Decarbonizing Concrete

Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China

industrial sustainability analysis lab

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The views and opinions expressed in this report are purely those of the authors and do not necessarily reflect those of the external reviewers or ClimateWorks. Any remaining errors are the sole responsibility of the authors.

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List of abbreviations

BECCS	Bioenergy with carbon capture and storage
BIM	Building Information Modeling
BYF	Belite-ye’elimite-ferrite cement
C$AB	Calcium sulfoaluminate cement
CCS	Carbon capture and sequestration
CCSC	Carbonatable calcium silicate cement
CCU	Carbon capture and utilization
CH4	Methane
CSA	Calcium sulfoaluminate
GGBFS	ground granulated blast furnace slag
IEA	International Energy Agency
LCA	Life cycle assessment
MOMS	Magnesium oxides derived from magnesium silicates
OPC	Ordinary portland cement
RCA	Recycled concrete aggregate
RTS	Reference Technology Scenario
SCM	Supplementary cementitious material

Report overview

Cement and concrete are integral to our modern civilization. They are the most consumed construction materials, owing to their abundant resource availability, good workability, long-lasting durability, and versatility. In 2019, their production, transport, use, and demolition was estimated to account for roughly 9-10% of global energy-related CO_2 emissions, including carbonate decomposition, fuel combustion, and electricity use. At the same time, their emissions-intensive manufacturing processes have been slow to change, making the cement and concrete sector one of the world's most difficult-to-abate sources of CO_2 emissions.

To achieve the "well below 2 degrees" vision of the Paris Agreement, it is imperative that the industrial sector reaches net-zero emissions by mid-century. For the cement and concrete cycle, reaching this goal will require a broader portfolio of low-carbon levers, extending from conventional production-side measures (e.g., cement plant technology options and clinker substitution) to emerging production-side measures (e.g., lower-carbon cement chemistries, carbon capture and sequestration, and carbon utilization) to emerging demand-side measures (e.g., material efficiency strategies and end-of-life options).

In this report, we assess the combined effect of all available low-carbon levers using a new integrated modeling framework—the IMAGINE Concrete model—which is capable of analyzing the underlying technology characteristics of each lever and the nexus between materials flows, energy use, CO_2 emissions, and CO_2 uptake across the entire cement and concrete cycle. While our new model is potentially applicable to other countries or regions, we limit our scope to the three largest cement-producing and cement-consuming countries: the United States, China, and India. We design systems scenarios to explore possible decarbonization pathways using combinations of these levers. More specifically, we assess mass and energy flows, CO_2 emissions, and CO_2 uptake spanning the whole cement and concrete cycle to identify new CO_2 mitigation opportunities.

Highlights

- The cement and concrete sector is one of the world's most difficult-to-abate sources of CO_2 emissions.
- Current stakeholder ambitions in the cement and concrete cycle will likely fall far short of achieving net-zero emissions by mid-century.
- We design a Production-Centric pathway, which will mainly rely on the mitigation efforts of cement and concrete producers.
- We design a Whole-Systems pathway, which will engage more stakeholders, empowering a broader range of actors in decarbonization initiatives with a focus on more efficient use of cement and concrete in the built environment.
- These two diverging pathways, the Production-Centric and Whole-Systems Scenarios, can cut CO_2 emissions to zero by 2060.
- Irrespective of the pathway, immediate actions are required to accelerate the pace of innovative technology and policy adoption and to unlock the emissions reduction opportunities for different stakeholder groups across the cement and concrete cycle (see the next page).

Net-zero emissions for the cement and concrete cycle are achievable with concerted efforts by key stakeholders

Life cycle stage	Lever	Production-Centric scenario	Whole-Systems scenario	Key stakeholders		
Cement manufacturing	L1a-Kiln thermal efficiency			Cement producers	Government	
	L1b-Electrical efficiency			Cement producers	Government	
	L1c-Low-carbon fuel			Waste managers	Government	
	L2-Lower-carbon cement chemistries			Cement producers	Government	
	L3-Clinker-to-cement ratio reductions			Cement producers	Government	
	L4-At-plant CCS			Cement producers	Government	
Aggregate production	L5b-f-CO_2 mineralization			Aggregate producers	Waste managers	Government
Concrete manufacturing	L5a-CO_2 curing			Concrete producers		
Construction	L6a-Material-efficient design			Designers	Construction engineers	Government
	L6b-Material substitution			Designers	Construction engineers	Government
	L6c-Fabrication yield improvement			Construction managers	Government	
Use	L6d-More intensive use			Designers	Urban planners	Government
	L6e-Lifetime extension			Property owners	Road managers	Government
End-of-life	L7a-Downcycling			Demolishers	Concrete producers	Government
	L7b-Component reuse			Demolishers	Designers	Government
	L7c-Demolition waste stockpiling			Waste managers	Government	

CO_2 savings (Gt) 1 Gt

Note: numbers represent the combined CO_2 savings of all three considered countries; a more detailed description of levers can be found in Chapter 3.

1. Introduction

1.1. Cement and concrete: the basics

Concrete is integral to modern societies. Concrete is the most consumed construction material because of its abundant resource availability, good workability, long-lasting durability, and versatility. Concrete has been widely used for structures that deliver essential physical services (e.g., shelter, workplace, and transport infrastructure) to fulfill basic human needs[1,2]. In 2017, the world consumed 4.1 Gt of cement, of which ~69.6% was used for concrete. Given that 1 tonne of concrete requires ~0.13 tonnes of cement on average, global concrete production in 2017 amounted to 17.7 Gt, enough to pave an 8-lane highway that could circle the Earth at the equator roughly 27 times[i].

So what exactly is concrete? It starts with cement, which is the binding material that holds concrete together. Typically, cement is made by heating a mixture of calcareous materials (e.g., limestone) and siliceous materials (e.g., clay) to about 1450 °C to form a substance known as clinker (equivalent to OPC clinker unless specified otherwise). This clinker is then finely ground and mixed with gypsum and other additives to make cement (equivalent to OPC unless specified otherwise). Given its high-temperature requirements, making clinker is one of the most energy-intensive industrial processes. Producing a tonne of clinker can require 3.3-5.7 GJ of energy, which is enough to drive a Toyota Corolla for about 1900-3300 kilometers (1200-2100 miles)[ii]. Currently, the clinker making process is largely fueled by fossil fuels, whose combustion leads to CO_2 emissions. However, the process chemistry also emits copious amounts of CO_2 due to chemical reactions—which is known as carbonate decomposition. On global average, the typical tonne of clinker produced in 2017 comes with 837.8 kg of CO_2 emissions (excluding electricity use), 64.2% of which is due to unavoidable carbonate decomposition-related CO_2 emissions[3]. When placed in concrete in the built environment, cement gradually absorbs CO_2 from the atmosphere over time, a process known as cement carbonation[4,5]. While its contribution to climate change mitigation is uncertain, the carbonation process has been recently recognized as a significant CO_2 sink[6,7].

As shown in Figure 1-1, apart from its most energy-intensive ingredient—cement, concrete has two other essential ingredients—aggregates (both coarse and fine) and water. Coarse aggregates are typically 9.5-37.5 mm in diameter and sourced from local gravel quarries, generally granite, limestone, or dolomite. Fine aggregates are essentially sand, generally sourced from riverbeds or other inland sources. Additionally, various admixtures (i.e., minerals or chemical additives other than cement, aggregates, and water) can be added to the mix to control setting and improve in-place performance characteristics, such as workability, corrosion resistance, and thermal cracking resistance. As a result of hydration (i.e., chemical reactions between the cement minerals and water), cement develops its binding property. Cement hydrates coat the surface of aggregates and harden over time, thereby gaining strength to form the rock-like mass known as concrete. Concrete is typically manufactured in batch processes and at dedicated “ready-mix” plants, wherein the cement, aggregates, water, and additives are mixed together, then transported to construction sites in trucks where the concrete is poured and hardened/cured. Precast concrete product plants will conduct batching, forming, and curing on-site.

Figure 1-1. Basic ingredients of typical concrete by mass.

Note: coarse aggregates[iii], fine aggregates[iv], water[v], cement[vi], and air[vii] from left to right.

1.2. Historical production and future demand

Because of its widespread use for infrastructure, global quantities of cement and concrete have been growing rapidly, mainly to fuel rapid growth in emerging economies. In Figure 1-2, due to data limitations, we use cement production as a proxy for concrete production to present key trends at regional levels. The growth pattern of cement production varies by region. While cement production in industrialized regions shows a fluctuating but overall descending trend over the past decade, accelerating cement production is particularly evident in emerging regions, where it is driven by rapid economic development and population growth. Another important trend is that, from the 1990s onward, emerging regions have dominated global production. In 2017, China and India's cement production accounted for over 60% (2.6 Gt) of global cement production. In contrast, while Europe and North America together accounted for 40.4% (356.6 Mt) of global cement production in 1980, by 2017 these two regions accounted for only about 6.9% (282.6 Mt).

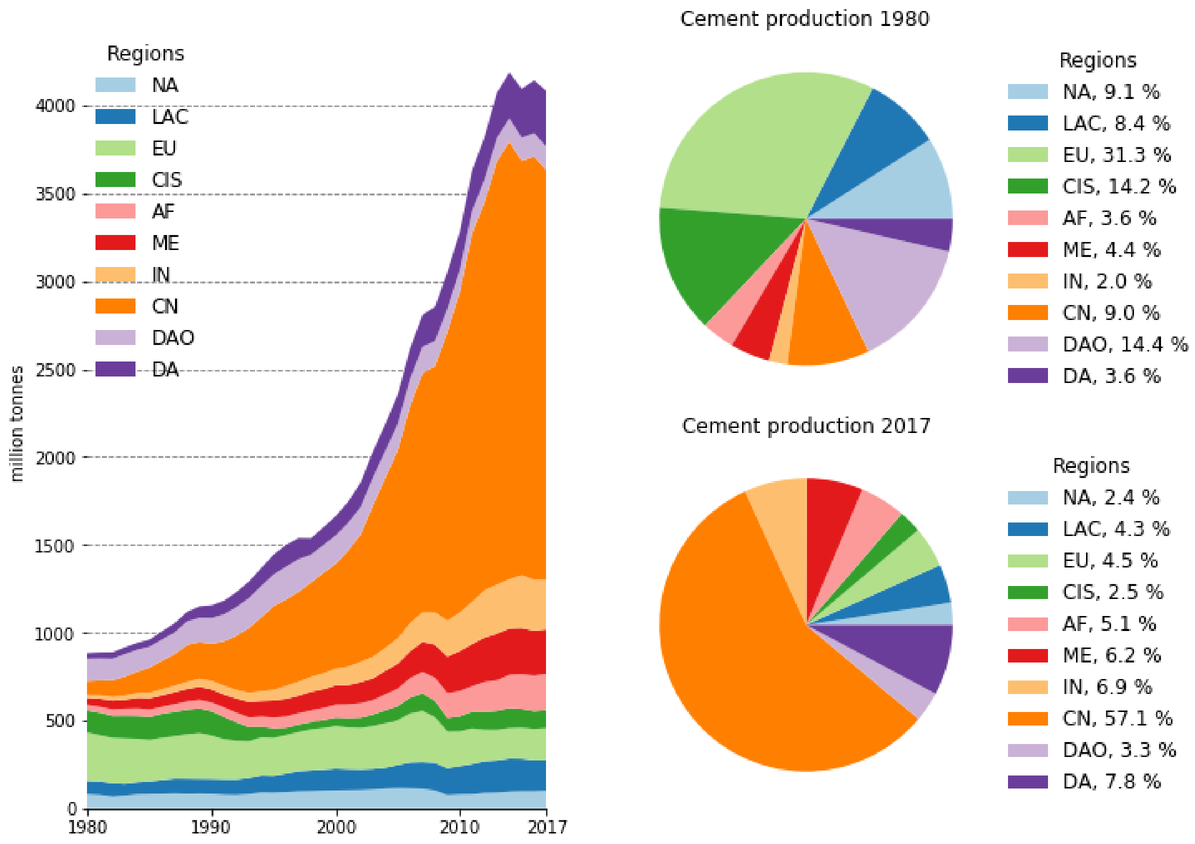

Figure 1-2. Cement production by region from 1980 to 2017.

Note: the underlying data are collected from USGS Mineral Yearbooks[8]; NA=North America, LAC=Latin America & Caribbean, EU=Europe, CIS=Commonwealth of Independent States, AF=Africa, ME=Middle East, IN=India, CN=China, DAO=Developed Asia & Oceania, and DA=Developing Asia[2].

Massive production and use of cement and concrete, driven by soaring needs for housing and infrastructure development, has positioned the global cement and concrete sector as a major source of CO_2 emissions[9,10]. In 2019, cement and concrete manufacturing was attributable to 9-10% of global energy-related CO_2 emissions[1,11,12]. Cement manufacturing contributes ~77% of the total CO_2 emissions arising from the whole life cycle of cement and concrete (Figure 1-3). According to estimates for 2017[3,8], the CO_2 emissions of global cement manufacturing have amounted to 3.1 Gt, comprised of three primary sources: carbonate decomposition (~55%), fuel combustion (~31%), and electricity use (~14%).

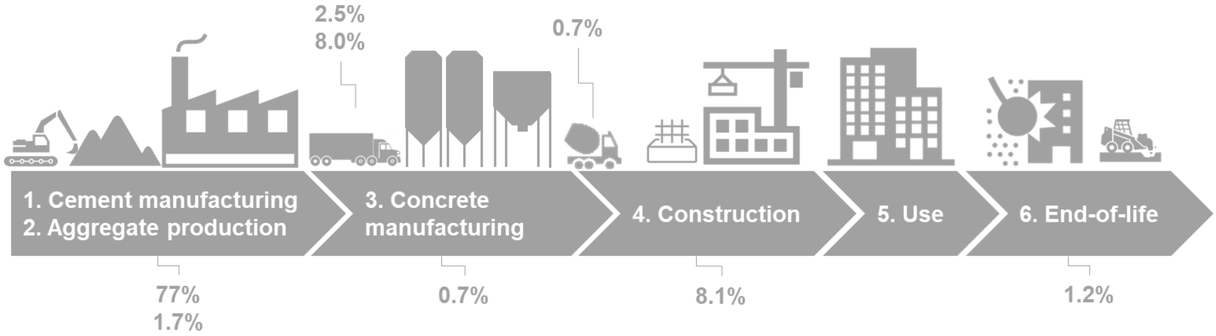

Figure 1-3. Life cycle of cement and concrete.

As shown in Figure 1-4, it is expected that the world's insatiable appetite for cement will continue through mid-century, with further shifts from developed to emerging or developing economies, particularly those in Africa. China is set to lose its dominance of global cement demand over the next decades but will be on the rebound after 2030 if the lifetime of cement-based products keeps constant. Therefore, without significant change, cement and concrete manufacturing will continue to be a major source of CO_2 emissions, imperiling global climate ambitions.

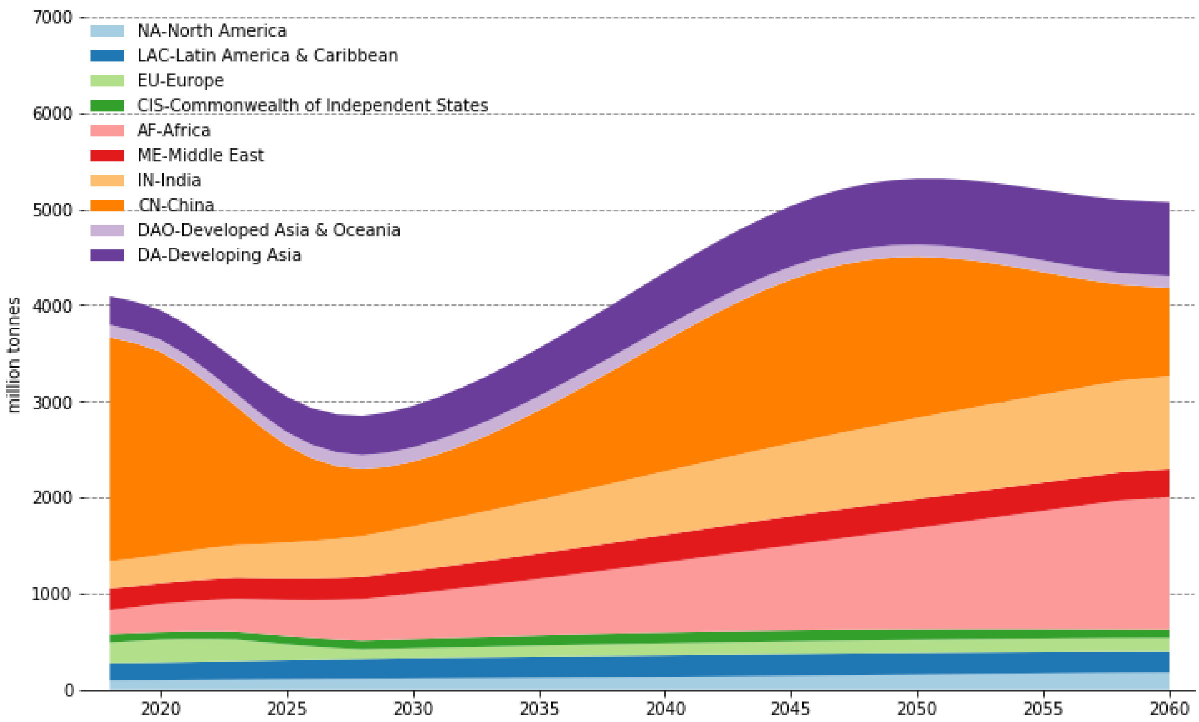

Figure 1-4. Projections of cement demand by region.

Note: the underlying data are derived from the medium scenario in a prior study[7]. The projections of cement demand depend on two drivers: cement-based product lifetimes and in-use cement stocks. In the aforementioned study, the lifetimes of cement-based products are assumed to keep constant over the next decades, and saturation and aging of in-use cement stocks will therefore lead to cyclical trends in cement demand, most prominently in China. Similar cyclical trends have been observed in Europe's and CIS's cement production data[2]. In our analysis, we assume that existing cement plants in China will operate at low capacity or be idled during downturns.

1.3. Overview of decarbonization levers

The world's current climate ambitions were codified in the 2015 Paris Agreement, which called for international efforts to limit the increase in the global average temperature to well below 2 °C above pre-industrial levels, and pursuing further efforts to limit the increase to 1.5 °C above pre-industrial levels (hereafter referred to as 1.5 °C limit). The 1.5 °C limit entails a transition toward industrial and energy systems with net-zero CO_2 emissions by mid-century[13]. In this report, we construct scenarios for how the cement and concrete industries can contribute to the goals of the Paris Agreement by achieving net-zero CO_2 emissions by mid-century. While this avoids the contentious process of assigning emissions budgets to specific sectors, it also represents a very ambitious pathway that will be difficult to achieve without concerted efforts by all cement and concrete cycle stakeholders. To do so, as depicted in Figure 1-5, we examine alternative pathways by considering levers across the entire life cycle, inclusive of plant technology options, clinker substitution, lower-carbon cement chemistries, carbon capture and sequestration (CCS), carbon utilization, material efficiency strategies, and end-of-life options. Extending the scope of decarbonization efforts from the production phases to the whole life cycle of cement and concrete will open up new opportunities for achieving net-zero CO_2 emissions by mid-century.

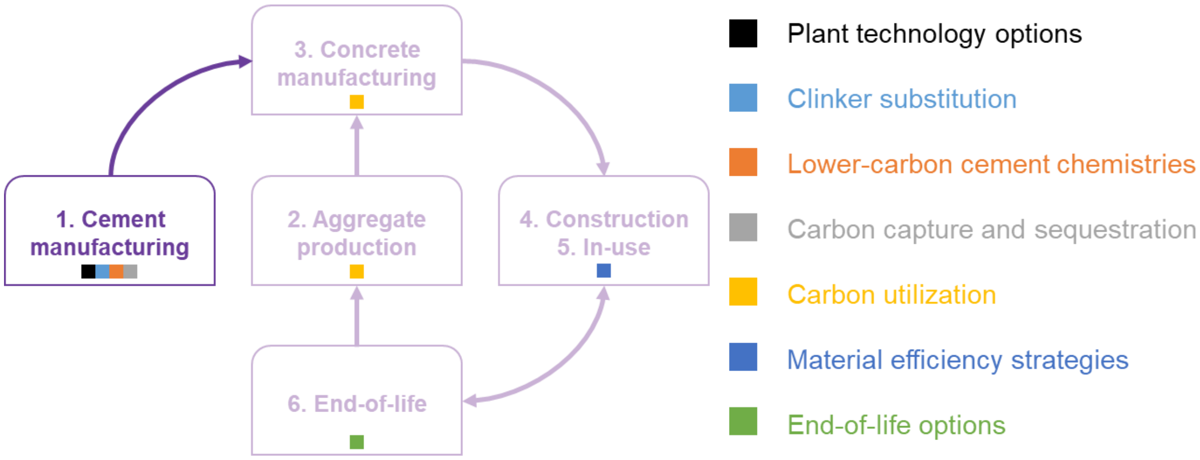

Figure 1-5. Low-carbon levers across the life cycle of cement and concrete.

Note: Chapter 3 gives a more comprehensive description of these low-carbon levers.

While some of these levers have been well modeled or studied, others have not. For example, previous studies have been mainly focused on energy savings and CO_2 mitigation strategies within the cement manufacturing process itself[9,10,14,15], inclusive of thermal energy efficiency, grinding electrical efficiency, low-carbon fuel utilization, clinker substitution, and at-plant carbon capture and sequestration. However, progress in the first four of these strategies has stagnated over the past decades (Figure 1-6). At-plant carbon capture for the cement industry—the only of these strategies to address CO_2 emissions arising from carbonate decomposition—is still in a nascent stage. It is clear that these strategies alone may not be enough, highlighting the need for broadening the portfolio of low-carbon levers.

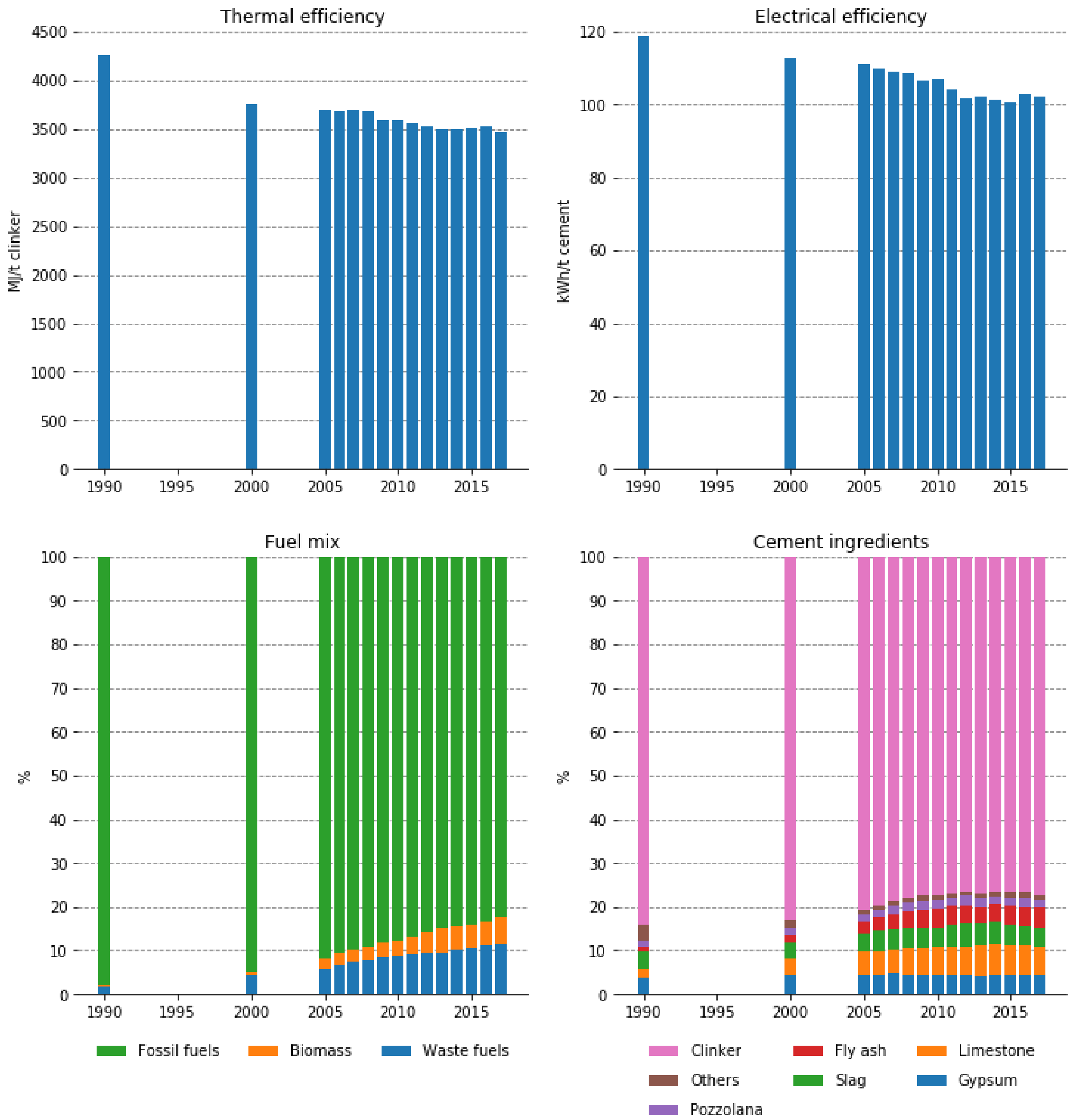

Figure 1-6. World averages of reported data for thermal efficiency, electrical efficiency, low-carbon fuel utilization, and clinker-to-cement ratio reductions.

Note: the underlying data are derived from GNR 2018[3]. The GNR database includes 865 cement plants, covering 21% of the global capacity of cement production. The GNR database covers 80%, 5%, and 100% of cement production capacity in the United States, China, and India, respectively.

In light of the pressing need to meet the 1.5 °C limit, CO_2 mitigation strategies that are beyond the cement manufacturing stage should be further explored. A recent cement technology roadmap released by IEA has recognized the need to consider CO_2 mitigation strategies in the broader context of the whole life cycle of cement and concrete, though no quantitative analysis was conducted[10]. Another report led by IEA has looked into the role of material efficiency in reducing industrial CO_2 emissions[16], and analyses alike have highlighted the importance of material efficiency[17–20]. Aside from material efficiency strategies, two groups of disruptive CO_2 mitigation strategies (i.e., lower-carbon cement chemistries and CO_2 utilization) have gained attention. The former refers to alternative cement binding materials that rely on different raw material mixes compared to ordinary portland cement clinker[21]; the latter refers to producing valuable products using CO_2, thereby reducing raw material consumption in the concrete sector[22]. While research on CO_2 mitigation strategies beyond the cement manufacturing stage has gained momentum, these new strategies have previously been examined mostly in isolation. Therefore, it remains unclear to what extent they can contribute to deep decarbonization of the cement and concrete cycle. Finally, since all measures are interrelated (or non-additive), they need to be considered synergistically. Hence, a systems analysis that explores the opportunities carried in these new strategies can fill these pressing knowledge gaps. Understanding the combined contribution of these new strategies is the most significant contribution of this report.

1.4. Scope and objectives

In this report, the geographical scope of our analysis is limited to the three largest cement-producing and cement-consuming countries: **the United States, China, and India**. In 2017, cement production in the United States increased to 86.8 Mt. The increasing trend of cement production in the United States is largely related to its aging infrastructure and buildings, and this trend is expected to continue in the coming decades. Driven by rapid economic growth, China's cement production quadrupled from 2001 to 2014; in 2017, China's cement production reached 2.4 Gt, accounting for about half of the global total. India's cement production followed the same trend as China, but its growth rate was slower compared to China. In 2017, India's cement production reached 0.3 Gt, and it is expected to grow in the next decades. Selecting three countries with diverse trends of cement production helps ensure that conclusions arrived from analyzing these three countries are generalizable to other countries or regions. The three chosen countries represent three states of cement-consuming economies: mature, transitioning, and emerging.

In this report, we assemble the aforementioned suite of well-studied and new low-carbon levers across the whole life cycle of cement and concrete to assess the combined effect of all low-carbon levers based on the underlying technology characteristics of each lever. To shed light on how to achieve the ambitious target implied by the 1.5 °C limit, we develop an integrated modeling framework and design scenarios to explore two possible decarbonization pathways using combinations of these levers, namely, a **Production-Centric** scenario and a **Whole-Systems** scenario. We align the timeframe of our scenario analysis to the IEA ETP 2017 scenarios[11], covering the period from 2018 to 2060. More specifically, technological characteristics of each low-carbon lever are modeled with analytical rigor and transparency, and designed scenarios are aligned with plausible future socio-economic development pathways.

The utility of our decarbonization scenarios is demonstrated through deep dives into several key end-use segments of cement and concrete, which can be grouped into two broad categories: **buildings and roads**. These two broad categories contribute to a large portion (~50%) of today's total cement and concrete demand. Our analysis involves estimating cement and concrete demand using data on construction activity levels and cement and concrete intensities, which is referred to as a bottom-up approach. Our analysis cannot cover all end-use segments of cement and concrete due to data incompleteness. However, using a bottom-up approach allows us to consider material efficiency strategies and end-of-life options at high granularity through linking cement and concrete demand to meaningful drivers (e.g., newly-constructed floor area and newly-paved road length).

The remainder of this report is structured as follows. Chapter 2 outlines the main stages of the cement and concrete cycle and examines future cement and concrete demand. Chapter 3 identifies the main technology and policy options for decarbonization and provides an overview of how these decarbonization levers might contribute to cement and concrete cycle CO_2 emissions mitigation. Chapter 4 explores three decarbonization scenarios (i.e., Current Ambitions, Production-Centric, and Whole-Systems) for the cement and concrete cycle and analyzes the contribution of each decarbonization lever within each scenario. Chapter 5 concludes with key findings from our analysis and outlines recommended near-term actions for cement and concrete cycle stakeholders.

2. Understanding the cement and concrete cycle

While Chapter 1 provides an overview of the main stages of the cement and concrete cycle, the first half of this chapter delivers more details on the technological characteristics of each stage, as well as the associated material and energy flows contributing to CO_2 emissions at each stage. The second half of this chapter elucidates trends in cement and concrete demand in the past and introduces an outlook for future demand.

2.1. Stages of the cement and concrete cycle

As shown in Figure 2-1, the cement and concrete cycle encompasses multiple stages: cement production, transport of cement, aggregate production, transport of aggregate, concrete manufacturing, transport of concrete, construction, in-use, and disposal of end-of-life concrete.

Cement production

The cycle starts with cement production, which is a complex process. As shown in Figure 2-2, it consists of multiple processing steps: raw materials quarrying, raw materials crushing, raw meal preparation, pre-heating, pre-calcining, clinkering, cooling, blending, grinding, and storing and packaging. For simplicity, these processing steps are grouped into three stages: raw materials preparation, clinker production, and cement grinding. Quarried raw materials (e.g., limestone and clay) are typically ground up into a fine powder (i.e., raw meal) with an electricity-driven mill. The compositions of the raw meal are constantly monitored and controlled to ensure consistent and high-quality clinker. The main technology used for producing clinker is a kiln, whose purpose is to heat up the raw materials to drive the necessary chemical reactions. Kilns are generally run on fossil fuels due to their high energy density, but can also accommodate other types of fuel, such as biomass. The most efficient kilns recycle heat from the preheating, precalcining, and cooling stages. During clinker production, CO_2 emissions arise when calcium carbonate (e.g., limestone, marble) thermally decomposes into calcium oxide and carbon dioxide, and the resulting calcium oxide reacts with silicate, aluminate, and ferrite to form clinker when the temperature rises up to 1450 °C. These reactions are very energy-intensive. Hence, a key goal of lower-carbon cement chemistries (see Section 3.2) is to use alternative chemical reactions that reduce or eliminate carbonate decomposition-related CO_2, while also requiring lower reaction energies to reduce kiln fuel inputs. After cooling, the clinker is mixed with gypsum and other materials to control the setting time of cement. The mixture of clinker, gypsum, and additives is ground into a grey power, which is known as ordinary portland cement (OPC).

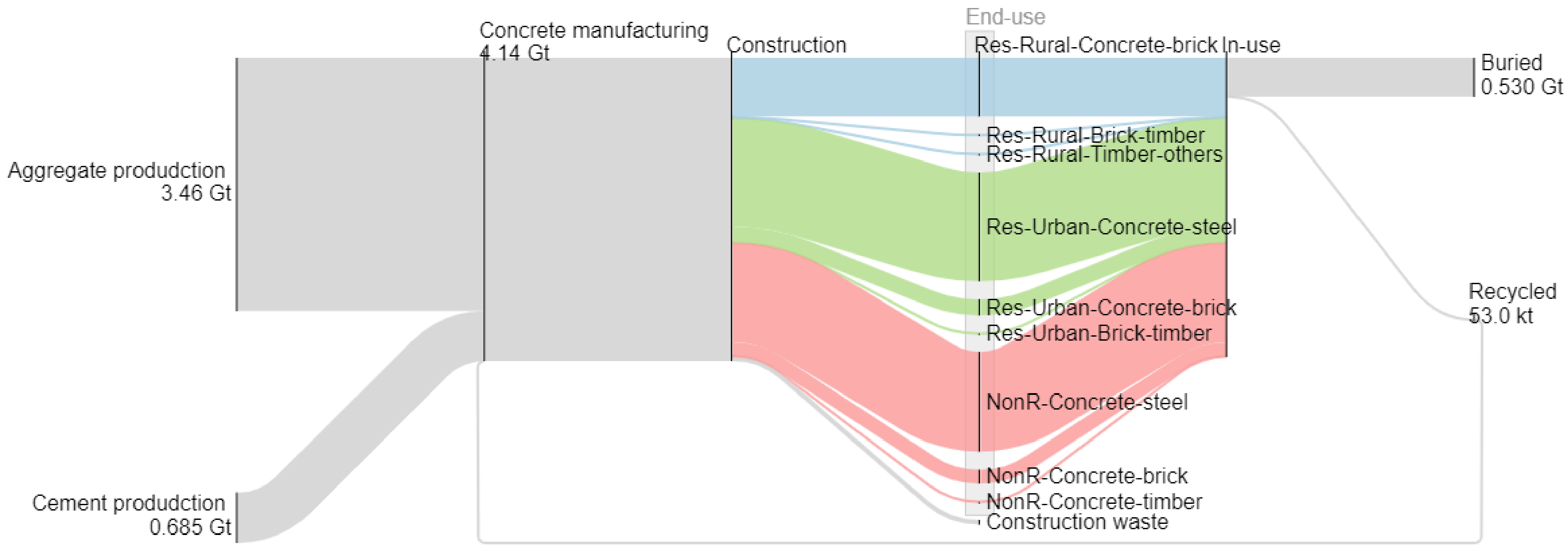

Figure 2-1. Mass flows along the cement and concrete cycle associated with China's building sector in 2017.

Note: mass flows of other countries and roads are presented in the Appendix. End-use sectors of cement and concrete are differentiated with color.

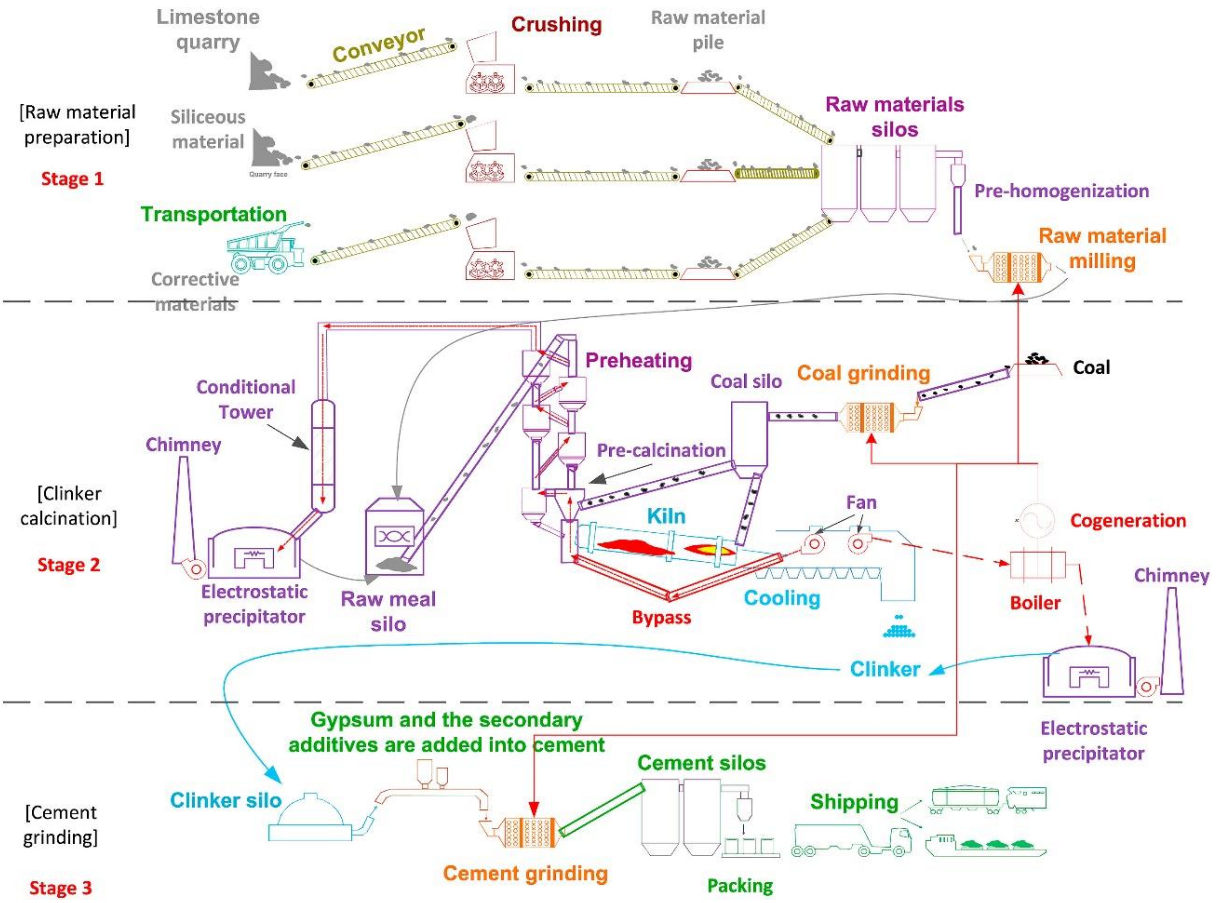

Figure 2-2. Cement manufacturing process[viii].

Note: this diagram represents a cement plant with a dry process kiln[23].

Aggregate and concrete production

Aggregates mixed in concrete are particulate materials of varying sizes. Fine aggregates are mainly sand and small-diameter smooth gravel, while coarse aggregates are crushed stones. Sand and gravel are excavated from open-pits, produced from crushing stones, or dredged from riverbeds, lakes, or seabeds; crushed stones are extracted by drilling and blasting from inland quarries. Aggregate excavation, processing, and transport use different energy forms. Inland quarries and transport typically use diesel-fueled equipment and trucks; dredging ships and inland water transport may use fuel oils; sea transport may use bunker fuel. Extracted aggregates are subjected to a series of processes that use electricity, predominantly screening and mechanical crushing. Aggregates are separated by size gradation, which is necessary to meet size requirements for concrete. Processed aggregates may be dewatered by forced heaters using small quantities of natural gas before being transported to concrete plants.

Concrete production involves two primary processes: batching and mixing. Batching refers to the process of measuring, preparing, and combining aggregates, cement, and additives in a dry fashion, which is primarily driven by electricity-propelled conveyors. Dry mixtures are transferred to elevated bins or silos by bucket elevators or conveyors. Batching occurs at “ready-mix” plants for concrete that will be shipped to job sites for pouring but would also occur at precast plants. Other energy uses at ready-mix and precast plants for batching include water and space heating, typically by natural gas. Mixing is the process of adding water and agitating for uniform distribution. For most concrete, this occurs in diesel-fueled ready-mix trucks on the way to the job site. For precast plants, this occurs on-site in mixers and uses electricity.

Construction, demolition, and transport

Once the mixed concrete is delivered to the construction site, it is placed into forms, which define its final position and shape. Concrete placing can be done by pouring, pumping, or even spraying. After placing the mixed concrete, it may also require consolidating or compacting. The most common methods of consolidation are vibration and roller compaction. The equipment used for concrete on the construction site is usually fueled by diesel or gasoline.

Over the use phase of concrete, atmospheric CO_2 dissolves in the pore water of concrete and forms carbonic acid. The carbonic acid reacts with hydrated calcium silicates and forms calcium carbonate, the process of which is called carbonation. This process starts at the concrete surface, then slowly penetrates deeper over time. Although it requires a great length of time, cement carbonation will eventually soak up a substantial amount of CO_2. Cement carbonation is well known as a deterioration mechanism of cement-based materials, but its contribution as an anthropogenic CO_2 sink is not equally recognized as compared to its contribution to CO_2 emissions.

When concrete structures come to their end-of-life, demolished concrete is broken into larger pieces for hauling, using industrial crushing equipment with jaws and large impactors. After the concrete is broken up, a certain portion of the larger concrete pieces is screened and crushed into smaller pieces by a secondary impactor. Crushed pieces are then used as recycled concrete aggregate. While the recycling rate varies a lot by country, recycling end-of-life concrete has been increasingly promoted across the world. The rest of the larger concrete pieces are trucked away and buried (e.g., landfilled or used as road base). Therefore, fossil fuels (e.g., diesel and gasoline) are used for material hauling, screening, and mechanical crushing.

Between life cycle stages, the transport of materials (e.g., cement, aggregate, concrete, and end-of-life demolition wastes) is usually done by land carriers, such as diesel-fueled trucks and diesel or electric locomotives. However, it can also occur sporadically via inland waterways or overseas vessels, which are driven by diesel or fuel oil.

Life cycle CO_2 emissions

Figure 2-3 depicts the overall CO_2 emissions associated with the cement and concrete cycle, using China's building sector as an illustrative example. In Figure 2-3a, it can be seen that cement production accounts for about ¾ of total emissions, which underscores the importance of decarbonizing cement production and reducing cement demand through material efficiency strategies. This contribution is followed by transport of aggregates and equipment operation associated with concrete placing at construction sites, which stand out as the next two largest contributors to CO_2 emissions along the cement and concrete cycle. As shown in Figure 2-3b, carbonate decomposition and fuel combustion together contribute about 90% to the total CO_2 emissions resulting from cement production, with the rest arising from cement plant electricity use.

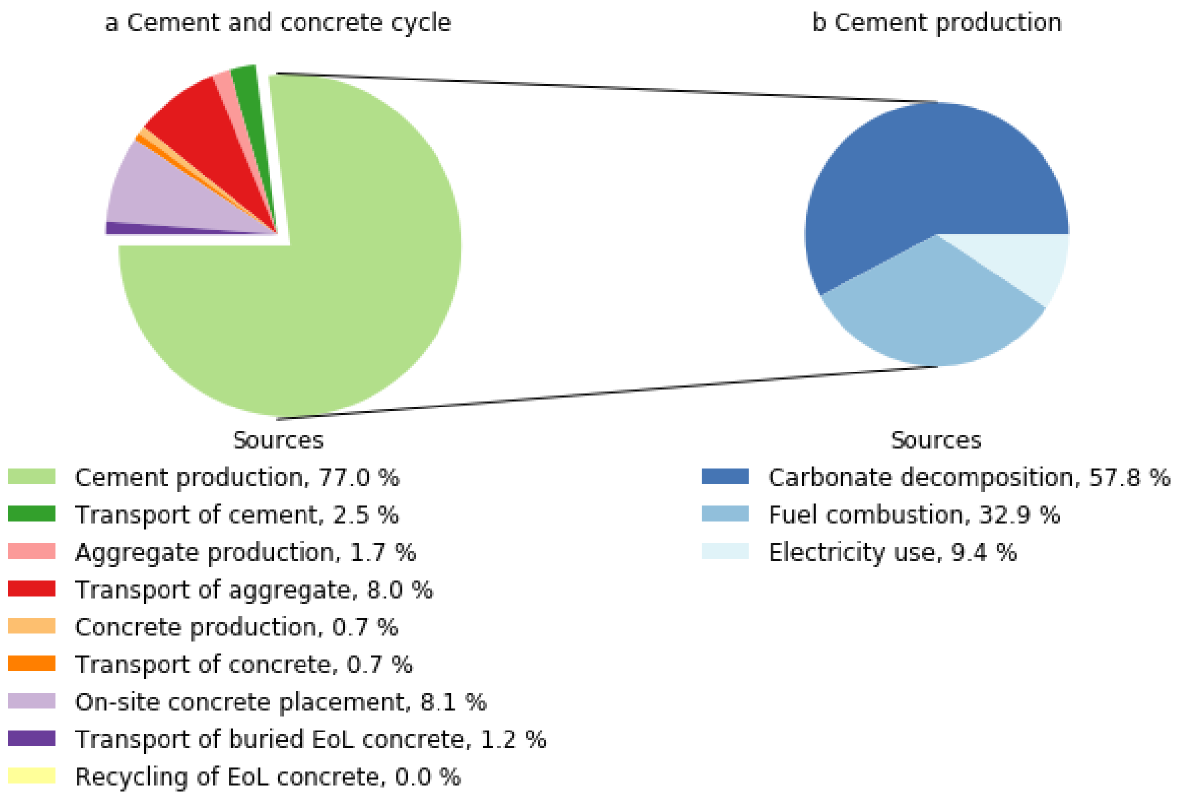

Figure 2-3. Breakdown of the 2017 CO_2 emissions along the cement and concrete cycle associated with China's building sector.

Note: values are derived from the authors' calculations.

2.2. Construction activity trends

The CO_2 emissions arising from the cement and concrete cycle in the future will hinge, in part, on the amounts of cement and concrete demanded by societies moving forward. These amounts are driven by myriad needs, which are often highly country-specific. In developing economies, cement and concrete demand is expected to grow due to an expanding population and the infrastructure needs (e.g., housing, mobility, and other built environment services) necessary for decent living standards and economic growth. In developed economies, cement and concrete demand is slowing or saturated, with future needs largely driven by infrastructure replacement rather than expansion. Indeed, these regional disparities can be seen in the cement demand projections in Chapter 1.

To explore possible ways of reducing future CO_2 emissions, it is therefore necessary to understand trends and drivers of cement and concrete demand in buildings and roadways. We develop and apply a comprehensive stock-flow model for quantifying annual cement and concrete demand as a function of two drivers: newly-constructed floor area (which includes both building replacements and building stock expansion) and newly-paved road length (which includes both existing roadway maintenance and roadway length expansions). Scenarios for these drivers are used to estimate annual concrete demand quantities, which are then related to cement demand quantities through assumptions regarding cement proportions in concrete mixes. Further details on the stock-flow model are provided in the Appendix.

Rising population and development of building stocks and road stocks have driven the growth of newly-constructed floor area and newly-paved road length across all three countries. Urbanization patterns and building framing transitions also have significant influences on cement and concrete demand from buildings. For instance, urban buildings in China tend to have higher cement intensities than rural buildings. Concrete-steel framed buildings tend to require more cement and concrete than brick-timber framed buildings. Analogously, paving standards (paved or unpaved) and paving materials (concrete or asphalt) affect cement and concrete demand from roads. To take into account these factors, we disaggregate the building stocks and road stocks into segments according to each country's practices and international standards (see the definition of segmentation for buildings and roads in the Appendix).

Figure 2-4 shows that the new building floor area in China almost quadrupled from 1990 to 2014, but gradually dropped and leveled off afterward. Historical trends of new road length are slightly different. The new road length (including newly-constructed and reconstructed) in China experienced a sudden boost around 2005 due to China's massive expansion targeted at rural roads (i.e., Classes III-V highways) in the time.

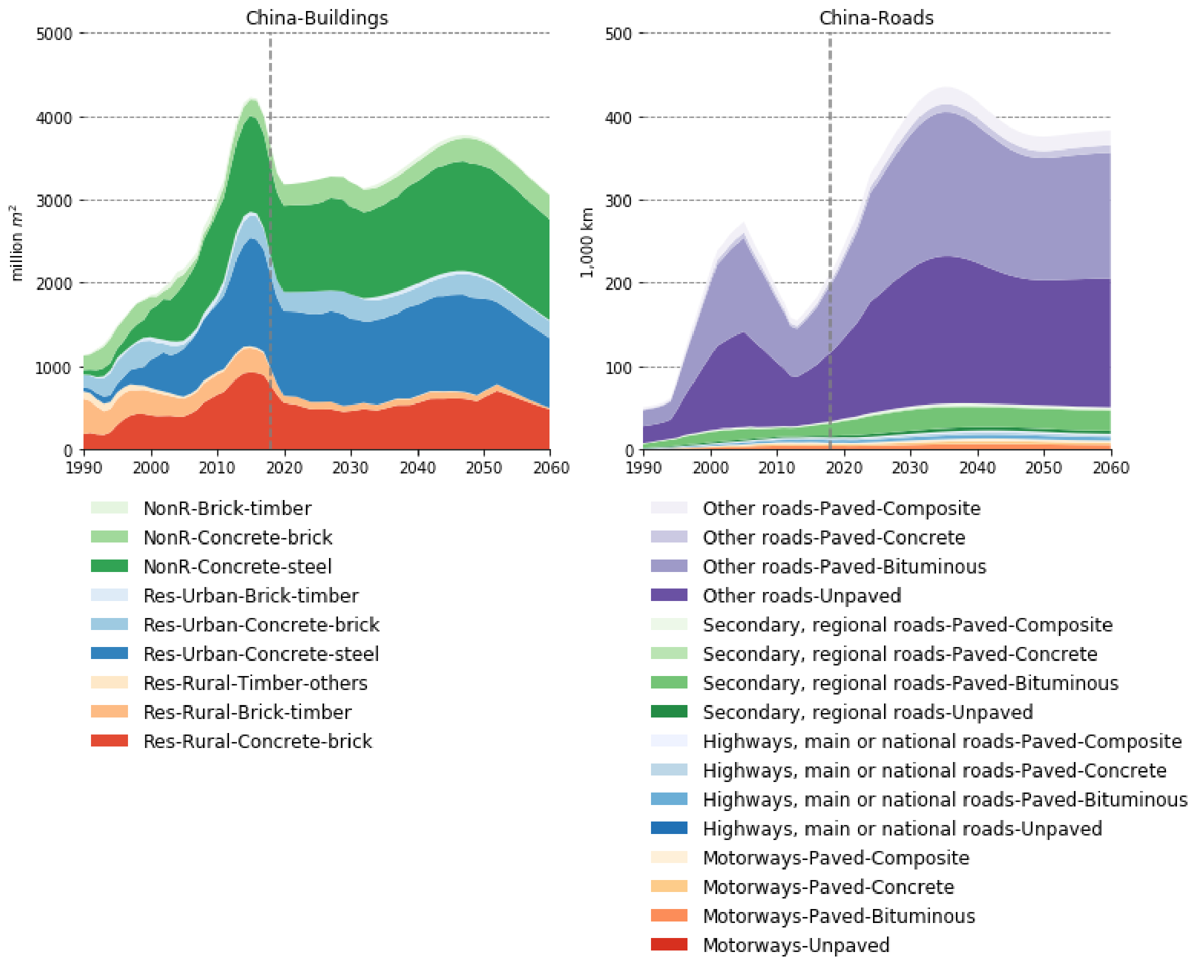

Figure 2-4. Projections of newly-constructed building floor area and road length in China.

Note: values for the years before the dashed line are historical data, and values for the years after the dashed line are projected results. Our projected values of newly-constructed building floor area differ from recent projections by Hong et al.[24], which used a similar stock accounting approach but relied on different floor area data (our report is aligned with IEA RTS's projections[11]). Therefore, our projections envisage higher values of residential and non-residential floor area in 2060.

Over the same period, as shown in Figure 2-5, the new building floor area in the United States grew at a relatively stable rate, but dropped to a low due to the 2007-2008 financial crisis, during which time many cement plants were operated at low capacity or idled[25]. The trends of new road length in the United States remained relatively stable from 1990 to 2017.

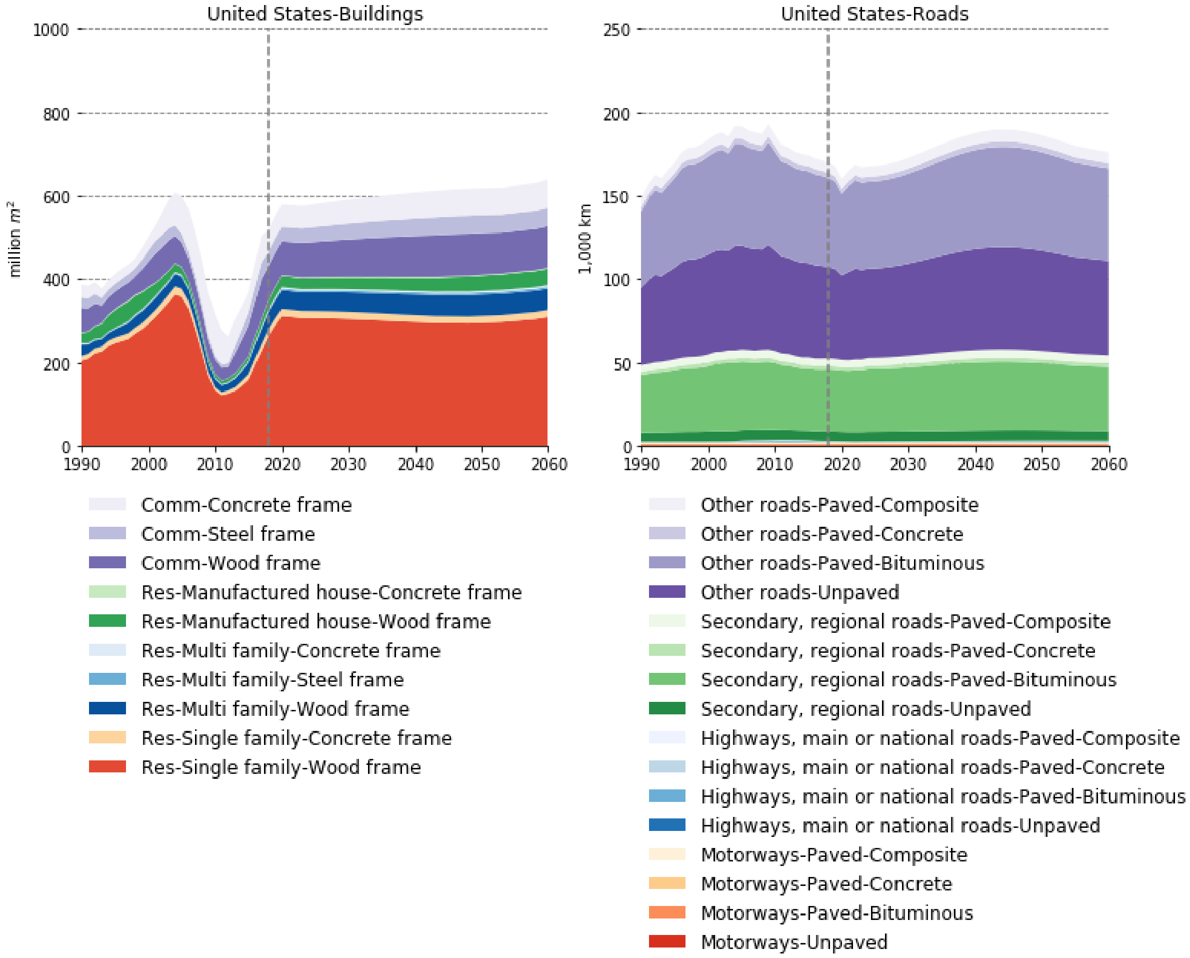

Figure 2-5. Projections of newly-constructed building floor area and road length in the United States.

Note: values for the years before the dashed line are historical data, and values for the years after the dashed line are projected results.

Unlike the United States and China, the new building floor area in India maintained a steady growth from 1990 to 2017, as shown in Figure 2-6. India's road length also had a boost around 2005, predominantly driven by the growth of roads in rural areas (i.e., Other roads). Figures 2-4, 2-5, and 2-6 also present the projections for new building floor area and new road length under expected trends in the United States, India, and China through 2060. These projections form the basis of the following projections of cement and concrete demand, as well as the decarbonization scenarios for the cement and concrete cycle presented in Chapter 4. Additionally, tracking the temporal dynamics of cement and concrete consumed over time provides necessary inputs for quantifying how much cement and concrete is expected to exit from the use phase and how much CO_2 uptake is expected to occur within the cement and concrete cycle.

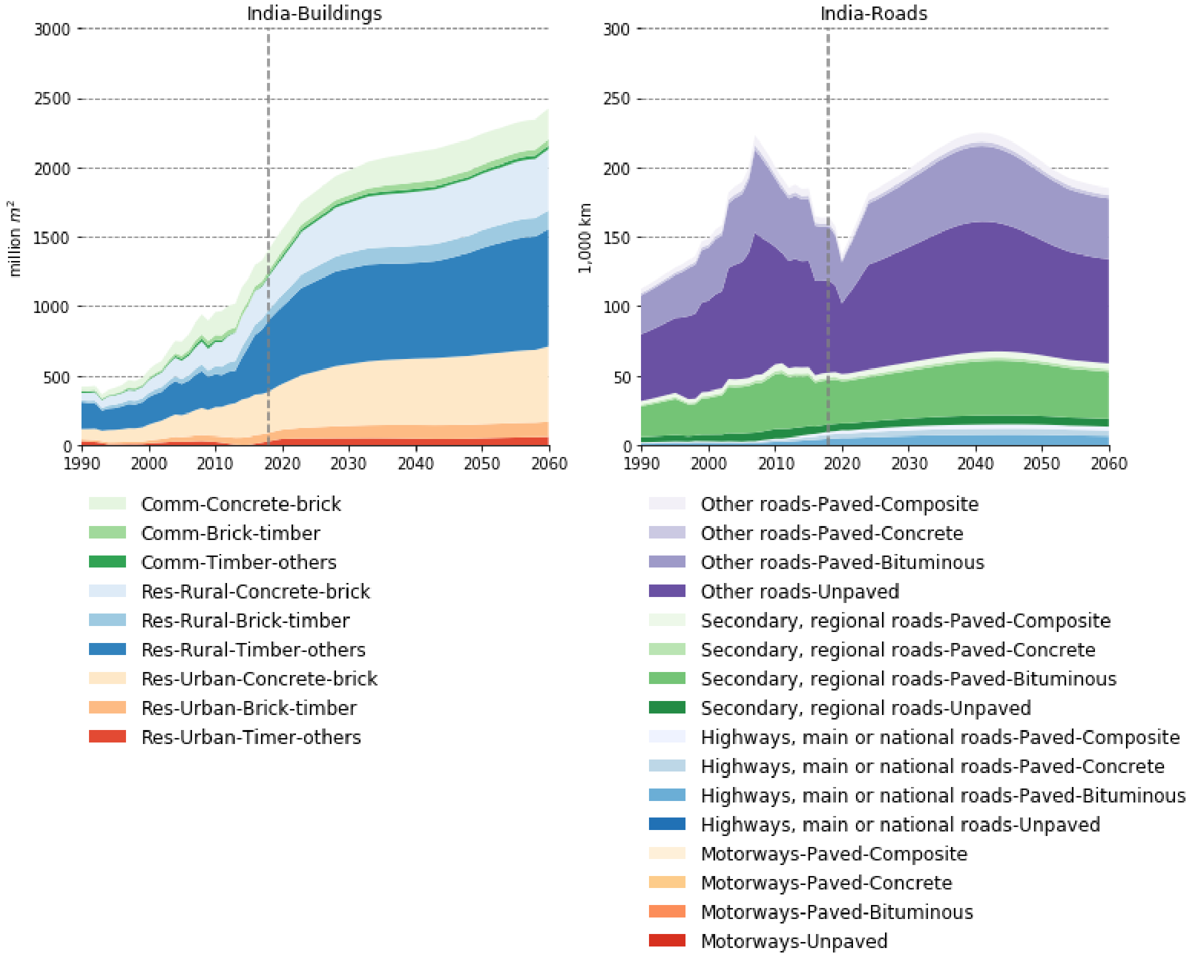

Figure 2-6. Projections of newly-constructed building floor area and road length in India.

Note: values for the years before the dashed line are historical data, and values for the years after the dashed line are projected results.

2.3. Cement and concrete demand trends

As shown in Figure 2-7, cement demand trends are in line with concrete demand under expected future conditions, because cement quantities are a function of concrete quantities and cement proportions. Urbanization patterns and building framing transitions also shape the cement and concrete demand trends. The current outlook for cement and concrete demand in China is that it will remain stable for a decade, gradually climb to a peak at around 2050, and slowly decline afterward. These trends are due to plateauing population and increasing stock turnovers of buildings and roads. Cement and concrete demand in the United States will remain relatively stable thanks to moderate increases in residential and commercial floor area, due to the slow but steady growth of population and building and road stocks. For India, cement and concrete demand is poised to grow at a relatively more rapid pace, driven by rising population and continuous growth of building and road stocks. India's demand for cement and concrete is overall lower than China's because concrete is less used in India's rural buildings. Across all three countries, the building sector accounts for the lion's share of cement and concrete demand, underscoring the critical role it must play in any decarbonization efforts. The road sector accounts for smaller shares of cement and concrete demand, but it holds great potential for accommodating artificial aggregates made from CO_2 mineralization, which is considered as an important decarbonization lever in Chapter 3. Our bottom-up analysis is aligned sufficiently with previous estimates using the same bottom-up approach (e.g., Figure 34 in the IEA Material Efficiency report[16]), albeit its scope differs from top-down statistics (more detailed analysis can be found in the Appendix).

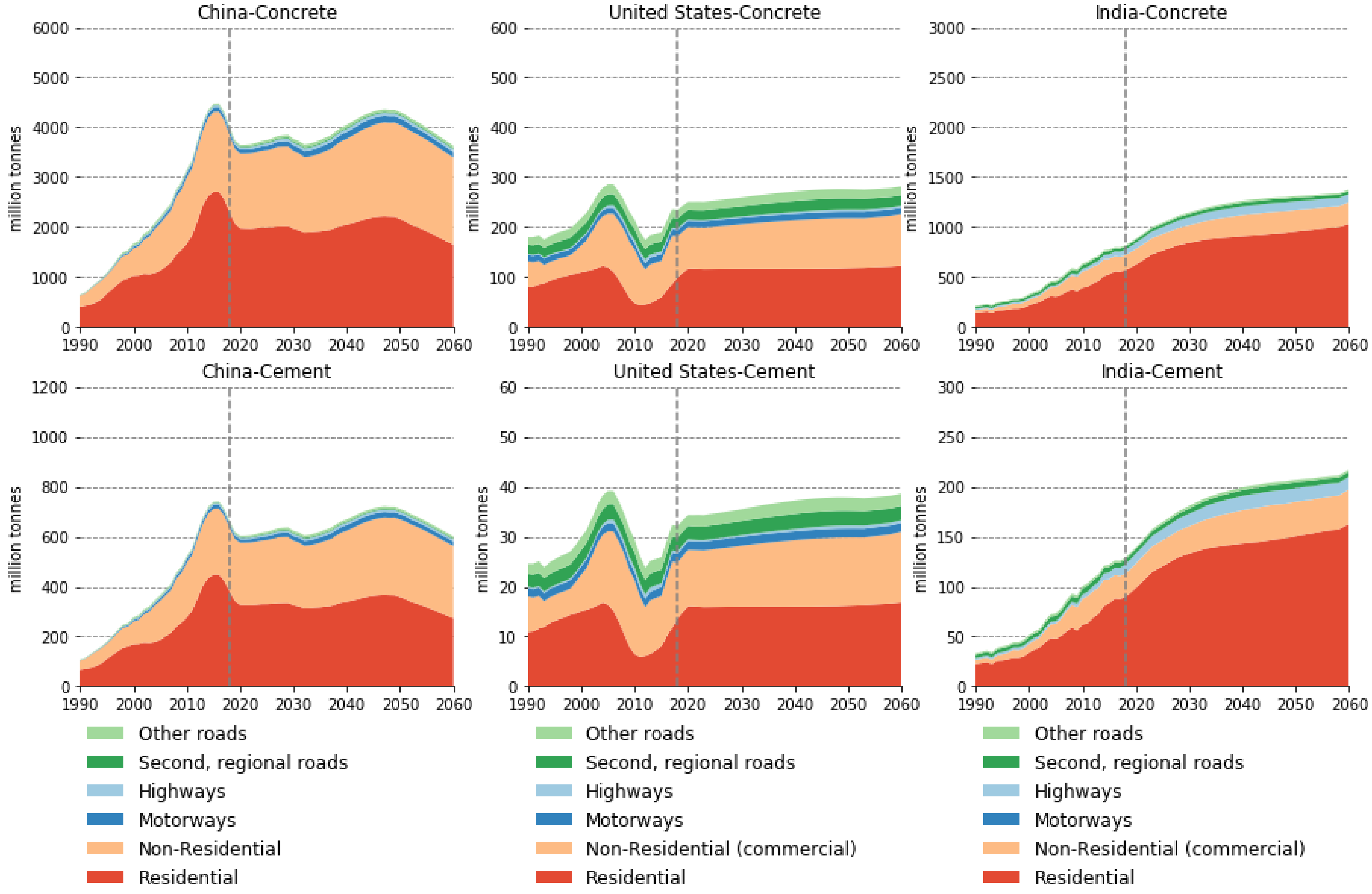

Figure 2-7. Projections of cement and concrete demand by end-use segment in China, the United States, and India.

3. Technology and policy options for decarbonization

As discussed in the preceding chapter, cement and concrete demand will remain high through mid-century, and substantial decarbonization efforts are needed for achieving climate change mitigation goals. This chapter reviews the major technology and policy options for decarbonizing the cement and concrete cycle, based on an extensive review of the literature. The review starts with what we refer to as conventional levers, which have traditionally been pursued by firms and generally present proven options with low economic risk, yet untapped potential remains. Next, we discuss key emerging levers, which we define as technologies that have been or are currently being proven at the pilot or demonstration scale, or are in the early stages of commercialization but are not yet widely adopted. As shown in Table 3-1, emerging levers generally face market barriers, such as perceived risk, high initial investment costs, or potential feedstock constraints. Conventional and emerging levers are further categorized into production-side levers and demand-side levers. The former category is generally within the direct control of cement and concrete manufacturers, while the latter category must be implemented by a broader range of stakeholders, including architects, construction companies, urban planners, and property owners. While we consider improvements in electricity grids, transport efficiency and efficiencies in the production of aggregates and concrete that are expected to occur over our analysis period, these improvements are not explicitly considered as low-carbon levers.

Table 3-1. Decarbonization levers considered in this report.

Decarbonization lever	Technology maturity	Stakeholder involvement	Current status	Key barriers
L1-Cement plant technology options	C	P	Commercial-scale	High investment
L3-Clinker-to-cement ratio reductions	C	P	Commercial-scale	Low-reactivity Resource scarcity
L2-Lower-carbon cement chemistries	E	P	Pilot-scale	Low market penetration
L4-At-plant carbon capture and sequestration	E	P	Pilot-scale	Very-high investment
L5-Carbon utilization	E	P	Commercial-scale	Low market penetration
L6-Material efficiency strategies	C/E	D	Commercial-scale	Risk concern Lack of awareness Higher price
L7-End-of-life options	E	D	Pilot-scale	Regulatory framework Higher price

Note: C stands for Conventional; E stands for Emerging; P stands for Production-side; D stands for Demand-side.

3.1. Conventional levers

Conventional at-plant CO_2 mitigation measures can be categorized into two groups: cement plant technology options and clinker-to-cement ratio reductions. Historically, these measures have been adopted by firms to improve their energy and resource productivities for economic benefit, but their implementation has delivered significant CO_2 emission reductions at cement plants worldwide compared to past practices.

Cement plant technology options

The cement sector has progressed significantly in energy efficiency and CO_2 mitigation by adopting conventional technology options that target the thermal efficiency, electrical efficiency, and low-carbon fuel utilization of cement kilns.

Dry-process kilns with a pre-calciner, a multi-stage cyclone pre-heater, and multi-channel burners are regarded as the state-of-the-art technology for clinker production. However, the adoption of dry-process kilns with pre-heaters and pre-calciners varies by country. As shown in Figure 3-1, the average thermal intensity of US cement manufacturing decreased from 4946 MJ/t clinker to 3768 MJ/t clinker from 1990 to 2017. Over the same period, the average thermal intensity of China and India decreased from 4791 MJ/t clinker to 3264 MJ/t clinker and from 3922 MJ/t clinker to 3102 MJ/t clinker, respectively. The thermal efficiency leapfrogging in China and India is mainly attributable to the rapid expansion of cement production capacities in these two countries, wherein efficient dry kilns were rapidly adopted, while the cement production capacities in the United States have evolved more slowly over the past several decades.

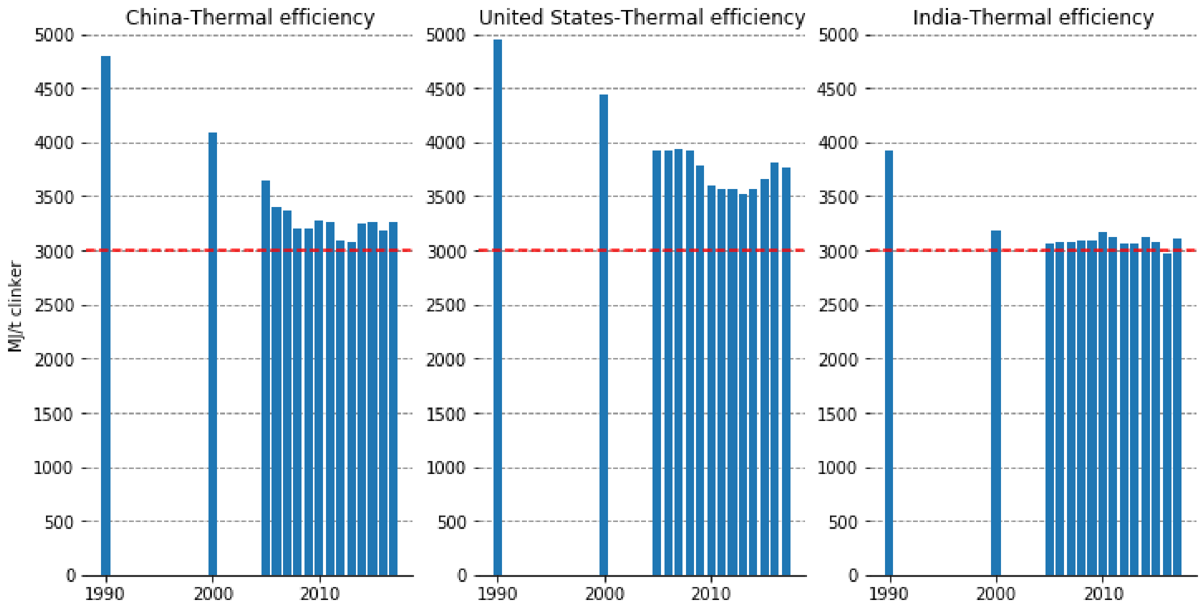

Figure 3-1. Reported thermal efficiency improvements in China, the United States, and India.

Note: the underlying data are derived from GNR 2018[3]. Red dashed lines represent the average thermal efficiency of the global 10% best in class (~3000 MJ/t clinker)[26].

Moving forward, there are two important aspects affecting the outlook for plant energy efficiency improvements. First, China and India are closing in on the practical minimum values of kiln thermal efficiency[26] (3000 MJ/t clinker). Second, cement kilns are long-lived capital assets with a typical lifetime of 30-50 years[12], limiting the pace at which they can be replaced with new ones. This is especially the case for the United States, of which the cement kilns are 34 years old on average[27].

As shown in Figure 3-2, similar trends are observable for cement plant electrical efficiency as compared to thermal efficiency. In 2017, the average reported electrical intensity of cement plants in China and India was 102 kWh/t cement and 74 kWh/t cement, respectively, while the average reported electrical intensity of the United States was 134 kWh/t cement. Because of the slow turnover of cement production capacities, further electrical efficiency improvements will be challenging in China and India, but there is room for doing so in the United States. Cement plants in India are already among the most efficient in the world, because India's cement industry has phased out old technologies[28].

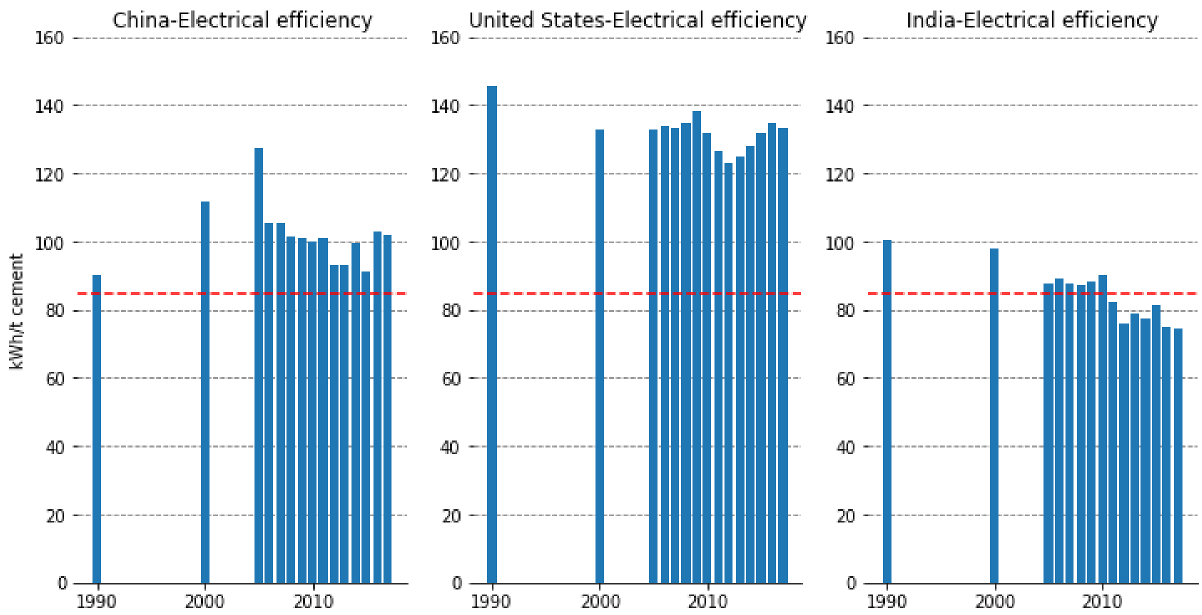

Figure 3-2. Reported electrical efficiency improvements in China, the United States, and India.

Note: the underlying data are derived from GNR 2018[3]. Red dashed lines represent the average reported electrical efficiency of the global 10% best in class (85 kWh/t cement)[26]. Electrical efficiency is expressed in kWh/t cement because electricity is used throughout the entire process of cement manufacturing, and using kWh/t cement is the convention for CO_2 emissions accounting for cement production.

As shown in Figure 3-3, the predominant fuels used in cement kilns have historically been coal and natural gas due to their widespread availability, high heating values, and generally low costs. In 2017, coal represented 88.6%, 66.2%, and 95.3% of the reported cement thermal energy consumption in China, the United States, and India, respectively. Natural gas and oil jointly represented 18.3% of reported thermal energy consumption in the United States, whereas these two fossil fuels contributed negligibly to the reported thermal energy consumption in China and India. However, low-carbon fuel options exist and are becoming increasingly common as firms seek to reduce costs and CO_2 emissions. Low-carbon fuels fall into two broad categories: waste fuels (shredded tires, waste oils, plastics, textiles, paper residues, etc.) and biogenic fuels (agricultural residues, biomass crops, etc.). Waste fuels can be 20-25% less CO_2-intensive than coal[28]. From a life cycle perspective, these wastes would otherwise be incinerated or landfilled, leading to unnecessary additional CO_2 emissions or methane emissions[10]. Biomass-based fuels are generally considered carbon-neutral when sustainably harvested because future biomass regrowth can compensate for CO_2 emissions arising from biomass combustion. In 2017, biomass and waste fuels together accounted for 11.4%, 15.5%, and 3.4% of the reported thermal energy consumption in China, the United States, and India, respectively. In theory, cement kilns can utilize up to 100% of alternative low-carbon fuels, albeit subject to kiln heating value requirements, local availability, and contamination of these fuels. Therefore, switching to less carbon-intensive fuels (particularly biomass) is a viable option. Moving forward, there is ample room for incorporating less carbon-intensive fuels into cement kilns.

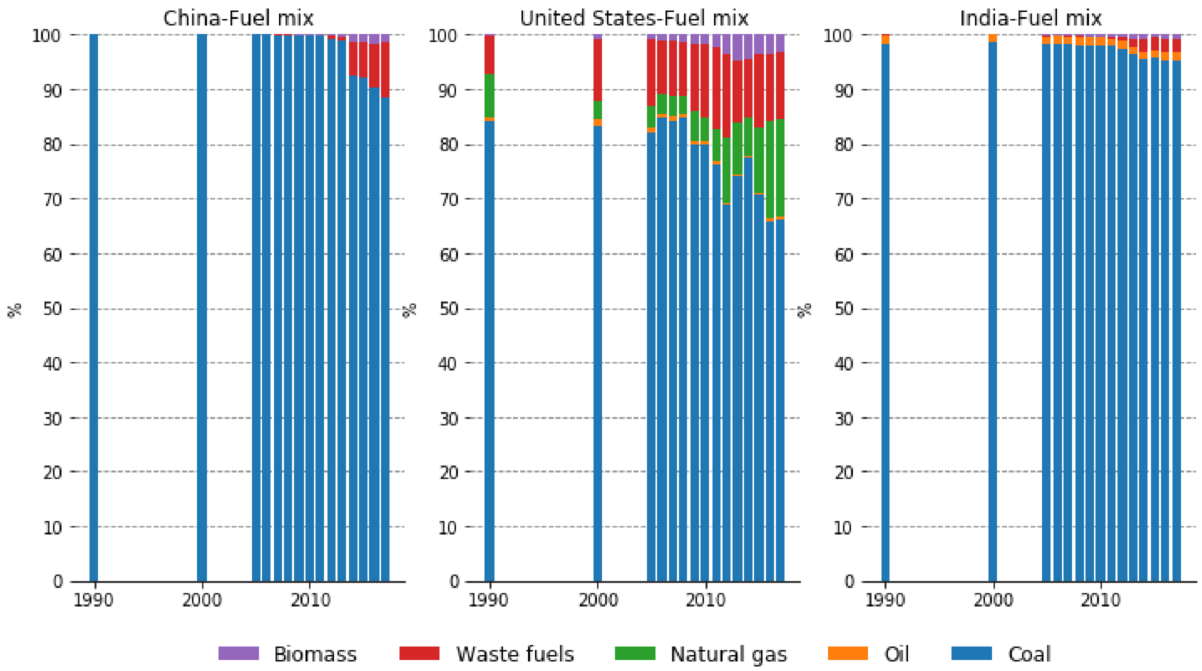

Figure 3-3. Fuel mix of cement thermal energy consumption in China, the United States, and India.

Note: the underlying data are derived from various sources[8,28,29].

Clinker-to-cement ratio reductions

The clinker-to-cement ratio refers to the share of clinker in cement on a mass basis. Reducing the clinker-to-cement ratio is another conventional low-carbon lever, which has historically been pursued for economic reasons since clinker substitutes cost less than pyroprocessed clinker or can enhance concrete's properties. Clinker can be substituted by various supplementary cementitious materials (SCMs), including limestone, fly ash, ground granulated blast furnace slag (GGBFS), natural pozzolana, and calcined clay. In the United States, SCMs are often proportioned during concrete mixing. The use of SCMs in concrete can reduce the amount of binder made from OPC, consequently resulting in a lesser amount of OPC clinker. For consistency across countries, we treat clinker-to-cement ratio reductions as a mitigation lever targeting cement production. As shown in Figure 3-4, in 2017, the average clinker-to-cement ratio reported for cements in China, the United States, and India decreased to 78.9%, 89.6%, and 69.3%, respectively. From a technical point of view, the clinker-to-cement ratio can be reduced up to around 60% without sacrificing key cement or concrete properties[26]. In practice, however, the implementation of clinker-to-cement ratio reductions relies on local material availability and regional standards that regulate the proportions of SCMs. For instance, the availability of GGBFS hinges on the locations and output of pig iron production. However, recent climate change scenarios project that the iron and steel industry may shift from pig iron to secondary steel in a low-carbon future, thereby reducing global available quantities of GGBFS[30]. Likewise, the availability of fly ash is subject to the local capacities of coal-based thermal power plants, and the share of coal-based power capacity is expected to decrease moving forward[10]. While calcined clay is not limited by feedstock supply, its activation requires calcination, but leads to no process CO_2 emissions from carbonate decomposition and consumes 45% less energy compared to OPC clinker[31].

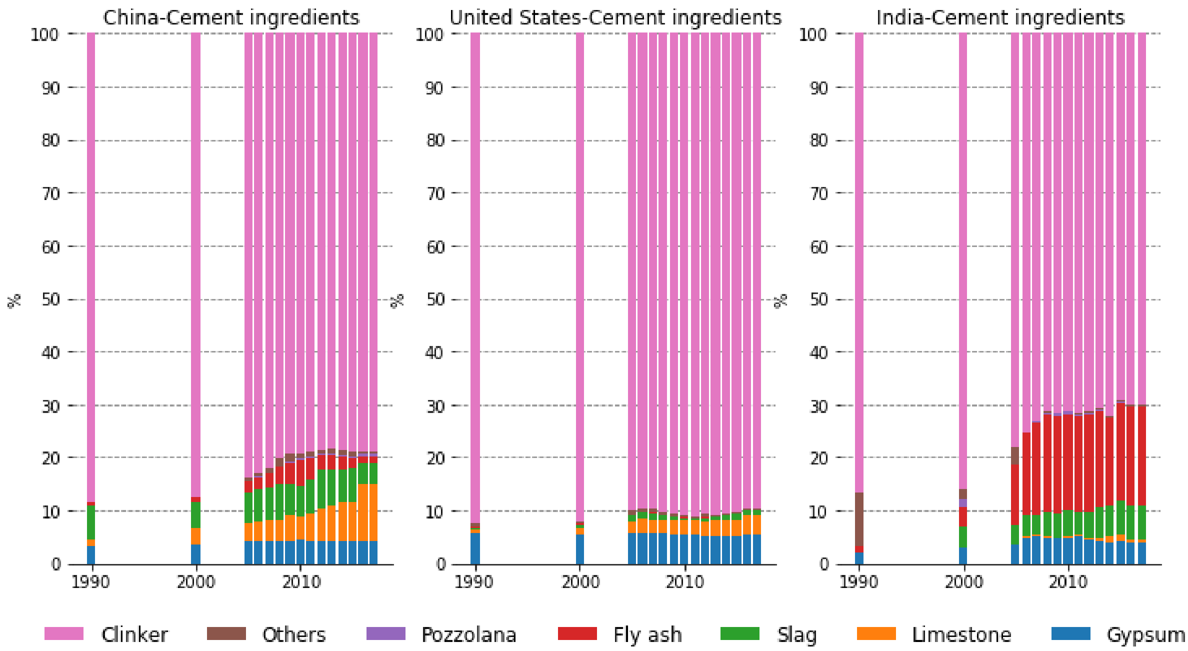

Figure 3-4. Reported cement ingredients in China, the United States, and India.

Note: the underlying data are derived from GNR 2018[3]; although the GNR sample size is small for China, its clinker-to-cement ratio is aligned with an independent plant-level survey (see the Appendix).

3.2. Emerging production-side levers

The aforementioned conventional levers have contributed significantly to energy efficiency improvements and CO_2 mitigation in cement production over the past decades. However, the CO_2 mitigation potential of these conventional at-plant CO_2 mitigation measures is subject to theoretical limits, availability of input materials, and cement producers' willingness to replace their assets. Therefore, cement and concrete producers will need to consider additional disruptive and innovative measures for delivering CO_2 emission reductions in line with the 1.5 °C target of the Paris Agreement. Below, we discuss three emerging levers that are applicable to cement and concrete production—referred to here as the "production-side" of the cement and concrete cycle, and that could provide significant decarbonization potentials by mid-century. The first two levers (lower-carbon cement chemistries and at-plant carbon capture and sequestration or “CCS”) are applicable to cement producers, whereas the third lever (carbon utilization) is applicable to the concrete and construction industries, as well as aggregates producers.

Lower-carbon cement chemistries

Lower-carbon cement chemistries rely on different raw materials and/or raw material mixes that reduce process CO_2 emissions (and sometimes thermal energy requirements) compared to OPC clinkers[32] (Table 3-2).

Table 3-2. Process CO_2 and energy savings of lower-carbon cement clinker compared to OPC clinker.

Cement type	Process CO_2[33]	Thermal Energy[33]
Reactive belite cement	3.1%	8.2%
Belite-ye’elimite-ferrite cement (BYF)	29.1%	34.9%
Carbonatable calcium silicate cement (CCSC)	24.8%	38.9%
Calcium sulfoaluminate cement (C$AB)	42.0%	46.9%
Celitement	33.2%	50.6%
Magnesium oxides derived from magnesium silicates (MOMS)	100%	46.5%

This section reviews six lower-carbon cement chemistries from the lime-silica-alumina system (Box 1) that are either commercially available or have been piloted or demonstrated on small production scales[21]. While there are other chemistries being investigated, these six cement chemistries have been identified in previous studies as having reasonable commercial market potential within the next decade[21,34]. Another alternative to OPC clinkers is alkali-activated binders, but this type of binder relies on the same raw materials used for blended cement. The use of fly ash, GGBFS, natural pozzolana, and calcined clay in alkali-activated binders brings less environmental benefits compared to blended cement[19]. Hence, the focus of this report is limited to these cement chemistries.

Reactive belite cement clinker (typically composed of 28.2% C_3S, 53.3% C_2S, 6.3% C_3A, and 12.1% C_4AF) is produced with lower amounts of calcium, and it contains up to 90% C_2S by mass. Compared to C_3S, the formation of C_2S is attained at a lower temperature (800-1000 °C). Compared to OPC, reactive belite cement clinker, in theory, saves 8.2% of thermal

Box 1. Basics of Cement Chemistry

Notation: C = CaO; SiO_2 = S; Al_2O_3 = A; Fe_2O_3 = F; SO_3 = $; H_2O = H

The hydraulicity of cement is dictated by several key factors. First, hydrates resulting from mixing cement and water have a higher volume than the dissolving cement. Second, the ions forming the hydrates are able to migrate from the original particles into the previously water-filled space. Third, the hydrates themselves have low solubility to persist for a long period. In terms of hydraulicity, the key contributing ions are those of silicon, calcium, and aluminum. Therefore, the most viable chemistries for hydraulic cement should derive from the lime-silica-alumina (CaO-SiO2-Al2O3) system. Within this system, alite (C3S), belite (C2S), and calcium aluminates (e.g., C3A, C12A7, CA, and C4A3$) are the main minerals of significant hydraulicity.

To understand how each alternative chemistry can reduce CO_2 emissions in clinker production, we review the stoichiometry and final composition of clinker phases. The principle reactions taking place in clinker formation can be roughly divided into two stages: reactions below 1300 °C and reactions at 1300-1450 °C. Lime, belite, aluminate, and ferrite are present at the first stage, and alite is formed at the second stage. The principle reactions in clinker formation are listed as follows.

$$CaCO_3 \xrightarrow{750℃-1000℃} CaO + CO_2 \uparrow$$

$$2CaO + SiO_2 \xrightarrow{800℃} C_2S$$

$$CaO + Al_2O_3 \xrightarrow{800℃} CA$$

$$2CaO + Fe_2O_3 \xrightarrow{800℃} C_2F$$

$$7CA + 5CaO \xrightarrow{800℃-900℃} C_{12}A_7$$

$$C_{12}A_7 + 9CaO \xrightarrow{900℃-1000℃} 7C_3A$$

$$2CaO + 7C_2F + C_{12}A_7 \xrightarrow{900℃-1000℃} 7C_4AF$$

$$C_2S + CaO \xrightarrow{1300℃-1450℃} C_3S$$

Thermochemistry and enthalpy equations are used for calculating thermal energy requirements and carbonate decomposition related CO_2 emissions in OPC clinker production.

energy and releases 3.1% less CO_2 emissions that are associated with carbonate decomposition[32,33]. A key barrier to large-scale adoption of reactive belite cement clinker is that it gains strength more slowly than OPC clinker, leading to longer curing periods which can be undesirable for many construction projects where rapid build times are prioritized.

Belite-ye'elimite-ferrite (BYF) cement clinker (typically composed of 43.5% C_2S, 19.8% C_4AF, and 36.7% $C_4A\$$) is usually regarded as one type of calcium sulfoaluminate (CSA) cement because it contains ye'elimite ($C_4A_3\$$). However, the relative abundance of minerals (or clinker phases) in BYF cement clinker is belite>ye'elimite>ferrite. BYF cement clinker can be considered intermediate between OPC clinker and CSA cement clinker in terms of ye'elimite content[34]. As with CSA cement clinker, BYF cement clinker can be manufactured in standard cement plants, without causing significant reconfiguration in cement manufacturing processes. The main difference between BYF cement clinker and CSA cement clinker is the former contains less ye'elimite and thus requires less high-cost aluminous raw materials. Compared to OPC clinker, BYF cement clinker, in theory, saves 34.9% of thermal energy and releases 29.1% less CO_2 emissions that are associated with carbonate decomposition[32,33]. The major barrier to BYF cement's commercialization is related to its high demand for expensive aluminous materials and the availability of these materials.

Carbonatable calcium silicate cement (CCSC) clinker (typically composed of 13.0% C_3A, 83.0% CS, and 4.0% C_3S_2) is inspired by a simple fact that calcium silicates harden by atmospheric carbonation, which is a slow process due to low CO_2 concentration in the atmosphere[34]. Another issue with natural carbonation is atmospheric carbonation occurs from the surface and gradually diffuses toward the inside, leading to an inhomogeneous hardening profile. CCSC clinker (e.g., Solidia) is made for rapid carbonation enabled by controlled curing conditions, thereby overcoming the two issues stated above. CCSC clinker contains low-calcium silicates such as wollastonite (CS) and can be manufactured in standard cement plants. On top of CO_2 savings coming from energy savings (38.9%) and less carbonate decomposition (24.8%)[32,33], CCSC clinker sequesters CO_2, thus offering additional CO_2 mitigation opportunities. Because the alkalinity of CCSC is greatly reduced when cured, CCSC-based concrete is unable to protect reinforced steel bars from corrosion, making it currently unsuitable for traditional reinforced concrete applications.

Calcium sulfoaluminate (CSA) cement clinker (typically composed of 23.0% C_2S, 15.1% C_4AF, and 61.7% $C_4A\$$) contains ye'elimite and belite as the main constituents[10]. CSA cement clinker was developed in China. CSA cement is a commercial product and mainly targets a niche market—cement with fast strength development and shrinkage reduction properties. Thanks to its clinker compositions, CSA cement clinker, in theory, saves 46.9% of thermal energy and releases 42.0% less CO_2 emissions that are associated with carbonate decomposition[32,33]. As with BYF cement, wide-scale adoption of CSA cement will be constrained by the availability of aluminous materials.

Celitement clinker (typically composed of 92.8% CS and 7.2% H_2O) refers to calciumhydrosilicates (CHS) synthesized from quartz and CaO by a hydrothermal process. The benefit of Celitement lies in the fact that a non-hydraulic calcium silicate compound (α-C_2SH) can be manufactured by a low-temperature autoclaving process (~200 °C at 12 bar). The resulting non-hydraulic α-C_2SH is then interground with a siliceous filler such as quartz to form a binder that is very close to belite but far more reactive. Celitement represents a wide range of binders based on CHS. Although the overall manufacturing process is rather complex, Celitemen clinker can, in theory, save 46.5% of thermal energy and release 33.2% less CO_2 emissions that are associated with carbonate decomposition[32,33]. The manufacturing process of Celitement is still complex and thus relatively more expensive than OPC[35], which will be the main barrier to its wide-scale adoption.

Magnesium oxides derived from magnesium silicates (MOMS) cement clinker (typically composed of 100% magnesium oxysulfate, $3Mg(OH)_2 \cdot MgSO_4 \cdot 8H_2O$) refers to MgO-based cement clinker sourced from ultramafic rocks that are rich in magnesium silicates[21]. MOMS cement clinker can save 46.5% of thermal energy and avoid all CO_2 emissions that are associated with carbonate decomposition[32,33]. As with CCSC cement, MOMS can sequester and store CO_2 permanently as magnesium carbonates, thus offering great opportunities for CO_2 mitigation. Minerals carrying magnesium silicate are abundant, but they are much more localized than limestone[34].

At-plant carbon capture and sequestration

Carbon capture and sequestration (CCS) has long been considered a substantial and necessary CO_2 mitigation option for cement plants. It is a technology class that includes two distinct stages: carbon capture occurs on the kiln flue to remove CO_2 from the mixture of CO_2 emissions arising from carbonation decomposition and fuel combustion, whereas sequestration involves the subsequent compression and transport of captured CO_2 for permanent geological storage[15]. In this report, we consider two promising classes of carbon capture technology for cement plants: oxy-fuel firing and post-combustion. Other carbon capture technologies (e.g., pre-combustion and direct separation) also exist, but they are less efficient for capturing CO_2 emissions from limestone calcination or less mature than the two considered carbon capture technologies, and are therefore not considered[10,12].

Oxy-fuel firing refers to carbon capture technologies that use pure oxygen instead of ambient air for fuel combustion, resulting in a mostly pure CO_2 stream exiting the kiln's flue. Oxy-fuel firing technologies will ease subsequent CO_2 purification. Oxy-fuel firing technologies can be applied to combustion in both the pre-calciner and the main kiln, and the separation efficiency of oxy-fuel firing technologies depends on to what extent the kiln is retrofitted. It is reported that oxy-fuel firing can yield separation efficiencies ranging from 80% to 99%[10,26]. Deploying oxy-fuel firing technologies requires sophisticated redesigns of heat recovery systems, potentially limiting waste heat utilization.

Post-combustion technologies are a form of "end-of-pipe" abatement, thus requiring no fundamental changes to the kiln firing process provided there is enough physical space for the carbon capture equipment[10]. The most mature post-combustion technology is chemical absorption using amines (e.g., monoethanolamine), which has been operated for a long time in many other industries (e.g., chemical industries). Calcium looping is a promising alternative option for post-combustion CCS, which separates CO_2 through a regenerative sorbent—CaO. Solid calcium carbonate is calcined and decomposed into CaO and CO_2 at high temperatures (850-950 °C). The CaO is recycled and carbonated in contact with a flue gas that contains a low to medium concentration of CO_2. Compared to chemical absorption using amines, calcium looping can reduce the additional energy penalty associated with sorbent regeneration by ~58%[36]. Recently, amine-based absorption and calcium-looping technologies have been piloted in the cement sector, such as Anhui Conch in China[37] and Norcem in Norway[38].

Membrane technology allows CO_2 to flow through, thus separating CO_2 from unwanted gas streams. Membrane technology seems to be an excellent substitute in the long run, but it is still limited to a lab scale[26]. Therefore, membrane technology is not considered in this report.

While captured CO_2 can be transported by rail, truck, or ship, large-scale transport is usually operated through pipelines. Therefore, wide-scale deployment of at plant CCS will require expansion of the existing pipeline infrastructure. The success of CCS also depends on the proximity of cement production facilities to CO_2-enhanced oil recovery operations or geological storage sites. Recent studies indicate that the CO_2 storage capacity in the United States and China is abundant[39], but the incentive to deploy CCS is highly dependent on future economic and political conditions[40,41].

Carbon utilization

In the context of mineral products, carbon utilization refers to utilizing captured CO_2 for concrete curing and for converting alkaline minerals (e.g., industrial wastes and end-of-life cement products) into value-added products, such as natural aggregate substitutes.

In the natural carbonation process, cement binder in concrete will absorb CO_2 as it hardens and continues to absorb CO_2 throughout its life (also known as "cement carbonation" or "natural weathering"). However, concrete curing with CO_2 is an accelerated carbonation process that injects CO_2 gas more thoroughly into the concrete mix during concrete batching and mixing or during the curing process for precast products[42]. This process leads to ~12% more CO_2 being stored in concrete over its service life compared to natural carbonation process, thereby delivering an additional CO_2 sink[42]. Furthermore, the introduced CO_2 reacts with calcium silicates in concrete, through which the compressive strength of concrete is substantially improved. A recent study suggests that the compressive strength of concrete can be improved by ~15% on average compared to natural curing[42], which leads to ~13% less need for carbon-intensive cement for binding[42]. Therefore, CO_2 curing for concrete can reduce the CO_2 footprint of concrete in two ways: boosting CO_2 absorption by accelerated carbonation and saving binder to deliver the same required compressive strength. CO_2 used for curing would typically come from industrial sources, e.g., power plants and cement plants. Energy used for CO_2 processing and transport offsets ~16% of the CO_2 uptake[43].

Mineralizing CO_2 using alkaline minerals is another emerging option for sequestering CO_2 permanently and valorizing low-value solid wastes[22]. Industrial wastes suitable for CO_2 mineralization include end-of-life cement-based materials, iron and steel slag, fly ash, lime mud, and red mud, which are all classified as "alkaline" wastes based on their high pH. CO_2 mineralization using alkaline solid wastes is essentially an ex-situ mineralization technology that enables these wastes to react with CO_2. The core benefit of CO_2 mineralization using alkaline solid wastes is it provides permanent CO_2 storage. Using alkaline solid wastes as a reactant for CO_2 mineralization is appealing because those wastes are already available, cheap, and often generated near CO_2 emissions sources[44]. However, it must be acknowledged that some of these industrial wastes can also be used as SCMs to substitute clinker. Our analysis considers either utilization route to avoid double counting. The resulting products from CO_2 mineralization can be used as substitutes for natural aggregates (also known as synthetic aggregates), and a few companies (e.g., Carbon8[45] and Blue Planet[46]) have already developed commercial products by doing so[45–47]. The amount of CO_2 stored can vary considerably by input alkaline material. The total CO_2 uptake potential through CO_2 mineralization depends on the availability of alkaline materials. Because the impact of utilizing synthetic aggregates on concrete compressive strength is uncertain[42], we assume that the compressive strength of concrete incorporating synthetic aggregates remains unaffected.

Concrete curing with CO_2 and CO_2 mineralization have both proven to be commercially viable[45–47], but additional research and development are needed for understanding their economics, logistics, and potential for market acceptance.

3.3. Emerging demand-side levers

In this report, the "demand-side" refers to the systems and stakeholders that put concrete to use in the built environment for meeting societal needs, inclusive of architects, road designers, contractors, urban planners, and waste managers. While conventional measures for decarbonizing the cement and concrete cycle have focused mostly on the "production-side", considering changes in concrete use can open up new mitigation opportunities. This whole-systems approach can give agency to more stakeholders along the construction value chain to seek out the most efficient interventions and to seize mitigation opportunities in the whole cement and concrete cycle. Below, we discuss the "demand-side" technology/policy options considered in this report, which we further group into material efficiency strategies and end-of-life options.

Material efficiency strategies

The CO_2 emissions arising from the whole cement and concrete cycle depend on the carbon footprint per unit of cement and concrete and the quantity of cement and concrete consumed. The basic tenet of materials efficiency is that decarbonization is made easier if less cement and concrete is consumed in the first place. Material efficiency options for reducing cement and concrete demand have been given increasing attention in the literature, inclusive of the IEA Cement Roadmap[10], the UNEP Eco-efficient cements report[21], an ETHZ/EPFL report[48], the Energy Innovation report[49], a US lifetime extension study[50], the IEA Material Efficiency report[16], a Material Economics report[18], a recent review of global industrial decarbonization[51], a UK cement efficiency study[17], a McKinsey report[52], and the UNEP RECC report[53]. While material efficiency options considered in past literature vary, in this report, we consider the following main options: material-efficient design, material substitution, fabrication yield improvement, more intensive use, and lifetime extension.

Material-efficient design encompasses several at-construction measures that reduce cementitious binder intensity: performance-based concrete design, using precast concrete elements, post-tensioning, and avoiding over-design of concrete structures[17]. Performance-based design enables architects or contractors to design concrete mixes satisfying the required mechanical and durability requirements with less cement. Precast elements allow designers to manufacture concrete parts with greater precision and more confidence when using less cement. Post-tensioning techniques stress rebar in concrete floor slabs before applying external loads, thus allowing thinner parts in concrete elements. Over-design is a common phenomenon due to the cautiousness of designers, especially for structural elements. These at-construction measures could potentially reduce the cementitious binder intensity by 15-25%[17], but wide-scale deployment of these design-oriented measures will hinge on how fast designers or contractors will take them up, as well as adequate policy intervention (e.g., financial incentives, mandatory requirements, and proper exemplars). Good examples of cement use optimization in buildings or roads will offer benchmarks for designers or contractors. For instance, the National Ready Mixed Concrete Association (NRMCA) of the United States has established the Prescription to Performance (P2P) initiative to foster acceptance of new designs at a faster pace[54]. Promoting the use of innovative construction technologies (e.g., prefabrication, modular design, and building information modeling) could potentially unlock more opportunities. For instance, the Ministry of Housing and Urban-Rural Development of China has established a guiding framework for promoting the use of building information modeling (BIM) in the construction industry, through which variability and uncertainty in construction can be minized[55].

Material substitution refers to increasing the use of more sustainable alternative materials, such as engineered timber, to reduce the necessary quantities of concrete in buildings. The use of traditional timber in construction has a long history, but several undesirable characteristics (e.g., anisotropic strength and shrinkage, combustibility) of wood have limited the structural use of traditional timber (e.g., lumber) in all but low-rise residential buildings[56]. Apart from engineered timber, there exist a number of other natural materials[57], such as earth, clay, and straw bale construction. However, these natural materials are usually limited to non-load-bearing components and thus not considered in this report. Engineered timber now comes in various forms, such as glue-laminated beams, nail-laminated timber, dowel-laminated timber, and cross-laminated timber. These modern engineered timber products through lamination have recently been proven reliable for large structural components of mid-rise buildings (4-18 stories)[58]. The use of engineered timber can achieve net CO_2 emission reductions by substituting concrete in buildings and by storing carbon in long-life buildings. For example, in a recent case study, the use of engineered timber resulted in approximately 25-42% less concrete for structures[56], albeit concrete is still used in foundations and for strengthening engineered timber-based floor elements[59]. Regarding CO_2 storage, a tonne of engineered timber will store ~1.8 tonnes of CO_2, meaning a typical 1000 m^2 building will store ~220 tonnes of CO_2 for ~77 years[59]. While engineered timber is a viable alternative to concrete, its use is subject to local availability of forest resources, building codes (particularly those associated with fire safety), and engineered timber manufacturing capacities and workforce. For instance, over the past years, numerous engineered timber projects have been constructed across the United States[60]. In China, timber structures have been widely used in traditional buildings, but the use of engineered timber in mid- or high-rise buildings is still in its infancy[61].

Fabrication yield improvement targets material losses due to wasteful operations in construction companies, such as over-ordering cement. Cement lost during construction accounts for 1-3% of total cement use, according to construction manuals[62] and on-site surveys[6,63]. Material losses during construction can be avoided through improved architectural or engineering specifications of cement or channeling over-ordered cement for other purposes[16]. Promoting prefabrication technology or digitalization could facilitate the adoption of practices that reduce construction waste.

More intensive use refers to policy options aiming to reduce total societal needs for building space and road infrastructure. These policy options can potentially reduce the total building floor area or road length needed for delivering the same level of services. A recent study exploring a "low energy demand scenario" deemed that 30 m^2 per capita can offer a decent living standard[64], which is far below the current per capita housing floor area in the United States (~61 m^2). More sustainable lifestyles (e.g., reasonably-sized building designs, space-sharing, and ride-sharing) could reduce the need for building space and road infrastructure, but the transition toward these lifestyles will require fundamental societal and behavioral changes[18,19]. For example, the 2014-2020 New Urbanization Plan of China has stressed the importance of reasonably-sized housing in securing a transition toward sustainable urbanization[65].

Lifetime extension means extending the service life of buildings or roads. Lifetime extension requires not only technological measures (e.g., more adaptable and durable designs) but also policy actions (e.g., better zoning policies) because the physical durability of buildings and roads does not always determine their real lifetime. For example, a case study on 1732 demolished buildings in China reveals that premature demolition is more likely to occur for buildings adjacent to business centers, whose land-use values have increased significantly[66]. As reported in the recent literature, the average lifetime of buildings in the United States is 77.5 years[67,68], while China and India's buildings only stood for 32.4 years[24,69–83] and 30.7 years[30,71,84], respectively. As for the concrete layer of roads, the average maintenance intervals in the United States, China, and India are 40 years[85], 30.3 years[71,74,80–83], 33.5 years[71], respectively. Lifetime extension could save a significant amount of cement demand. For example, a recent case study on the U.S. cement stocks shows that a 50% (counterfactual) increase in cement longevity could have reduced the cement demand by 14% from 1900 to 2015[50]. Extending the lifetime of buildings and roads will require improved design, cultural transition, and better planning.

End-of-life options

Improved management of end-of-life materials or components could offer additional CO_2 mitigation opportunities at the end-of-life stage of the cement and concrete cycle. In this report, we consider three end-of-life options: downcycling, component reuse, and demolition waste stockpiling.

Downcycling refers to recycling end-of-life concrete for substituting virgin aggregates in new concrete. While it saves natural aggregates, which is an important goal for natural resource conservation and environmental protection, the CO_2 benefits of downcycling are generally small, on average saving 15.2 kg CO_2 per tonne of recycled concrete aggregate (RCA)[86]. Increasing the use of RCA in new concrete will require more incentives and market acceptance. For instance, a survey conducted in Ohio and California reveals that construction companies, demolition waste recyclers, and property managers are all aware of the environmental benefits of downcycling[87]. However, improved downcycling will require more external support from the government, effective communication among stakeholders, and affordable recycling technologies.

Component reuse refers to reusing modular components for new construction projects, which could be enabled by reversible or circular design (e.g., design for disassembly). For example, a recent case study of a nine-story building found that 60-90% of its columns, beams, hollow core slabs, and core walls could be potentially reused[88]. Taking into account the concrete fraction of each element, this case study implies that component reuse could save 68.3% of the concrete used. Therefore, reuse savings can be much higher than savings from recycling because reuse eliminates the need for CO_2-intensive cement production for new products. While component reuse is a promising end-of-life option, it faces deployment challenges. For example, a key barrier to component reuse could be building energy efficiency policies[89]. These policies usually pursue good thermal insulation through airtight connections between building components, which may not always be compatible with reversible or circular designs. Another key barrier is the accountability of end-of-life components is not clarified between construction companies and property owners.

Demolition waste stockpiling refers to extending the length of time that demolished concrete is stockpiled. During demolition, concrete rubble is crushed into smaller pieces, thereby increasing its total surface area and accelerating the carbonation process. Crushed concrete pieces are usually stockpiled for 0.4 years on average[6]. Extending the stockpiling duration will boost the CO_2 absorption process of demolished concrete. However, the maximum length of time that demolished concrete can stay stockpiled and the willingness of road agencies to stockpile should be taken into consideration. For example, the EU Construction and Demolition Waste Management Protocol and Guidelines suggest that the maximum stockpiling time is limited to one year[90].

3.4. Overview of considered low-carbon levers

The decarbonization levers considered in this report target different processes across the cement and concrete cycle (Figure 3-5) and offer CO_2 mitigations opportunities in various ways (Table 3-3). For example, clinker-to-cement ratio reductions can directly reduce CO_2 emissions, but they also decrease the CO_2 uptake capacity of cement. To analyze the CO_2 reduction mechanism of each lever, we integrate material, energy, CO_2 emission, and CO_2 uptake into a stock-flow model and develop a bottom-up, technology-rich, multilayered, cradle-to-cradle modeling framework.

This integrated modeling framework can capture the complex and non-additive interplay between the decarbonization levers mentioned above. In this integrated framework, we define parameters that can depict the impact of decarbonization levers, which will be used for scenario analysis. For different scenarios, we specify a target value for each parameter and quantify the resulting decarbonization effects. The decarbonization levers considered in this report are coded (e.g., L1a) and mapped onto the life cycle stages of the cement and concrete cycle (Figure 3-5). We name this integrated modeling framework **IMAGINE Concrete**, short for Integrated modeling of the MAterial-enerGy-emIssion-uptake NExus in the cement and concrete cycle. Further details on the IMAGINE Concrete model, its publicly available code, and its simplified web-based user interface are available in the Appendix.

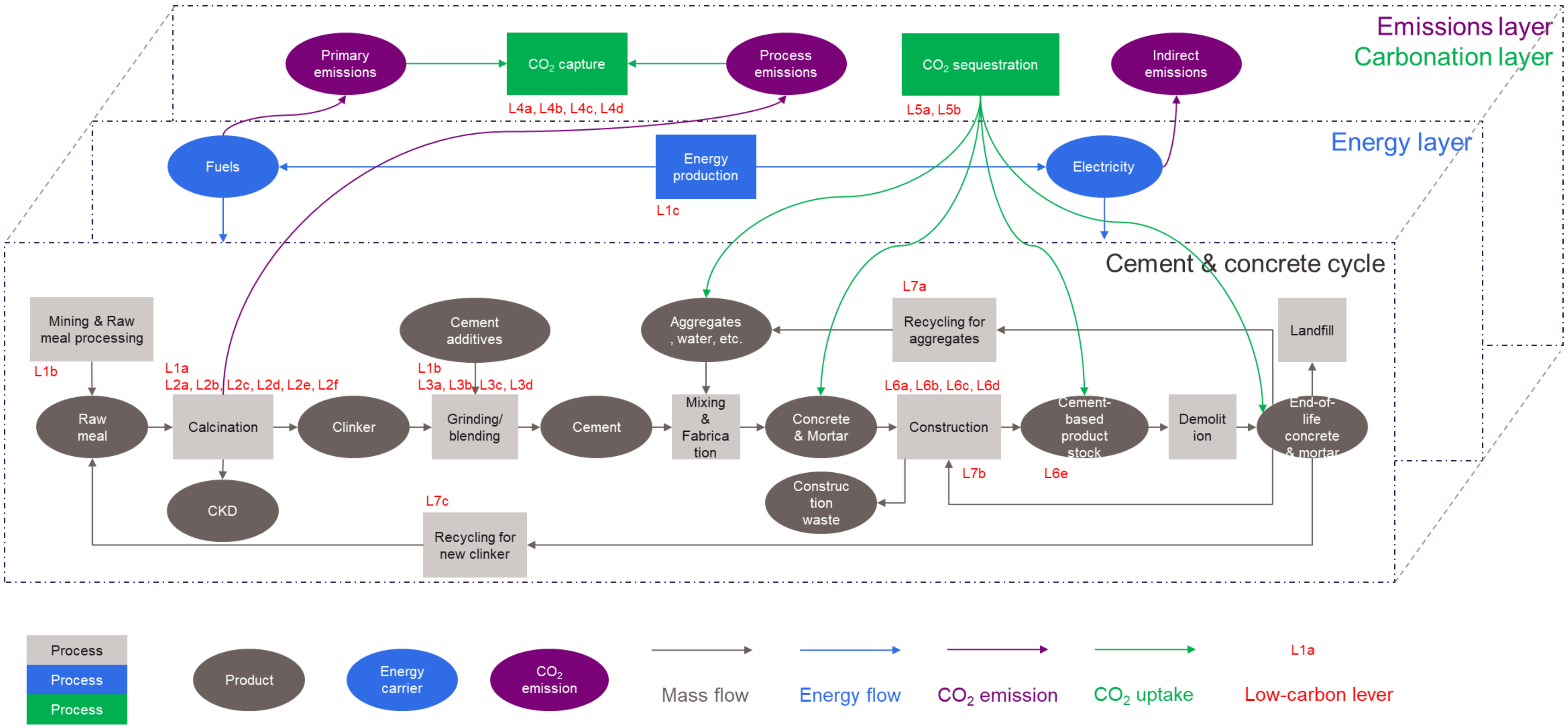

Figure 3-5. Integrated modeling of the MAterial-enerGy-emIssion-uptake NExus in the cement and concrete cycle (IMAGINE Concrete). Note: further details are provided in the Appendix.

Table 3-3. Impacts of each low-carbon lever on CO_2 fluxes within cement and concrete cycle.

Code	Low-carbon lever	Code	Technology option	Impacts on CO_2 fluxes
L1	Cement plant technology options	L1a	Kiln thermal efficiency improvements	Lower thermal energy intensity of clinker
		L1b	Milling/grinding electrical efficiency improvements	Lower electrical energy intensity of cement
		L1c	Low-carbon fuel utilization	Lower fuel CO_2 emission intensity of clinker
L2	Lower-carbon cement chemistries	L2a	Reactive belite cement	Lower process CO_2 emission intensity of clinker Lower thermal energy intensity of clinker Lower carbonation capacity of clinker
		L2b	Belite-ye'elimite-ferrite cement (BYF)	
		L2c	Carbonatable calcium silicate cement (CCSC)	
		L2d	Calcium sulfoaluminate cement (C$AB)	
		L2e	Celitement	
		L2f	Magnesium oxides derived from magnesium silicates (MOMS)	
L3	Clinker-to-cement ratio reductions	L3a	Blended cement with limestone	Lower process CO_2 emission intensity of cement Lower fuel CO_2 emission intensity of cement Lower carbon storage capacity of cement
		L3b	Blended cement with fly ash	
		L3c	Blended cement with ground granulated blast furnace slag	
		L3d	Blended cement with natural pozzolana	
		L3e	Blended cement with calcined clay	
L4	At-plant carbon capture and sequestration	L4a	Oxy-fuel firing	Increased CO_2 uptake
		L4b	Post-combustion	
L5	Carbon utilization	L5a	Concrete curing with CO_2	Increased carbonation rate of in-use concrete Lower cement intensity of concrete
		L5b	Mineralization to aggregates using end-of-life cement-based materials	Carbonation rate of end-of-life cement Less virgin aggregate demand
		L5c	Mineralization to aggregates using iron and steel slag	Increased carbonation capacity of concrete Less virgin aggregate demand
		L5d	Mineralization to aggregates using fly ash	
		L5e	Mineralization to aggregates using lime mud	
		L5f	Mineralization to aggregates using red mud	

Code	Low-carbon lever	Code	Technology option	Impacts on CO_2 fluxes
L6	Material efficiency strategies	L6a	Material-efficient design	Lower concrete or cement intensity per m^2 or km
		L6b	Material substitution	Lower concrete intensity per m^2 Increased CO_2 uptake
		L6c	Fabrication yield improvement	Lower concrete intensity per m^2 or km
		L6d	More intensive use	Lower construction activity levels
		L6e	Lifetime extension	Lower construction activity levels Increased carbonation time of in-use concrete
L7	End-of-life options	L7a	Downcycling	Less virgin aggregate demand Increased carbonation time of end-of-life concrete
		L7b	Component reuse	Less concrete demand per m^2 Increased carbonation time of end-of-life concrete
		L7c	Demolition waste stockpiling	Increased carbonation time of end-of-life concrete

3.5. Accounting for positive and negative CO_2 fluxes

As shown in Figure 3-6, the entire cement and concrete cycle is associated with numerous positive and negative CO_2 fluxes. Establishing proper accounting principles for the overall CO_2 balance is key to generating credible numbers for the CO_2 mitigation potential of each low-carbon lever. In the model, the following accounting principles are utilized. The first two accounting principles target bioenergy with carbon capture and storage (BECCS). The **first** accounting principle treats CO_2 emissions from burning bioenergy as neutral, assuming that biomass cultivation and associated land-use change are practiced sustainably. The **second** accounting principle regards CO_2 removed by carbon capture and storage as a negative CO_2 flux. Following these two principles, BECCS can deliver net-negative emissions. These accounting principles of BECCS have been commonly used in global energy transition analysis[11]. The **third** accounting principle targets CO_2 utilization technologies, which treats CO_2 sequestered through CO_2 utilization technologies as a negative CO_2 flux. The **fourth** accounting principle targets natural cement carbonation, which treats CO_2 sequestered by natural cement carbonation as a negative CO_2 flux. This CO_2 flux is a function of time, and the rate of cement carbonation varies by life cycle stage and location (see details in the Appendix).

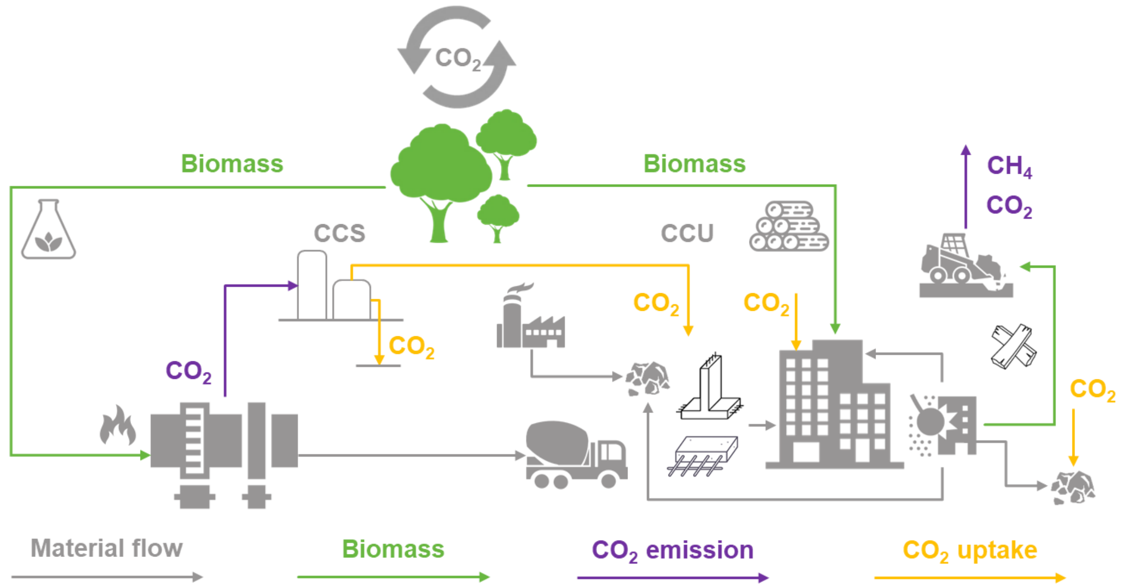

Figure 3-6. Accounting principles for positive and negative CO_2 fluxes related to biomass use, CCS, natural carbonation, and carbon utilization in the IMAGINE Concrete modeling framework.

The **fifth** accounting principle targets the in-use stage of engineered timber. It regards carbon locked in structural timber materials as a negative CO_2 flux[ix]. This CO_2 flux is expressed as CO_2 equivalents in the year when the timber is put into place in new construction. The **sixth** accounting principle targets the production and end-of-life stages of timber. It takes into account CO_2 released during its production stage and end-of-life stage. After the timber is discarded, it can either be landfilled or combusted with or without energy recovery. Combusted timber will release CO_2, whereas a fraction of landfilled timber will decompose and release methane into the atmosphere. For landfilled timber not subject to decomposition, it is assumed that CO_2 will be permanently sequestered.

4. Pathways toward net-zero emissions

In the preceding chapter, we have identified decarbonization levers spanning the whole cement and concrete cycle. In this chapter, different possible futures for the cement and concrete cycle are explored, reflecting different combinations of these identified levers. As summarized in Figure 4-1, prior studies have considered pathways for decarbonizing cement production at regional and global levels. In general, most of them have focused on levers aimed at the cement plant, inclusive of kiln efficiency, low-carbon fuels, and clinker-to-cement ratio reductions. As discussed above, these levers face limitations, and there is a high reliance on CCS to reach CO_2 emission reduction targets. However, it is becoming more apparent that CCS is far behind where it needs to be, raising the need for exploring a more comprehensive portfolio of levers[91]. A few studies have further considered materials efficiency strategies but in a limited fashion; however, they indicate additional mitigation potential. Few or no studies have comprehensively considered lower-carbon cement chemistries or carbon utilization, while studies on material substitution have typically been done on case-specific and/or static bases that don't consider the role of materials substitution as part of an interrelated package of levers. IMAGINE Concrete includes all levers and can be used to explore different combinations of these levers involving various stakeholders and leading to different decarbonization pathways. Therefore, our scenario analysis provides a more complete and useful view of the decarbonization opportunity space, which goes beyond those pathways envisaged in prior studies.

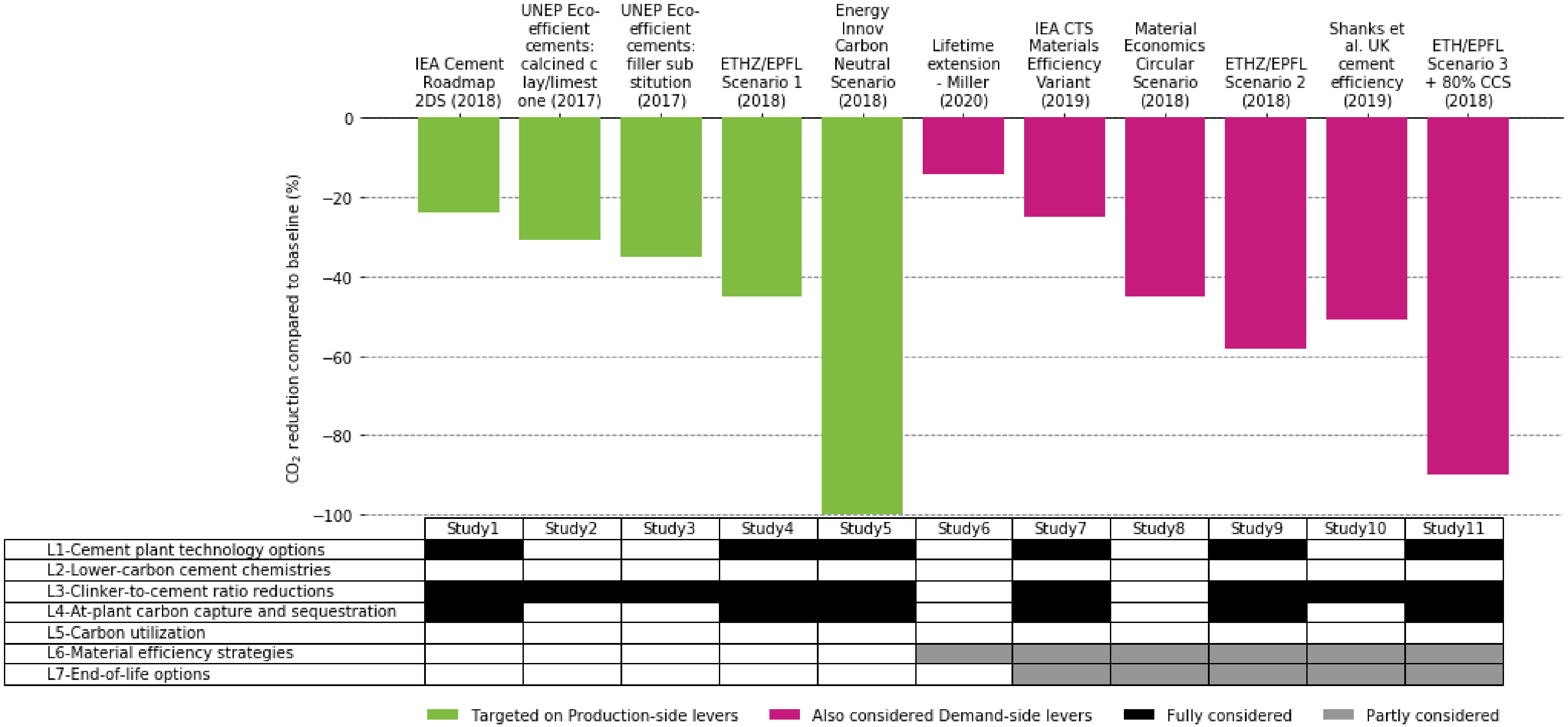

Figure 4-1. Overview of decarbonization levers considered in previous studies.

Note: "fully considered" means all levers in a category are considered, whereas "partly considered" means not all levers in a category are considered. Sources: IEA Cement Roadmap[10]; UNEP Eco-efficient cements[21]; ETHZ/EPFL report[48]; Energy innovation report[49]; US lifetime extension study[50]; IEA Material efficiency report[16]; Material economics report[18]; UK cement efficiency study[17].

4.1. Scenarios and narratives

Our scenario analysis aims to assess pathways for reaching net-zero around mid-century, consistent with the goals of the Paris Agreement. Scenario analysis involves identifying coherent storylines that describe plausible future emission trajectories characterized by imagined sequences of events. Scenario building allows us to explore decarbonization possibilities for the cement and concrete cycle with specific contexts for these possible futures, but it demands some degree of narration for social and institutional factors that are unquantifiable (e.g., businesses' willingness to invest in emerging levers, societal acceptance of more compact living spaces, and market acceptance of material efficiency strategies). Therefore, the decarbonization scenarios presented here weave together qualitative narratives and quantitative indicators, and each scenario represents a plausible future for the cement and concrete cycle within specific contexts.

In this report, four illustrative scenarios are constructed, which are discussed below and summarized in Table 4-1.

- The **Current Ambitions** scenario embodies the best available estimates for future cement and concrete demand and expected energy efficiency gains and CO_2 emission mitigation efforts across the cement and concrete cycle between now and mid-century. As such, it reflects the current ambitions of system-wide stakeholders, capturing the expected joint efforts taken by governments and industry. Simply put, it represents the best guess at where total cement and concrete cycle emissions may be headed. The Current Ambitions scenario is constructed by emulating trends in socio-economic drivers and technology and policy progress in the IEA's Reference Technology Scenario (RTS) from ETP 2017[11].
- In contrast, the **Frozen Progress** scenario assumes the same demand trends for cement and concrete as the Current Ambitions scenario, but it reflects a future where no technological progress will take place in cement and concrete production. As such, it is solely a counterfactual scenario whose intended purpose is to quantify how much of the decarbonization challenge may already be met by expected deployments of various levers in the Current Ambitions scenario.

However, there is still a large gap between the projections in the Current Ambitions scenario and a trajectory consistent with achieving net-zero emissions around mid-century. To explore how this gap can be closed, we construct two deep decarbonization scenarios that reflect substantially different portfolios of levers and different degrees of engagement of stakeholders across the cement and concrete cycle.

- The **Production-Centric** scenario reaches net-zero emissions solely through low-carbon levers (i.e., L1-L5) that reduce the CO_2 intensities of cement and concrete production. There is no reduction in cement and concrete demand compared to the Current Ambitions scenario. As such, this scenario adheres to the traditional business models of the cement and concrete industries, and mainly relies on actions that can be taken by stakeholders in these two industries to achieve the net-zero vision.
- In the **Whole-Systems** scenario, the full portfolio of levers (i.e., L1-L7) is deployed with an emphasis on reducing societal demand for cement and concrete and relieving the pressure on production-centric levers. This scenario embraces new business models

and policy regimes in which efforts by the cement and concrete industries are complemented with efforts by architects, road designers, urban planners, construction companies, standards organizations, and the public to seize synergistic decarbonization opportunities along the whole cement and concrete cycle.

Table 4-1. Summary of scenario narratives.

Scenario	Narrative
Frozen Progress	Production CO_2 intensities for cement and concrete are frozen at 2018 values. Cement and concrete demands follow projections in the Current Ambitions scenario.
Current Ambitions	Technology and policy progress and socio-economic drivers of concrete demand emulate the IEA ETP 2017 Reference Technology Scenario (RTS).
Production-Centric	Aggressive deployment of production-centric levers (L1-L5) will take place, preserving the traditional business models of the cement and concrete industries. Cement and concrete demands follow projections in the Current Ambitions scenario.
Whole-Systems	Levers to reduce cement and concrete demand (L6-L7) are deployed in parallel to production-centric levers (L1-L5), relieving pressure on the latter while engaging a broader community of stakeholders. Cement and concrete demand is significantly reduced compared to the Current Ambitions scenario.

Table 4-2 summarizes how these scenario narratives map to the inclusion and aggressiveness of each considered low-carbon lever. In the **Frozen Progress** scenario, none of the low-carbon levers is considered, with resulting CO_2 fluxes across the cement and concrete cycle following the trends of cement and concrete demand assumed in the Current Ambitions scenario and depicted in Figure 2-7. In the **Current Ambitions** scenario, two traditional levers (L1 and L3) and one emerging production-side lever (L4) are considered, to a large extent, emulating the narratives of the IEA ETP 2017 RTS[10,26]. In the **Production-Centric** scenario, two additional emerging production-side levers (L2 and L5) are included, and aggressive deployment of all considered levers will take place. In the **Whole-Systems** scenario, the reliance on L2 and L4 is relieved by the inclusion of L6 and L7, meaning that deployment of L2 and L4 is less aggressive compared with the Production-Centric scenario. The quantitative assumptions regarding the aggressiveness of deployment for each lever in each scenario are summarized in Table 4-3. As mentioned at the beginning of Chapter 3, on top of the preceding seven low-carbon levers, we consider improvements in electricity grids, transport efficiency, and energy efficiencies in the production of virgin aggregates, recycled aggregates, and concrete, which are aligned with recent scenario analyses[92,93]. More specifically, CO_2 emission reductions pertaining to electricity grids, transport efficiency, and aggregates and concrete production efficiencies are more aggressive in our two deep decarbonization scenarios.

Table 4-2. Deployment of low-carbon levers in each scenario.

Code	Lever	Frozen Progress	Current Ambitions	Production-Centric	Whole-Systems
L1a	Kiln thermal efficiency improvements		+	++	++
L1b	Milling/grinding electrical efficiency improvements		+	++	++
L1c	Low-carbon fuel utilization		+	++	++
L2a	Reactive belite cement			++	+
L2b	Belite-ye’elimite-ferrite cement (BYF)			++	+
L2c	Carbonatable calcium silicate cement (CCSC)			++	+
L2d	Calcium sulfoaluminate cement (C$AB)			++	+
L2e	Celitement			++	+
L2f	Magnesium oxides derived from magnesium silicates (MOMS)			++	+
L3a	Blended cement with limestone		+	++	++
L3b	Blended cement with fly ash		+	++	++
L3c	Blended cement with ground granulated blast furnace slag		+	++	++
L3d	Blended cement with natural pozzolana		+	++	++
L3e	Blended cement with calcined clay		+	++	++
L4a	Oxy-fuel firing		+	++	+
L4b	Post-combustion		+	++	+
L5a	Concrete curing with CO_2			++	++
L5b	Mineralization to aggregates using end-of-life cement-based materials			++	++
L5c	Mineralization to aggregates using iron and steel slag			++	++
L5d	Mineralization to aggregates using fly ash			++	++
L5e	Mineralization to aggregates using lime mud			++	++
L5f	Mineralization to aggregates using red mud			++	++
L6a	Material-efficient design				++
L6b	Material substitution				++
L6c	Fabrication yield improvement				++
L6d	More intensive use				++
L6e	Lifetime extension				++
L7a	Downcycling				++
L7b	Component reuse				++
L7c	Demolition waste stockpiling				++

Note: + stands for less aggressive targets; ++ stands for aggressive targets.

4.2. Quantitative assessment of deployment levels

In this section, we conduct a global literature review to identify data sources, compile and integrate those data into a cohesive picture of both present-day values and values achievable by 2060, and (when possible) differentiate target values by country. Whenever possible, target values of technology and policy options were derived based on existing roadmaps and scenario analyses, many of which take into account achievable paces of adoption for each lever (Table 4-3). In choosing our target values, we only considered technical feasibility and availability of required feedstocks, with no consideration of investment or deployment costs. For each lever, we assume a linear trend between now and 2060 as a simplifying assumption, albeit a quicker adoption could lead to faster CO_2 emission reduction. However, the IMAGINE Concrete model (see Appendix) enables the user to consider any combination of levers and deployment rates to generate their own custom decarbonization scenarios.

Table 4-3. Target values of each low-carbon lever.

Lever	Present-day value 2017	Target value 2060 (+)	Target value 2060 (++)
L1a Kiln thermal efficiency improvements	MJ/t clinker	MJ/t clinker	MJ/t clinker
China	3264	3250	3150
United States	3768	3250	3150
India	3101	3075	3050
L1b Milling/grinding electrical efficiency improvements	kWh/t cement	kWh/t cement	kWh/t cement
China	102	95	90
United States	134	95	90
India	74	71	70
L1c Low-carbon fuel utilization	Share of low-carbon fuel	Share of low-carbon fuel	Share of low-carbon fuel
China	~11%	~30%	~45%
United States	~15%	~30%	~45%
India	~3%	~25%	~40%
L2 Lower-carbon cement chemistries	Share of lower-carbon cement chemistries	Share of lower-carbon cement chemistries	Share of lower-carbon cement chemistries
China	0%	~37%	~47%
United States	0%	~47%	~69%
India	0%	~37%	~47%
L3 Clinker-to-cement ratio reductions	Share of clinker	Share of clinker	Share of clinker
China	79%	65%	60%
United States	90%	65%	60%
India	69%	65%	60%
L4 At-plant carbon capture and sequestration	Adoption rate	Adoption rate	Adoption rate
China	0%	18%	100%
United States	0%	18%	100%
India	0%	18%	100%
L5a Concrete curing with CO_2	Adoption rate	Adoption rate	Adoption rate

Lever	Present-day value 2017	Target value 2060 (+)	Target value 2060 (++)
China	0%	N/A	100%
United States	0%	N/A	100%
India	0%	N/A	100%
L5b **Mineralization to aggregates using end-of-life cement-based materials**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	10%
United States	0%	N/A	10%
India	0%	N/A	10%
L5c **Mineralization to aggregates using iron and steel slag**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	1%
United States	0%	N/A	1%
India	0%	N/A	1%
L5d **Mineralization to aggregates using fly ash**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	1%
United States	0%	N/A	1%
India	0%	N/A	1%
L5e **Mineralization to aggregates using lime mud**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	0.5%
United States	0%	N/A	0.5%
India	0%	N/A	0.5%
L5f **Mineralization to aggregates using red mud**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	1%
United States	0%	N/A	1%
India	0%	N/A	1%
L6a **Material-efficient design**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	100%
United States	0%	N/A	100%
India	0%	N/A	100%
L6b **Material substitution**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	10%
United States	0%	N/A	10%
India	0%	N/A	10%
L6c **Fabrication yield improvement**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	100%
United States	0%	N/A	100%
India	0%	N/A	100%
L6d **More intensive use**	Reduction rate	Reduction rate	Reduction rate
China	0%	N/A	7%
United States	0%	N/A	7%
India	0%	N/A	7%

Lever	Present-day value 2017	Target value 2060 (+)	Target value 2060 (++)
L6e **Lifetime extension**	Years	Years	Years
China	32 (Buildings) 30 (Roads)	N/A	70 (Buildings) 40 (Roads)
United States	78 (Buildings) 40 (Roads)	N/A	90 (Buildings) 45 (Roads)
India	31 (Buildings) 34 (Roads)	N/A	70 (Buildings) 40 (Roads)
L7a **Downcycling**			
China	0.01%	N/A	10%
United States	3.6%	N/A	10%
India	1%	N/A	10%
L7b **Component reuse**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	10%
United States	0%	N/A	10%
India	0%	N/A	10%
L7c **Demolition waste stockpiling**	Adoption rate	Adoption rate	Adoption rate
China	0%	N/A	100%
United States	0%	N/A	100%
India	0%	N/A	100%

Note: + stands for less aggressive targets; ++ stands for aggressive targets.

Cement plant technology options

L1a-Kiln thermal efficiency improvements. As discussed in Chapter 3, conventional cement kiln technologies are approaching their practical efficiency limit, particularly in India where best available kiln adoption is widespread. However, potential remains in the United States and China for upgrading kilns to the state-of-the-art by mid-century. The current state-of-the-art kiln is the dry kiln with 6 cyclone preheating stages and precalcination, for which theoretical modeling and empirical data indicate thermal efficiency within a range of 3000 to 3400 MJ/t clinker[26]. The average thermal efficiency of today's kilns is 3768 and 3264MJ/t clinker in the United States and China, respectively [3], as shown in Figure 3-1. Given a typical cement kiln lifespan of 40 years, it is assumed that a full stock turnover of all kilns is technically feasible in the United States and China by 2060[26]. Conservatively, we adopt a range of 3150 MJ/t clinker (++) to 3250 MJ/t clinker (+) by 2060 to reflect uncertainty in technological progress. In the absence of a detailed kiln technology stock turnover model, we assume that the thermal efficiency improvement will be linear between 2019 and 2060 as a simplifying assumption, consistent with the CSI/ECRA-Technology Papers 2017[26]. The more aggressive target (++) reflects that more kilns will be upgraded to the state-of-the-art.

L1b-Milling/grinding electrical efficiency improvements. The reported average electrical efficiency of today's milling/grinding capacity is 134, 102, and 74 kWh/t cement for the United States, China, and India[3], respectively, as shown in Figure 3-2. The electrical efficiency differences are partly explainable by differences in fineness requirements between countries, wherein increasing fineness increases average energy intensity. Theoretical analysis indicates that single-particle comminution requires much less energy than largescale industrial grinding equipment[26]. The average electrical efficiency of the global 10% best in class is 85 kWh/t cement, but expected improvements in electrical efficiency will be partly offset by energy penalties induced by other low-carbon levers. Therefore, we conservatively assume that the 2060 electrical efficiency will range from 90 to 95 kWh/t cement with linear improvement rates, consistent with the CSI/ECRA-Technology Papers 2017[26]. Likewise, the most aggressive target (++) reflects that more cement plants will be equipped with state-of-the-art single-particle comminution grinding technologies. We assume that India's electrical efficiency improvements will be minimal, consistent with the IEA Indian Cement Technology Roadmap[28].

L1c-Low-carbon fuel utilization. While waste fuels and biomass are currently used in limited quantities in all three countries (see Chapter 3), these quantities could increase considerably when sufficient supplies exist. In theory, cement kilns can operate 100% from waste fuels and biomass[94]; however, the calorific values of waste fuels and biomass is usually lower than conventional fuels. The pre-calciner of modern cement kilns, which burns up to ~60% fuels, allows the use of low-calorific fuels. Low-calorific waste fuels and biomass can be mixed into conventional fuels and burned in high-temperature combustion zones if such fuel mixes could satisfy the calorific requirement. Nevertheless, the future availability of low-carbon fuels in each country is subject to a range of technical, economic, political, and societal factors that are beyond the scope of this study. Therefore, we rely on IEA estimates for the quantities of low-carbon fuels that could be adopted. Expressly, we assume that ~25% (+) to ~40% (++) can be adopted by 2060 in India, per the IEA India Cement Technology Roadmap[28], and that China and the United States could adopt ~30% (+) to ~45% (++)[26]. The values for the United States and China reflect global average estimates given the lack of projections in these two countries. The more aggressive (++) target assumes that more kilns will be equipped with a pre-calciner and that sufficient supplies of low-carbon fuels will be available.

Lower-carbon cement chemistries

L2-Lower-carbon cement chemistries. While some of the considered low-carbon cement chemistries (e.g., Belite, BYF, CCSC, and CSA) can be produced in conventional cement kilns, they are currently limited to niche markets due to comparatively higher raw material costs, lack of reliable test methods, and lack of product standardization[26]. Although research on these cement chemistries has increased recently, the durability of these cement chemistries within the context of their use in concrete is less understood[34]. We assume that the applications of these cement chemistries will be limited to mortar and low compressive strength concrete (largely used for non-structural purposes) because they are usually used for applications subject to less load and thus associated with lower failure risk (e.g., floor binding, internal floor slabs, driveways, garages, and drainage). According to recent industry statistics[8,95], ~89% of cement is used for concrete in the United States. The strength class ≤C15 and strength class C16-C23 respectively account for ~40% and ~25% of the U.S. concrete market[95]. For China, an industry survey shows that ~72% of cement is used for concrete, and ≤C15 and C16-C23 respectively account for ~13% and ~13%[6]. We assume that China's values are applicable to India due to lack of available data. The adoption outlook for each of our considered low-carbon cement chemistries is uncertain[21]; therefore, we assume that each will be adopted equally and that their market shares will grow linearly to the maximum values assumed in 2060. The less aggressive value (+) assumes that the application of lower-carbon cement chemistries is limited to mortar and concrete products with strength class ⩽C15 in each country. The more aggressive value (++) assumes that the application of lower-carbon cement chemistries will further expand to the strength class C16-C23 market in each country.

Clinker-to-cement ratio reductions

L3-Clinker-to-cement ratio reductions. As discussed in Chapter 3, clinker substitution is a conventional lever that is pursued everywhere, but actual deployment levels vary widely. Currently, reported ratios are 89.6%, 78.9%, and 69.3% in the United States, China, and India, respectively, as shown in Figure 3-4. Values as low as 60% are currently possible[26], but the degree to which each country can achieve this level depends on several factors. Materials supply of SCMs is one factor, particularly for fly ash and slag, which may diminish in quantities in the future when the power sector is expected to be less coal-reliant and the steel sector more circular[96]. The supply of limestone and gypsum is less constrained. Another factor is the extent to which SCMs are permissible by local construction standards, which may limit what clinker-to-cement ratio can be attained[26]. Numerous scenarios for reducing the clinker-to-cement ratio have been published with target values ranging from 50% to 70%[18,21,48]. For all three countries, we assume that the CSI/ECRA target of 60% (++) is attainable, with a conservative assumption of 65% (+) as a less aggressive value. As a simplifying assumption, we also assume that the adoption of SCMs will grow linearly, which is consistent with gradual changes in operations and construction codes between today and 2060[10]. The more aggressive (++) value reflects a more promising future, where more SCMs are available, and utilization of SCMs is scaled up at a more rapid pace.

At-plant carbon capture and sequestration

L4-At-plant carbon capture and sequestration. Presently, only a few industrial-scale demonstrations globally (e.g., LEILAC in Belgium[97], Anhui Conch in China[37], and Norcem in Norway[38]) have equipped cement production with CCS, although several projects are in the pipeline[98,99]. Moreover, as a general-purpose decarbonization technology, CCS is far behind the deployment pace needed[12]. In this report, CCS is deployed aggressively in the Production-Centric scenario, given that it is necessary because other production measures alone cannot deliver net-zero emissions. In the Whole-Systems scenario, pressure is reduced and less aggressive deployment is required. For any at-plant CCS, we assume a capture efficiency range of 80% to 99% for both oxy-fuel firing and post-combustion, which is a function of various parameters that affect the gas-liquid equilibrium or gas-solid equilibrium, inclusive of equilibrium design, sorbent type, sorbent flow rate, temperature, pressure, etc[100,101]. The lower capture efficiency, which we apply to our less aggressive (+) target, reflects the current state-of-the-art CCS, which is based on a preliminary study of 10-20 large cement kilns[26]. Higher capture efficiency tends to increase the cost of CCS[102]. Therefore, assigning a higher capture efficiency for the aggressive (++) target implies that optimal but more costly CCS technologies will be deployed[26]. The CSI/ECRA-Technology Papers 2017 projects that 20-33% of the existing capacities will be replaced by new ones, depending on how aggressive the CCS deployment would be. The report assumes that 50% of the new capacities will be equipped with CCS and that 10% of the remaining existing capacities will be equipped with CCS. Therefore, we consider 18% as a less aggressive target and 100% as a more aggressive target. The aggressiveness of CCS deployment reflects future technical, political, and social conditions and cement plant lifetime.

Carbon utilization

L5a-CO_2 curing. CO_2 curing is not a new technology, but it is gaining increasing attention due to a greater focus on cement sector decarbonizations, with high profile examples including CarbonCure[47] and Solidia[103]. We consider CO_2 curing for both ready-mix and precast concrete products. For ready-mix, CO_2 curing involves installing a CO_2 injection unit[43,104], whereby a controlled supply of pressurized liquid CO_2 is injected into fresh concrete in the ready-mix truck or mixer. For precast products, CO_2 gas is injected into a chamber with constant pressure to facilitate CO_2 uptake during curing[105]. Both technologies are commercially available and technically feasible in any concrete application, and therefore we assume that 100% adoption by 2060 is attainable[42] (i.e., 100% of ready-mix and precast concrete will have CO_2 curing) in all three countries in 2060. We assume that the present penetration of CO_2 curing is negligible (i.e., 0%) for both ready-mix and precast plants in all countries because it is still at the early stages of commercialization. We assume that new plants will be built with CO_2 injection units or CO_2 curing chambers and that existing plants will be retrofitted. We assume linear adoption between now and 2060 as a simplifying assumption. We assume no differences between countries because CO_2 curing is technically applicable to all concrete demands each year. To calculate the net CO_2 savings, we consider three major effects. First, we estimate an average energy penalty of CO_2 transport and CO_2 injection, which is assumed to be 2.7 kg CO_2/t concrete[43]. Second, we assume that CO_2 injection will lead to a ~12% increase in the total CO_2 uptake of the concrete over its lifespan based on literature data[42]. The CO_2 uptake is expected to be different for OPC and lower-carbon cement chemistries because the alkali content of the latter ones is less. Third, we assume that CO_2 injection will improve the compressive strength of concrete by ~15% and assume that binder in both ready-mix and precast applications will be reduced by ~13% based on literature data[42]. As a simplifying assumption, we assume that CO_2 curing will be adopted linearly between now and 2060.

L5a-CO_2 mineralization. CO_2 mineralization is similar to CO_2 curing for precast concrete, which permanently sequesters CO_2 within the built environment. We consider five forms of waste as feedstocks for CO_2 mineralization: end-of-life cement-based materials, iron and steel slag, fly ash, lime mud, and red mud. The adoption of CO_2 mineralization is subject to the availability of these industrial wastes[22]. Due to the lack of regional data, we base our 2060 targets on global average estimates. Taking into account the supply limit to each waste, we assume that the global output of iron and steel slag, fly ash, lime mud, and red mud will respectively make up 1%, 1%, 0.5%, and 1% of the global concrete production by 2060. These percentages are based on estimated quantities of globally-available waste outputs[22] divided by the total concrete production. The percentages of iron and steel slag and fly ash ensure that feedstocks for clinker-to-cement ratio reductions are not affected. Moreover, we assume that the quantities of end-of-life cement-based materials will make up 10% of the global concrete production by 2060 because no supply limits exist. The adoption rate of this lever could be higher and play more important roles, if more feedstock is available. While wide-scale deployment of CO_2 mineralization depends on a range of factors (e.g., logistics of feedstock, technology scalability, and market viability), we assume that aggregates produced from CO_2 mineralization will substitute natural aggregates. Because CO_2 mineralization is still in its infancy, we assume that it will start from 0% and penetrate the market at a linear pace. Since the process of CO_2 mineralization is similar to CO_2 curing and no relevant public data are available, we assume that the energy penalty associated with CO_2 mineralization is the same as for CO_2 curing.

Material efficiency strategies

Our analysis involves estimating cement and concrete demand that relies on data on construction activity levels and cement and concrete intensities for different built environment end uses, which is referred to as a bottom-up approach.

As shown in Figure 4-2, estimated cement intensities or concrete intensities vary greatly by building type, and they are determined by various factors, such as a building's framing, height, construction practices, and building codes. Timber-frame buildings typically require less concrete than concrete-brick-frame or concrete-steel-frame buildings. Depending on data availability in each country, the building stock in China, the United States, and India is segmented into 9, 24, and 9 categories, respectively.

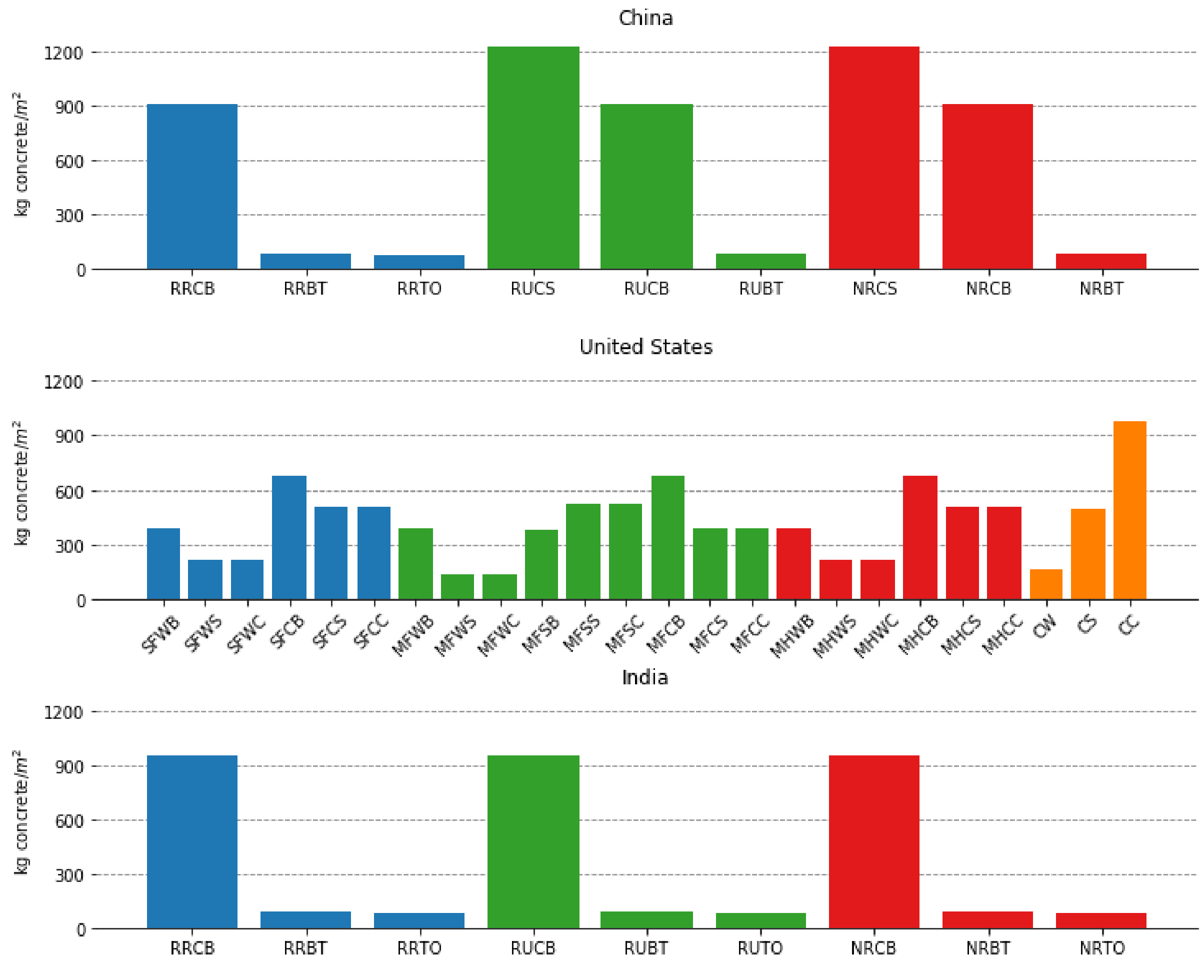

Figure 4-2. Concrete used per floor area in China, the United States, and India.

Note: the definition of segmentation for buildings is detailed in the Appendix. Abbreviations for China: RR-Residential-Rural; RU-Residential-Urban; NR-Non-Residential; CB-Concrete-Brick; BT-Brick-Timber; TO-Timber-Others; CS-Concrete-Steel. Abbreviations for the United States: SF-Single family; MF-Multi family; MH-Manufactured house; C-Commerical; WB-Wood frame-Basement; WS-Wood frame-Slab; WC-Wood frame-Crawlspace; SB-Steel frame-Basement;

SS-Steel frame-Slab; SC-Steel frame-Crawlspace; CB-Concrete frame-Basement; CS-Concrete frame-Slab; CC-Concrete frame-Crawlspace; WB-Wood frame-Basement; WS-Wood frame-Slab; WC-Wood frame-Crawlspace; CB-Concrete frame-Basement; CS-Concrete frame-Slab; CC-Concrete frame-Crawlspace; W-Wood frame; S-Steel frame; C-Concrete frame. Abbreviations for India: RR-Residential-Rural; RU-Residential-Urban; NR-Nonresidential; CB-Concrete-Brick; BT-Brick-Timber; TO-Timber-Others. Due to data availability, India's material intensities are assumed to be the same as China's. Sources: China and India[106,107], and United States[108,109,109,110].

As for roads, cement intensities or concrete intensities vary by road type, as shown in Figure 4-3. These variations are primarily determined by the geometric designs of roads, such as pavement layer thickness, lane width, and material choice. These design elements are usually subject to roadway design regulations, traffic volumes, common paving practices, local environmental conditions, and maintenance activities.

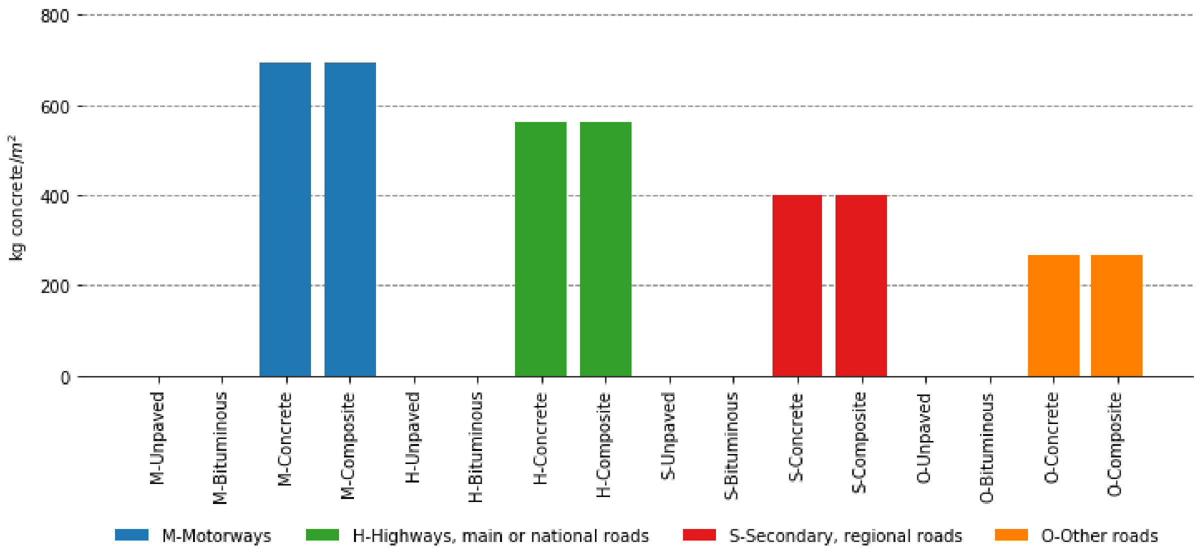

Figure 4-3. Assumptions for concrete used per pavement area in China, the United States, and India in 2017.

Note: the definition of segmentation for roads is detailed in the Appendix; due to data availability, India and China's material intensities are assumed to be the same as those of the United States[85].

It should be noted that in our decarbonizaton scenarios, the CO_2 savings of each material efficiency lever diminish over time because the CO_2 intensity of concrete also decreases due to the implementation of other levers.

L6a-Material-efficient designs. As stated in Chapter 3, we consider several at-construction measures that reduce binder intensity: performance-based concrete design, precast concrete, post-tensioning, and avoiding over-design of concrete structures. According to a UK case study[17], performance-based concrete design is applicable to all cement and concrete products, inclusive of building elements and pavement slabs. Precast concrete is applicable to floor slabs, ground floors, beams, and columns. Post-tensioning is applicable to floor slabs, beams, foundations, and columns. Avoiding over-design is applicable to floor slabs, ground floors, screeds, beams, and columns. These four measures combined could reduce concrete intensities by ~23%[17]. Due to lack of data for different types of building, we assume that this rate will be adopted by all building types and that the deployment of material-efficient design will linearly grow from 0% to 100% between now and 2060. Since material-efficient design is only included in the Whole-Systems scenario where the goal is to reduce cement and concrete demand, we do not consider a less aggressive target.

L6b-Material substitution. As discussed in Chapter 3, while engineered timber has been proven reliable for large structural components of mid-rise buildings (4-18 stories), the use of traditional timber has been primarily limited to low-rise residential and rural buildings. Nevertheless, given recent developments in engineered timber construction and an increasing number of successful applications[59], there is vast potential for utilizing more engineered timber in newly-built mid- or high-rise buildings moving forward. We assume that engineered timber can be applied to those concrete-intensive building types whose concrete intensity is greater than 300 kg/m^2, because previous studies indicate that buildings whose concrete intensity surpasses this value will also use concrete in building elements other than foundations[108,109,109–111].

According to 2017 estimates[69,112–115], the total share of floor area of new concrete-intensive buildings in China, the United States, and India that can potentially adopt engineered timber is approximately 92%, 43%, and 51%, respectively. In 2060, these shares will be approximately 99%, 45%, and 50%. A recent analysis indicates that engineered timber is suitable for replacing concrete in load-bearing components and enclosure systems above ground, and that the percent of concrete in residential and non-residential concrete-intensive buildings replaceable by engineered timber is ~55% and ~73%, respectively[56]. Given the lightweight property of engineered timber, the analysis further found that 1 tonne of concrete in residential and non-residential concrete-intensive buildings can be replaced by ~769 kg timber and ~344 kg timber, respectively[56]. Due to data limitations, we assume these replacement factors apply to all concrete-intensive framing types with concrete intensities greater than 300 kg/m^2.

Consistent with the aforementioned analysis[56], we also assume that 10% of new concrete-intensive buildings will be designed with engineered timber by 2060, which will come from sustainably managed forests. This assumption implies that all these countries will develop engineered timber manufacturing capacities and that building codes will be adjusted to allow the adoption of engineered timber. In addition, the increased demand for engineered timber could potentially be covered by harvesting roundwood[116,117] and bamboo[118], and diverting roundwood from use as fuelwood[119]. According to statistics from FAO (detailed in the Appendix), a large fraction of roundwood produced in China and India is used as fuelwood. We assume that the adoption rate for engineered timber construction will linearly grow from 0% to 10% between now and 2060. Another important assumption is end-of-life treatment of engineered timber will follow the same protocol as traditional timber, which is an assumption that should be revisited in future studies when engineered timber waste management is further developed.

L6c-Fabrication yield improvement. Fabrication yield losses arise primarily from on-site construction activities for which too much quantity is ordered, formworks are filled sloppily, and building components and paving slabs are not accurately specified[63]. While these practices vary widely from site to site, it is estimated that 1-3% of cement and concrete presently shipped to construction sites end up as waste[6]. Better design and improved material flow management can reduce fabrication yield losses. Introducing digital technologies (e.g., building information modeling) can facilitate the zero waste transition. Case studies show that it is technically possible to eliminate 100% of these losses by improving construction practices[16,17]. Therefore, we assume that 100% of fabrication yield losses will be avoided by 2060 and that fabrication yield will be improved linearly between now and then.

L6d-More intensive use. The climate change and sustainable development research communities have been looking into decent living space requirements that are consistent with low societal energy demand[64]. For example, a recent low energy demand scenario proposes that 30 m^2 per capita can offer a decent living standard globally[64], which is far below the per capita housing floor space in the United States (~61 m^2). According to our estimates, the present-day per capita housing floor area is ~35 m^2 in China and ~13 m^2 in India. For per capita non-residential/commercial buildings, the present-day per capita values for the United States, China, and India are ~25 m^2, ~17 m^2, and ~3 m^2, respectively. Similarly, road length per thousand people varies by country, and its present-day values are ~21 km in the United States, ~3.4 km in China, and ~3.5 km in India, respectively. Therefore, the acceptability of this material efficiency lever is uncertain and is likely to vary by country[120]. Moreover, a transition toward more sustainable lifestyles (e.g., reasonably-sized building design, space-sharing, and ride-sharing) will require fundamental societal and behavioral changes. For instance, space reduction entails profound changes in people's attitudes toward living and working with less space. Our baseline projections of floor area are consistent with the IEA RTS projections[11,121]. We assume that the growth rate of road length will slow down and approach 0% by 2060. In the Whole-Systems scenario, we assume that the 2060 projected per-capita values of building stocks and road stocks will be reduced by ~7%, reflecting a moderate level of take-up and leading to a 10-14% reduction in newly-constructed floor area and road length compared to our Current Ambitions scenario in 2060.

L6e-Lifetime extension. The lifetimes of buildings and roads are not merely determined by physical durability, but also social and economic factors. The current average lifetime of buildings (both residential and non-residential) is ~78 years, ~32 years, and 31 years in the United States[67,68], China[24,69–83], and India[30,71,84], respectively. For the concrete layer of roadways, the average maintenance interval is ~40 years, ~30 years, and 34 years in the United States[85], China[74,80–83], and India[71], respectively. As stated in Chapter 3, improved design and better planning could extend the actual lifespan. Extending the lifetime implies that new buildings and new/renovated roads will be built with more adaptable and durable designs and better urban planning. We consider this lever for new buildings and new/renovated roads. For both residential and non-residential buildings, we assume that the lifetime will increase linearly to 90 years, 70 years, and 70 years by 2060 in the United States, China, and India, respectively. For roads, we assume that the maintenance intervals will increase linearly to 45 years, 40 years, and 40 years in the United States, China, and India, respectively. These values may be attainable through targeted policies and behavioral changes (e.g., less traffic flow), as indicated in previous studies[64,84,122].

End-of-life options

L7a-Downcycling. As discussed in Chapter 3, we consider downcycling as a measure of substituting virgin aggregates in new concrete. Utilizing RCA can avoid mining and transport of virgin aggregates. Moreover, incorporating more RCA in new concrete can boost the CO_2 uptake of uncarbonated cement in RCA because cement carbonation is more rapid in the use stage as compared to the end-of-life stage during which end-of-life concrete is buried. Two other opportunities exist. First, RCA can also be used as road base materials (e.g., sand and gravel), but whether doing so has CO_2 reduction benefits highly depends on transport distance[123]. Second, recycled unhydrated cement fines from end-of-life cement-based materials can be potentially used as binders in new concrete[124]; however, this end-of-life option requires high upfront investment because its yield is marginal. Therefore, we did not include these two options. We assume that the downcycling rate for demolished concrete will increase to 10% at a linear pace between now and 2060. The value reflects the supply limits of end-of-life cement-based materials arising from buildings and roads, which are computed by the stock-flow model in the IMAGINE Concrete framework (see the Appendix).

L7b-Component reuse. This lever is enabled by reversible or circular design in new buildings (e.g., design for disassembly). We assume that 10% of newly-constructed building floor area can adopt this design by 2060 and that it will penetrate the market at a linear pace, reflecting a moderate level of take-up. Component reuse will avoid virgin concrete use in newly-built buildings, but the material efficiency strategies discussed above will also diminish the quantities of end-of-life concrete components. The availability of end-of-life cement-based materials is simulated by IMAGINE Concrete's stock-flow model. In addition, we assume that component reuse enabled by reversible or circular design does not lead to extra energy consumption in end-of-life building deconstruction and nor in new construction materials transport[88].

L7c-Demolition waste stockpiling. This lever aims to extend the length of time stockpiling demolished concrete, thereby allowing for more CO_2 uptake by demolished concrete[125]. Crushed concrete pieces are usually stockpiled for 0.4 years on average[6], and we assume that the stockpiling time will be extended to one year. While the maximum length of stockpiling is restricted by regulations, it is technically feasible to deploy this lever to 100% of demolished concrete. Therefore, we assume that the adoption of demolition waste stockpiling can reach 100% with a linear growth rate between now and 2060 to explore the mitigation potential of this lever.

4.3. Today's ambitions

Figure 4-4 summarizes the projected CO_2 emission reductions associated with the Current Ambitions scenario as compared to the Frozen Progress scenario. These results suggest that, while expected improvements related to cement plant efficiencies, clinker-to-cement ratio reductions, low-carbon fuel utilization, and at-plant CCS will lead to substantial CO_2 savings in each country, current ambitions will fall far short of achieving net-zero emissions across the cement and concrete cycle by mid-century. The extent to which each lever contributes to expected CO_2 emission reductions varies considerably by country, given key differences in their underlying technology makeup, fuel mixes, and production practices.

For instance, expected kiln thermal efficiency improvements (lever L1a) and milling/grinding electrical efficiency improvements (lever L1b) are projected to save considerable amounts of CO_2 in the United States because there is still ample room for improving energy efficiency in many US cement plants, whereas plants in China and India are already highly energy efficient. Similarly, expected clinker-to-cement ratio reductions (lever L3) will contribute the most to CO_2 savings in the United States and China, but will deliver limited future savings in India, where low clinker-to-cement ratios have largely already been adopted. At-plant CCS (lever L4) is expected to deliver modest absolute CO_2 reductions in all three countries, but still represents the largest mitigation wedge in India given small expected improvements to low-carbon fuel use and clinker-to-cement ratio reductions.

Overall, in the Current Ambitions scenario, the combined 2060 emissions of buildings and roads are approximately 117, 11, and 31 Mt of CO_2 lower than the Frozen Progress scenario in China, the United States, and India, respectively. To reach net-zero emissions, however, an additional 282, 19, and 105 Mt of CO_2 emissions must be eliminated by 2060 in China, the United States, and India, respectively, which represent substantial emissions gaps to be closed in all three countries.

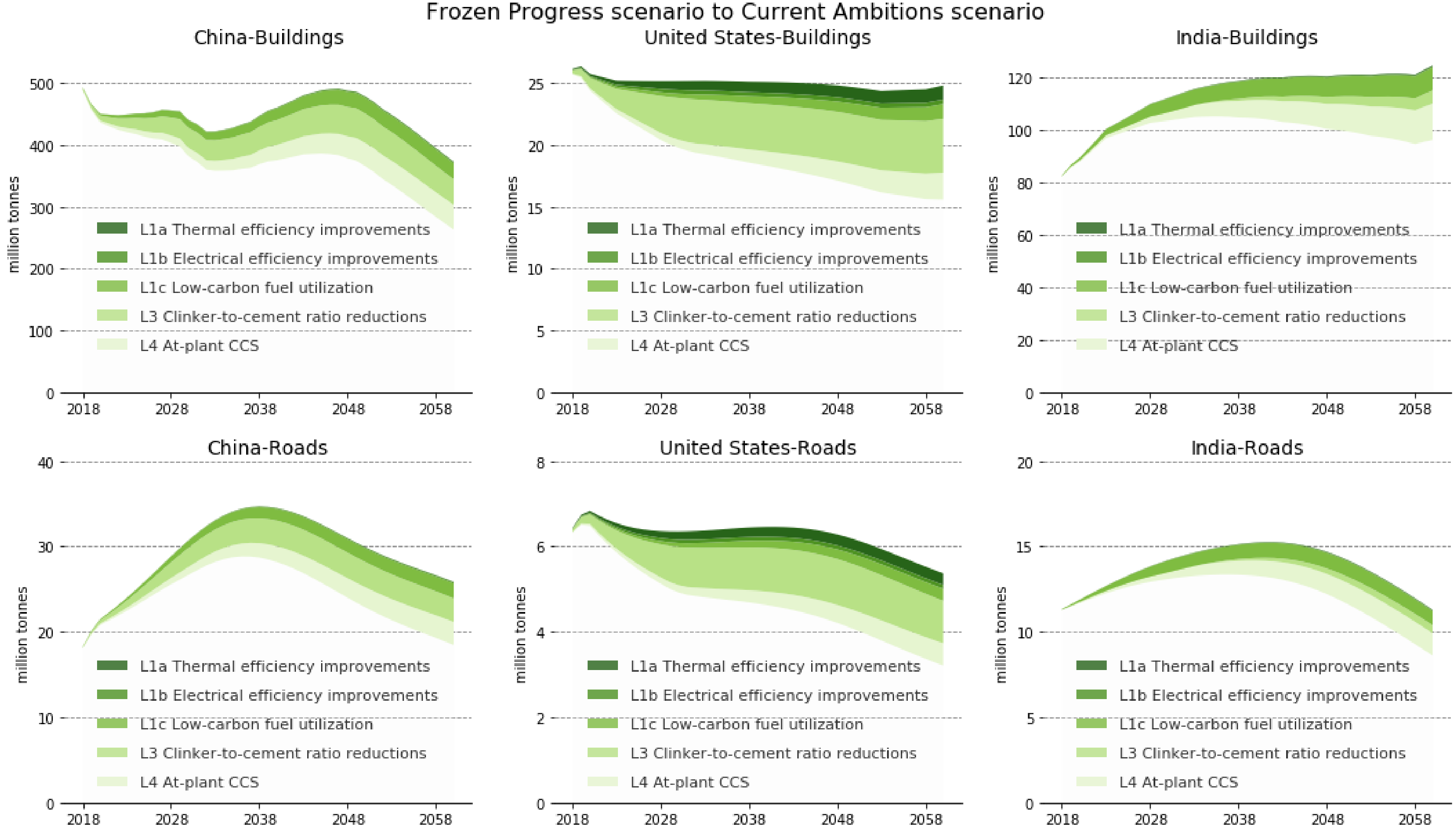

Figure 4-4. CO_2 emissions in the Frozen Progress scenario (upper bound) and CO_2 emission reductions by decarbonization levers considered in the Current Ambitions scenario (lower bound).

Note: values presented are net CO_2 emissions.

4.4. Two diverging pathways to deep decarbonization

As discussed in Section 4.1, the Production-Centric and Whole-Systems scenarios represent two different visions for achieving net-zero CO_2 emissions across the cement and concrete cycle by mid-century on top of the Current Ambitions scenario. The former scenario focuses primarily on actions that can be taken by cement and concrete producers within existing business models and that do not require reductions in societal demand for cement and concrete. The latter scenario integrates stakeholders across the entire value chain to consider how substantial reductions in societal demand for cement and concrete can contribute to the decarbonization agenda. While both scenarios reach net-zero emissions, there are major differences with respect to the timing and scales of the levers involved and the value chain participants needed for their adoption.

Production-Centric scenario

As shown in the upper panel of Figures 4-5 through 4-10, in the Production-Centric scenario, on top of the progress envisaged in the Current Ambitions scenario, all three countries can further seize kiln thermal efficiency improvements (lever L1a), milling/grinding electrical efficiency improvements (lever L1b), low-carbon fuel utilization (lever L1c), and clinker-to-cement ratio reductions (lever L3) over the coming decades. The additional emission reductions associated with these traditional cement plant levers vary by country. In the United States, China, and India, an additional abatement of ~3, ~37, and ~13 Mt is associated with these levers, respectively. However, the relative importance of clinker-to-cement ratio reductions differs by country due to the varying present-day ratios adopted in each country. Whereas China has substantial room for improvement, additional savings in India are modest, given the already-low clinker-to-cement ratios achieved by today's Indian cement industry.

Even after the full potential of conventional cement plant levers is seized, emissions gaps of 16, 245, and 92 Mt CO_2 must be closed by mid-century to achieve net-zero emissions in the United States, China, and India, respectively. To close these gaps, each country will have to aggressively pursue the adoption of at-plant CCS (L4), lower-carbon cement chemistries (L2), CO_2 curing (L5a), and mineralization of captured CO_2 (L5b). L4 and L5 represent different CO_2 utilization routes, with the former targeting the cement production stage and the latter targeting the concrete manufacturing stage. All of these levers are currently commercialized but have minimal market deployment[12], which means that substantial acceleration of their adoption will be required to achieve the vision of the Production-Centric scenario.

In particular, at-plant CCS (L4) must rise to roughly 30% of all cement plants in each country by 2030—a level that is substantially higher compared to the IEA Cement Technology Roadmap[10]—and to 100% of all cement plants by 2060. Such a shift will require an across-the-board transformation in the production technologies of cement plants, which is a monumental task. Even with 100% adoption of at-plant CCS (L4), considerable emissions gaps will remain due to capture efficiency limits and emissions occurring elsewhere in the cement and concrete cycle. These gaps are partially filled by the use of lower-carbon cement chemistries (L2), which must be applied to 69%, 47%, and 47% of cement production in the United States, China, and India by mid-century, respectively, and by greater adoption of CO_2 curing (L5a) in both precast products and ready-mix concrete. The former measure (L2) saves more CO_2 in the United States compared with its contribution to CO_2 savings in China and India, because the U.S. share of low compressive strength concrete is relatively higher. CO_2

curing (L5a) must be applied to 100% of cement and concrete in the United States, China, and India by mid-century, respectively.

Finally, mineralization of captured CO_2 to produce artificial aggregates (L5b) must also be pursued to reach net zero, although the contributions of this lever are more limited due to materials supply constraints. Namely, limited quantities of alkaline industrial wastes will constrain the uptake of this lever, also considering that some of these wastes are already deployed as SCMs for clinker substitutes (L3). Our estimates of CO_2 sequestered via mineralization are smaller than a recent global study[22] that considers the same lever because the scope of our analysis is limited to several specific cement end-use segments within three countries. Still, this lever must be deployed to generate 44, 545, and 180 Mt of artificial aggregate by mid-century in the United States, China, and India, respectively. For context, these levels will substitute 13%, 16%, and 14% of total aggregate demand in 2060 in these three respective countries. These modest replacement levels underscore that limited alkaline waste quantities are the critical barrier to further adoption, as opposed to limits imposed by the aggregate market. Higher adoption levels may be feasible through mineralization of feedstock other than the considered industrial wastes[126], which could be the subject of future work.

Whole-Systems scenario

As indicated in the lower panel of Figures 4-5 through 4-10, in the Whole-Systems scenario, the traditional cement plant levers (L1 and L3) deliver similar savings as in the Production-Centric scenario, since these levers are already well-proven, broadly attainable given the technology stock turnover that will occur by mid-century, and present limited financial risk to cement producers. However, as shown in Table 4-3, to close the remaining emissions gap, the Whole-Systems scenario gives priority to levers that reduce societal demand for cement and concrete (L6 and L7). Through demand reductions, net-zero emissions can be achieved by mid-century with much less reliance on lower-carbon cement chemistries and at-plant carbon capture and sequestration, both of which need substantial R&D investments and perceived risk and cost reduction efforts to be deployed at the large scales required in the Production-Centric scenario. However, the role of lower-carbon cement chemistries (L2) will remain substantial, which is primarily related to the high share of mortar and low compressive strength concrete in all three countries. Carbon utilization (L5) spans over ready-mix plants and construction sites, potentially offering added-value for either concrete producers or construction industries. Therefore, the deployment of this lever remains unchanged in the Whole-Systems scenario.

Moreover, inclusion of demand reduction levers engages many more stakeholders than the Production-Centric scenario, including architects, road designers, construction companies, urban planners, and the general public, empowering a broader range of actors in decarbonization initiatives beyond traditional cement and concrete production companies. In particular, the reliance on at-plant CCS (L4) is substantially reduced by emissions savings delivered through material efficiency and material substitution. In the Whole-System scenario, the adoption rate of at-plant CCS (L4) rises to only 18% of cement production by 2060 in the United States, China, and India, as indicated in Tables 4-2 and 4-3.

For buildings, as shown in the lower panel of Figures 4-5, 4-7, and 4-9, material-efficient design (L6a) contributes significantly to reduced reliance on CCS, but the predominant driver of at-plant CCS elimination is the substitution of concrete by engineered timber (L6b) in all three countries. The CO_2 emission savings by this lever come from the combined effect of reduced concrete demand and CO_2 sequestered in engineered timber. Lifetime extension (L6e) emerges as an important lever in both China and India by mid-century but plays a much smaller role in decarbonization in the United States, where current building lifespans are already substantially longer. As the lifetime increases linearly to the target value, the CO_2 saving effect of lifetime extension starts appearing around 2040 in China and India. However, due to the greater existing longevities of US buildings, this lever hardly takes effect within the considered time horizon. Combined, the concrete demand reduction measures for buildings result in avoidance of 2286, 45728, and 13909 Mt of concrete demand cumulatively compared to the Production-Centric scenario in the United States, China, and India, respectively. Demand reduction measures implemented in buildings could collectively reduce ~62 Gt of concrete, enough to pave an 8-lane highway for ~3 million km.

For roadways, as shown in the lower panel of Figures 4-6, 4-8, and 4-10, reduced reliance on CCS is predominantly due to material-efficient design (L6a), end-of-life options (L7), and more intensive use (L6d) in all three countries. Roadway maintenance interval extension (L6e) also plays a significant role in China and India than it does in the United States because of longer roadway maintenance intervals already in place in the United States. Collectively, these measures reduce cumulative concrete demand for roadways by 470, 2275, and 1131 Mt compared to the Production-Centric scenario in the United States, China, and India, respectively.

In Figures 4-5 through 4-10, it is evident that the emissions savings associated with material substitution by engineered timber begin to shrink beginning in around 2050 in China and India. This effect is attributable to two factors in the Whole-Systems scenario. First, rising quantities of end-of-life timber will be generated as buildings reach the end of their design lifetimes. Second, a fraction of the timber sent to landfill will generate positive fluxes of methane (CH4) due to anaerobic decomposition, and timber sent for energy recovery will generate positive fluxes of CO_2 (due to timber combustion). These two end-of-life emissions sources will tend to counteract the CO_2 sequestration benefits of engineered timber as more waste is generated. These factors are less prominent by the mid-century in the United States, where longer building lifespans already exist. However, it is important to note that such shrinking emissions savings are not predestined to occur; they can be avoided through more aggressive lifespan extension, increased landfill methane capture (particularly in China and India), and innovative timber reuse strategies (e.g., reused for decorative purposes) that were not considered in the Whole-Systems scenario.

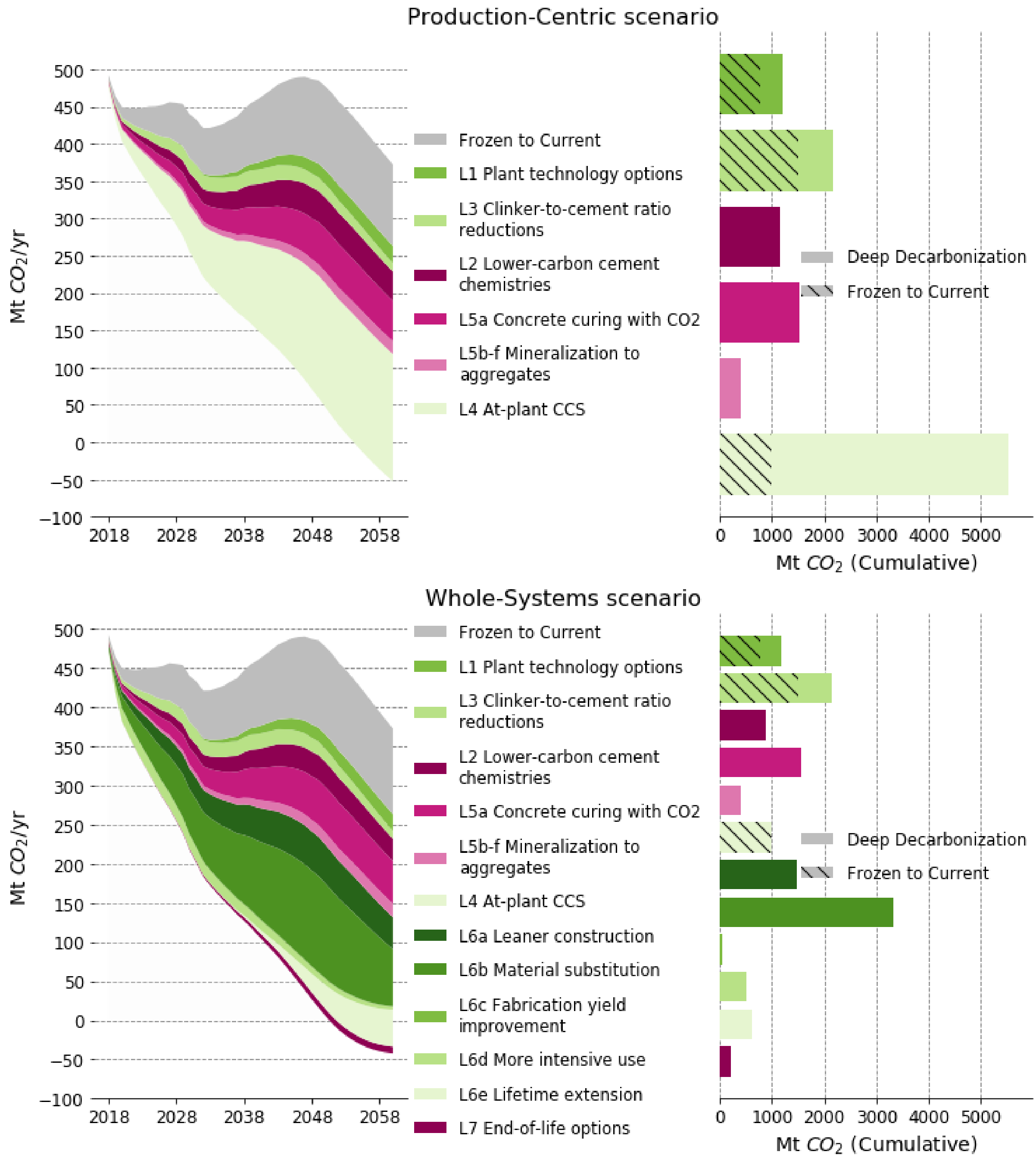

Figure 4-5. CO_2 emission reductions by decarbonization lever in the Production-Centric and Whole-Systems decarbonization pathways for the cement and concrete cycle associated with China's building sector.

Note: the legend in the middle is applicable to charts on both sides; values presented are net CO_2 emissions.

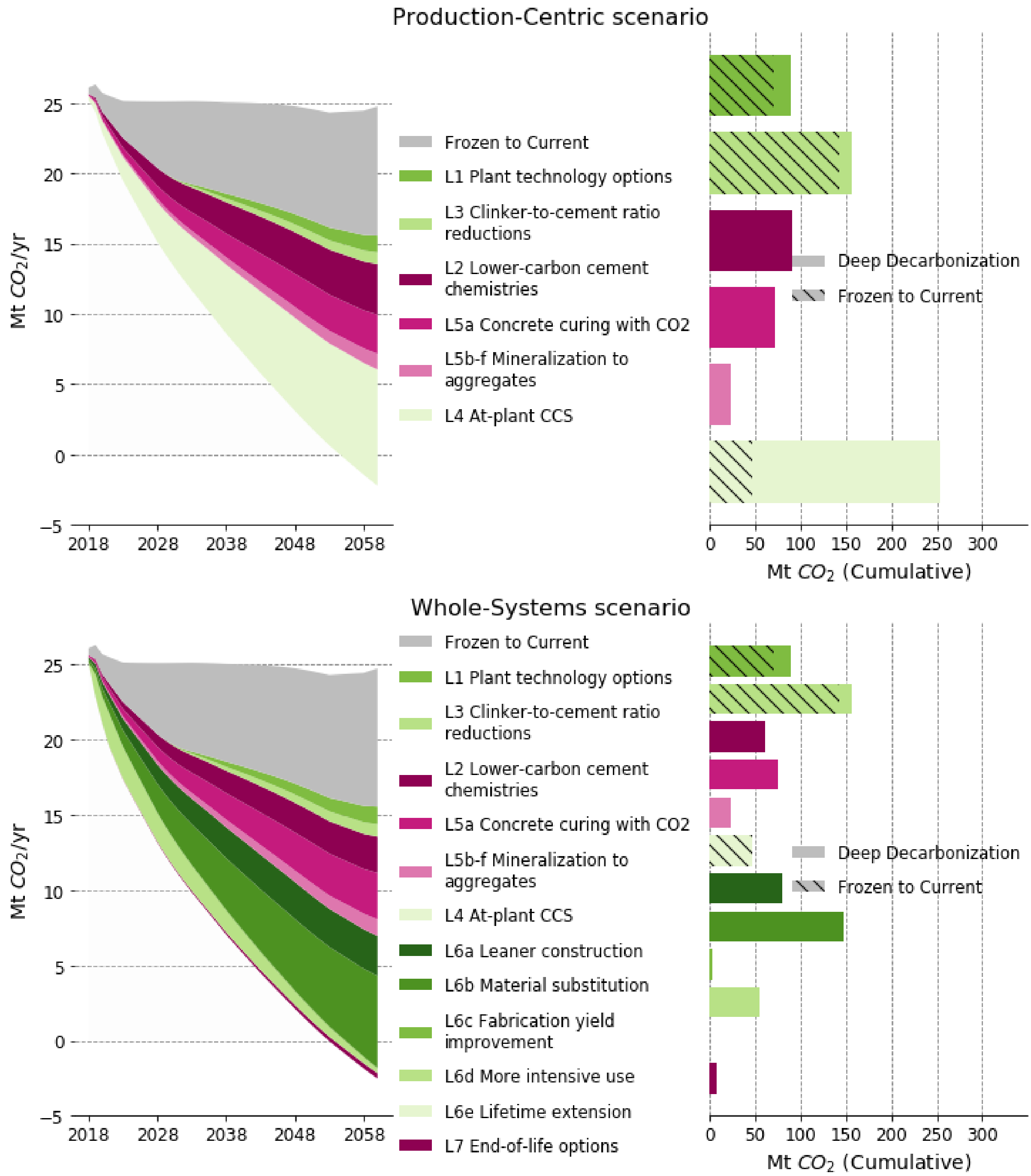

Figure 4-6. CO_2 emission reductions by decarbonization lever in the Production-Centric and Whole-Systems decarbonization pathways for the cement and concrete cycle associated with the U.S. building sector.

Note: the legend in the middle is applicable to charts on both sides; values presented are net CO_2 emissions.

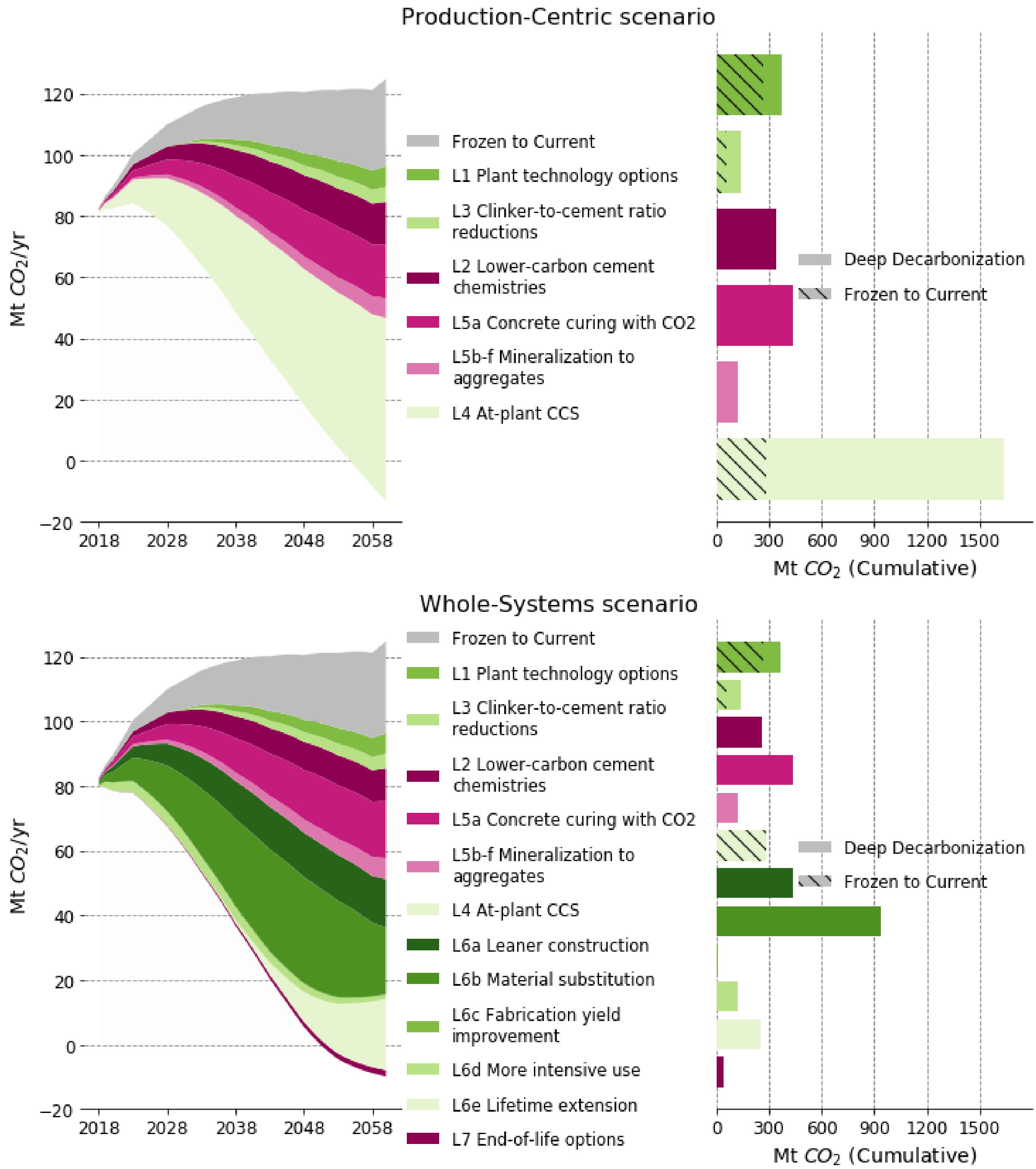

Figure 4-7. CO_2 emission reductions by decarbonization lever in the Production-Centric and Whole-Systems decarbonization pathways for the cement and concrete cycle associated with India’s building sector.

Note: the legend in the middle is applicable to charts on both sides; values presented are net CO_2 emissions.

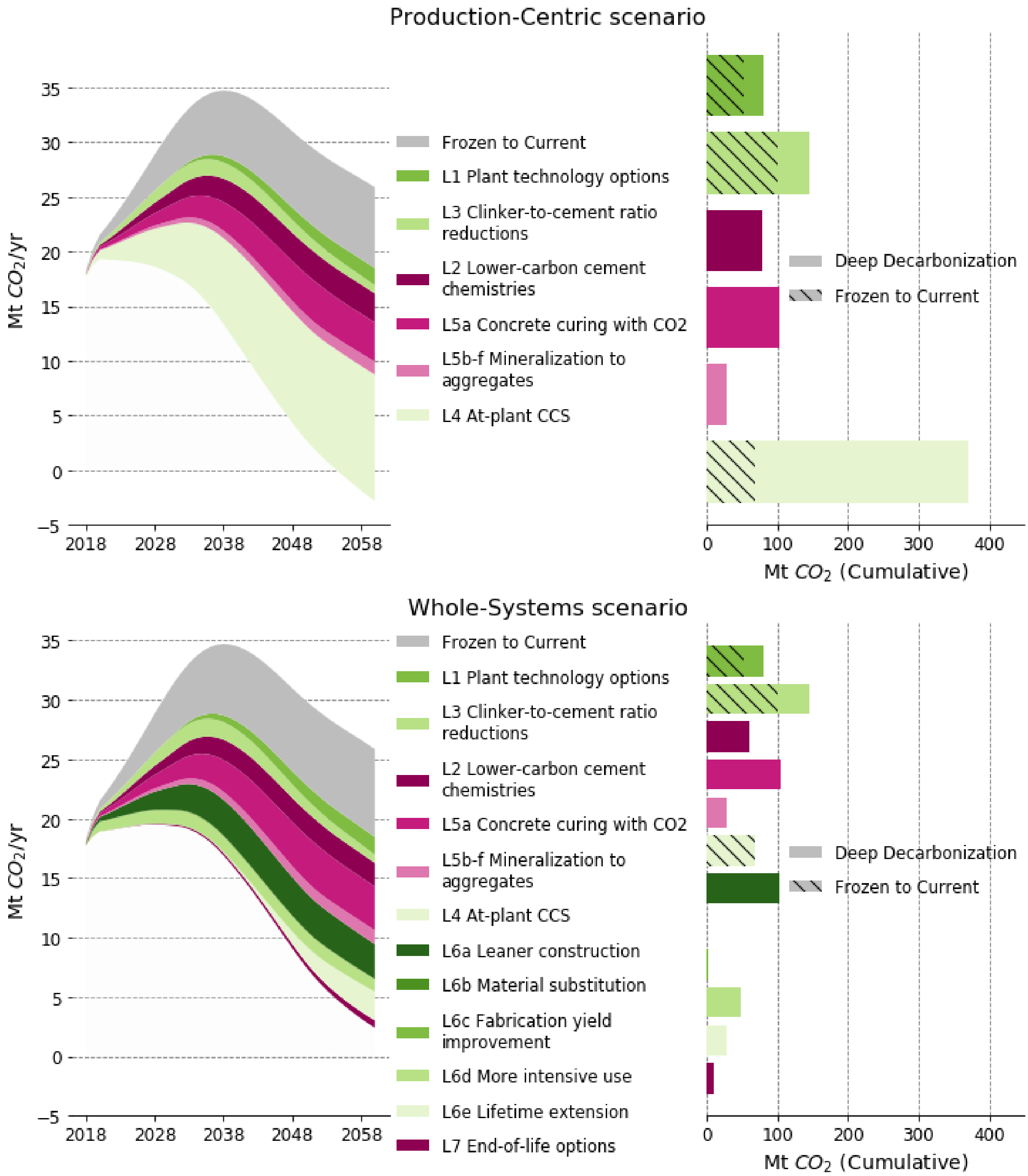

Figure 4-8. CO_2 emission reductions by decarbonization lever in the Production-Centric and Whole-Systems decarbonization pathways for the cement and concrete cycle associated with China's road sector.

Note: the legend in the middle is applicable to charts on both sides; values presented are net CO_2 emissions.

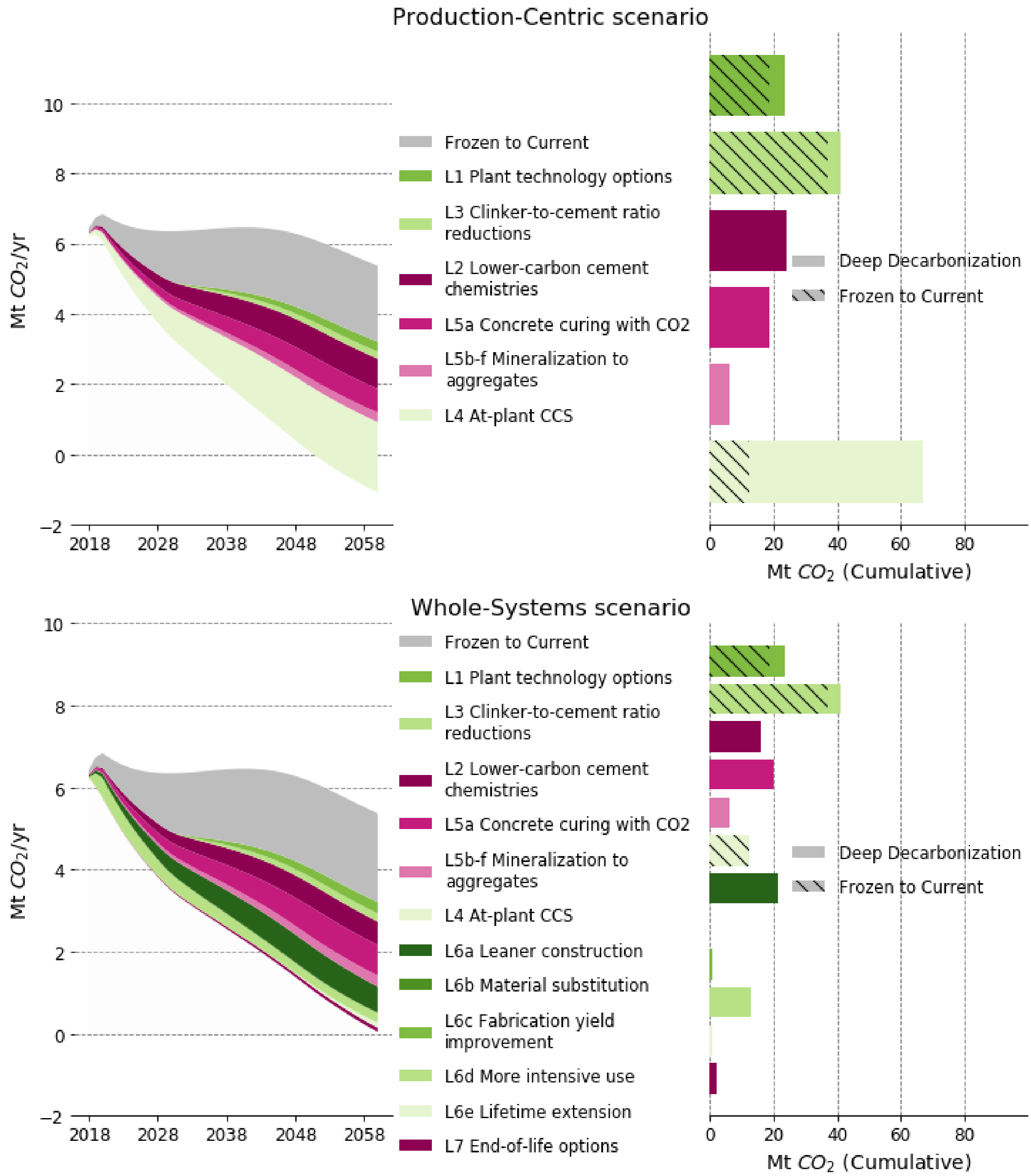

Figure 4-9. CO_2 emission reductions by decarbonization lever in the Production-Centric and Whole-Systems decarbonization pathways for the cement and concrete cycle associated with the U.S. road sector.

Note: the legend in the middle is applicable to charts on both sides; values presented are net CO_2 emissions.

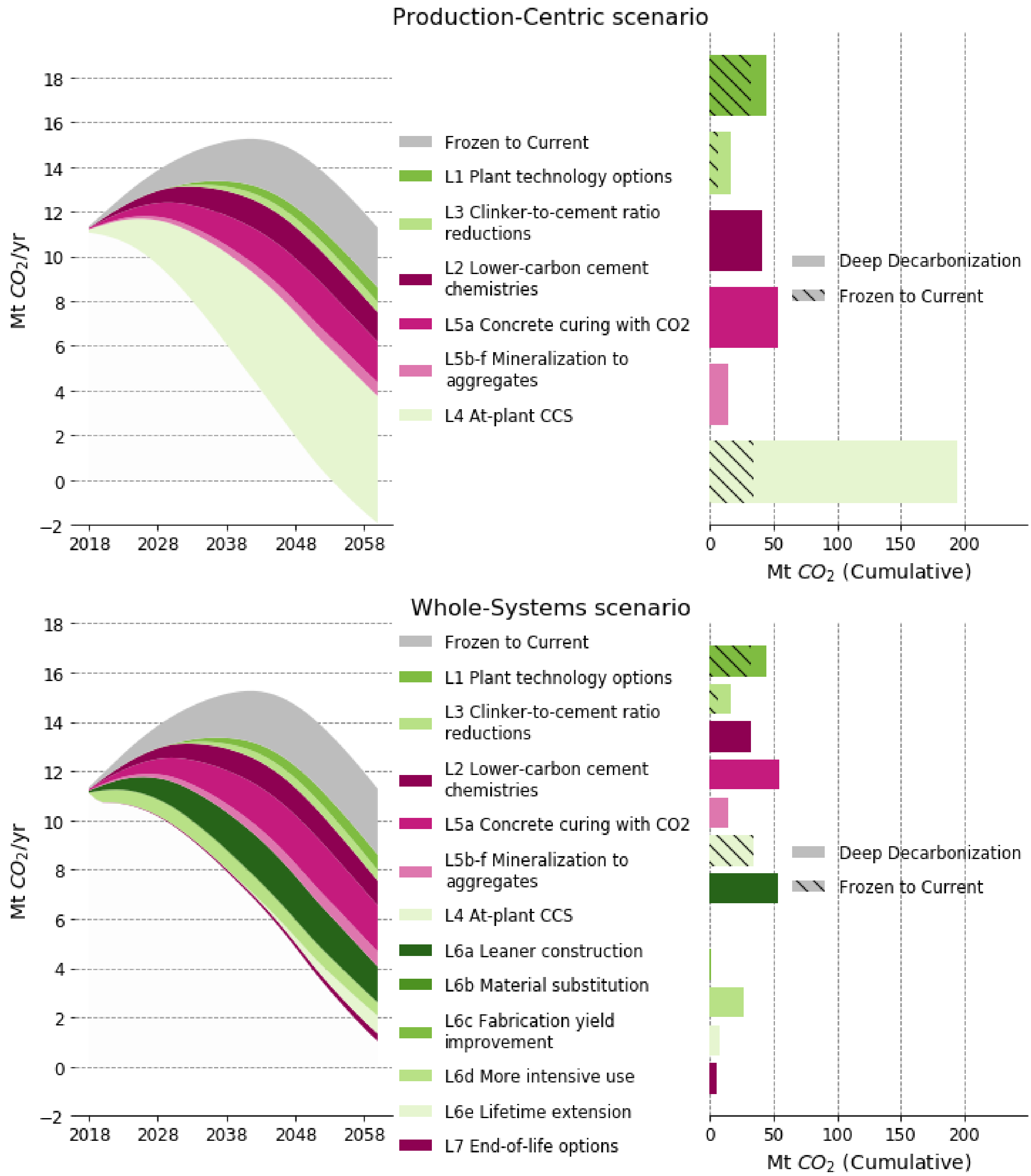

Figure 4-10. CO_2 emission reductions by decarbonization lever in the Production-Centric and Whole-Systems decarbonization pathways for the cement and concrete cycle associated with India's road sector.

Note: the legend in the middle is applicable to charts on both sides; values presented are net CO_2 emissions.

5. Near-term actions and priorities

The scenario results indicate that it is possible to achieve net-zero emissions across the cement and concrete cycle for buildings and roadways in China, the United States, and India. Our analysis has also shown that there are different pathways to achieving this goal, each of which may involve different combinations and timings of technology levers that will require the actions and engagements of different sets of stakeholders. What is clear from the scenario results is that, irrespective of the pathway, immediate actions are required to accelerate the pace of innovative technology and policy adoption well beyond what is expected in the Current Ambitions scenario. Therefore, this chapter focuses on the most important near-term actions required for such accelerations by different stakeholder groups across the cement and concrete cycle.

More specifically, Table 5-1 lists key near-term actions and priorities for unlocking the emissions reduction opportunities quantified in this report, and for each major stakeholder group highlighted in Figure 5-1. These recommendations have been synthesized from previous reports that have identified and reviewed the stakeholders, barriers, and needed actions associated with various decarbonization levers in greater detail. For further information on each recommendation, readers are referred to the original research reports listed below the table.

Table 5-1 also indicates the primary lever categories that can be influenced by each stakeholder group, providing a rough indication of the emissions savings that depend—either wholly or partly—on their engagements and actions. For simplicity, only the major lever categories (e.g., L6-Material efficiency strategies) are listed, as opposed to the specific levers within each category (e.g., L6b-Material substitution). Critically, governments must play a leading role in all possible pathways through actions such as making increased investments in R&D, providing technology deployment incentives, changing construction codes and standards, and encouraging public-private partnerships to develop, demonstrate, and deploy key technology innovations.

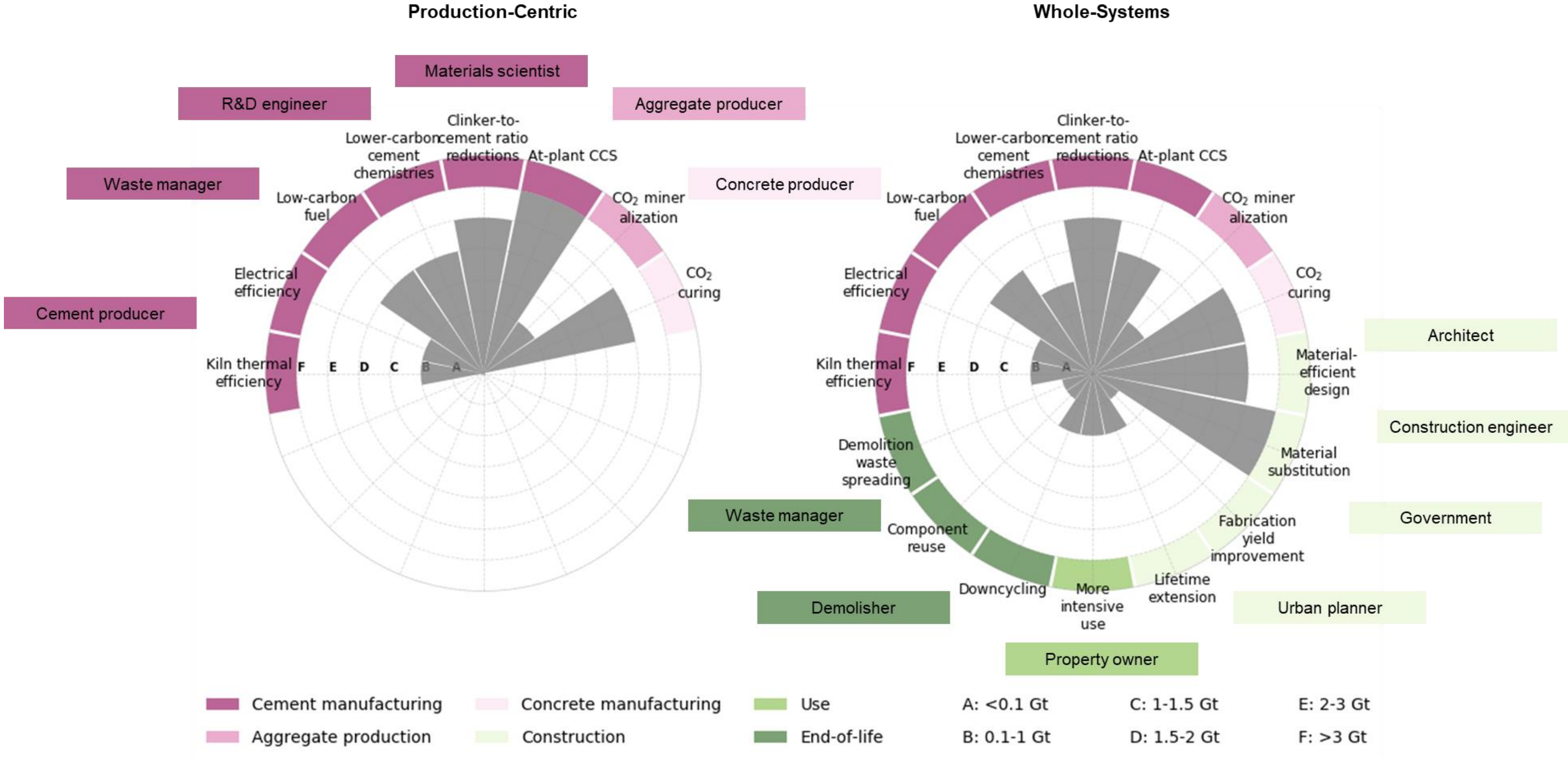

Figure 5-1. Engagement of stakeholder groups in the Production-Centric and Whole-Systems decarbonization scenarios.

Note: each gray bar in the circular bar charts corresponds to the sum of cumulative net CO_2 savings in three countries and two sectors.

Table 5-1. Near-term actions and priorities by key stakeholder and decarbonization lever.

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	Subcategory		L1	L2	L3	L4	L5	L6	L7
Government	Financial/ market incentives	• Increase financial incentives for lower-carbon technology adoption by materials producers, inclusive of purchase and tax incentives (e.g., the U.S. 45Q tax credit), and particularly for emerging technologies such as lower-carbon cement chemistries and at-plant carbon capture and sequestration • Increase financial incentives for deep building retrofits to extend building lifespans without locking in energy inefficiencies • Facilitate public-private partnerships that can develop and implement credible “embodied” carbon standards and labels to enable lower-carbon material and component selections by architects, designers, and engineers • Incorporate externalities into fuel prices, such as carbon taxes, while eliminating fuel price subsidies that discourage energy efficiency investments • Develop and implement built environment life-cycle carbon rating systems, rewarding value-chain solutions that minimize total carbon emissions across the entire life cycle • Specification of lower-carbon materials and practices in public sector construction contracts	✓	✓	✓	✓	✓	✓	✓
	R&D funding	• Increase funding to accelerate the development, testing, and commercialization of lower-carbon cement chemistries, at-plant CCS, CO_2 mineralization technologies, reusable building components, and novel concrete mixes that minimize binder requirements • Support/subsidize pilot demonstrations of emerging technologies and materials to reduce perceived market risks, share best practices, and	✓	✓	✓	✓	✓	✓	✓

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	Subcategory		L1	L2	L3	L4	L5	L6	L7
		accelerate market adoption, inclusive of mass-timber buildings for substituting concrete • Support basic and applied research funding toward novel techniques for reducing the concrete intensity of the built environment, such as additive manufactured structures and building components that show promise in reducing material use • Increase funding for evaluating the long-term performance of low-carbon materials substitutes, such as novel concrete mixes, reusable building components, and mass-timber designs • Fund the development of life-cycle assessment models, studies, and datasets that can improve the assessment of different technology and policy interventions in the cement and concrete cycle, inclusive of public-private partnerships to develop collection systems and repositories for built environment materials intensity data							
	Codes & standards	• Develop new, or revise existing, codes applicable to cement and concrete formulations to increase the adoption of lower-carbon cement chemistries, blended cements, and performance-based concrete mixes • Incorporate "embodied carbon" considerations into building codes to encourage materials and components selections that can minimize life-cycle carbon footprints, inclusive of concrete substitutes such as engineered timber • Develop new, or revise existing, building codes to enable adoption of reusable components in new and retrofit construction	×	✓	✓	×	×	✓	✓
	Urban planning	• Encourage mixed-use and multi-family development construction to reduce per-capita floor area requirements (buildings) and roadway infrastructure needs	×	×	×	×	×	✓	×

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	**Subcategory**		**L1**	**L2**	**L3**	**L4**	**L5**	**L6**	**L7**
		• Develop new, or revise existing, building zone requirements to enable mixed uses and repurposing of existing structures to extend building lifespans • Incentivize shared office spaces and priority permitting close to transportation hubs to encourage sharing economy principles							
	Environment, energy, and commerce agencies	• Establish protocols for improved reporting of energy use and emissions coupled with performance benchmarking and rewards programs for encouraging low-carbon investments by materials producers • Establish mechanisms for sharing and transfer of best practices among material producers, architects, construction companies, and building operators, thereby reducing knowledge barriers to the adoption of low-carbon technology and strategies • Implement resource efficiency and circular economy policies that encourage minimization of material footprints, elimination of waste, and optimal reuse and recycling of built environment materials across their entire life cycles • Develop educational materials and awareness campaigns to target building owners and general society about the benefits of built environment longevity/lifespan extension and the sharing economy							
Materials producers	Aggregates	• Encourage development of and investments in CO_2 mineralization as a substitute for natural aggregates • Develop partnerships with demolition companies and waste handlers to increase use of recycled concrete aggregate and identify attractive waste streams for CO_2 mineralization • Promote adoption of low-carbon freight modes for aggregates transport	×	×	×	×	✓	×	×
	Cement	• Accelerate the phase-out of inefficient kilns, grinding, and milling processes and replace with best available technologies	✓	✓	✓	✓	×	×	×

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	Subcategory		L1	L2	L3	L4	L5	L6	L7
		• Increase industry investments in the development and demonstration of lower-carbon cement chemistries and alternative cement production processes, including via partnerships with academic and research institutions • Accelerate the demonstration and adoption of at plant CCS • Increase shares of low-carbon and renewable kiln fuels to the maximum extent feasible considering technical and supply constraints • Continuously reduce clinker-to-cement ratios and advocate for changes to cement codes and standards to achieve maximal reductions • Foster new business models and partnerships that decouple revenue from cement quantities sold, thereby enabling greater cement and concrete efficiency in end-use products • Commit to reporting of plant- and company-level energy, emissions, and production data, participation in industry benchmarking activities, and to science-based carbon emissions reduction targets							
	Ready-mix	• Encourage transitions to low-carbon truck fleets, inclusive of improved vehicle efficiencies and adoption of electrified or fuel-cell options as available • Promote adoption of CO_2 injection technologies to maximize its binder reduction and CO_2 sequestration benefits in ready mixes • Foster R&D partnerships with academia and research institutions to innovate, test, and demonstrate performance-based concrete mixes • Foster business partnerships with cement producers to minimize binder requirements while retaining ready-mix product market values	×	×	×	×	✓	✓	×

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	Subcategory		L1	L2	L3	L4	L5	L6	L7
		• Collaborations with construction companies to reduce "over-ordering" of ready-mix quantities and unnecessary site waste generation							
	Precast products	• Promote adoption of CO_2 curing technologies to maximize binder reduction and CO_2 sequestration benefits in precast products • Foster R&D partnerships with academia and research institutions to innovate, test, and demonstrate innovative component designs and manufacturing techniques (e.g., additive manufacturing) for material-efficient precast products • Foster public-private partnerships to test and monitor the performance of reusable precast concrete components	×	×	×	×	✓	✓	✓
Built environment	Architects, designers, and engineers	• Develop and share education and training materials (e.g., by professional societies) to promote the selection of materials and use of innovative design principles to minimize total life-cycle footprints • Create markets for engineered timber and other low-carbon building innovations by incorporating and highlighting these features in completed projects • Promote greater public sharing of materials intensity and design data for building and roadway projects, leading to better energy-materials-emissions models of the cement and concrete cycle • Create markets for "embodied carbon" and performance-based standards and ratings that can be employed in the design process through advocacy to governments, trade associations, and architectural software providers	×	×	×	×	×	✓	✓
	Construction	• Promote adoption of lean construction practices to reduce on-site materials waste • Foster public-private partnerships to promote the specification and use of reusable components where technically feasible	×	×	×	×	×	✓	✓

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	Subcategory		L1	L2	L3	L4	L5	L6	L7
		• Promote better management of project cycles to enable the use of low-carbon concrete mixes that may require extended curing periods							
	Building owners	• Consider deep retrofits to extend the lifespan of the building closer to its technical limits while maximizing energy efficiency • Facilitate shared working practices and other strategies to maximize space utilization to minimize floor area requirements • Embrace smaller footprint buildings as a key climate mitigation strategy	×	×	×	×	×	✓	×
Waste industries	Demolition	• Develop customized on-site (or decentralized) recycling to complement the current off-site (or centralized) recycling practices • Create partnerships with local businesses for salvaged or reusable products	×	×	×	×	×	×	✓
	Waste management	• Ensure national and local waste disposal policies to enable co-processing of alternative fuel and biomass in the cement industry • Develop certification systems for salvaged or reusable concrete products • Establish information sharing platforms for demand and supply of end-of-life products • Develop demolition waste management protocols that enable demolition waste to carbonate at an accelerated rate • Develop waste management protocols for end-of-life engineered timber that prevent landfill methane	✓	×	✓	×	✓	×	✓
Research	Modeling and analysis	• Develop new models capable of assessing the economic, geographical, and regulatory potential of different low-carbon levers • Refine existing, or develop new, cement carbonation models with more empirical data on cement-based products	✓	✓	✓	✓	✓	✓	✓

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	Subcategory		L1	L2	L3	L4	L5	L6	L7
		• Develop more models capable of capturing the impacts of engineered timber on forest ecosystems, such as forest carbon, soil carbon, and forest biodiversity • Construct new models capable of predicting the durability of lower-carbon cement chemistries, blended cements, and performance-based concrete mixes • Develop an assessment framework for evaluating the availability, recyclability, and reusability of cement-based materials stocked in buildings and roadways, aligned with the concept of "urban mining" or "anthropogenic resources mining", which treats materials as potential resources for future uses • Establish open data platforms to document built environment information (e.g., building passports or material passports) and extract knowledge to inform new product or building designs							
	Technology R&D	• Develop innovative CO_2 mineralization processes that target industrial wastes or other alkaline materials that do not directly compete with uses as supplementary cementitious materials • Promote continuous innovation to reduce the cost of at-plant carbon capture and sequestration and/or to engineer synergistic CO_2 utilization strategies • Develop more widespread testing, performance monitoring, and failure diagnostics for novel cement chemistries and concrete blends to reduce perceived market risks • Promote development and testing of innovative material-efficient designs and fabrication techniques for building structures and components,	×	✓	✓	✓	✓	✓	✓

Stakeholder group		Near-term actions and priorities	Most applicable lever(s)						
Category	Subcategory		L1	L2	L3	L4	L5	L6	L7
		including via additive manufacturing methods that have promise in reducing material use • Increase focus on low-energy reaction pathways for ordinary portland cement substitutes • Increase focus on kiln process innovations that can enable low-carbon heat sources, such as process electrification or green hydrogen							

Sources: Technology Roadmap: Low-Carbon Transition in the Cement Industry (IEA, 2018)[10]; Material efficiency in clean energy transitions (IEA, 2019)[16]; Making concrete change: Innovation in low-carbon cement and concrete (Lehne and Preston, 2018)[127]; Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry (Scrivener et al., 2018)[21]; A Sustainable Future for the European Cement and Concrete Industry: Technology Assessment for full decarbonisation of the industry by 2050 (Favier et al., 2018)[48]; The circular economy–a powerful force for climate mitigation: transformative innovation for prosperous and low-carbon industry (Enkvist et al., 2018)[18].

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Appendix

The appendix presents methodological notes and additional results.

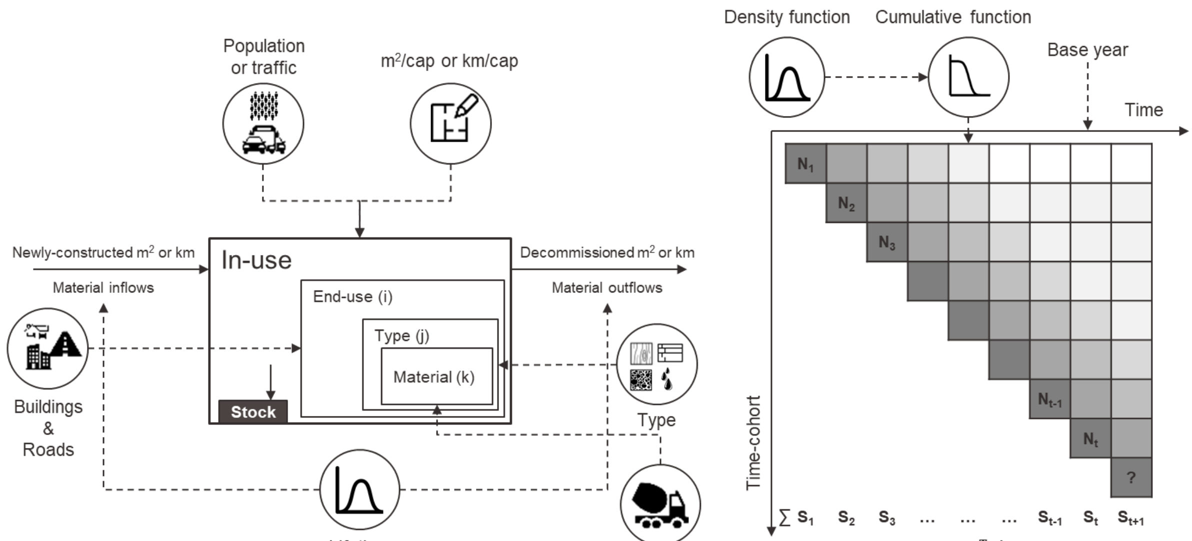
Data and code availability

The IMAGINE Concrete model is available for public use in two versions. A simplified web-based version of IMAGINE Concrete is available at the following URL: https://imagine-concrete.herokuapp.com/. The web-based version enables deployment of each major lever category considered in this report, subject to predefined numerical assumptions and limits aligned with our scenarios. It is meant for simple “what if” explorations of how different combinations of levers can lead to future emissions reductions in our considered end-use sectors (buildings and roadways) in China, the United States, and India.

For advanced modelers, the full Python modeling code for IMAGINE Concrete is available for download at the following URL: https://github.com/ZhiCaoIE/imagine-concrete. The Python version gives the user full control over all variables in the model, enabling generation of fully-customizable scenarios.

Stock-flow modeling

Following several prior studies[7,106], IMAGINE Concrete employs a stock-flow model to project future cement demands by end-use segment. The stock-flow model is tailored for buildings and roadways and grounded on dynamic material flow analytics[128]. The stock-flow model accounts for material entering and leaving a system over a period of time, ensuring the mass balance principle is consistently followed. Mathematically, the floor area of newly-constructed buildings, or the length of roadways, is the sum of stock turnovers and net stock changes. Therefore, the longevity of buildings and roads will pose lock-in effects on cement and concrete demands. The stock-flow model is able to capture the impacts of multiple factors, including population, living standards, building codes and regulations, construction practice, material selection, lifetime of structures, and historical cement consumption (or stock development).



$$N_{t+1} = S_{t+1} - S_t + \sum_{T=1}^{T=t} N_T \times L_T(t, t+1)$$

Figure A1. Stock-flow modeling tailored for buildings and roadways.

Our analysis relies on forecasts from the United Nations Population Division, which project that the populations of the United States and India will reach 404.6 million and 1.7 billion in 2060, respectively, while the population of China is projected to peak at 1.4 billion in 2030 and decline to 1.3 billion in 2060[129].

Our projections of per capita floor area of residential buildings and non-residential buildings are aligned with IEA RTS's projections[11]. Historical data for road length are obtained from the U.S. Highway Statistics 2019[130], the National Bureau of Statistics of China[131], and the Ministry of Road Transport and Highways of India[132]. We assume that road length in all three countries will continue growing at historical rates but become gradually saturated. We assume that the growth rate of road length will slow down and approach 0% by 2060. Under these assumptions, the total length of roadways in the United States, China, and India is expected to expand from 6.7 to 7.3 million km, 4.8 to 12.1 million km, and 4.7 to 6.6 million km, respectively.

Classification of buildings and roads

The classification of buildings and roads depends on each country's convention and data availability. For China, concrete-steel refers to buildings using reinforced concrete for main load-bearing components; concrete-brick refers to buildings using bricks for vertical load-bearing walls and reinforced concrete for load-bearing columns and lateral load-bearing beams; brick-timber refers to buildings using bricks for vertical load-bearing components and timber for floors and roof trusses; timber-others refers to buildings using timber for main load-bearing components. For the United States, buildings are classified by framing material and foundation type. The classification of buildings for China is applied to India.

Table A1. Segmentation of building stocks.

Country	End-use	Subcategory	Abbreviation
China	Residential-Rural	Concrete-Brick	RRCB
		Brick-Timber	RRBT
		Timber-Others	RRTO
	Residential-Urban	Concrete-Steel	RUCS
		Concrete-Brick	RUCB
		Brick-Timber	RUBT
	Non-Residential	Concrete-Steel	NRCS
		Concrete-Brick	NRCB
		Brick-Timber	NRBT
United States	Residential-Single family	Wood frame-Basement	SFWB
		Wood frame-Slab	SFWS
		Wood frame-Crawlspace	SFWC
		Concrete frame-Basement	SFCB
		Concrete frame-Slab	SFCS
		Concrete frame-Crawlspace	SFCC
	Residential-Multi family	Wood frame-Basement	MFWB
		Wood frame-Slab	MFWS
		Wood frame-Crawlspace	MFWC
		Steel frame-Basement	MFSB
		Steel frame-Slab	MFSS
		Steel frame-Crawlspace	MFSC

Country	End-use	Subcategory	Abbreviation
		Concrete frame-Basement	MFCB
		Concrete frame-Slab	MFCS
		Concrete frame-Crawlspace	MFCC
	Manufactured house	Wood frame-Basement	MHWB
		Wood frame-Slab	MHWS
		Wood frame-Crawlspace	MHWC
		Concrete frame-Basement	MHCB
		Concrete frame-Slab	MHCS
		Concrete frame-Crawlspace	MHCC
	Nonresidential (Commercial)	Wood frame	CW
		Steel frame	CS
		Concrete frame	CC
India	Residential-Urban	Timber-Others	RUTO
		Brick-Timber	RUBT
		Concrete-Brick	RUCB
	Residential-Rural	Timber-Others	RRTO
		Brick-Timber	RRBT
		Concrete-Brick	RRCB
	Nonresidential (Commercial)	Timber-Others	NRTO
		Brick-Timber	NRBT
		Concrete-Brick	NRCB

The classifications of roadways are harmonized to align with the classification of the International Road Federation. Motorways are roads specifically designed and built for motor traffic, which does not serve properties bordering on it, and which: (a) is provided, except at special points or temporarily, with separate carriageways for the two directions of traffic, separated from each other, either by a dividing strip not intended for traffic, or exceptionally by other means; (b) does not cross at level with any road, railway or tramway track, or footpath; (c) is especially sign-posted as a motorway and is reserved for specific categories of road motor vehicles. Highways, main or national roads are A-level roads that are outside urban areas and that are not motorways but belong to the top-level road network. A-level roads are characterized by a comparatively high-quality standard, either non-divided roads with oncoming traffic or similar to motorways. Secondary, regional roads are roads that are the main feeder routes into and provide the main links between highways, main or national roads. Other roads are remaining roads not included in the above-mentioned categories. Each category is further divided into four types: unpaved, paved-bituminous, paved-composite, and paved-concrete.

Table A2. Segmentation of roadways.

Country	Original classification	Classification of International Road Federation
China	Expressway	Motorways
	First Class Highways	Highways, main or national roads
	Second Class Highways	Secondary, regional roads
	III-V Class Highways	Other roads
United States	Rural Interstate Urban Interstate	Motorways
	Rural Other Freeways and Expressways Urban Other Freeways and Expressways	Highways, main or national roads
	Rural Other Principal Arterial Rural Minor Arterial Rural Major Collector Rural Minor Collector Urban Other Principal Arterial Urban Minor Arterial Urban Major Collector Urban Minor Collector	Secondary, regional roads
	Rural local Urban local	Other roads
India	National Highways	Highways, main or national roads
	State Highways Other PWD Roads	Secondary, regional roads
	Panchayati Raj Roads JRY& PMGSY Roads Urban Roads Project Roads	Other roads

Cement demand: bottom-up estimates vs. top-down statistics

While top-down statistics for broad end-use categories exist, such as cement sales for residential construction, comprehensive statistics on cement and concrete demand by specific end-use segment do not currently exist, such as cement sales for single-family home construction. In order to arrive at estimates of cement and concrete demand at the level of building types, our bottom-up analysis relies on a variety of data sources, inclusive of individual LCA studies and building material intensity datasets. As shown in Figures A2 and A3, these bottom-up estimates only account for a portion of cement sales associated with top-down statistics, mainly due to the discrepancy between the scope of these two accounting approaches.

Specifically, for buildings, our bottom-up analysis only captures materials used in new building construction, whereas top-down statistics for residential and commercial construction may also include garages, parking structures, and carports, driveways, sidewalks, and other end uses associated with residential and commercial housing projects. Furthermore, our assumed materials intensities come from available LCA studies (China and India[106,107], and United States[108,109,109,110]) that may not capture the full range of variations that exist across construction projects within each of our three considered countries. For roadways, our bottom-up analysis only considers materials used in pavements (i.e., in the typical cross-section of a roadway), whereas top-down statistics may also include materials used in tunnels, ramps, bridges, and curbs that are considered roadway sector end uses in cement industry statistics. Closing the gaps between top-down and bottom-up estimates remains an area for additional efforts moving forward. Irrespective of the identified discrepancy, our bottom-up assessment is aligned sufficiently with previous estimates using the same bottom-up approach (e.g., Figure 34 in the IEA Material Efficiency report[16]).

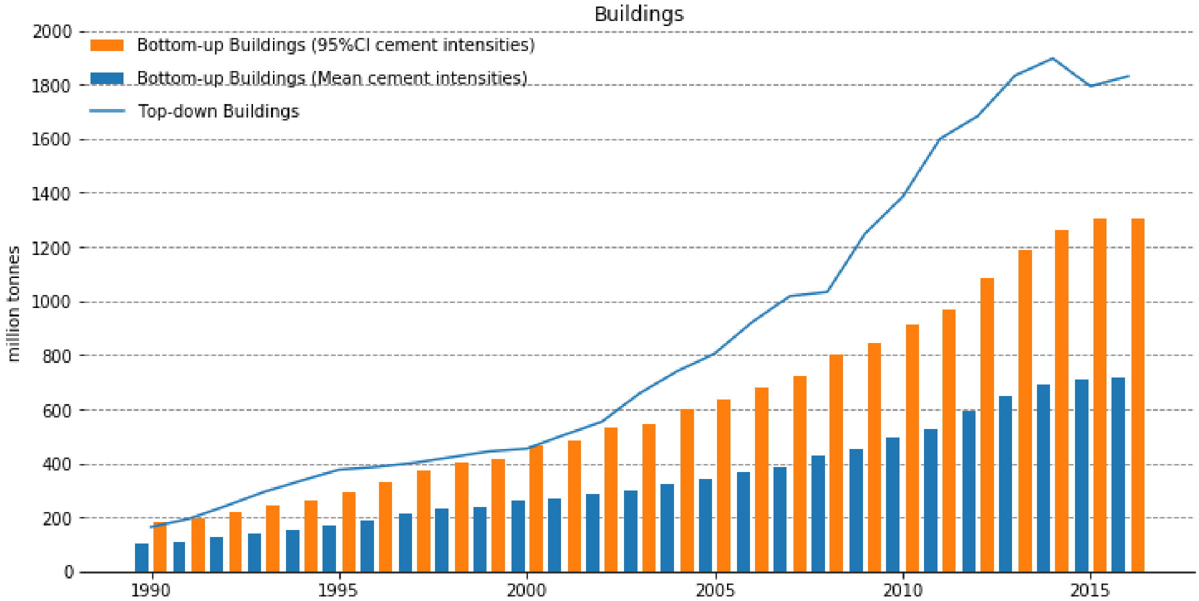


Figure A2. Comparisons between top-down statistics and bottom-up estimates for cement demand in China's building sector.

Note: top-down statistics are collected from USGS Mineral Yearbooks[8] and China Statistical Yearbook on Construction[112].

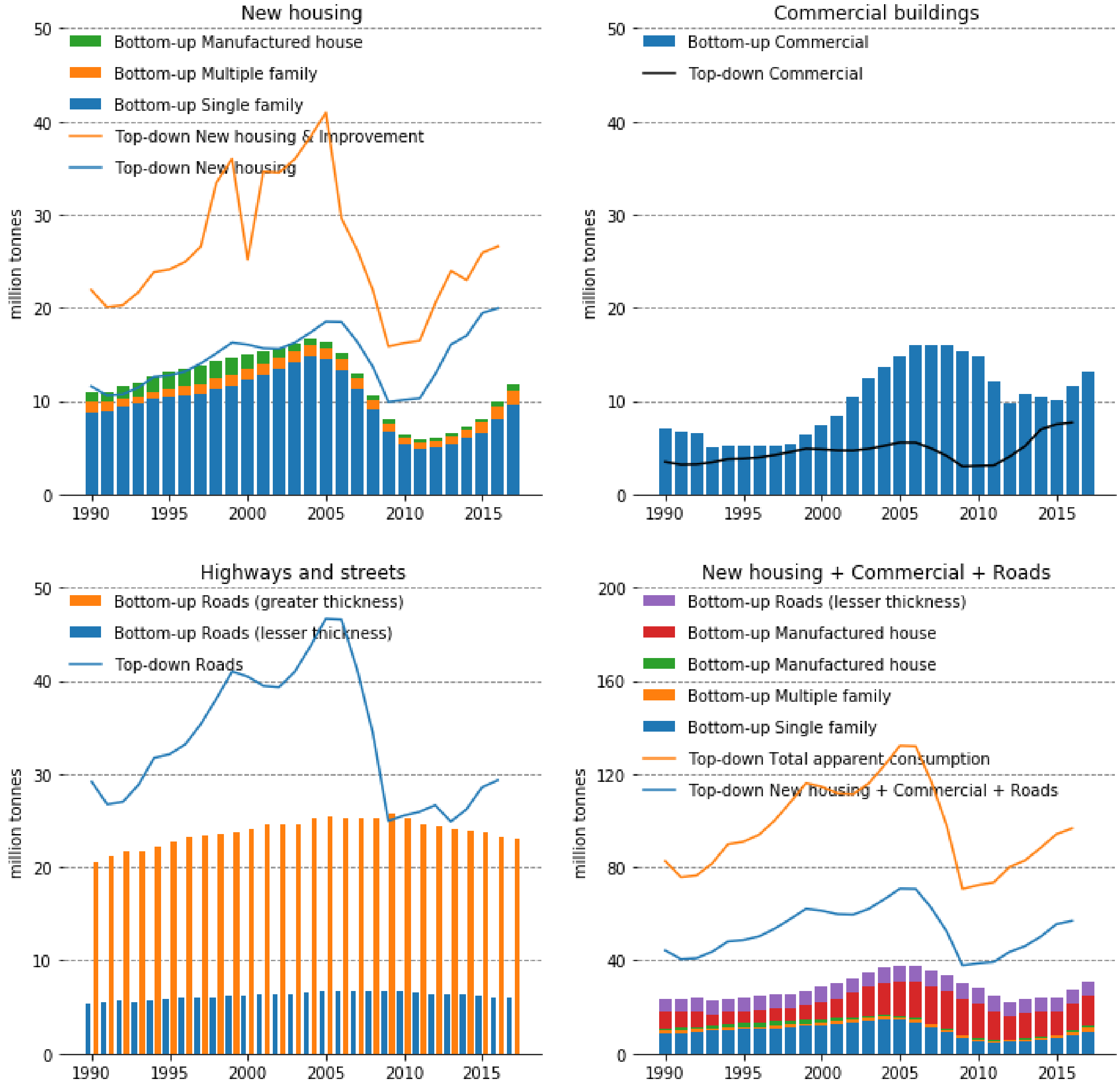


Figure A3. Comparisons between top-down statistics and bottom-up estimates for cement demand in the United States.

Note: top-down statistics are collected from USGS Mineral Yearbooks[8] and US Cement Industry Annual Yearbook[133]. Greater thickness means that bituminous roads have a concrete layer, of which the thickness is half the thickness of paved-concrete roads; lesser thickness means that bituminous roads do not have a concrete layer. We assume that bituminous roads do not have a concrete layer and that cement-based stabilizers are excluded due to lack of sufficient data. Future work should consider accounting for cement use in bituminous roadways when data emerge.

Cement and concrete cycle by country and sector

For buildings, mass flows along the cement and concrete cycle are estimated based on the floor area and concrete intensity of each end-use segment. For roads, mass flows along the cement and concrete cycle are estimated based on the road length and concrete intensity of each end-use segment.

United States-Buildings

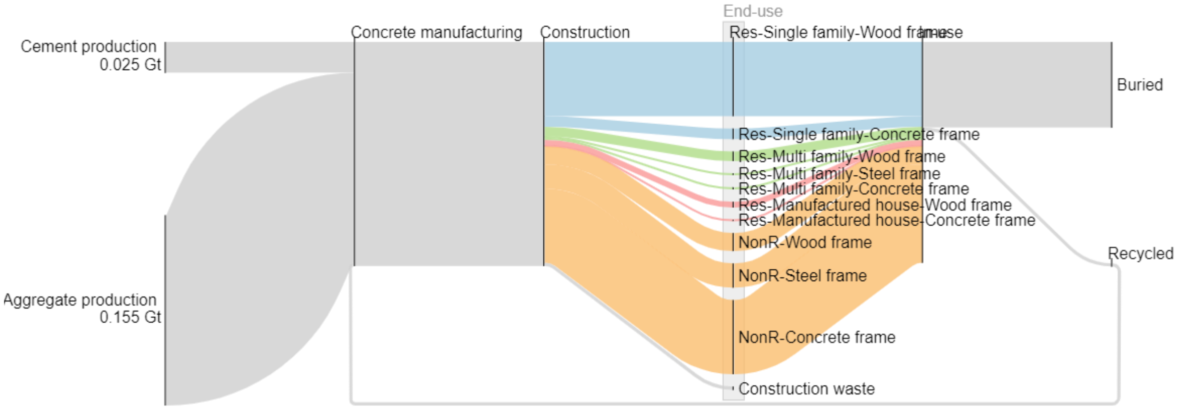


Figure A4. Mass flows along the cement and concrete cycle associated with the United States building sector in 2017.

Note: buried refers to end-of-life concrete used as base materials or sent to landfill.

India-Buildings

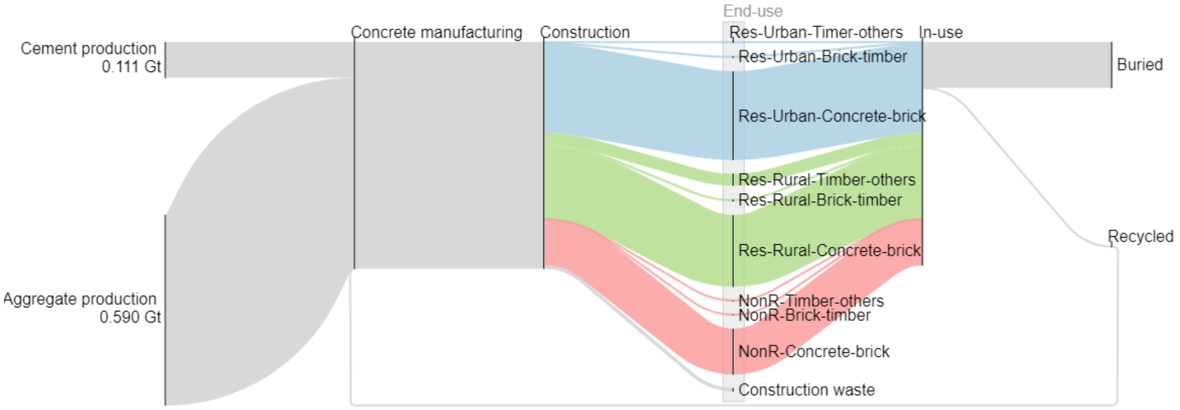


Figure A5. Mass flows along the cement and concrete cycle associated with India's building sector in 2017.

Note: buried refers to end-of-life concrete used as base materials or sent to landfill.

China-Roads

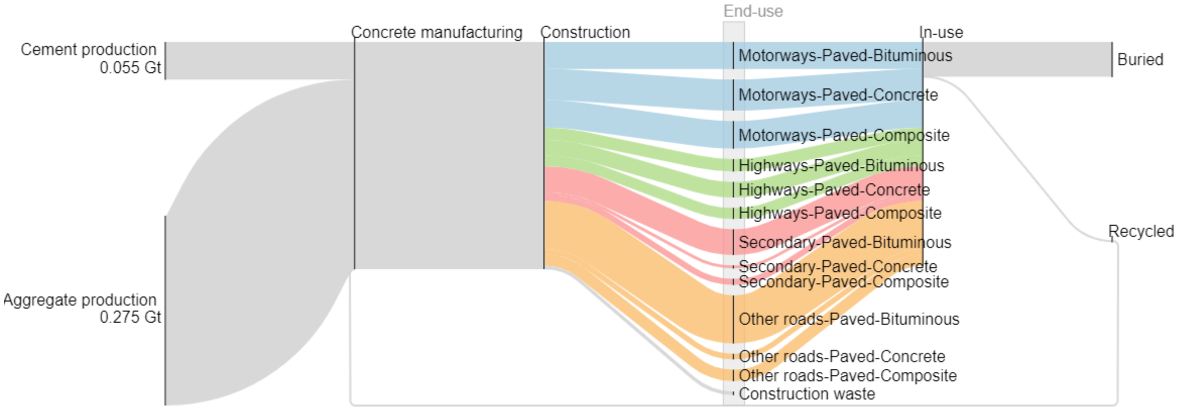


Figure A6. Mass flows along the cement and concrete cycle associated with China's road sector in 2017.

Note: buried refers to end-of-life concrete used as base materials or sent to landfill.

United States-Roads

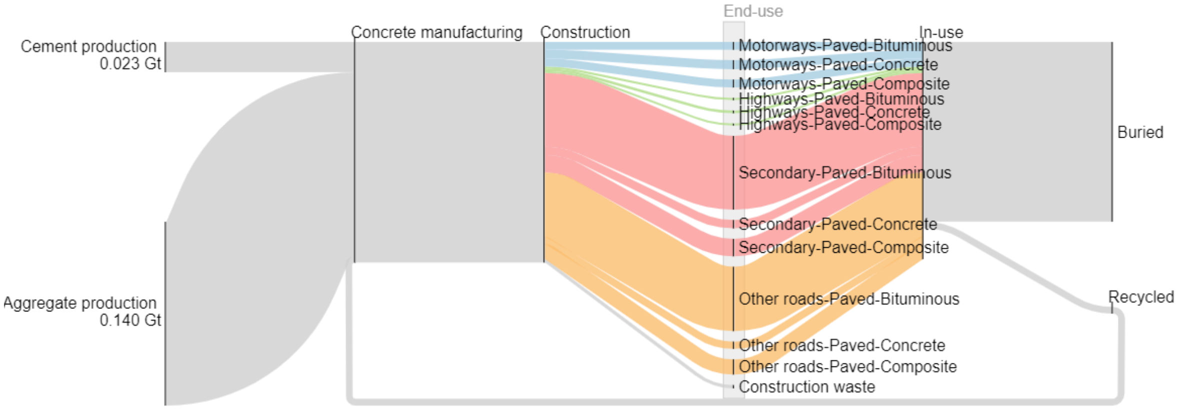


Figure A7. Mass flows along the cement and concrete cycle associated with the United States road sector in 2017.

Note: buried refers to end-of-life concrete used as base materials or sent to landfill.

India-Roads

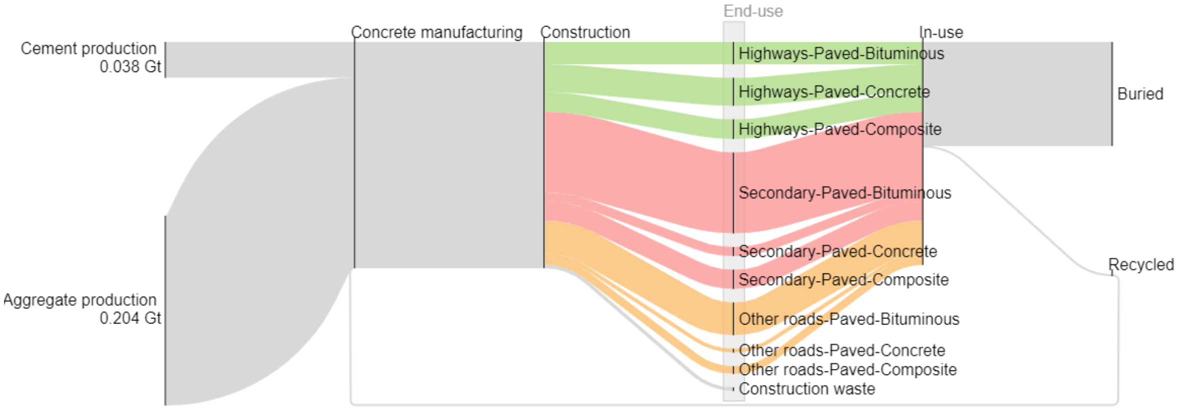


Figure A8. Mass flows along the cement and concrete cycle associated with India's road sector in 2017.

Note: buried refers to end-of-life concrete used as base materials or sent to landfill.

Cement carbonation model

Within IMAGINE Concrete, a physicochemical model was employed to characterize cement carbonation and estimate CO_2 uptake spanning the cement and concrete cycle[7]. The model takes into account the thicknesses of different cement-related materials, exposure conditions in all life-cycle stages, and atmospheric CO_2 concentrations in different regions. The total CO_2 uptake consists of four sources: cement kiln dust generated from the production stage, construction waste, in-use cement stocks, and demolition waste.

- Absorption of CO_2 by construction cement waste and cement kiln dust is estimated using their generation rates and carbonation fraction. A detailed description of parameters relevant to construction cement waste and cement kiln dust is available in Supplementary Notes 4.1 and 4.2 of Cao et al. (2020)[7].
- The CO_2 absorbed by concrete and mortar is determined by the carbonation rate, CaO content, proportion of CaO that converts to $CaCO_3$ (at complete carbonation), and mole ratio of CO_2 to CaO. The carbonation rates are explicitly modeled using Fick's diffusion law. Carbonation rates of in-use concrete and in-use mortar are adjusted by considering the effects of exposed surface area, thickness, compressive strength class, exposure condition, cement additives, atmospheric CO_2 concentration, coatings and coverings, as well as exposure time. A detailed description of parameters relevant to in-use concrete is available in Cao et al. (2020) Supplementary Tables 7-10[7]. A detailed description of parameters relevant to in-use mortar is available in Cao et al. (2020) Supplementary Tables 13-16[7].
- Carbonation rates of demolished concrete are modeled assuming a spherical shape for waste particles. Carbonation rates of demolished mortar are determined by its utilization. A detailed description of parameters relevant to demolition waste is available in Cao et al. (2020) Supplementary Tables 11-12[7].

China's clinker-to-cement ratios: plant-level survey

In order to verify the accuracy of the GNR data, plant-level data are plotted in a violin chart to show summary statistics such as mean or median and interquartile ranges.

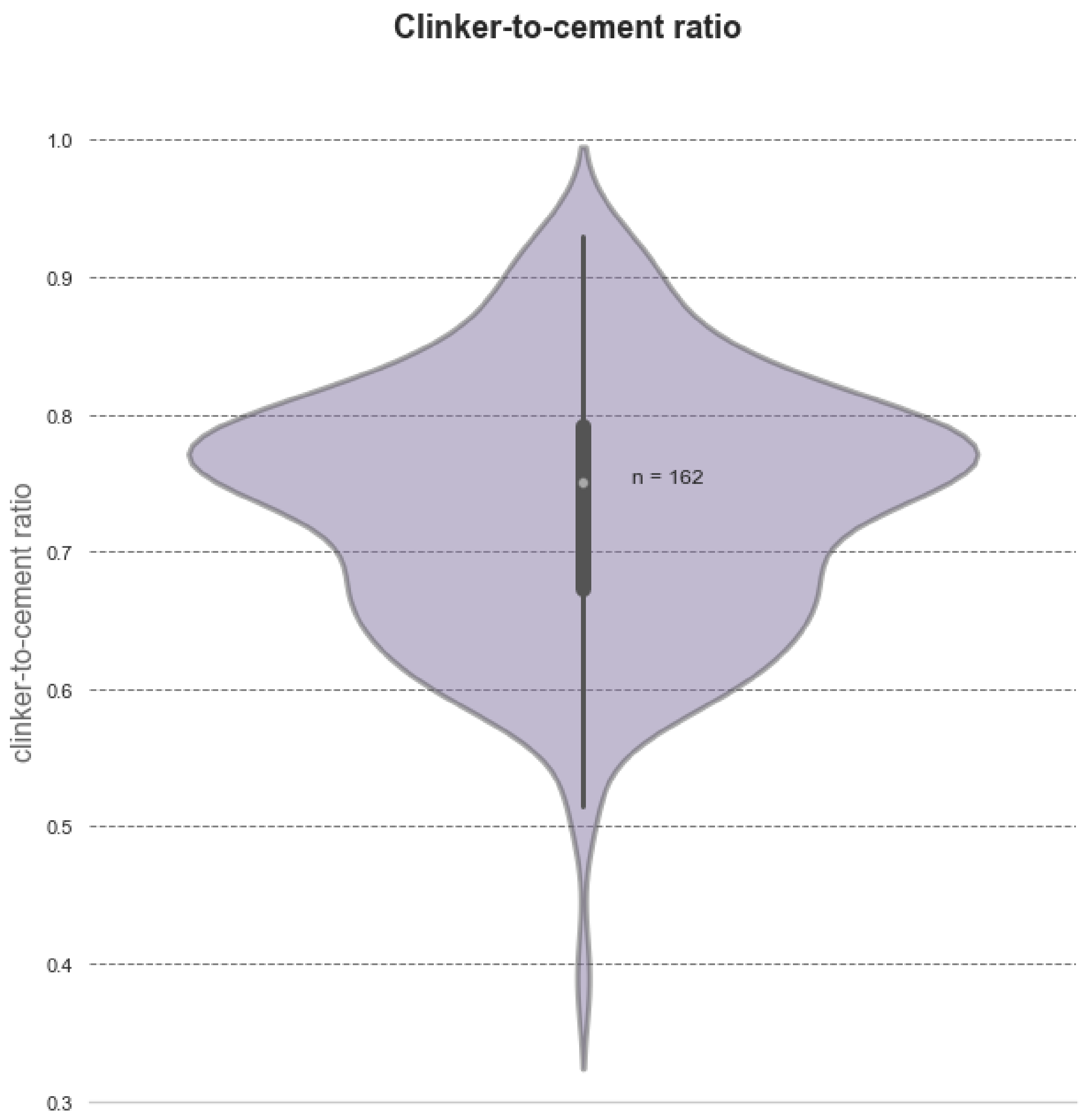


Figure A9. Clinker-to-cement ratio of cement plants in China.

Note: clinker-to-cement ratio data were derived from a plant-level survey[23] from 2011 to 2015. 162 out of the 197 surveyed cement plants produce cement products, with the remaining plants only producing clinker; the clinker-to-cement ratio of each cement plant is derived from its annual clinker production and annual cement production.

Prospects for timber supply and demand

As shown in Figure A10, a large fraction of roundwood produced in China and India is used as fuelwood. The increased demand for engineered timber could potentially be covered by harvesting roundwood[116,117] and bamboo[118], and diverting roundwood from use as fuelwood[119].

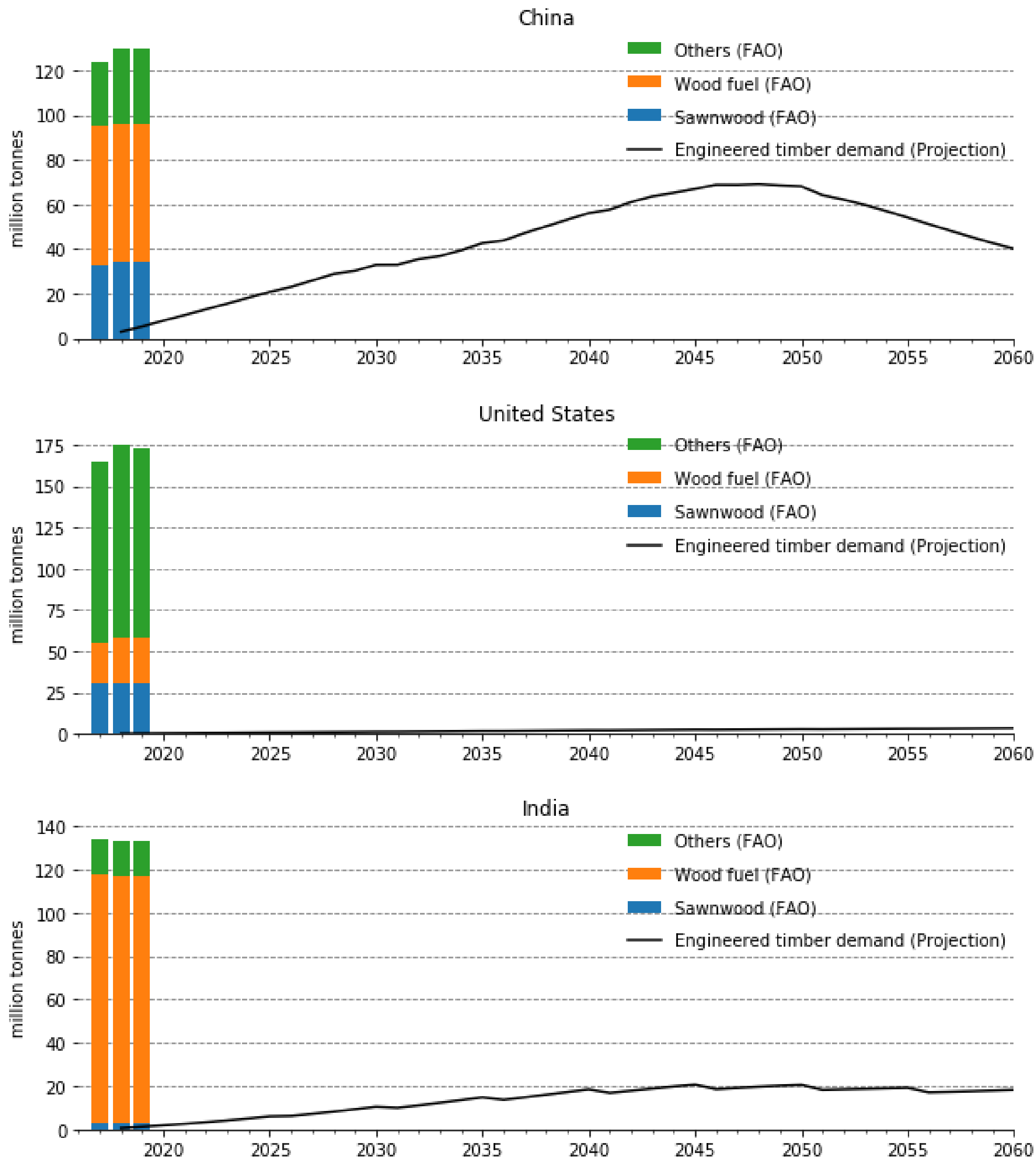


Figure A10. Prospects for timber supply and demand in China, the United States, and India.

Note: data for timber production (including wood fuels, sawnwood, and other uses) are obtained from FAOSTAT (http://www.fao.org/faostat/en/#data/FO). "Others" includes other roundwood uses besides wood fuels and sawnwood. Projected values of engineered timber demand are derived from the results of the Whole-Systems scenario.

[i] In 2017, the world cement production amounted to 4.1 Gt, of which ~69.6% was used for concrete. 1 tonne of concrete requires ~0.13 tonnes of cement. An 8-lane highway with a ~30 cm thick concrete surface requires ~20,000 tonnes of concrete.

[ii] Fuel efficiency of Toyota Corolla: 34.5 mile/gallon * 1.61 km/mile * 0.264 gallon/liter = 14.7 km/liter. The calorific value of petrol is roughly 25.3 MJ/liter.

[iii] Credit: https://theconstructor.org/practical-guide/fineness-modulus-of-coarse-aggregates-and-its-calculation/12472/

[iv] Credit: https://theconstructor.org/practical-guide/fineness-modulus-of-coarse-aggregates-and-its-calculation/12472/

[v] Credit: https://phys.org/news/2019-05-unknown-compounds.html

[vi] Credit: https://en.wikipedia.org/wiki/Energetically_modified_cement

[vii] Credit: https://www.elveflow.com/microfluidic-reviews/general-microfluidics/air-bubbles-and-microfluidics/

[viii] Permission to reuse or adapt the original figure has been granted by the publisher.

[ix] A caveat for this assumption is this CO_2 flux should not be double-counted in forestry models that consider harvested wood products as CO_2 sinks.