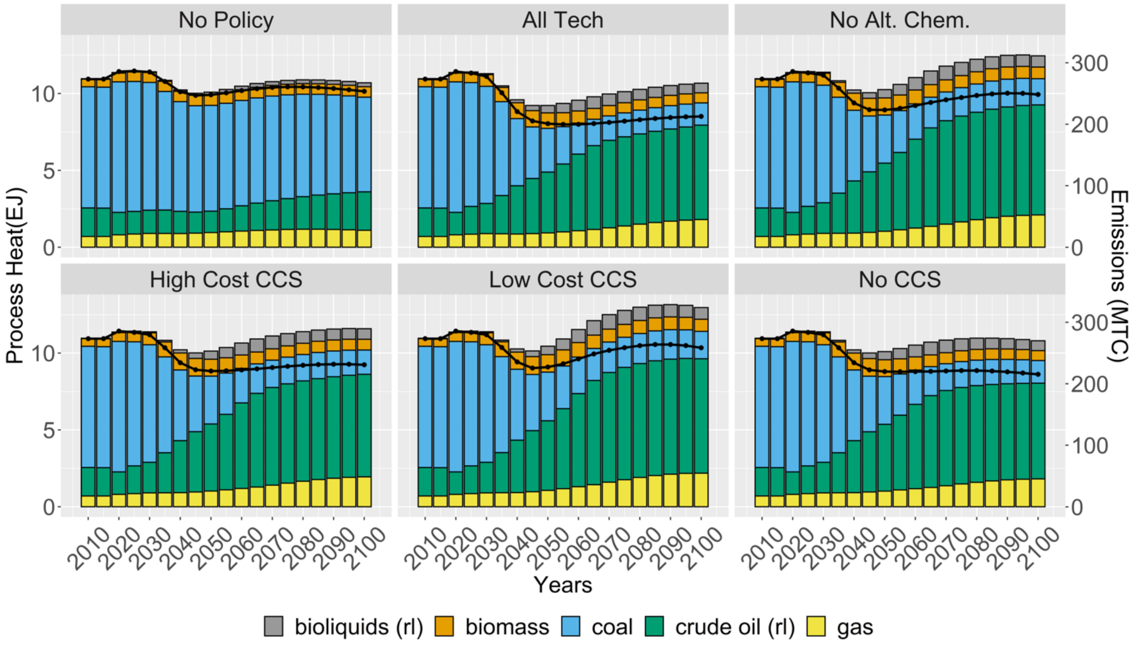

Figure 7. The bar plot represents the fuel used for cement production in terms of GJ between the years 2020 and 2100. The associated emission profile of these fuels is shown by the dotted black line in terms of MT of carbon.

The emerging cement technologies deployed in the no CCS scenario are similar to technologies deployed in the no policy scenario, but there is a huge difference in the fuels used under these scenarios. In the no CCS scenario, there is a large scale up of refined liquids made with crude oil, while in the no policy case there is a continuous use of coal. The phase out of coal and scale up of refined liquids produced from crude oil is due to the carbon policy placed in 2025. The scale up of crude oil from refined liquids in the process heat fuel use is the same dynamic in each policy scenario. There is a drastic increase in liquid fuels derived from crude oil in cement production from 2025 to around 2070 while there is a similarly drastic decrease in coal usage.

While the fuel usage is dominated by crude oil, there is a slight increase in bioliquids used in cement production, and a linear increase in gas used. With the adoption of alternative fuels, there is a slight decrease in process heat emissions. But the greatest drop in process heat emissions occurs from the deployment of cement SCM technologies. As cement SCM get deployed, there is a drop in the required process heat due to a drop in the clinker to cement ratio resulting in a drop in process heat emissions. Aggreging with the LCA results, fuel switching can only reduce emissions from cement production, where the deployment of cements blended with SCMs sees greater reductions in emission.

4. Discussion and Conclusions

Cement production is a major contributor to global CO_2 emissions and so decarbonizing the industry will be critical for limiting global scale warming. While a number of emerging cement technologies have been described in the literature, their impact on global scale decarbonization pathways have not been explored in the integrated assessment modeling literature. Using life-cycle analysis and technoeconomic analysis we looked at the dynamics of emerging cement technologies in the future under different policy scenarios.

Our analysis finds that emerging cement technologies stand to play a significant and growing role in near-term decarbonization of the sector. The technology that plays the most important role in the cement industry under each scenario is cement blended with SCMs. Whether that material is FA, limestone, or GBFS, cement blended with SCMs provides near term reductions in cement emissions. In each scenario, SCM cements are the largest, or one of the largest cement technologies. It will be critical to invest in emerging cement technologies and consider regional dynamics such as material availability to limit risks associated with these technologies not scaling up. But these emissions reduction stall out after a decade or two of declines, principally because of the absence of cost-effective technologies that can drive down emissions even farther. While cement coupled with carbon capture and storage could deliver the kinds of emissions reductions needed to meet global targets, the technology is much too costly and uncertain at this point. In contrast, alternative chemistries, most limestone calcined clay cement (LC3) as well as carbonated calcium silicate cements could play a vital role in the coming decades, particularly as costs for these materials go down.

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