Beyond Mitigation Targets: Spatiotemporal Implementation Strategies for the Cement Industry

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Beyond Mitigation Targets: Spatiotemporal Implementation Strategies for the Cement Industry

This study represents the first case study designed to examine how accurately the high resolution greenhouse gas emissions data that the Korea Carbon Project (KCP) seeks to develop and utilize can characterize actual industrial emission structures, and whether such data can be translated into actionable units for mitigation policy implementation.

Whereas conventional national greenhouse gas inventories primarily provide annual, sector level aggregates, this study disaggregates process-related emissions from the cement industry into plant-level and monthly time series to analyze their temporal and spatial distributions. The objective extends beyond simply estimating emissions at a finer resolution. Detailed emissions information is intended to help determine when and where limited mitigation resources should be prioritized, thereby providing a basis for operationalizing national mitigation pathways.

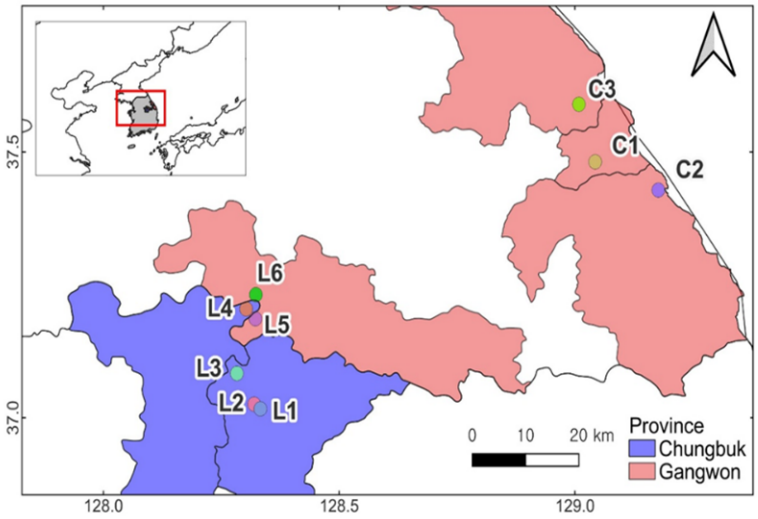
By assessing the applicability of KCP data across cement plants nationwide, this study also seeks to demonstrate how KCP can move beyond national- and sector-level emissions statistics and serve as a data foundation for setting plant-level mitigation priorities and evaluating implementation progress.

Ⅰ. From Targets to Implementation: A Time for a Fundamental Shift

1. Clinker: The Core of Cement-Sector Emissions

- Cement is produced by quarrying and crushing limestone($CaCO_3$), heating it in kilns at an average temperature of approximately 1,450°C to produce rock-like clinker, and subsequently grinding the clinker together with supplementary materials.
  - The resulting cement is the principal binding material in concrete and is used in the construction of buildings and infrastructure such as roads and bridges.
- In 2023, direct emissions from South Korea's cement industry amounted to approximately 38MtCO_2, accounting for 6.5% of national net CO_2 emissions. Of these emissions, approximately 22.7MtCO_2 were generated during clinker production through the conversion of limestone to clinker($CaCO_3 \rightarrow CaO + CO_2\uparrow$), representing about 60% of the cement industry's direct emissions (Greenhouse Gas Inventory and Research Center of Korea, 2024).[1)]
- For this reason, greenhouse gas mitigation in the cement industry must begin at the plants where clinker is produced. Domestic clinker-producing facilities are concentrated in Gangwon and Chungbuk provinces, where limestone is readily available, and nine plants account for 98.3% of national clinker production(Korea Cement Association, 2022; Greenhouse Gas Inventory and Research Center of Korea, 2024).
  - Among them, three large coastal plants in Gangwon Province account for approximately 50% of national clinker production, meaning that the operation of a small number of large plants can substantially shape the national emissions trajectory(Figure 1).
- Ultimately, achieving net zero in the cement industry requires reducing both emissions from clinker production and the quantity of clinker used. Material transition and substitution are therefore central to the sector's decarbonization strategy.

1) The remaining 40%, approximately 15.3 MtCO_2, is generated from energy-related fuel combustion.



Code	Region	2022 production (Mt yr^{-1})	2022 Share (%)
C1	Coastal	9.38	22.2
C2	Coastal	6.78	16.0
C3	Coastal	5.20	12.3
L5	Inland	2.40	5.7
L4	Inland	3.10	7.3
L2	Inland	5.00	11.8
L3	Inland	1.08	2.6
L6	Inland	3.36	7.9
L1	Inland	5.98	14.1
Total		42.89	100

Figure 1. Locations and production shares of major clinker-producing facilities in South Korea

2. Material Transition for Clinker Reduction and Constraints on Alternative Resources

- In accordance with South Korea's 2030 Nationally Determined Contribution(NDC), the cement industry has established reduction targets of 12% by 2030 and 53% by 2050 relative to 2018 levels. As sectoral mitigation pathways reflecting the 2035 NDC are further specified, the principle of progression is expected to require more ambitious targets and corresponding implementation efforts from the cement industry.
- Current material-transition measures can be broadly divided into three categories according to the stage at which they are applied.

  ① Replacing part of the limestone($CaCO_3$) used to produce clinker with noncarbonate raw materials

  : Because limestone releases CO_2 when heated, reducing limestone use lowers the process emissions generated per tonne of clinker. (Limestone substitution rate: 2% by 2030 and 12% by 2050)

  ② Replacing part of the clinker used in conventional cement, such as ordinary Portland cement, with supplementary materials such as blast furnace slag, fly ash, and limestone powder

  : Reducing the amount of clinker required per tonne of cement directly

reduces the amount of clinker that must be produced. (Supplementary material substitution rate: 15% by 2030 and 20% by 2050)

③ Increasing the share of low-carbon cement, such as blast furnace slag cement

: Greater use of cement containing a lower proportion of clinker reduces overall clinker demand and, consequently, clinker production. (Blended cement share: 20% by 2030 and 29% by 2050)

- These mitigation measures are closely linked to the use of circular and alternative resources. However, the availability of these resources depends on conditions in related industries that the cement sector itself cannot control.
  - As the steel industry shifts from blast furnaces toward electric arc furnaces and hydrogen based reduction ironmaking, the possibility of declining blast furnace slag supply cannot be excluded (Lee et al., 2025).
  - A more detailed approach is therefore required to determine when, where, and how limited alternative resources should be prioritized. Such prioritization is a critical factor in determining the effectiveness of mitigation-target implementation.

Ⅱ. Spatiotemporal Mitigation Opportunities

1. Opportunities for Spring and Autumn Mitigation Identified through Monthly Emissions

- Cement-sector emissions have generally followed a gradual downward trend since 2016. Domestic process-related emissions decreased by approximately 7%, from 24.5MtCO_2 in 2018 to 22.7MtCO_2 in 2023. However, examining the same emissions at a monthly resolution reveals a clear seasonal pattern.
  - During spring(March–May) and autumn(September–November), emissions were up to 10.1% and 9.4% higher, respectively, than the annual average, whereas winter emissions were up to 12.5% lower.

- In 2020, average monthly emissions were 1.86MtCO_2, but rose to 2.00MtCO_2 in autumn(+7.9%) and fell to 1.71MtCO_2 in summer(−7.8%). This pattern was not unique to a particular year but recurred throughout the 2016–2023 period (Figure 2).

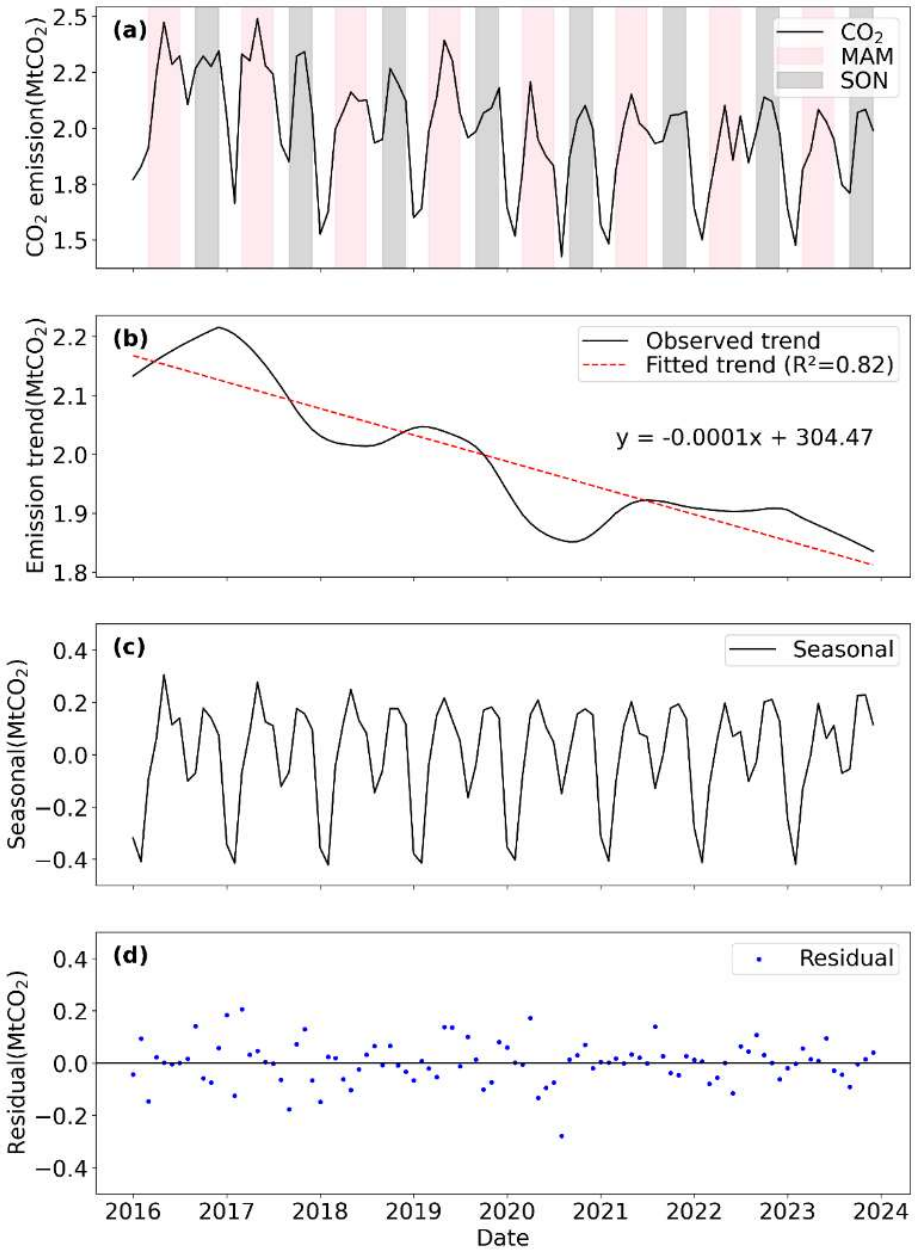


Figure 2. Trends and seasonal patterns in process-related CO_2 emissions from the cement industry (2016–2024).

(a) Monthly emissions, with spring and autumn periods shaded; (b) long-term trend; (c) annually recurring seasonal variation; and (d) residual variation after removing trend and seasonal components.

- This seasonal pattern reflects the characteristics of construction demand. Demand-side seasonality is directly reflected in clinker production and emissions: plant operating rates are approximately 10% above average in spring and autumn and around 30% below average in summer and winter (Park, 2023).
  - Cement is mixed with water and aggregates at construction sites to produce concrete.
  - Concrete can generally be placed and cured most effectively at temperatures of approximately 10–27°C. Below 0°C, there is a risk of freezing before the concrete hardens; above 32°C, rapid drying can increase the risk of cracking. Concrete placement is also difficult during rainfall exceeding 3 mm per hour for more than 15 minutes(ACI, 2016; 2020).
- Monthly emission patterns driven by demand therefore provide more than an indication of high-emission peak periods. They can identify practical windows in which mitigation measures could be prioritized.

2. Mitigation Opportunities at Large Plants Revealed by Plant-Level Emissions

- National cement-process emissions increased by approximately 1.3% in 2019 relative to 2018. Over the same period, emissions from the three coastal plants increased by 4.1%, from 12.5MtCO_2 to 13.0MtCO_2.
  - The increase from coastal plants exceeded the increase in total national emissions, offsetting declines at inland plants and ultimately driving the national increase.
  - Conversely, the decline after 2020 was largely attributable to production reductions at plants C1 and L5, which are operated by the same company and together account for approximately 28–29% of national production (Figure 3).

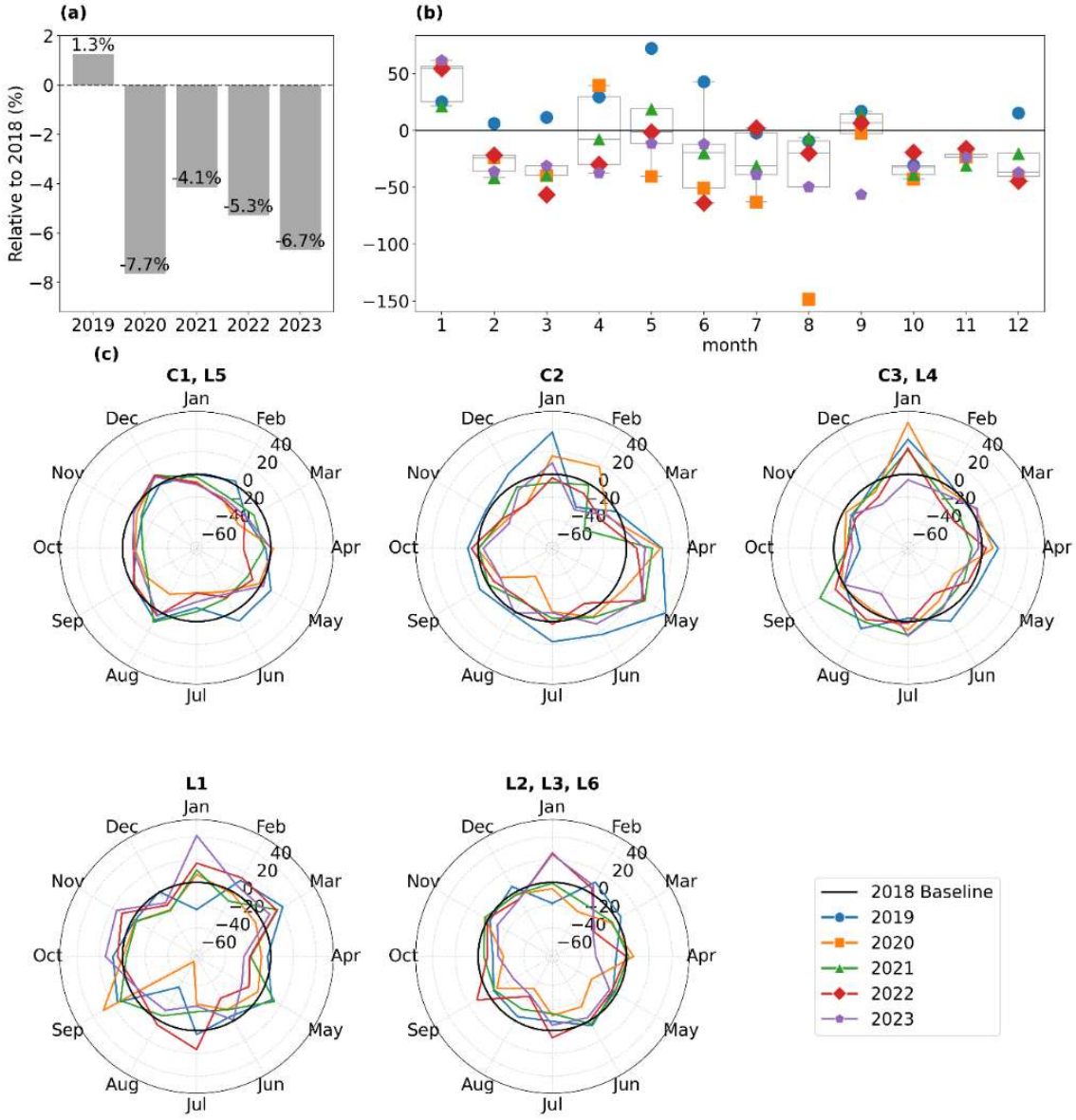


Figure 3. Changes in cement process emissions relative to 2018 (2019–2023).
(a) Annual rates of change; (b) monthly rates of change; and
(c) monthly changes in emissions from plants grouped by company.

- At the national level, the pattern appears relatively simple: emissions are higher in spring and autumn and lower in summer and winter. At the plant level, however, the months of highest emissions differ substantially among facilities.

  - Most plants exhibited higher emissions during spring (March–May) and autumn (September–November), whereas the C1–L5 group showed distinct peaks in August, November, and December.

- The national seasonal pattern can therefore be understood as the aggregate outcome of plant-specific market areas, demand timing, and corresponding production schedules(Korea Cement Association, 2022).

- Monthly and plant-level data thus reveal the “when” and “where” that remain invisible in annual national aggregates.
  - Detailed emissions information is necessary to answer the central implementation question identified above: when, where, and how should limited alternative resources be prioritized?

III. High-Resolution Mitigation Pathways through What-If Scenarios

1. Multiple Strategic Options from a Single Mitigation Measure

- As shown above, cement emissions are higher in spring and autumn, while coastal plants exert a disproportionate influence on the national trajectory of process-related emissions. Reflecting these characteristics, three what-if scenarios were constructed based on a single mitigation measure: non-carbonate raw material substitution.
  - The what-if scenarios are not forecasts of the future. Instead, they compare outcomes under hypothetical cases in which the same mitigation measure is applied at different plants and at different times.
- The scenarios are defined as follows: (**Scenario 1**) substitution is applied only to the three coastal plants during spring and autumn, when production and emissions are high. (**Scenario 2**) substitution is applied to all plants during spring and autumn. (**Scenario 3**) substitution is applied to all plants throughout the entire year.
  - This does not imply switching mitigation technologies from one season to another. Rather, it represents a prioritization strategy in which scarce alternative resources are first allocated to the plants and periods where emissions are concentrated.

Box 1. Scenario Design

Mitigation measure: Non-carbonate raw material substitution. In accordance with the industry roadmap, the substitution rate is assumed to increase linearly from 0% in 2024 to 2% in 2030 and 12% in 2050 (Lee et al., 2023; Kim, 2024). The corresponding values were incorporated into the emission factor following the 2006 IPCC Guidelines.

Production assumption: To isolate the effect of the mitigation measure, clinker production at all plants is assumed to remain at 2018 levels, and the same substitution rate is applied uniformly across all plants. Differences among scenarios therefore arise not from differences in mitigation efficiency but from the scope of application, that is, the amount of production covered.

Table 3. Scenario design and assumptions

Scenario	Plants covered	Timing
Scenario 1	Three coastal plants	Spring and autumn
Scenario 2	All plants	Spring and autumn
Scenario 3	All plants	Year-round

- By 2050, estimated emission reductions are:

  : (**Scenario 1**) approximately 1.3 $MtCO_2$, equivalent to 5.4% below the 2018 level

  : (**Scenario 2**) approximately 2.5 $MtCO_2$, equivalent to 10.5% below the 2018 level

  : (**Scenario 3**) approximately 4.3 $MtCO_2$, equivalent to 17.8% below the 2018 level

  - These reductions are comparable in magnitude to the annual emissions of, respectively, one medium-sized inland plant, one large inland plant, and one large coastal plant.

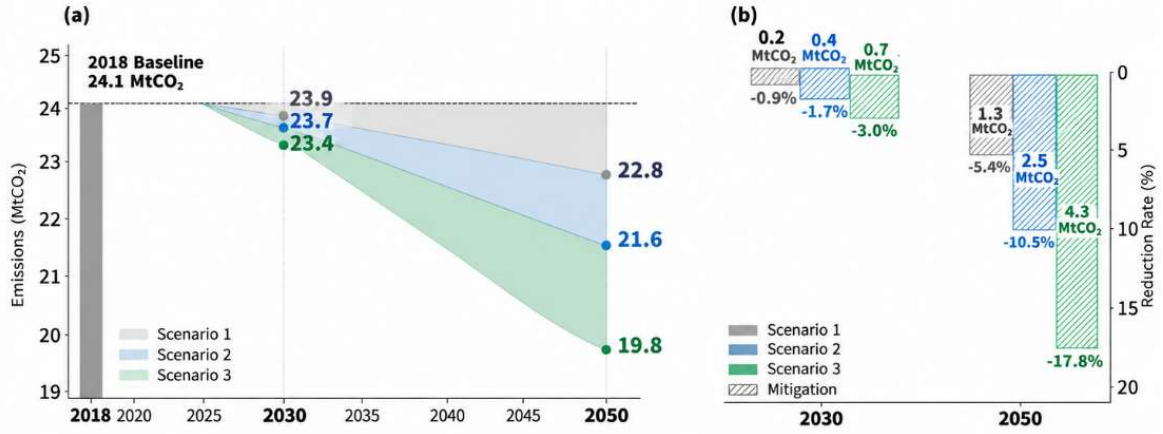


Figure 4. Emissions and mitigation effects under non-carbonate raw material substitution scenarios (2025–2050).

(a) Emissions and emission reductions;

(b) reduction rates in 2030 and 2050 relative to the 2018 baseline.

- The differences among the three scenarios arise not from mitigation efficiency but from the scope of application. The purpose is therefore not to determine which scenario is inherently more efficient, but rather to demonstrate when and where the same mitigation measure could first be deployed.
  - If alternative resources remain supply-constrained even as their sources are diversified, a phased pathway could begin with coastal plants during high-emission spring and autumn periods (Scenario 1), expand to all plants during spring and autumn as resource availability increases (Scenario 2), and ultimately progress to year-round, industry-wide deployment (Scenario 3).
  - Annual national totals indicate how much emissions need to be reduced, whereas monthly and plant-level emissions data can serve as a practical tool for translating mitigation targets into actual implementation.

2. Linking Value-Chain Mitigation through Spatiotemporal Information

- Although this analysis considers only one mitigation measure—non-carbonate raw material substitution at the clinker-production stage—mitigation opportunities in the cement industry extend across the entire value chain.
  - Clinker production: raw material and fuel substitution
  - Cement production: increasing the share of supplementary materials
  - Concrete production: use of supplementary materials
  - Construction: reducing cement demand through greater use of blended cement and improved design efficiency (CEMBUREAU, 2018; Miller et al., 2021)
- Mitigation measures at each stage differ in terms of responsible actors, timing of deployment, and required resources. Decisions at the clinker and cement stages are primarily made by cement producers, whereas decisions at the concrete and construction stages involve ready-mixed concrete producers and construction companies.
  - In some cases, multiple stages also compete for the same resources, as in the case of blast furnace slag.
  - Monthly and plant-level emissions data can therefore provide a common spatiotemporal reference frame through which mitigation measures across different stages can be assessed together.

- In particular, the fact that seasonal patterns in cement emissions are driven by construction demand indicates potential for aligning the timing of mitigation measures between the supply side (cement plants) and the demand side (ready-mixed concrete producers and construction companies).
  - For example, increasing the use of blended cement during peak construction periods while simultaneously concentrating raw material substitution at the clinker-production stage could generate mitigation effects on both the supply and demand sides.
  - Beginning with a single mitigation measure, the present analysis can serve as a starting point for progressively incorporating additional measures at each stage and designing an integrated implementation pathway across the entire value chain.

IV. A Granular Implementation Strategy for Achieving the 2035 NDC

- Since its establishment in February 2021, the Cement Green New Deal Committee has presented directions for the development and deployment of mitigation technologies—including raw material and fuel substitution, process-efficiency improvements, and CCUS—to support the achievement of carbon neutrality by 2050 (Kim & Bae, 2021).
  - Future mitigation strategies need to consider not only the maximum reduction potential of each technology, but also which facilities should adopt them and when.
  - For supply-constrained resources such as alternative raw materials, the location and timing of deployment can themselves become important policy variables.
- Carbon-neutrality strategies therefore need to expand beyond “How much?” and “What?” to incorporate “Where?” and “When?”
  - Under the national mitigation pathway, implementation pathways need to be connected at the Plant × Month × Technology level, with progress monitored against this framework.
- The timing and scale of raw material substitution depend on the supply of circular resources from related industries such as steel and power generation, while the timing of cement production and associated emissions is driven by demand from

the construction and concrete sectors. Implementation strategies therefore cannot be designed within the cement industry alone.

- The Cement Green New Deal Committee could serve as a platform for establishing these linkages. If plant- and month-level emissions data from the cement industry, projections of circular-resource supply from the steel and power sectors, and demand information from the construction and ready-mixed concrete industries were collected and shared using a common spatiotemporal framework, transition plans across industries could be designed in a mutually coordinated manner.
  - The next step, therefore, is not simply to increase the resolution of emissions information, but to connect the time and space in which demand generates emissions with the time and space in which circular resources become available.
- The challenge is no longer only to determine how much emissions should be reduced. The next stage is to determine and implement when, where, and how those reductions should occur.

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