Princeton's Net-Zero America study
Annex K: Cement Industry Transition

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1 Industry overview

Shipments from the U.S. domestic cement industry represent 0.1% of total shipments from the entire U.S. industrial sector [1]. However, the cement industry has played a core role in building and maintaining the infrastructure underpinning nearly all sectors of the U.S. economy [2]. In addition, despite a minimal economic role in the U.S. economy, the domestic cement industry was the fourth largest source of domestic greenhouse gas (GHG) emissions in 2017, after fossil fuel combustion, non-energy industrial feedstocks (largely used in the bulk chemicals sector), and the iron and steel industry [3]. GHG emissions from the domestic cement industry must therefore be minimized or offset in all scenarios in which the U.S. deeply decarbonizes its economy by 2050.

The approach to mitigating emissions from the cement industry described herein is consistent with the approach used by the U.S.'s Energy Information Administration's (EIA) Annual Energy Outlook (AEO) [1], [4], covering only those emissions from *cement manufacturing* unit operations as defined by the North American Industrial Classification System (NAICS) code 327310 [5]. Figure 1, which depicts life cycle steps in the production of cement, includes raw materials grinding, kiln operations and finish grinding as part of cement manufacturing (contained within dashed line).

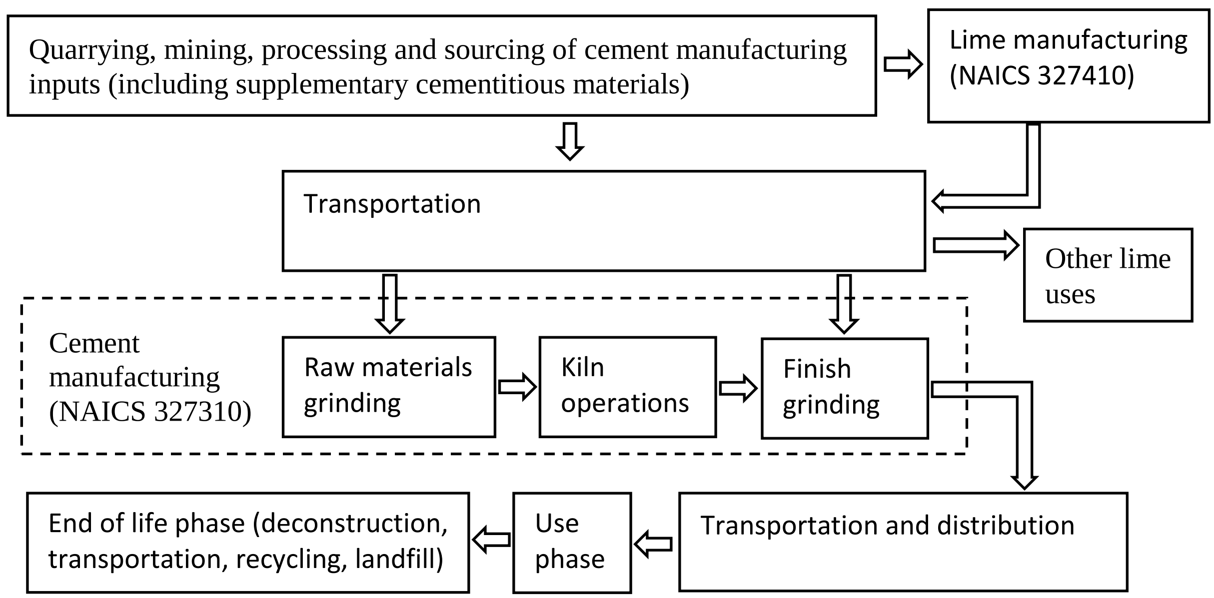

Figure 1 Full life-cycle consideration of the domestic cement industry and analysis boundary (dashed line) [5]–[7]

Figure 1 also shows upstream and downstream processes not explicitly included in the cement manufacturing analysis. Upstream activities involve the quarrying and mining of key ingredients such as lime and clay,[1] the sourcing of supplementary cementitious materials (SCM), the manufacture of lime, and the transportation of all materials to cement manufacturing facilities. Downstream activities which include transportation and distribution of cement, use of cement by end-users, and end-of-life processes (deconstruction, transportation, recycling, landfill).[2] With

[1] The AEO aggregates mining and quarrying of limestone into other AEO sectors.
[2] Xi et al. [8] indicate that cement acts as a carbon sink (via carbonation) during its use and end of life phases. We have not systematically and comprehensively included all potential emissions sources and sinks in the analysis. Until then, the potential for global cement stock to serve as a carbon sink is excluded from this analysis.

the exception of lime manufacturing (NAICS 327410) [9], all non-cement manufacturing processes in Figure 1 will be captured in mining, construction, industrial and other sectors in both AEO and EER models.[3]

Although some cement manufacturers are directly involved in mining and quarrying limestone and/or the manufacture of lime (for which the AEO reports data for the cement and lime sectors together), NZAP handles lime manufacturing separately from cement manufacturing because the AEO [1], [4] runs a separate but related model for lime manufacturing as part of its analysis. We describe NZAP's handling of lime manufacturing and provide a short analysis and narrative for the lime manufacturing sector later in this appendix.

The main processes included in the NZAP cement manufacturing model include the grinding of raw materials, high temperature calcination to convert the raw materials to clinker, and a finish grinding process in which additional materials are ground with the clinker to create the fine powder generally referred to as cement. The two main carbon dioxide (CO_2) emission sources during the manufacture of cement are combustion emissions that arise from the onsite burning of fossil fuels for power and heat,[4] and process emissions that arise from the release of CO_2 from limestone during the calcination process. Table 1 provides estimates of process, combustion and total CO_2 emissions in million metric tons (MMT) of CO_2 equivalent (CO_2e) from the cement manufacturing sector from 2013 to 2017.

Table 1 Process and combustion emissions in MMT CO_2e and shares for U.S. Cement sector from 2013 and 2017 [3], [10]

Emissions measure	Source/formula	2013	2014	2015	2016	2017
1. Process CO_2 emissions (MMT CO_2e)	EPA [3] Inventory	36.4	39.4	39.9	39.4	40.3
2. Total CO_2 emissions (MMT CO_2e)	EPA [10] Flight	62.7	67.0	68.2	66.1	66.5
3. Total GHG emissions (MMT CO_2e)	EPA [10] Flight	62.9	67.3	68.4	66.3	66.7
4. Combustion CO_2 emissions (MMT CO_2e)	2 - 1	26.3	27.6	28.3	26.7	26.2
5. Process emissions share of CO_2 (%)	1 / 2	58.0%	58.8%	58.5%	59.6%	60.6%
6. Combustion emissions share of CO_2 (%)	4 / 2	42.0%	41.2%	41.5%	40.4%	39.4%

According to Table 1, the EPA's [3] estimate of the process emissions arising from cement manufacturing in 2017 was 40.3 MMT of CO_2.[5] The industry reported an onsite total of 66.5 MMT of CO_2 emissions in the same year [10]. By subtracting process emissions from total onsite CO_2 emissions, we arrive at an estimate for combustion emissions of 26.2 MMT of CO_2 from cement manufacturing for 2017. This method leads to the allocation of process and combustion emission shares of 60.6% and 39.4% respectively in 2017. While acknowledging this allocation

[3] AEO data is a core input into the EER modelling system.
[4] Does not include emissions from electricity purchase.
[5] The inventory does not provide an estimate of fossil fuel emissions from cement production due to the aggregation of fossil fuel combustion emissions across multiple industrial sectors. Table 7 and Table 8 place cement emissions in the broader context of the entire U.S. GHG inventory and major sectoral emitters respectively.

method, derived from two data sets, is imperfect,[6] we note that this aligns with general findings for process emissions of 60% for the cement manufacturing process [11].

Various literature sources discuss methods for reducing CO_2 emissions from global [12]–[14], regional [15], and national [7], [16], [17] cement industries. Central options considered for the decarbonization of the global cement sector include alternative fuel use [18], improvements in thermal and electric efficiency [19], [20], substitution of supplementary cementitious materials (SCM) for clinker in cements [11], [21], development of low carbon cements [11], [22], and adding carbon capture and storage (CCS) to cement production facilities [23]–[25]. This analysis selects a core narrative, uses a parameterized model to project forward a build/retirement schedule for cement facilities in the U.S., and conducts a preliminary bottleneck analysis for the decarbonization of the U.S. domestic cement industry by mid-century.

2 Core narrative

Cement industry CO_2 emissions are minimized as part of a US economy-wide effort to reach net-zero anthropogenic GHG emissions by 2050. The transformation of the cement industry begins in earnest in after 2025, allowing a lead time for industry stakeholder engagement and the conduct of feasibility studies, permitting and investment decisions to be made in advance of the first plant construction. The industry selects supplementary cementitious materials and CO_2 capture and storage (CCS) as the key technologies to underpin decarbonization of cement manufacturing. The industry commissions its first state-of-the-art kiln/plant with CCS in 2026. The industry retires the last two cement kilns lacking CCS in 2051 – 35 years after they came on-stream in 2016. By 2050, the industry has reduced its average national clinker to cement ratio from historic average ratios of 90% or greater to 80%. By the end of 2051 all U.S. domestic cement kiln/plant capacity is state-of-the-art and has CCS, making it a world leading industry in the production of low carbon cements.

This approach is but one of a range potential decarbonization pathways for the U.S. cement sector. The core narrative combines AEO data with engineering estimates and expert opinion solicited through a discussion with a leading academic expert.

3 Model parameters for all deep-decarbonization scenarios

The proposed approach to decarbonize domestic cement manufacture by 2050 is formulated within the context of cement industry shipment and energy use projections from 2015 – 2050, as described (in data) by the AEO [1], [26]. Emissions reduction contributions for cement manufacture are included/excluded as follows:

- **Substitution of sustainable biogenic, low-, and zero-carbon fuels in the sector is not explicitly considered[7].** We include all energy carrier transitions specified in the AEO's [26] reference case. Cement industry energy demand in the AEO reference case arises from the Industrial Demand Module (IDM) of the EIA's National Energy Modeling

[6] The EPA's flight database is meant to track combustion and process emissions separately. However, the Continuous Emission Monitoring Systems (CEMS) used by most cement manufacturing companies results in the combustion and process emissions from kilns being reported together. The EPA plans to work with companies to improve disaggregation in future reporting years [3].

[7] Some of the fuels consumed in the cement plant are decarbonized upstream, e.g. biofuels, pipeline gas, and coal and coke replacements made with pyrolysis. This may lead to an over estimate of the CO_2 being captured at the facility.

System (NEMS) [5], [27]. A detailed and technology rich cement model within the IDM determines energy demand. Adjustments to that cement model might allow alternative fuel use demand projections through 2050 to be specified, but neither the 2017 [26] or 2019 [1] AEO explicitly included this transition pathway.

- **Improvements in the thermal and electric efficiency of cement facilities are not explicitly included.** AEO projections cover the dollar value of shipments from the sector, but do not specify physical output from the sector. Cement (and Lime) manufacturing shipments are imported into the IDM from the NEMS Macroeconomic Activity Module (MAM) [28]. In terms of overall energy efficiency of the cement sector per dollar of shipments, the sector shows a 7.7% total efficiency improvement over the 35 years between 2015 and 2050, which is consistent with a 0.23 % compound annual growth rate (CAGR) in shipment value energy efficiency. However, in order to ensure that thermal and electric efficiency is driving efficiency gains, rather than a higher cement price, we need to make the additional assumptions and projections found in Table 2 (e.g. clinker to cement ratio, imports of finished cement and clinker, cement prices in real terms).
- **The clinker to cement ratio is reduced to 80% by 2050.** Documentation for the IDM suggests that the AEO uses a national average clinker to cement ratio of 95%, with 5% of finished cement being composed of fly ash [5].[8] The potential to shift the clinker to cement ratio from a historical average of 92% [2] to 80% has been selected[9] to align the U.S. with a "reasonable" average global clinker to cement ratio of 60% in 2050 [11] - despite a potential mismatch with underlying AEO data.[10] We assume that lower clinker to cement ratios will be supported by changes in standards and practice that lead to more efficient use of clinker in mortar and concrete [11].
- **New low-carbon cements are not included, explicitly or implicitly.** The use of new low carbon cements has the potential to contribute to the decarbonization of the cement sector and future U.S. infrastructure. However, an expert assessment of options to decarbonize the cement industry [11] suggests that such use of low carbon cements was likely to offer greater potential for significant carbon emissions reductions beyond the horizon of this transition (to 2050).
- **The addition of CCS to cement facilities is explicitly included.** While some experts envisage a minimal role CCS in cement manufacturing in the short to medium-term – in part due to its high comparative cost against all other cement sector decarbonization options [11], a number of assessments project CCS to be a major mitigation option for cement manufacture,[13, 14, 15]. We have included CCUS explicitly in all net-zero pathways, taking advantage of new nationwide CO_2 transport and storage infrastructure proposed to serve not only the cement manufacturing sector but also to support decarbonization of other emissions-intensive sectors of the economy (power generation, bulk chemicals, iron and steel) and negative emissions technologies (direct air capture, bioenergy with carbon capture). The addition of post-combustion CCS to cement

[8] Documentation for the IDM further indicates that the cement model allows the clinker to cement ratio to be set below 95% should U.S. policy change. The IDM appears to have both a hard coded "additives" variable and a user specified variable specifically designed to vary the % of supplementary cementitious materials used in domestically produced cement. [5]

[9] In future iterations of NZAP, this arbitrarily selected domestic U.S. clinker to cement ratio will be refined for the U.S. through industry and expert consultations.

[10] The error involved in use of a lower clinker to cement ratio than modeled in underlying AEO cement data is expected to be low when considered against the error and uncertainty of the overall modeling effort.

facilities has the convenience of requiring no fundamental adjustments to underlying AEO data through 2050. The CO_2 capture rate is increased from 65% at start-up to 90% in year 3. A ramp up of the capture rate imposed to reflect the added complexity of CO_2 capture for cement manufacturers. The ultimate capture rate of 90% is consistent with a number of recent modelling studies [29], [30].

Table 2 lists the emissions reductions options included/excluded in decarbonization pathways, along with data sources, import assumptions, CCS assumptions, and data exclusions (if any).

Table 2 Data sources, assumptions, data exclusions and low-carbon option exclusions/inclusions in cement models

Aspect	Net-zero scenario(s) model
Cement shipment demand projection (IDM/MAM)	AEO2017
Cement import % cap (AEO ?%)	12.5%
Clinker import % cap (AEO 3.7%)	1.5%
Clinker to cement ratio 2017 (AEO 95%)	93%
Clinker to cement ratio 2050 (AEO 95%)	80%
Fuel Substitution	AEO2017
Thermal and Electric Efficiency	AEO2017
Low Carbon Cements	No
Carbon Capture and Storage (CCS)	Yes
CO_2 capture rate year one	65%
CO_2 capture final year rate	90%
CO_2 capture ramp (years)	3
Cement price in fixed USD2009/MT (USD2017/MT)	99.60
Energy line items excluded from AEO data	Boilers, HVAC[11]
Clinker kiln operational capacity factor (%)	93.4 %

4 Model results

According to AEO [26] and USGS [31] data, the U.S. domestic cement industry shipped 8.47 billion USD (US$2009) of cement in 2017 while producing of 86.1 million metric tons (MMT)

[11] These processes /stocks are assumed to be electrified in all low-carbon transition scenarios and are handled in their own stock in the wider model framework.

of cement and 76.5 MMT of clinker domestically, and importing 12.29 MMT of finished cement and 1.2 MMT of clinker from outside U.S. boundaries. According to the AEO [26], the U.S. cement industry is projected to ship 15.63 billion USD (US$2009) of cement in 2050. The AEO's [26] energy and shipment projections from 2015 to 2050 for the cement manufacturing sector are shown in Figure 9.

2050 cement sector shipments translate – using the NZAP model parameters in Table 2 – into the production of 156.9 million metric tons (MMT) of cement and 123.6 MMT of clinker, and the import 22.7 MMT of finished cement and 1.9 MMT of clinker from outside of U.S. boundaries in the same year.

Table 9 provides projections of shipment value US$2009 USD) from AEO [26] along with NZAP model projections for domestic cement and clinker production, and imports for clinker and cement from 2018 to 2050. Figure 2 shows the resulting projections of U.S. cement and clinker consumption (including imports) in MMt through 2050 in the net-zero pathways.

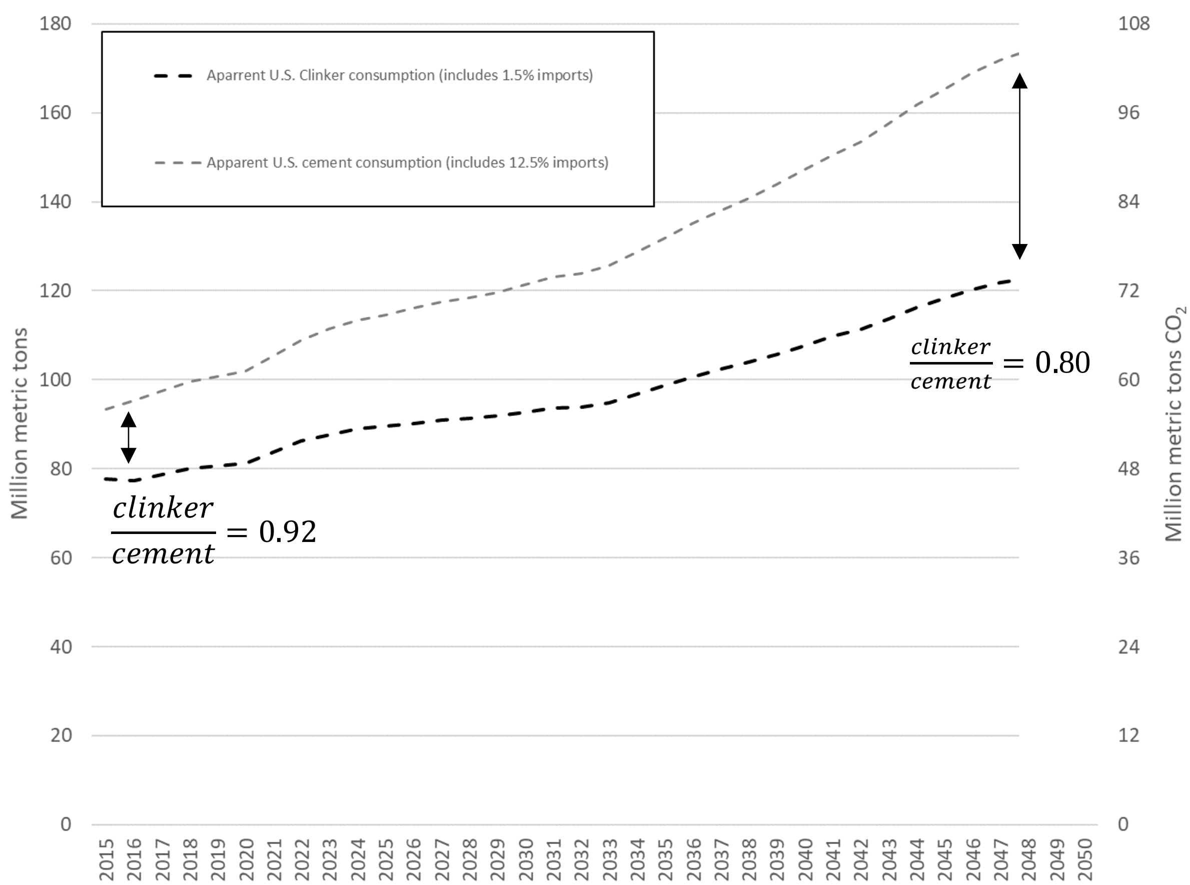

Figure 2 Projection of annual apparent U.S. cement and clinker consumption (in MMt) through 2050

Table 10 and Figure 3 present a retirement and build schedule that would allow domestic clinker capacity[12] to meet projected domestic clinker consumption (with clinker imports constant at

[12] Grinding capacity requirements are considered of secondary importance to kiln capacity in the model due to the potential for grinding capacity to be powered entirely by national electricity infrastructure – which is being decarbonized through separate, but potentially related measures (CCS) over a similar timeframe.

1.5% of projected consumption as shown in Figure 2), while maintaining historic relative capacity levels accross U.S. census regions and achieving a 90% reduction in onsite CO_2 emissions by 2050.

Table 11 presents model results for the onsite emission and capture of CO_2 at cement manufacturing facilities from 2020 – 2025.

It should be noted that when the model adds a kiln/plant to meet additional demand – and not just to replace retiring regional clinker capacity – the model allocates the plant/kiln to U.S. census divisions in descending order of the census divisions clinker capacity share in 2017, which can be observed in both Figure 14 and Table 12.[13] The model makes this assumption in order to preserve the regional balance of industry and jobs, while keeping plants near to traditional cement raw material sources.

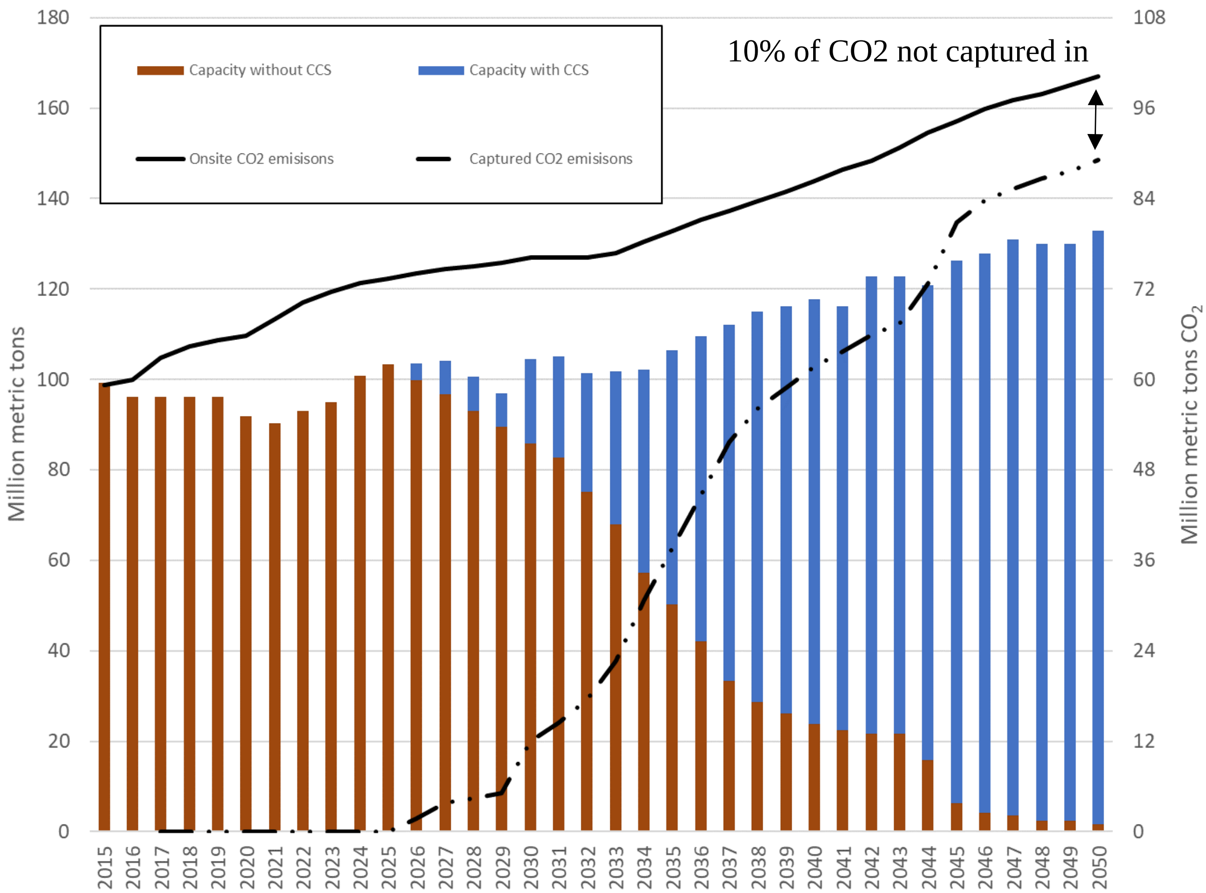

Figure 3 Cumulative clinker capacity with and without CCS from 2015 – 2050 (left vertical axis in MMt of clinker capacity); along with annual onsite CO_2 emissions and captured CO_2 emissions (right vertical axis in MMt of CO_2)

Table 10 and Figure 3 represent a retirement/build schedule that orders the retirement of clinker kiln capacity according to the kiln age reported in industry literature [32], with the oldest active kilns in the nation being retired first. Replacement kiln capacity is modeled in increments of single state-of-the-art 3.75 MMT/yr kilns constructed at state-of-the-art cement facilities operating at a 93.4% capacity factor. Table 3 presents the modeled characteristics of individual state-of-the-art facilities, along with expected industry totals in 2050. Table 4 provides a decade-

[13] This is an expedient decision that should be altered in future iterations to meet geospatially determined cement demand matching population, infrastructure and industry growth projections through 2050 – an area beyond the scope of the model in this iteration.

by-decade summary of the build schedule to meet projected demand while limiting cement and clinker imports to 12.5% and 1.5% respectively.

Table 3 Characteristics of individual state-of-the-art facilities [23], [33]–[36] used in modeling, along with expected industry totals in 2050

Plant aspect (unit)	Single Plant	Industry in 2050
Cement production capacity (MMt/y)	4.7	164.5
Clinker production capacity (MMt/y)	3.75	131.25
Clinker imports (MMt/y)	0.05	2
Raw materials input (MMt/y)	6.8 (76% limestone)	248
Total CO_2 generated from cement manufacture in 2050 (MMt CO_2/y)[14]	2.8	100
CO_2 captured in 2050 (MMt/y)	2.5	90
Total installed capital for new plant with CCS, (billion USD). No learning rate assumed.	3.5	126
Cost to build a CO_2 pipeline per km/mile for plant (million USD / 100 km)	NETL model (see CCS appendix)	
Time ,for feasibility studies, permitting, financing and construction of new greenfield facility (years)	7	

Table 4 Build-out of new state-of-the-art cement facilities with CCUS infrastructure by 2025 - 2050

Period	Plants commissioned w/CCS (single 3.75 MMT/yr kiln per plant)
2026 – 2030	5 New
2031 – 2040	15 New + 5 retrofits]
2041 – 2050	10 New

Table 4 indicates that the U.S. cement industry needs to build 5 state-of-the-art cement facilities with carbon capture equipment between 2025 and 2030, 15 similar facilities between 2031 and 2040 while retrofitting 5 facilities with carbon capture equipment, and 10 new facilities between 2041 and 2050. If projecting beyond 2050 and assuming no growth in cement demand, then a 5

[14] Does not include the emissions from any co-located lime facilities producing non-cement product.

to 10 year construction hiatus period[15] follows the rapid buildout of cement with CCS facilities, before recovering at a more modest facility replacement build rate.

Figure 4 presents the model's geospatial placement of cement plant/kiln new capacity builds with CCS in 2050, along with the final two cement plants without CCS in the U.S. – both of which are slated to be retired after 35 years of service in 2051 in NZAP net-zero scenarios.

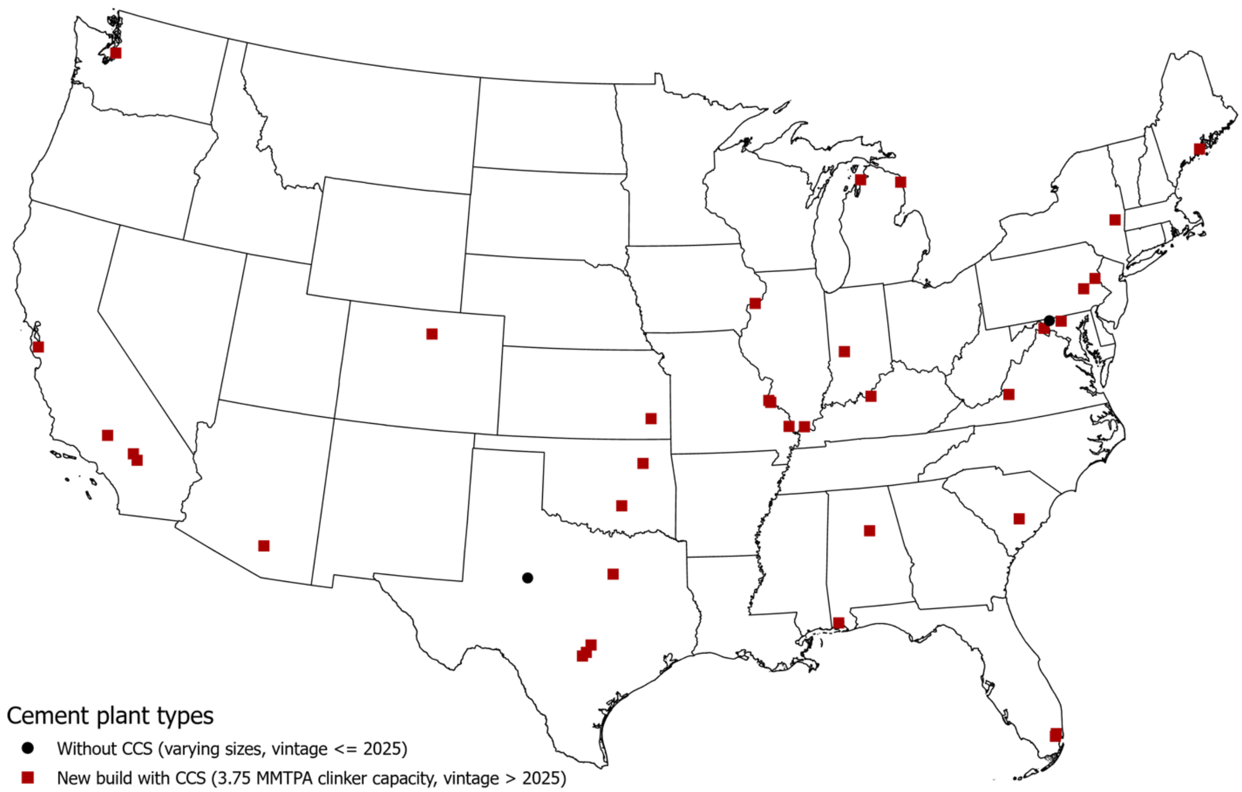

Figure 4 Cement facilities in 2050 with and without CCS

A full geospatial time-sequenced representation of net-zero scenario cement plant/kiln retirements and new capacity builds from 2025 through 2045 can be viewed in Figure 15 through Figure 20.

4.1 CCUS technology and infrastructure

The proposed cement industry transition relies heavily on CCUS technology being available for widespread commercial deployment by 2026. While there is considerable literature proposing CCS as a mitigation option for cement manufacture [13, 14, 15], there is scant literature reporting the industrial scale demonstration of carbon capture with a cement facility.

Net-Zero America scenarios described here rely on CO_2 transport and storage infrastructure. Plant location and deployment schedules aligned with the roll-out of CCS facilities and infrastructure developed through a coordinated, multi-sector geospatial assessment of major CO_2 sources and utilization and storage sites, describe in Appendix I. Early-mover new-build cement

[15] Depending on whether the modeled lifetime of a facility is 30 or 35 years.

plants should be sited near existing CO_2 pipelines and/or storage/utilization options with the most potential to be early movers in permanent CO_2 storage solutions.

4.2 Supplementary cementitious materials (SCM)

The proposed cement industry transition also relies on the timely, uninterrupted and abundant supply and utilization of suitable SCM. If the proposed uptake of SCM supply and utilization is not achieved then this will mean higher clinker to cement ratios and an increase the level process emissions to mitigating by CCUS.

The term SCM covers both nearly inert “fillers” such as limestone, and reactive by-product materials such as fly ash from coal fired power plants, silica flume, waste glass, vegetable ashes, natural pozzolan, granulated blast furnace slag (GBFS) from the production of iron and steel in integrated steel production facilities, and calcined clays [11]. Varying amounts and types of SCM are blended with clinker and calcium sulfate (e.g. gypsum) to make the cement type specified for a given application. The standards for Portland and blended cement types in the U.S. are codified by ASTM International in standards C150 [37] and C595 [37]. Standard Terminology Relating to Hydraulic Cement is covered in C219 [38]. Table 5 lists selected cement types in the U.S., along with their average SCM content and share of total physical cement shipments in 2015.

Table 5 Selected cement types in the U.S., SCM standards [37], [39]–[41] and percentage of total production in 2015 [36]

Type of cement	SCM content by mass (%)	% of shipments [36]
General use and moderate heat (Types I and II)	<= 6 % [37] [16]	77.48
Blended, Portland & pozzolans (IP) including fly ash	<= 40 % pozzolan [39]	01.11
Blended, Portland & GBFS (Type IS)	<= 95 % GBFS [39]	00.83
All other types	Varies [37], [39]–[41]	20.58
Totals		100.00

Table 5 makes it clear that “General Use” and Type II cement represented over three quarters of physical cement shipments in the U.S. in 2015. An analysis of industry data confirms that the average clinker to cement ratio of most common ASTM C150 cements manufactured across all industry was 92% [32] and had an average gypsum content of 5% [32], leaving roughly 3% for SCM. Materials mentioned as SCM in all domestic cement types included limestone (reported at 3% in most common ASTM C150 cements), GBFS (iron slag, steel slag), fly ash, copper slag, clay, alumina fines, clinker kiln dust (CKD), mill scale, brick (alumina source), cat. fines, diaspore, filter cake, calcined alumina, bauxite, iron ore, oil contaminated soil, FCC, and waste

[16] Allowed up to 5% inorganic SCM, of one type only, and 1% inorganic SCM.

by-products [32]. Table 6 provides historical usage of fly ash and GBFS as SCM in the U.S. from 2000 to 2014 along with trends connected to the source of each SCM.

Table 6 Historical usage of fly ash and GBFS in the U.S. from 1996 to 2014 along with trends connected to the source of each SCM. Modified from [2].

Year	Total domestic cement production (000 MT)	Fly ash (000 MT)	Coal as % of U.S. generation mix	GBFS (000 MT)	% of steel production via basic oxygen furnaces	Fly ash + GBFS (000 MT)
2000	82,825	18,213	-	1,931	53.0	20,144
2001	86,480	19,963	51.0	2,227	52.6	22,190
2002	85,977	24,157	50.1	2,775	49.6	26,932
2003	85,012	24,618	50.8	2,861	49.0	27,479
2004	89,687	25,464	49.8	3,309	47.8	28,773
2005	95,707	26,416	49.6	3,211	45.0	29,627
2006	94,006	29,414	49.0	3,299	32.9	32,713
2007	92,294	28,691	48.5	3,071	41.8	31,762
2008	85,363	27,345	48.2	2,734	42.6	30,079
2009	62,546	22,423	44.4	1,897	38.2	24,320
2010	64,871	23,336	44.8	1,845	38.7	25,181
2011	67,106	20,843	42.3	1,917	39.7	22,760
2012	73,758	21,051	37.4	2,151	40.9	23,202
2013	75,759	21,157	38.9	2,141	39.4	23,298
2014	81,420	21,030	38.6	2,271	37.4	23,301

Table 6 indicates that cement manufactured in 2014 incorporated both more fly ash and GBFS, than cement manufactured in 2000, roughly the last time that total domestic cement production was roughly the same, and that data was available for both categories. However, while fly ash and GBFS became more common in cements in the U.S. over that period, Table 6 indicates that the combined amount of fly ash and slag has leveled out at around 23,000 MMT/yr since 2011 – despite a fairly large resurgence in domestic cement production between 2011 and 2014. The inability of coal power generation and steel manufacturing industries to increase fly ash and GBFS supply to a recovering cement industry is likely directly related to their steadily declining market shares shown in Table 6.

4.3 Permitting challenges for greenfield cement plant construction

In the concluding comments of the USGS [36] Minerals Yearbook's chapter on cement, the author suggests that the "permitting difficulties in constructing new (greenfield) plants" represents the central challenge facing the ability of the U.S. domestic cement industry to meet cement demand at a return to 2005 cement demand levels of 128 MMT/yr. It is almost certain that NZAP net-zero cement projections which place domestic cement production at closer to 157 MMT/yr in 2050, would face even steeper difficulties if siting new facilities on greenfield sites. In an attempt to pre-empt this potential bottleneck, NZAP has cited all new state-of-the-art facilities on brownfield construction sites in its first iteration.

However, no systematic analysis was undertaken to ensure that each of the 35 sites selected met all of the criteria required to host a new state-of-the-art facility. A systematic multi-criteria analysis of the suitability of all potential brownfield cement sites should be undertaken as part of future iterations of cement analysis/models and could be combined with a synergistic analysis considering co-siting of new and replacement cement plants with other infrastructure on both brownfield and greenfield sites.

4.4 Implications of Net-Zero America scenarios for U.S. cement demand

Should even a fraction of the new infrastructure projects detailed in this report go forward, it is likely that domestic cement demand may even grow rapidly in the short term and in excess of the 180 MMT/yr projected for 2050. The proposed cement industry transition, based on recent AEOs [1], [26], does not take into account additional demand growth arising from a massive buildout of new infrastructure in the U.S.. Accordingly, we may be underestimating the capacity needed to service future U.S. domestic cement demand in any deep decarbonization scenario.

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6 Detailed model description

6.1 U.S. Cement energy data selection and cleaning

Although the U.S. Energy Information Agency (EIA) released the AEO2019 earlier this year, we have reverted to the AEO2017 data for the cement and lime industries. The energy demand data for the AEO2017 shown in Figure 5 appears more internally consistent than the AEO2019 cement industry demand data shown in Figure 6. This reversion leads to the loss of the greater cement industry model detail included in the AEO2019 version of the Industrial Demand Module (IDM) [5], [27]. However, it resolves an apparent conflict between shipment values and energy demand in initial years of the AEO2019 cement industry energy demand data.

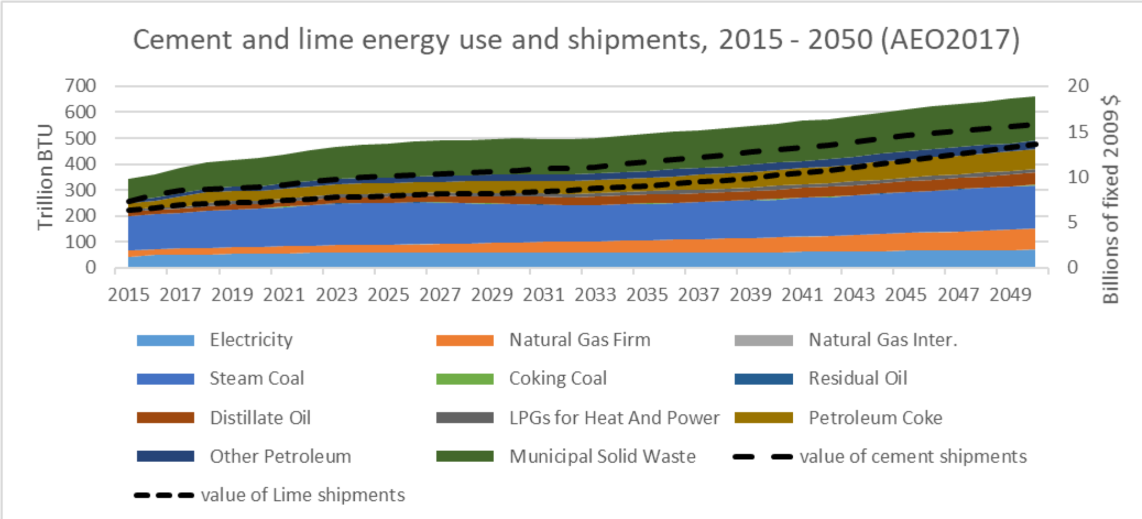

Figure 5 Energy demand for the cement and lime industries in the AEO2017

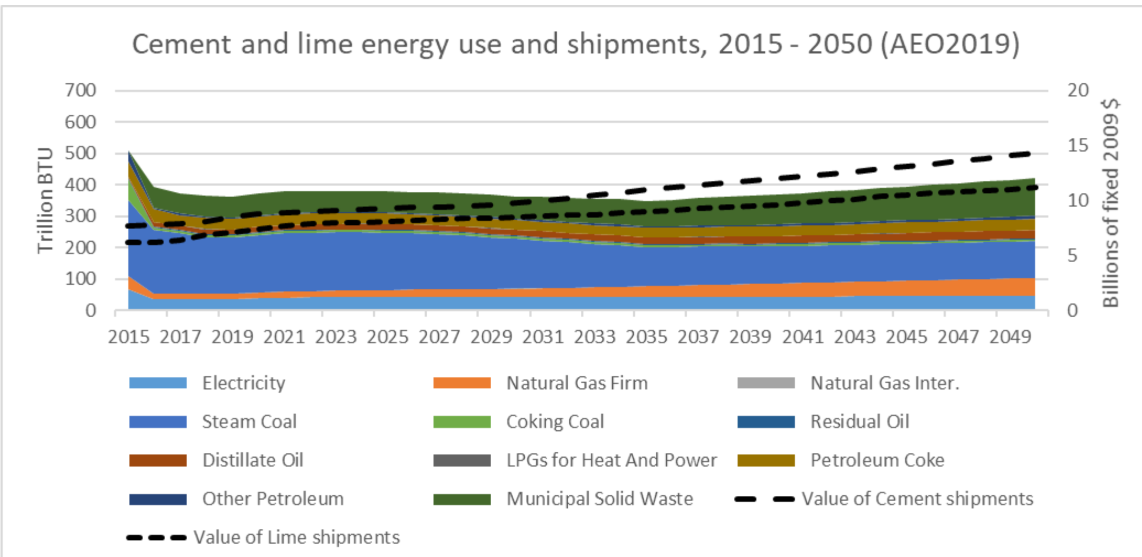

Figure 6 Energy demand for the cement and lime industries in the AEO2019

We expect that the internal conflict in cement energy industrial demand projections will resolve with the AEO2020, as happened with AEO projections between the initial implementation of more detailed model of the iron and steel sector model in the AEO2017 as shown in Figure 7, and the refinement of that model that led to the AEO2019 projections shown in Figure 8.

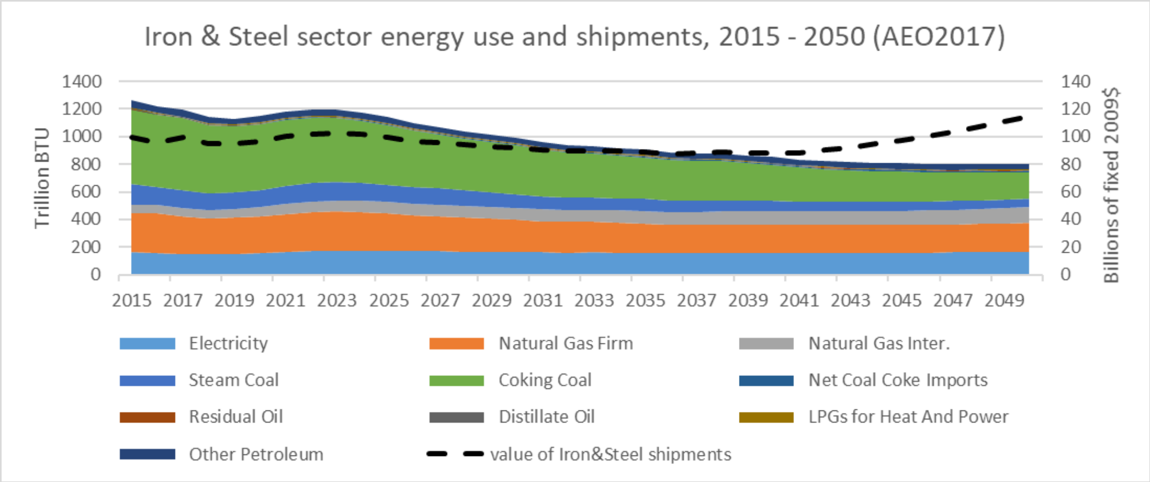

Figure 7 Energy demand for the iron and steel industries in the AEO2017

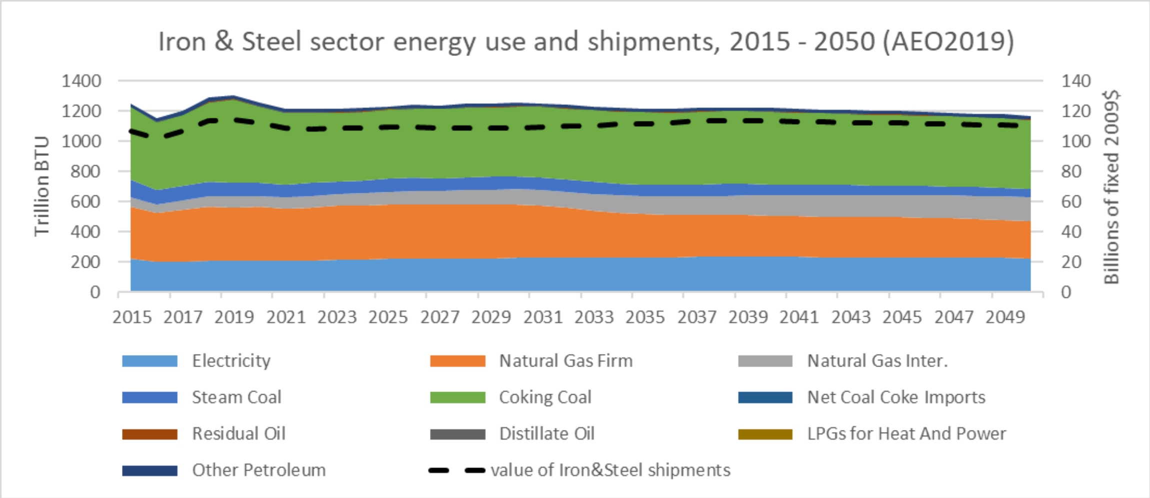

Figure 8 Energy demand for the iron and steel industries in the AEO2019

We take a few additional steps in order to aid modeling of the cement industry using AEO energy demand data. We first remove all lime industry energy demand from the AEO2017 cement and lime sector and place it in its own Lime (only) sector. The remaining energy demand is placed in a Cement (only) sector. We then use the Lime (only) to Cement (only) energy demand ratio to allocate relative portions of all remaining energy use (building, boiler, Cogen) to each individual sector. The appropriate shipment values from the Macroeconomic Activity Module (MAM) [28] that sits within the EIA's National Energy Modeling System (NEMS) output from the AEO2017 are then attached to the lime (only) and cement (only) sectors, resulting in the Cement and Lime sector energy use and shipments shown in Figure 9 and Figure 10. We use the AEO2017 [26] derived shipment values and energy demand projections for the cement industry shown in Figure 9 as the basis for all cement industry scenarios in our analysis. Likewise, we use the AEO2017 [26] derived shipment values and energy demand projections for the cement industry shown in Figure 10 as the basis for all lime industry scenarios in our analysis.

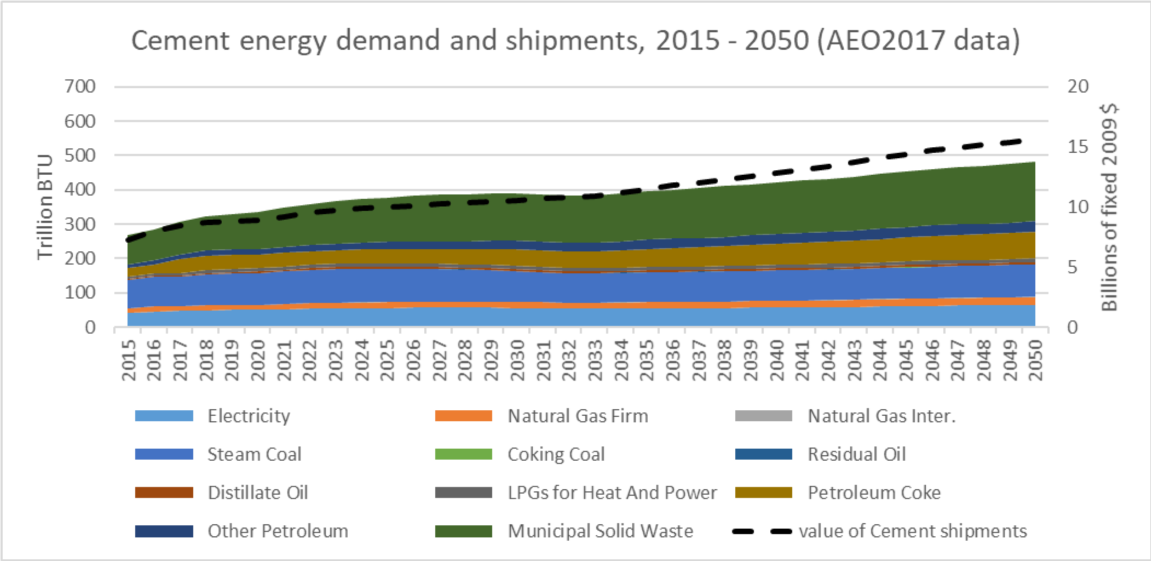

Figure 9 Energy demand for the cement industry (using AEO2017 data)

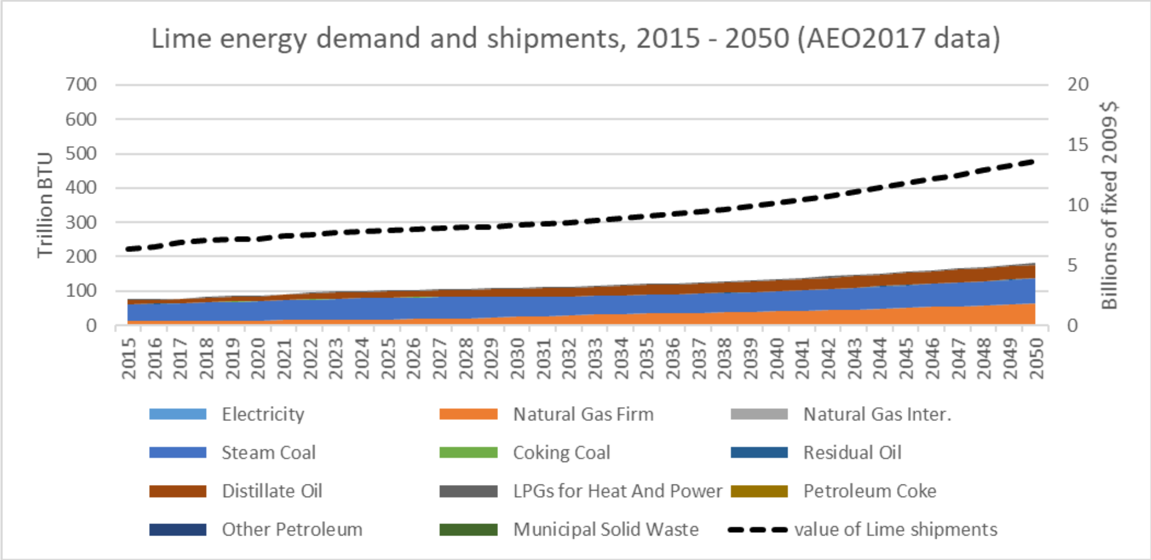

Figure 10 Energy demand for the lime industry (using AEO2017 data)

6.2 Projecting cement industry production and clinker capacity through 2050

According to the AEO2017 projections, the value of shipments from the cement industry more than doubles from 7.2 billion fixed 2009 US dollars in 2015 to 15.8 billion fixed 2009 US dollars in 2050. We assume that these fixed dollar figures, which are reported in the MAM [28], have been adjusted to remove increased valuation resulting from inflation. We also assume that these shipment values drive energy demand in the cement industry as described by documentation on the IDM [5], [27].

We then match shipment projections from the MAM with historic domestic production figures from the USGS [31] in 2017 in order to estimate a shipment ton to dollar of shipments relationship. We hold this relationship constant over the remainder of the projection period between 2018 and 2050.[17] This projection assumes that exports and cement produced from imported clinker are included in the total final shipments value reported by the MAM, and that imports of finished cement delivered to domestic buyers are excluded from that figure. Fixing prices at 2017 levels results in an average physical cement production growth 1.9% a year between 2020 and 2050. This growth rate is lower than the historical 2.2% growth rate for cement production in the U.S. between 1995 and 2006[18] as shown in Figure 11.

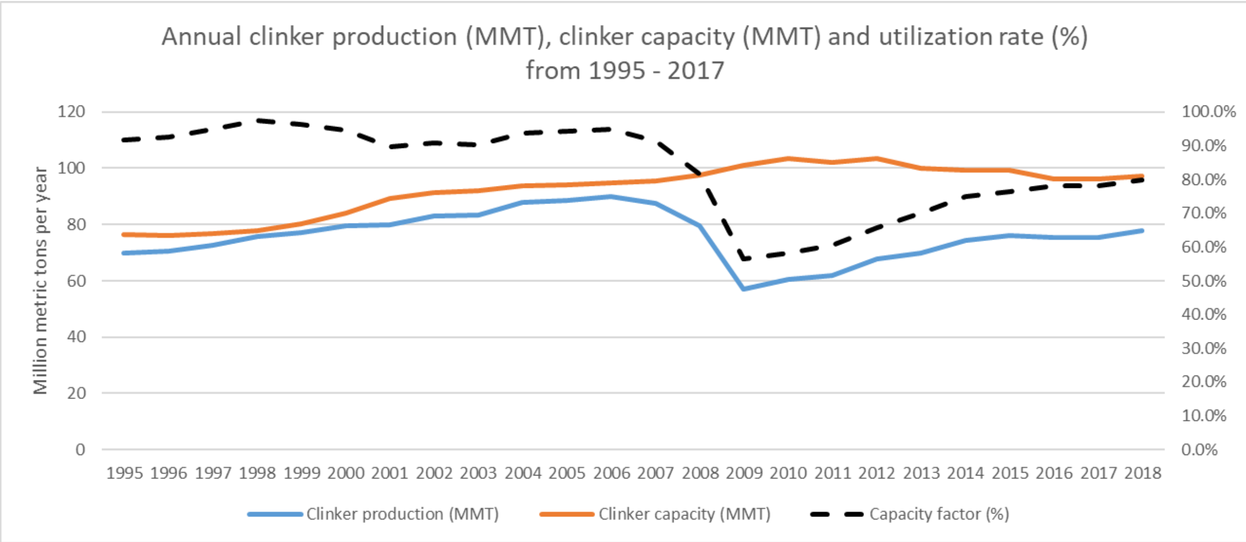

Figure 11 Clinker production (MMT), clinker capacity (MMT) and utilization rate (%) from 1995 - 2017, data from the PCA [2], [32] and USGS [31], [42]

Using such assumptions, we estimate that cement shipments arising from domestic production in the US increases from 83 million metric tons (MMT) in 2015 to 157 MMT in 2050. Over the same period, total final shipments in the US increase from 93 MMT to 180 MMT. The difference between total shipments and domestic production is filled by imported cement - which we hold constant at 12.6% of shipments to final customers from 2017-2050.[19] Holding imports constant at this level results in lower imports than were seen before that GFC as shown in Figure 12 or are predicted by the USGS [31] for 2018, but it is consistent with the principle adopted for NZAP analysis to limit the 'offshoring' of emissions.

[17] This results in an inflation adjusted cement price of $114/ton in 2017, which can be compared with the USGS's [31] report of a "Price, average mill value, dollars per ton" of $121 in 2017.
[18] We selected the period before the global financial crises' (GFC) started in 2007. The average growth rate since sectoral recovery appears to have begun in 2009, is 3.4%.
[19] This was the USGS [31] reported share in 2017.

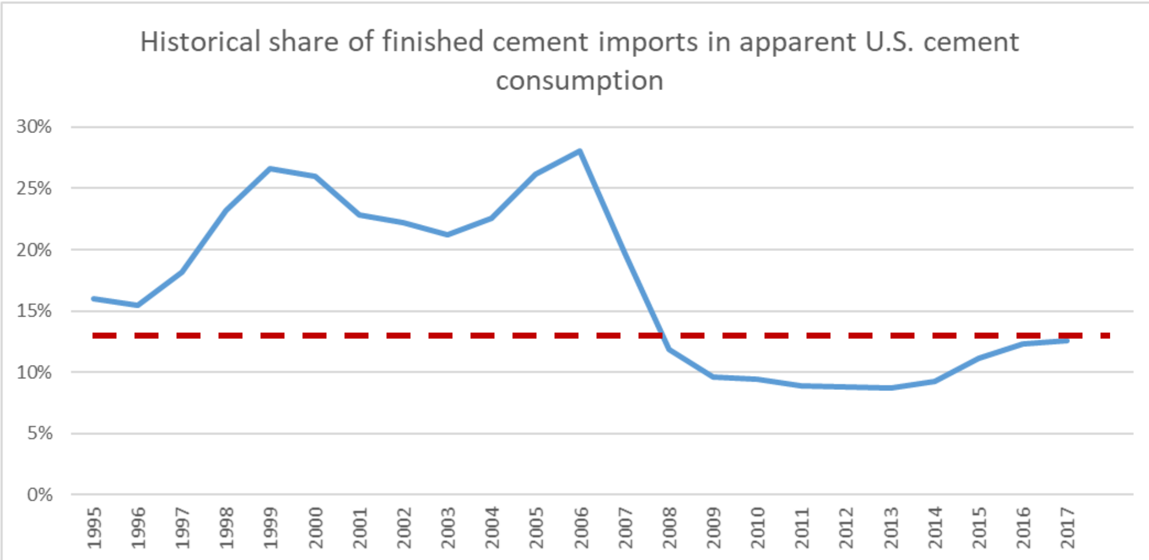

Figure 12 Historical share of finished cement imports in apparent U.S. cement consumption [2], [31]

Two factors are then needed in order to estimate the clinker capacity required to meet domestic production between 2015 and 2050. A capacity utilization factor of 93.4% is applied in all forward projections, implying that future cement production facilities will only be constructed to replace existing stock or meet increased demand, if that new capital is being utilized at the pre-global financial crisis (GFC) levels shown in Figure 11. Forward projections all also use the assumption that clinker transitions from representing an average of 92% by wt. of final cement production [2] in 2018, to 80% in 2050. Application of these two factors to projected annual cement production yields an increase in installed clinker production capacity from an actual capacity of 99 MMT/yr in 2015 [2] to a projected 132 MMT/yr in 2050.

6.3 Planning clinker kiln retirements and new builds through 2050 (spreadsheet model)

In order to estimate plant/kiln retirements and the addition of new cement plants, we consider three different kiln groupings.

- A first kiln type includes all plants that were still operating in 2018 [10], or reported as inactive but not retired in 2016 [32], and were installed before the year 2000. This group includes 92 kilns, has an average installation/modernization date of 1972 (46 years before 2018), has an average clinker capacity of 0.539 MMT/yr, and provides a combined annual production capacity of 49.6 MMT/yr.
- A second grouping of 38 kilns includes all kilns that were operating in 2018 and installed in or after the year 2000. This second group has an average installation/modernization date of 2005, has an average clinker capacity of 1.23 MMT/yr, and provides a combined annual production capacity of 46.7 MMT/yr. New kilns/plants that are already approved and planned to be commissioned between the start of the modelling period in 2018 and 2025 will be added to this group.
- A third grouping of kilns/plants consists of all new plants that are projected to be commissioned in the Net-Zero America scenarios, starting from 2026.

All plants/kilns from the first grouping retired by 2036. Retirements occur linearly at 3% of installed capacity per year between 2018 and 2025, and then more quickly at 7% of installed capacity per year from 2026 to 2036. A ramping up of the retirement rate in this older grouping is anticipated to occur due to the imposition of stricter environmental requirements starting in 2026. The 7% retirement rate ensures that all kilns installed before 2000 are retired before kilns built after 2000.

Retirement of all plants/kilns from the second and third grouping occur 35 years after installation/modernization. This kiln retirement age extends the IDM's assumed kiln lifespan of 30 years [5] by five years. However, our assumed lifespan is closer to the average age of the entire unretired kiln fleet in 2018 [10], [32], which was 36 years. The selection of this retirement age suggests that plants/kilns installed after 2015 will not be retired before the end of the analysis period in 2050.

For modelling purposes, all new capacity added to the second and third stock groupings will be based on a world class cement plant with a single kiln. An example cement plant/kiln of this type is Holcim's Bloomsdale, Missouri cement plant, which began production in 2009 and has an annual clinker capacity of 3,775 MMT/yr [43]. In all scenarios:

- all plants added to the third grouping will include a CCS facility; and
- all plants/kilns installed after 2015, but before 2026, are progressively retrofitted with CCS in order of the year in were constructed from 2031 to 2040.

Under this retrofit schedule, retrofits begin in 2031 (arbitrary) and finish within 10 years. Retrofits are assumed to be accompanied with upgrades/improvements that allow them to perform more like kilns/plants in the third grouping (purely for modelling ease). Figure 13 presents plant retirement and new build projections for three stock types in the US from 2015 through 2050.

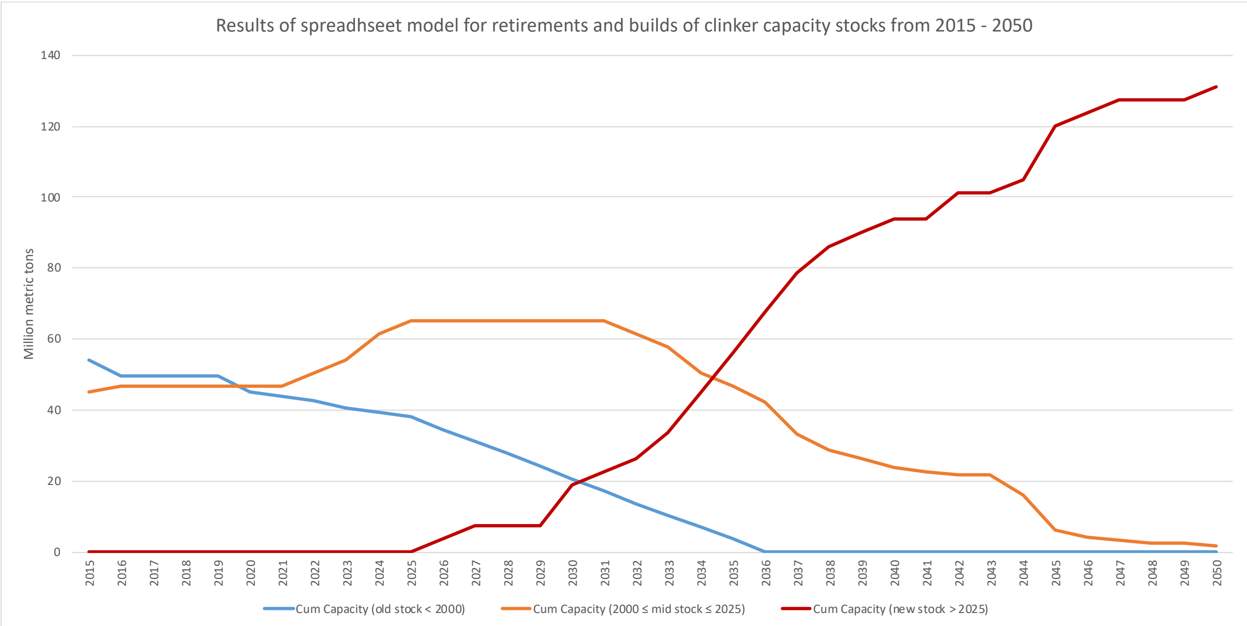

Figure 13 NZAP spreadsheet model results for plant retirement and new build projections for the three clinker kiln stock types used in the NZAP model from 2015 through 2050

6.4 Downscaling clinker retirements and new builds, to a regional level, through 2050

We then assume that all producing cement plants in the U.S., as reported by the Portland Cement Association (PCA) [32] and verified using Environmental Protection Agency (EPA) [10], [44] data, will be retired by cement kiln age and that the new plant/kilns will be added (in clinker production capacity increments of 3,775 MMT/yr) to maintain production levels and meet projected industry growth and located to retain a similar capacity spread across census regions. The first two kilns which are retired in downscaling, are located in Pennsylvania, and reportedly installed or last modernized before 1930, and have a combined annual production capacity of roughly 260 MMT/yr [32]. The last two kilns from PCA's [32] list are retired in 2051 after 35 years of service. Figure 14 shows the geospatial location of cement facilities that PCA reported in operation in 2017 along with the age of the facility as measured from 2018.

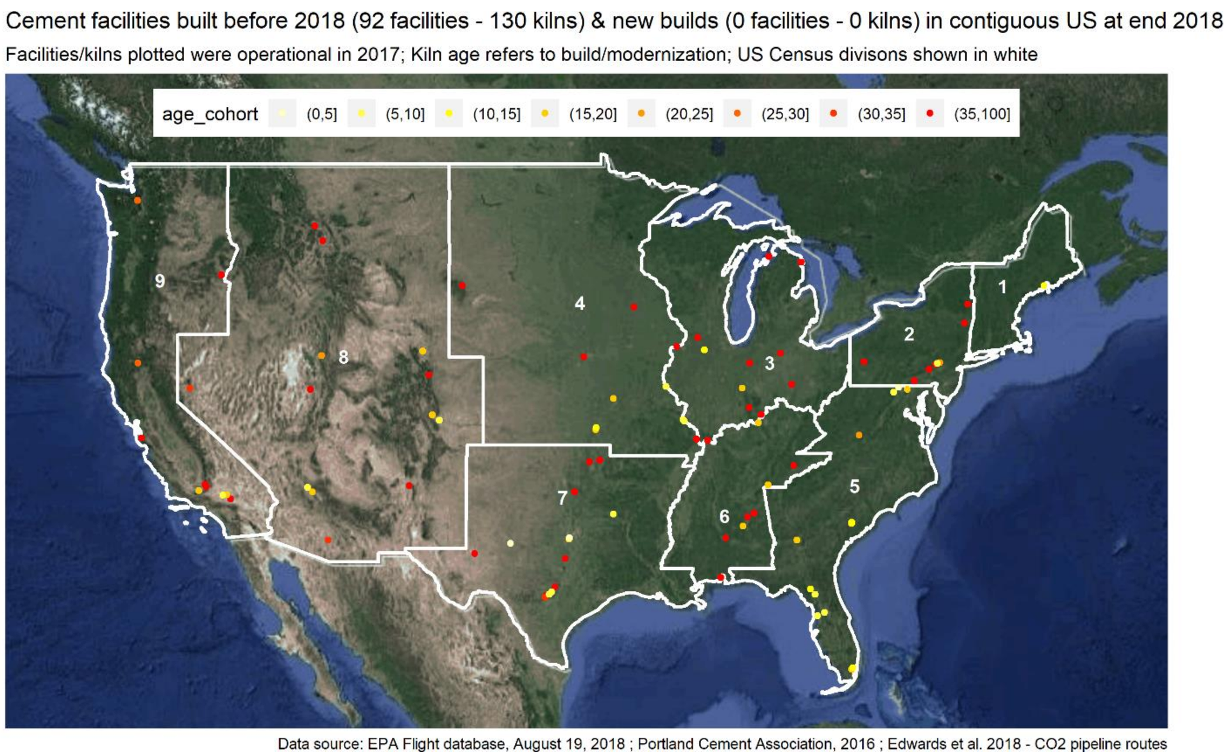

Figure 14 Geospatial location of cement facilities that were in operation in 2017 along with the age of the facility as measured from 2018

Table 10 details the full retirement schedule of all clinker kilns. In Table 10, a plant/kiln replacement is triggered when aggregate clinker kiln retirements in any U.S. census division reach 2.1 MMT/year of annual divisional production capacity (arbitrarily selected as 55% of a 3.75 MMT plant).

6.5 Estimating carbon dioxide (CO_2) emissions from plants and CCS specifications

Carbon dioxide emissions from cement manufacturing have been estimated in this analysis as follows. Each fuel reported to be used by the cement industry in the AEO2017 [26] is multiplied by a fuel specific CO_2 emissions coefficient provided by the EIA [45]. The resulting aggregate CO_2 emissions combustion total for the cement industry is then adjusted with a production-based process CO_2 emissions estimate in order to arrive at a total CO_2 emissions estimate. Cement process emissions are estimated using the method provided in the EPA [3] under which annual domestic clinker production figures in tons of clinker are first multiplied by a process emissions factor of 0.51 tons CO_2/ton clinker, and then increased by an additional 0.2% to account for emissions attributed clinker kiln dust.

CO_2 is also captured at cement manufacturing facilities. Capture rates are assumed to progressively increase from 65% of total CO_2 generated on site during start-up to 90% in year 3 as described in earlier (in Model parameters for all deep-decarbonization scenarios).

Table 11 provides NZAP projections for onsite CO_2 emissions generated by, and captured from cement manufacturing facilities from 2020 through 2050.

Capture rates are assumed to progressively increase from 65% of total CO_2 generated on site during commissioning to 90% within 3 years.

Table 11 provides NZAP projections CO_2 emissions captured at cement manufacturing facilities from 2020 through 2050.

7 Additional tables and figures

Table 7 Summary of U.S. Inventory of GHG's 1990 – 2017 [3]

Gas/Source	**1990**	**2005**	**2013**	**2014**	**2015**	**2016**	**2017**
CO2	5,121.20	6,130.60	5,522.90	5,572.10	5,423.00	5,306.70	5,270.70
Fossil Fuel Combustion	4,738.80	5,744.80	5,157.40	5,199.30	5,047.10	4,961.90	4,912.00
Transportation	1,469.10	1,857.00	1,682.70	1,721.60	1,734.00	1,779.00	1,800.60
Electric Power Sector	1,820.00	2,400.00	2,038.30	2,037.10	1,900.60	1,808.90	1,732.00
Industrial	857.5	853.4	840	819.6	807.9	807.6	810.7
Residential	338.2	357.9	329.3	346.8	317.8	292.9	294.5
Commercial	226.5	226.8	224.6	232.9	245.5	232.1	232.9
U.S. Territories	27.6	49.7	42.5	41.4	41.4	41.4	41.4
Non-Energy Use of Fuels	119.6	139.6	123.5	119.9	126.9	113.7	123.2
Iron and Steel Production & Metallurgical Coke Production	101.6	68.2	53.5	58.4	47.8	42.3	41.8
Cement Production	33.5	46.2	36.4	39.4	39.9	39.4	40.3
Petrochemical Production	21.2	26.8	26.4	26.5	28.1	28.1	28.2
Natural Gas Systems	30	22.6	25.1	25.5	25.1	25.5	26.3
Petroleum Systems	9	11.6	25.1	29.6	31.7	22.2	23.3
Ammonia Production	13	9.2	9.5	9.4	10.6	10.8	13.2
Lime Production	11.7	14.6	14	14.2	13.3	12.9	13.1
Incineration of Waste	8	12.5	10.3	10.4	10.7	10.8	10.8
Other Process Uses of Carbonates	6.3	7.6	11.5	13	12.2	11	10.1
(All other sources)	28.40	26.90	30.20	26.40	29.50	28.10	28.30
CH4	779.8	691.4	663	662.1	661.4	654.9	656.3

Enteric Fermentation	164.2	168.9	165.5	164.2	166.5	171.9	175.4
Natural Gas Systems	193.1	171.4	165.6	165.1	167.2	165.7	165.6
Landfills	179.6	131.4	112.9	112.5	111.2	108	107.7
Manure Management	37.1	53.7	58.1	57.8	60.9	61.5	61.7
Coal Mining	96.5	64.1	64.6	64.6	61.2	53.8	55.7
Petroleum Systems	42.1	36.7	41.6	42.1	39.5	38.2	37.7
Wastewater Treatment	15.3	15.4	14.3	14.3	14.5	14.2	14.2
Rice Cultivation	16	16.7	11.5	12.7	12.3	13.7	11.3
(All other sources)	35.9	33.1	28.9	28.8	28.1	27.9	27
N2O	370.3	375.8	365.4	362.7	374.1	364.5	360.5
Agricultural Soil Management	251.7	254.5	265.2	262.3	277.8	267.6	266.4
Stationary Combustion	25.1	34.3	32.7	33	30.6	30.1	28.6
Manure Management	14	16.5	17.4	17.4	17.6	18.2	18.7
Mobile Combustion	42	39	22.1	20.2	18.8	17.9	16.9
(All other sources)	37.5	31.5	28	29.8	29.3	30.7	29.9
HFCs	46.6	122.3	146.1	150.7	153.8	155	158.3
Substitution of Ozone Depleting Substances	0.3	102.1	141.7	145.2	149.2	151.7	152.7
(All other sources)	46.3	20.2	4.4	5.5	4.6	3.3	5.6
PFCs	24.3	6.7	5.9	5.6	5.1	4.4	4.1
SF6	28.8	11.8	6.3	6.3	5.8	6.3	6.1
NF3	< .05	0.5	0.5	0.5	0.6	0.6	0.6
Total Emissions	6,371.00	7,339.00	6,710.20	6,760.00	6,623.80	6,492.30	6,456.70
LULUCF Emissions	7.8	16	17.5	17.7	28.3	15.5	15.5
LULUCF CH4 Emissions	5	9	9.9	10.1	16.5	8.8	8.8
LULUCF N2O Emissions	2.8	7	7.6	7.7	11.8	6.7	6.7
LULUCF Carbon Stock Change	-814.8	-756.1	-731	-687.8	-739.4	-738.1	-729.6

LULUCF Sector Net Total	-807	-740	-713.5	-670	-711.1	-722.6	-714.1
Net Emissions (Sources and Sinks)	5,564.00	6,599.00	5,996.80	6,090.00	5,912.70	5,769.70	5,742.60

Table 8 Summary of CO_2 sources that emitted more than 10 MMT CO_2 in 2017, modified from EPA [3]

CO_2 Source	1990	2005	2013	2014	2015	2016	2017
01. Fossil Fuel Combustion	4,738.8	5,744.8	5,157.4	5,199.3	5,047.1	4,961.9	4,912.0
Transportation	1,469.1	1,857.0	1,682.7	1,721.6	1,734.0	1,779.0	1,800.6
Electric Power Sector	1,820.0	2,400.0	2,038.3	2,037.1	1,900.6	1,808.9	1,732.0
Industrial	857.5	853.4	840	819.6	807.9	807.6	810.7
Cement industry (from Table 1)	--	--	26.3	27.6	28.3	26.7	26.2
Residential	338.2	357.9	329.3	346.8	317.8	292.9	294.5
Commercial	226.5	226.8	224.6	232.9	245.5	232.1	232.9
U.S. Territories	27.6	49.7	42.5	41.4	41.4	41.4	41.4
02. Non-Energy Use of Fuels	119.6	139.6	123.5	119.9	126.9	113.7	123.2
03. Iron and Steel Production & Metallurgical Coke Production	101.6	68.2	53.5	58.4	47.8	42.3	41.8
04. Cement Production (process only)	33.5	46.2	36.4	39.4	39.9	39.4	40.3
05. Petrochemical Production	21.2	26.8	26.4	26.5	28.1	28.1	28.2
06. Natural Gas Systems	30	22.6	25.1	25.5	25.1	25.5	26.3
07. Petroleum Systems	9	11.6	25.1	29.6	31.7	22.2	23.3
08. Ammonia Production	13	9.2	9.5	9.4	10.6	10.8	13.2
09. Lime Production	11.7	14.6	14	14.2	13.3	12.9	13.1
10. Incineration of Waste	8	12.5	10.3	10.4	10.7	10.8	10.8
11. Other Process Uses of Carbonates	6.3	7.6	11.5	13	12.2	11	10.1

Table 9 Projections of shipment value (in fixed 2009 USD) from the AEO [26] along with NZAP model results for domestic cement and clinker production, along with imports for clinker and cement from 2018 to 2050

Year	Cement production	Clinker production	Imports of finished cement	Imports of clinker
2018	86,993	78,804	12,566	1,229
2019	88,085	79,468	12,723	1,240
2020	89,003	79,968	12,856	1,247
2021	92,133	82,440	13,308	1,286
2022	95,230	84,859	13,755	1,324
2023	97,329	86,371	14,059	1,347
2024	99,114	87,588	14,316	1,366
2025	100,129	88,116	14,463	1,375
2026	101,374	88,837	14,643	1,386
2027	102,564	89,501	14,815	1,396
2028	103,508	89,943	14,951	1,403
2029	104,574	90,483	15,105	1,412
2030	106,039	91,359	15,317	1,425
2031	107,569	92,280	15,538	1,440
2032	108,289	92,498	15,642	1,443
2033	109,732	93,325	15,850	1,456
2034	112,570	95,323	16,260	1,487
2035	115,285	97,197	16,652	1,516
2036	118,113	99,145	17,061	1,547
2037	120,608	100,794	17,421	1,572
2038	123,046	102,377	17,773	1,597
2039	125,702	104,123	18,157	1,624
2040	128,580	106,031	18,573	1,654
2041	131,569	108,011	19,004	1,685

2042	134,032	109,538	19,360	1,709
2043	137,569	111,920	19,871	1,746
2044	141,329	114,457	20,414	1,786
2045	144,474	116,471	20,868	1,817
2046	147,574	118,426	21,316	1,847
2047	150,105	119,902	21,682	1,870
2048	152,071	120,911	21,966	1,886
2049	154,420	122,208	22,305	1,906
2050	156,877	123,574	22,660	1,928

Table 10 Projection of kiln retirement, new capacity build, and retrofit schedule for the cement industry from 2016 to 2051 under the NZAP net-zero model

Action	year	state	Kiln clinker capacity (MMt)	National clinker capacity (MMt)	Cumulative clinker capacity with CCS (MMt)
BUILD	2016	md	0.744	94.6	0
BUILD	2016	tx	0.997	95.3	0
BASELINE [32]	2017	[redacted]		96.3	0
RETIRE	2020	pa	-0.132	96.19	0
RETIRE	2020	pa	-0.132	96.06	0
RETIRE	2020	az	-0.121	95.94	0
RETIRE	2020	tx	-0.145	95.80	0
RETIRE	2020	tx	-0.145	95.65	0
RETIRE	2020	tx	-0.163	95.49	0
RETIRE	2020	az	-0.121	95.37	0
RETIRE	2020	il	-0.146	95.22	0
RETIRE	2020	il	-0.146	95.08	0
RETIRE	2020	il	-0.146	94.93	0
RETIRE	2020	az	-0.121	94.81	0
RETIRE	2020	oh	-0.195	94.61	0
RETIRE	2020	oh	-0.195	94.42	0
RETIRE	2020	ok	-0.281	94.14	0
RETIRE	2020	ok	-0.281	93.86	0
RETIRE	2020	nm	-0.213	93.64	0
RETIRE	2020	tx	-0.229	93.41	0
RETIRE	2020	ok	-0.179	93.24	0
RETIRE	2020	nm	-0.213	93.02	0
RETIRE	2020	in	-0.229	92.79	0

RETIRE	2020	in	-0.234	92.56	0
RETIRE	2020	ok	-0.281	92.28	0
RETIRE	2020	in	-0.193	92.09	0
RETIRE	2020	ok	-0.179	91.91	0
RETIRE	2021	mt	-0.299	91.61	0
RETIRE	2021	ok	-0.299	91.31	0
RETIRE	2021	ny	-0.829	90.48	0
RETIRE	2022	nv	-0.226	90.25	0
RETIRE	2022	pa	-0.43	89.82	0
RETIRE	2022	pa	-0.502	89.32	0
BUILD	2022	ok	3.75	93.07	0
RETIRE	2023	pa	-0.502	92.57	0
RETIRE	2023	in	-0.193	92.38	0
RETIRE	2023	il	-0.388	91.99	0
RETIRE	2023	mi	-0.345	91.64	0
RETIRE	2023	mi	-0.345	91.30	0
BUILD	2023	ny	3.75	95.05	0
RETIRE	2024	mi	-0.346	94.70	0
RETIRE	2024	co	-0.483	94.22	0
RETIRE	2024	pa	-0.102	94.12	0
RETIRE	2024	tx	-0.101	94.02	0
RETIRE	2024	in	-0.298	93.72	0
RETIRE	2024	mt	-0.28	93.44	0
BUILD	2024	il	3.75	97.19	0
BUILD	2024	ok	3.75	100.94	0
RETIRE	2025	ny	-0.569	100.37	0
RETIRE	2025	oh	-0.663	99.71	0

BUILD	2025	co	3.75	103.46	0
RETIRE	2026	il	-0.629	102.83	0
RETIRE	2026	pa	-0.303	102.52	0
RETIRE	2026	pa	-0.327	102.20	0
RETIRE	2026	ne	-0.333	101.86	0
RETIRE	2026	mi	-0.617	101.25	0
RETIRE	2026	mi	-0.616	100.63	0
RETIRE	2026	al	-0.713	99.92	0
BUILD	2026	al	3.75	103.67	3.75
RETIRE	2027	in	-0.232	103.44	3.75
RETIRE	2027	al	-0.847	102.59	3.75
RETIRE	2027	al	-0.848	101.74	3.75
RETIRE	2027	tx	-1.168	100.57	3.75
BUILD	2027	mi	3.75	104.32	7.5
RETIRE	2028	ia	-0.73	103.59	7.5
RETIRE	2028	tn	-0.685	102.91	7.5
RETIRE	2028	pa	-1.216	101.69	7.5
RETIRE	2028	sd	-0.682	101.01	7.5
RETIRE	2028	tx	-0.259	100.75	7.5
RETIRE	2029	in	-0.621	100.13	7.5
RETIRE	2029	tx	-0.778	99.35	7.5
RETIRE	2029	or	-0.983	98.37	7.5
RETIRE	2029	mi	-1.238	97.13	7.5
RETIRE	2030	tx	-0.952	96.18	7.5
RETIRE	2030	ok	-0.268	95.91	7.5
RETIRE	2030	al	-1.504	94.41	7.5
RETIRE	2030	ia	-0.952	93.46	7.5

BUILD	2030	tx	3.75	97.21	11.25
BUILD	2030	mo	3.75	100.96	15
BUILD	2030	ia	3.75	104.71	22.5
RETIRE	2031	mo	-1.234	103.47	15
RETIRE	2031	ca	-0.492	102.98	15
RETIRE	2031	ca	-1.474	101.51	15
BUILD	2031	ca	3.75	105.26	18.75
RETIRE	2032	ut	-0.834	104.42	22.5
RETIRE	2032	ca	-1.384	103.04	22.5
RETIRE	2032	tx	-0.887	102.15	22.5
RETIRE	2032	ne	-0.574	101.58	22.5
RETROFIT	2032	ok	0	101.58	26.25
RETIRE	2033	ca	-1.544	100.03	26.25
RETIRE	2033	tx	-0.701	99.33	26.25
RETIRE	2033	az	-0.969	98.36	26.25
RETIRE	2033	nv	-0.226	98.14	26.25
RETROFIT	2033	ny	0	98.14	30
BUILD	2033	ca	3.75	101.89	33.75
RETIRE	2034	ca	-1.042	100.84	33.75
RETIRE	2034	tx	-0.633	100.21	33.75
RETIRE	2034	fl	-0.607	99.60	33.75
RETIRE	2034	ca	-0.988	98.62	33.75
RETROFIT	2034	il	0	98.62	37.5
RETROFIT	2034	ok	0	98.62	41.25
BUILD	2034	wa	3.75	102.37	45
RETIRE	2035	wa	-0.715	101.65	45
RETIRE	2035	pa	-0.581	101.07	45

RETIRE	2035	wy	-0.172	100.90	45
RETIRE	2035	va	-1.14	99.76	45
RETIRE	2035	sc	-0.627	99.13	45
RETROFIT	2035	co	0	99.13	48.75
BUILD	2035	va	3.75	102.88	52.5
BUILD	2035	pa	3.75	106.63	56.25
RETIRE	2036	ut	-0.716	105.92	56.25
RETIRE	2036	ca	-1.033	104.88	56.25
RETIRE	2036	wy	-0.401	104.48	56.25
RETIRE	2036	fl	-0.729	103.75	56.25
RETIRE	2036	ga	-0.757	103.00	56.25
RETIRE	2036	ky	-1.432	101.56	56.25
RETIRE	2036	tx	-0.925	100.64	56.25
RETIRE	2036	fl	-0.99	99.65	56.25
RETIRE	2036	in	-1.224	98.42	56.25
BUILD	2036	ca	3.75	102.17	60
BUILD	2036	fl	3.75	105.92	63.75
BUILD	2036	ky	3.75	109.67	67.5
RETIRE	2037	ks	-1.49	108.18	67.5
RETIRE	2037	tx	-2.089	106.10	67.5
RETIRE	2037	ca	-1.659	104.44	67.5
RETIRE	2037	tn	-0.816	103.62	67.5
RETIRE	2037	md	-2.087	101.53	67.5
RETIRE	2037	ks	-0.552	100.98	67.5
BUILD	2037	ks	3.75	104.73	71.25
BUILD	2037	md	3.75	108.48	75
BUILD	2037	tx	3.75	112.23	78.75

RETIRE	2038	al	-1.405	110.83	78.75
RETIRE	2038	co	-1.415	109.41	78.75
RETIRE	2038	mo	-0.943	108.47	78.75
RETIRE	2038	az	-0.912	107.56	78.75
BUILD	2038	mi	3.75	111.31	82.5
BUILD	2038	az	3.75	115.06	86.25
RETIRE	2039	fl	-0.807	114.25	86.25
RETIRE	2039	sc	-1.632	112.62	86.25
BUILD	2039	sc	3.75	116.37	90
RETIRE	2040	me	-0.638	115.73	90
RETIRE	2040	fl	-1.701	114.03	90
BUILD	2040	me	3.75	117.78	93.75
RETIRE	2041	sc	-0.852	116.93	93.75
RETIRE	2041	ks	-0.552	116.37	93.75
RETIRE	2042	il	-0.893	115.48	93.75
BUILD	2042	in	3.75	119.23	97.5
BUILD	2042	ca	3.75	122.98	101.25
RETIRE	2044	tx	-1.097	121.88	101.25
RETIRE	2044	mo	-1.007	120.88	101.25
RETIRE	2044	ca	-1.727	119.15	101.25
RETIRE	2044	co	-0.97	118.18	101.25
RETIRE	2044	fl	-0.944	117.24	101.25
BUILD	2044	pa	3.75	120.99	105
RETIRE	2045	mo	-2.268	118.72	105
RETIRE	2045	pa	-0.949	117.77	105
RETIRE	2045	wv	-1.6	116.17	105
RETIRE	2045	mo	-3.775	112.39	105

RETIRE	2045	fl	-0.991	111.40	105
BUILD	2045	mo	3.75	115.15	108.75
BUILD	2045	al	3.75	118.90	112.5
BUILD	2045	fl	3.75	122.65	116.25
BUILD	2045	mo	3.75	126.40	120
RETIRE	2046	ar	-1.386	125.02	120
RETIRE	2046	fl	-0.759	124.26	120
BUILD	2046	tx	3.75	128.01	123.75
RETIRE	2047	az	-0.599	127.41	123.75
BUILD	2047	wv	3.75	131.16	127.5
RETIRE	2048	tx	-1.143	130.02	127.5
RETIRE	2050	tx	-0.775	129.24	127.5
BUILD	2050	tx	3.75	132.99	131.25
RETIRE	2051	md	-0.744	132.25	131.25
RETIRE	2051	tx	-0.997	131.25	131.25

Table 11 Onsite cement manufacturing facility CO_2 emissions (in MMt CO_2) from both energy combustion and process sources from 2020 through 2050, along with total CO_2 captured via CCS

Year	Process related CO_2 emissions (MMt CO_2) [20]	Energy related CO_2 emissions (MMt CO_2)[21]	Total (MMt CO_2)	Captured via CCS (MMt CO_2)
2020	41.6	24.2	65.8	0.0
2021	42.9	25.1	68.0	0.0
2022	44.1	26.0	70.2	0.0
2023	44.9	26.7	71.7	0.0
2024	45.6	27.2	72.8	0.0
2025	45.8	27.5	73.4	0.0
2026	46.2	27.8	74.0	2.1
2027	46.6	28.1	74.7	4.8
2028	46.8	28.3	75.1	7.9
2029	47.1	28.4	75.5	11.5
2030	47.5	28.6	76.2	14.6
2031	48.0	28.1	76.1	18.7
2032	48.1	28.1	76.2	21.3
2033	48.5	28.2	76.8	25.3
2034	49.6	28.7	78.3	30.2
2035	50.6	29.1	79.7	34.9
2036	51.6	29.6	81.1	42.5
2037	52.4	29.9	82.4	50.6
2038	53.3	30.4	83.6	55.0
2039	54.2	30.8	84.9	58.1

[20] Using EPA [3] methods based on production.
[21] Using AEO [1] coefficients and excluding boilers or HVAC energy use as they are handled elsewhere in EER models.

2040	55.2	31.2	86.4	62.5
2041	56.2	31.6	87.8	64.8
2042	57.0	32.0	89.0	66.4
2043	58.2	32.5	90.8	68.1
2044	59.5	33.2	92.7	73.7
2045	60.6	33.7	94.3	81.7
2046	61.6	34.2	95.8	84.5
2047	62.4	34.7	97.0	86.0
2048	62.9	35.0	97.9	87.6
2049	63.6	35.4	99.0	88.6
2050	64.3	35.9	100.2	90.1

Table 12 Cement capacity share, by census division, ordered from most to least in 2017

Census Division	Share of national capacity in 2017 [10]
5	17.9%
7	16.7%
4	15.9%
9	13.7%
3	10.2%
8	9.5%
6	8.7%
2	6.6%
1	0.7%

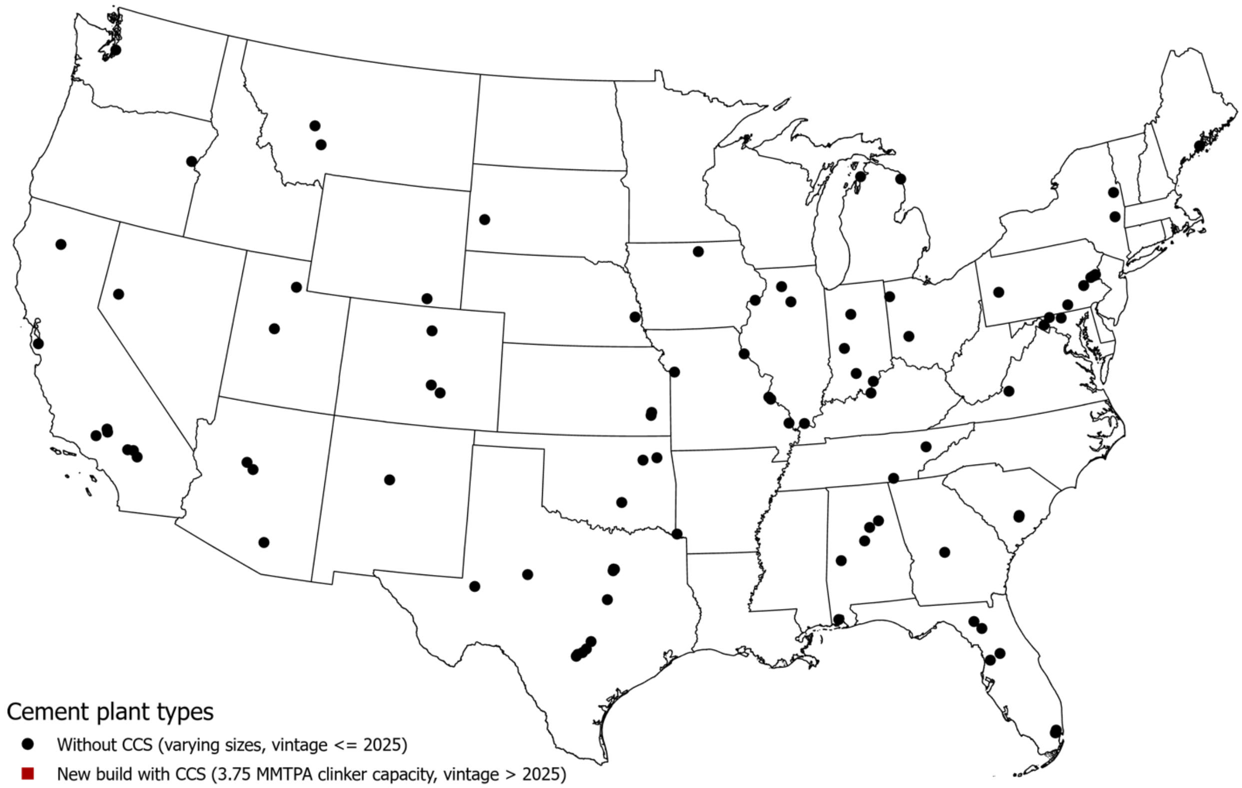

Figure 15 Cement facilities in 2020 with and without CCS

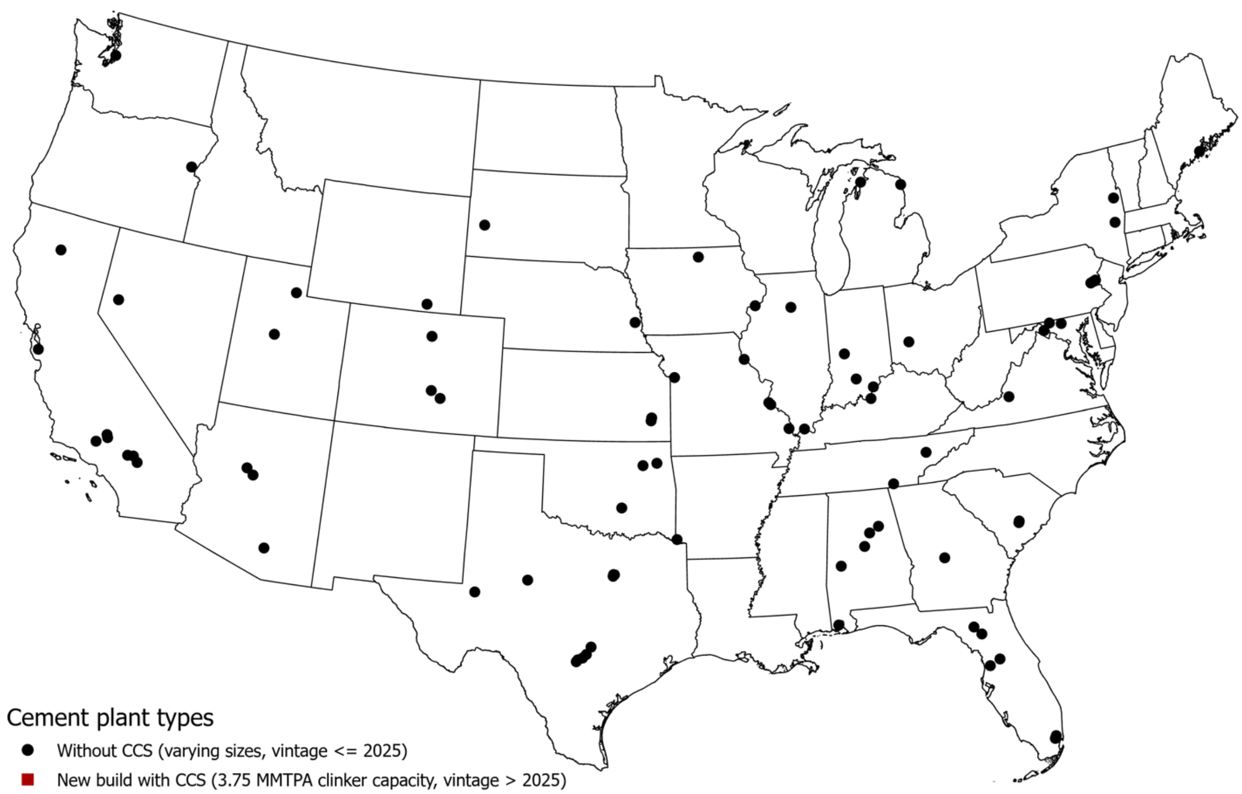

Figure 16 Cement facilities in 2025 with and without CCS

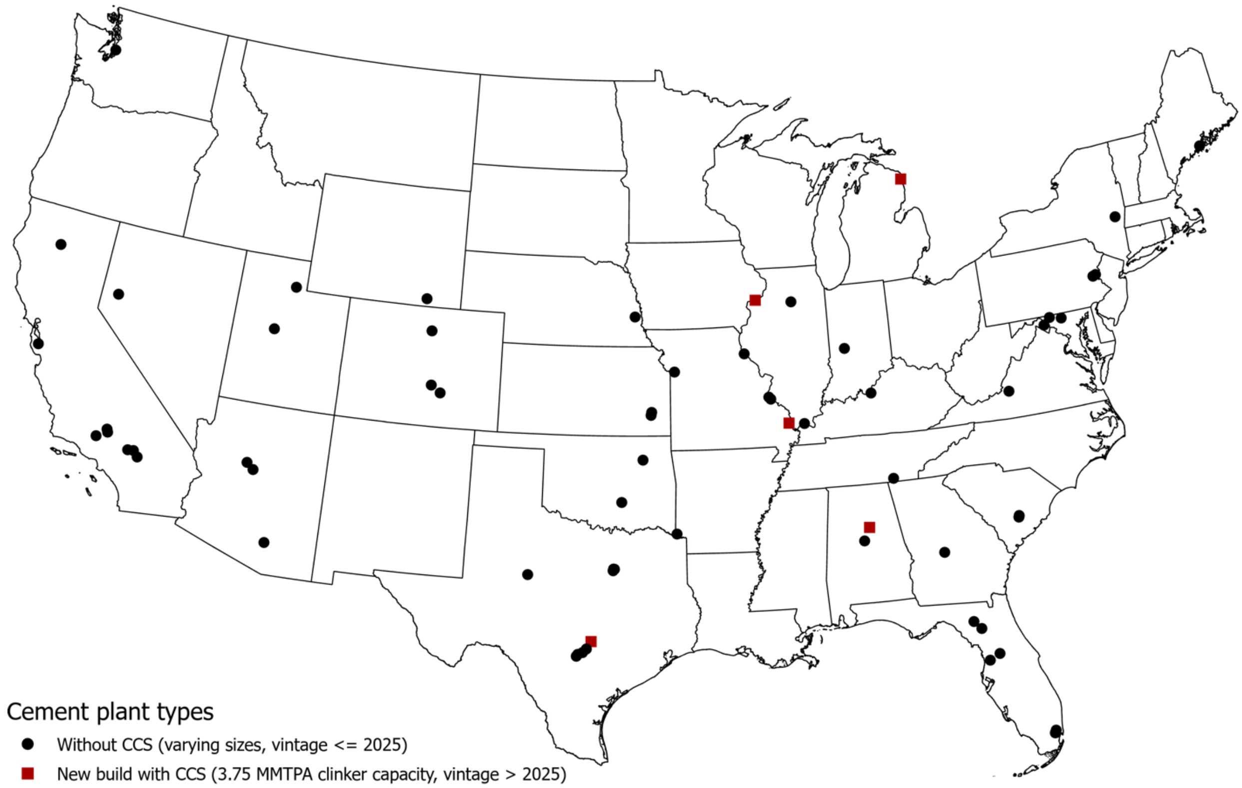

Figure 17 Cement facilities in 2030 with and without CCS

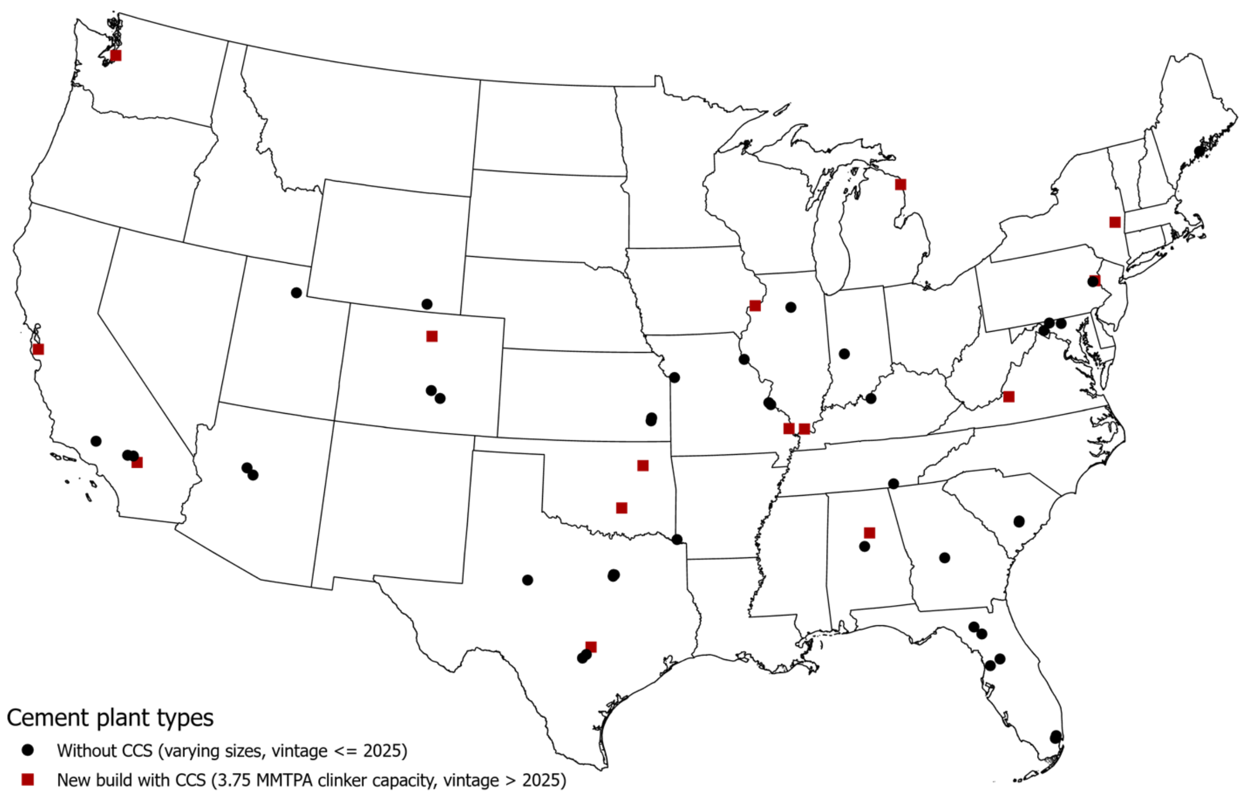

Figure 18 Cement facilities in 2035 with and without CCS

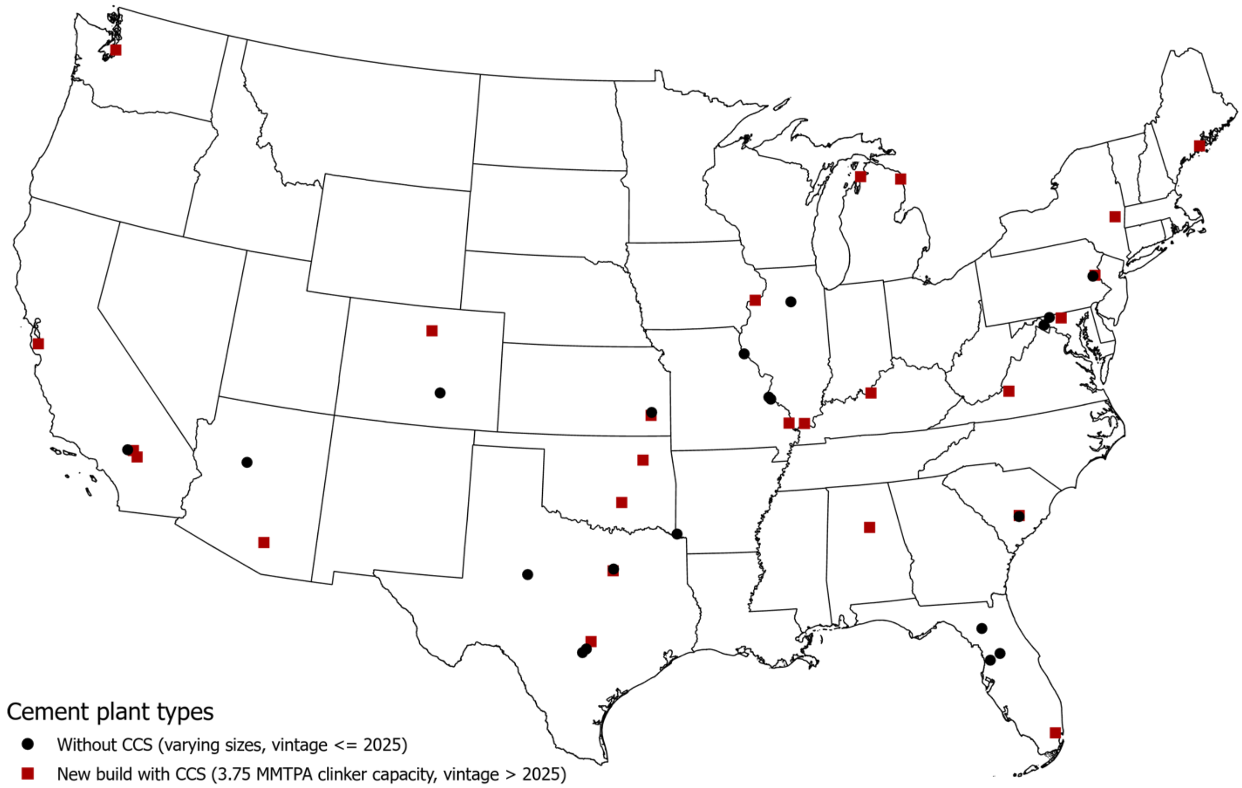

Figure 19 Cement facilities in 2040 with and without CCS

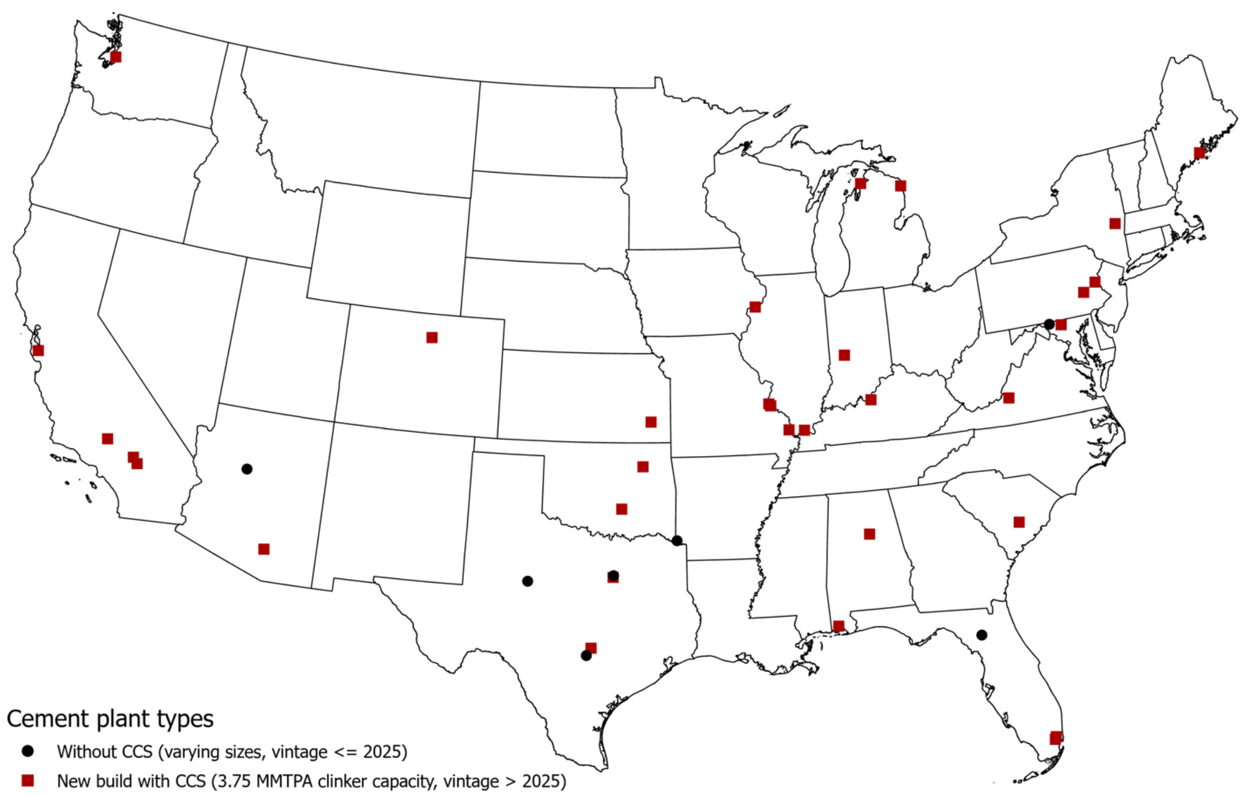

Figure 20 Cement facilities in 2045 with and without CCS

8 Appendix J2 – Lime manufacturing industry

The NZAP team had originally planned to model and downscale the lime manufacturing industry (NAICS 327410) to the same degree as the cement manufacturing industry. However, time and team availability constraints led to an extremely expedited treatment of the sector. The following simplified process was used to estimate the onsite CO_2 emission and capture totals reported in Table 13 for the sector from 2020 through 2050:

- Each fuel reported to be used by the lime manufacturing industry in the AEO2017 [26] is multiplied by a fuel specific CO_2 emissions coefficient provided by the EIA [45]. Emissions from boilers and HVAC specified by the AEO [26] are not included in total combustion emissions as these are handled elsewhere in the EER model.
- The resulting aggregate combustion CO_2 emissions total for the lime industry is then adjusted with a production-based process CO_2 emissions estimate in order to arrive at a total CO_2 emissions estimate.
    - A conversion ratio from dollars of shipments to physical production conversion is estimated using EPA [3] estimates for total lime production in 2017 and lime shipments in USD from the USGS [46] for the same year.
    - That conversion ratio is then held constant through 2050 and multiplied by AEO shipments totals in USD for all years between 2020 and 2050 in order to get a physical production estimate in MMt for each year of the analysis.
    - For all projection years through 2050, total physical lime shipments are split into EPA [3] tracked lime categories using each category's representative share in 2017 (16.7% for dolomite line and 83.3% for high calcium lime).
    - Lime process emissions are then estimated using the method provided in the EPA [3] under which:
        - annual physical shipments for dolomite lime are multiplied by a process emissions factor of 0.8675 tons CO_2/ton lime;
        - annual physical shipments for high calcium lime are multiplied by a process emissions factor of 0.7455 tons CO_2/ton lime;
        - the sum of the two lime CO_2 streams are multiplied by a factor of 1.2 in order to account for CO_2 emissions attributed lime kiln dust; and
        - total lime industry CO_2 emissions are discount by a factor to account for CO_2 captured and used in on-site processes.[22]
    - Lime process CO_2 emissions are added to lime industry CO_2 combustion emissions to arrive at an industry total in each analysis year.
- CO_2 capture rates in the lime industry were set to mirror national cement industry CO_2 capture rates between 2020 and 2050. This leads to the capture of 90% of lime industry emissions in 2050.
- As data for individual lime manufacturing facilities was not analysed and downscaled, it was further assumed that future state-of-the-art lime facilities are co-located on-site or in close proximity (within 35km) of new cement facilities with CCS in order to minimize

[22] Total sector CO_2 emissions were discounted by a factor of 0.03 figured from recovered CO2 emissions between 2013 and 2017 reported for the lime manufacturing industry in EPA [3].

transport of lime to a major end-use industry, and to take advantage of CCS pipe infrastructure built to service cement plants.

Table 13 Onsite lime manufacturing facility CO_2 emissions (in MMt CO_2) from both energy combustion and process sources from 2020 through 2050, along with total CO_2 captured via CCS

Year	Process related CO_2 emissions (MMt CO_2) [23]	Energy related CO_2 emissions (MMt CO_2)[24]	Total (MMt CO_2)	Captured via CCS (MMt CO_2)
2020	13.6	7.1	20.7	0.0
2021	14.0	7.4	21.5	0.0
2022	14.3	7.7	22.0	0.0
2023	14.7	7.9	22.6	0.0
2024	14.9	8.1	22.9	0.0
2025	15.0	8.2	23.2	0.0
2026	15.2	8.4	23.6	0.7
2027	15.4	8.5	23.8	1.5
2028	15.5	8.5	23.9	2.5
2029	15.6	8.5	24.0	3.7
2030	15.8	8.5	24.3	4.7
2031	16.0	8.6	24.6	6.1
2032	16.2	8.6	24.9	6.9
2033	16.6	8.8	25.4	8.4
2034	16.9	8.9	25.8	9.9
2035	17.2	9.1	26.3	11.5
2036	17.5	9.2	26.7	14.0
2037	18.0	9.4	27.4	16.8

[23] Using EPA [3] methods based on production.
[24] Using AEO [1] coefficients and excluding boilers or HVAC energy use as they are handled elsewhere in EER models.

2038	18.3	9.6	27.9	18.3
2039	18.7	9.8	28.5	19.5
2040	19.4	10.0	29.4	21.3
2041	19.9	10.3	30.2	22.3
2042	20.4	10.6	31.0	23.1
2043	21.0	10.9	31.9	23.9
2044	21.7	11.2	32.9	26.2
2045	22.3	11.5	33.9	29.3
2046	23.0	11.9	34.9	30.8
2047	23.7	12.2	35.8	31.8
2048	24.4	12.5	36.9	33.0
2049	25.2	12.8	38.0	34.0
2050	25.9	13.2	39.1	35.2

9 Note on combined cement and lime manufacturing emissions and capture entering the EER model

Note that although an annual CO_2 capture rate for cement and lime industries was supplied for entry into the EER model (capturing a maximum of 90% of combined cement and lime manufacturing industry emissions by 2050), it appears that the model used a 100% capture rate for cement and lime manufacturing industries in 2050. It is uncertain what annual capture percentages were used between in EER model years 2020 – 2049. This will lead to a minor discrepancy between EER and NZAP downscaled emissions in the areas of both annual and cumulative emissions captured by CCS. This will also lead to a small adjustment to EER's overall emissions trajectories from 2020 – 2050, potentially requiring an additional 0.1 Gt/year (E+) to 0.17 Gt/year (RE-) to be achieved by alternative emissions reductions options.