Deciphering the CO_2 emissions and emission intensity of cement sector in China through decomposition analysis

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Abstract

China produced over half of the global cement for its building and infrastructure construction and released huge amount of greenhouse gases. Despite a significant penetration of the new suspension pre-calciner (NSP) kilns was reported to benefit emission abatement in the past, whether CO_2 emissions has peaked and would some recent structural changes affect the low-carbon transition in China are yet to be investigated. Thus, this study develops a three-step framework to estimate the CO_2 emissions and investigate the socio-economic emission drivers and the recent structural change of the cement sector in China during 1990-2020. Results reveal that CO_2 emissions from cement production have yet peaked in China, as it increased again after the sharp decline in 2015. The aggregate emission intensity of cement production significantly decreased from 708.5 to 485.3 kg CO_2/t during 2000-2015 with the penetration of the NSP kilns, but after that it rebounded to 548.6 kg CO_2/t. The decomposition analysis reveals that the inter-sector impacts outweighed the intra-sectoral mitigation effects in the past three decades, and further decoupling analysis also reveals that the total emissions have yet been decoupled with economic development. Also, the rebound in emission intensity is attributed to the rebound in the clinker-to-cement ratio, which is further due to the recent abolishment of low-grade cement and expanding production of higher-grade cement. A 'reduce' approach, such as reducing construction activities and improving material efficiency, would be a much more effective policy option for short to medium term low-carbon transition, rather than merely implementing the intra-sectoral measures.

Keywords: CO_2 emissions; cement sector; socio-economic drivers; structural change; emission abatement

1. Introduction

Up to 8% of anthropogenic CO_2 emissions are released to the atmosphere during cement production, not only due to the amount of fuel burning but also because of its unique limestone decomposition. Yet, the industry generally considers that no material is capable of replacing reinforced concrete at a low economic cost at present or even in the mid to long-term future (Habert et al., 2020; D. Xu et al., 2015). From that perspective, how to decarbonize the cement production has always been a well-debated topic. From the energy crisis in 1970's to the Kyoto Protocol on climate change at the end of the last century, and now the 1.5 and 2.0°C climate targets after the Paris Agreement, the world's attention has shifted from energy efficiency to emission mitigation (Feng et al., 1995; Worrell et al., 2001), not to mention about the recent ambitious goal of a net-zero carbon industry (Dinga & Wen, 2022; Fennell et al., 2021; Miller et al., 2021).

As the largest cement producer worldwide, China's challenge may be more significant, despite the past mitigation efforts have begun to lead to bear fruit. Cement production has risen from 65 Mt to 2,395 Mt between 1978 and 2020, representing an average growth of around 9% per annum, and this not only accounted for 56% of the global total cement production in 2018 but also dominated the global growth by 74% in the past thirty years (Andrew, 2019; NBS, 2021). This huge production led to a 1.24 gigatons CO_2 emissions in 2019 (GID, 2021). Besides, the Chinese cement industry also encountered severe overcapacity as there were 1,233 cement plants with 1,792 production lines around the country by the end of 2020, while the overall utilization rate was always below 0.8 (Fig. 1). We can foresee the release of sizeable GHG emissions will continue from the existing infrastructure production, which would jeopardize the national climate target, i.e., to peak CO_2 emissions before 2030 and to achieve carbon neutrality before 2060 (Tong et al., 2019; Xinhua Press, 2020). Therefore, it is imperative to devise a pragmatic roadmap to decarbonize the cement industry under the carbon neutrality vision.

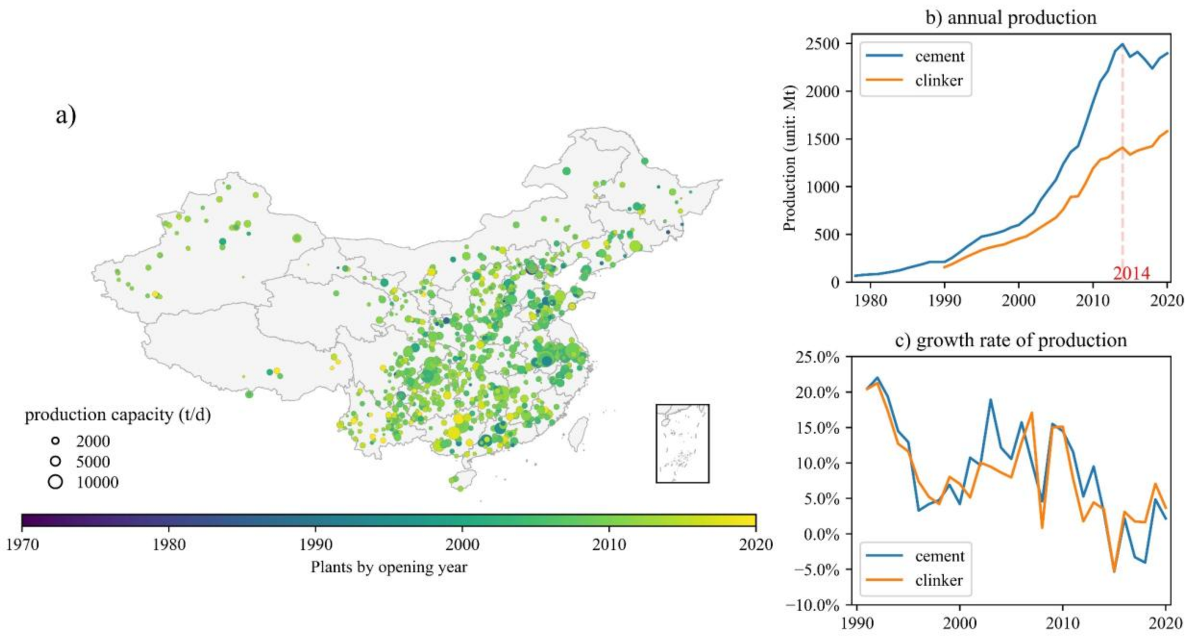

Fig. 1. The current layout of cement plants in China (a), historical cement and clinker production (b), and the growth rate of production (c). (Data source: production data are mainly collected from National Bureau of Statistics (https://data.stats.gov.cn/) and China Cement Almanac (CCA, 2015). The current location and production capacity size of cement plants are collected from relevant announcements by each provincial Department of Industry and Information Technology in recent two years, such as Anhui (2021), Guangdong (2021), and Guangxi (2021).)

However, previous studies concerning CO_2 emissions from cement production in China have several gaps that need to be addressed, when targeting a carbon-neutral industry. First, variations exist in the historical emission volume between different accounting studies, partly due to the process emission factors from different sources and the unavailable official energy statistics for heating kilns (J. Liu et al., 2021; L. Shen et al., 2014). Some studies even claimed that the total emissions appears to have peaked in 2014, as the cement production peaked in the same year (Shan et al., 2019). Second, the socio-economic drivers on the total emissions have not been fully examined in previous studies. Previous research has revealed that most emissions growth was from the exponential expanding scale of production activities (Y. Wang et al., 2013; J. Xu et al., 2012; Zheng et al., 2021), but the related socio-economic drivers and the connections with the construction sector were seldom discussed. Despite cement consumption per capita was adopted as a proxy to reflect the relationship between cement production and the socio-economic development, it exhibited diversified trajectories in different regions (van Ruijven et al., 2016). Third, recent structural changes after 2015 have yet been fully taken into account. Past emission mitigation mainly resulted from efficiency improvement from the penetration of new suspension pre-calciner (NSP) kilns and decreased clinker-to-cement ratio of cement grinding (T. Gao et al., 2017; J. Liu et al., 2021). However, both factors have reversed in recent years. The cement sector may encounter an efficiency stagnation after the saturation of NSP, like the iron and steel sector (P. Wang et al., 2021). The clinker-to-cement ratio may, therefore, rebound due to the stricter strength requirement from the recent change in regulations (Andrew, 2019).

To bridge the above research gaps, this study first re-estimates the total CO_2 emissions from the cement production in China during the past three decades based on the updated activity data and emission factors. We then adopt an extended Kaya identity to decompose the total emissions to the socio-economic drivers and apply a logarithmic mean Divisia index (LMDI) approach to quantitatively investigate the change of those factors on the total emissions. After that, we quantify the recent structural change on the aggregate emission intensity[1] of cement production in China. Finally, the key findings are summarized and policy recommendations are provided.

The remainder of this paper is structured as follows: Section 2 conducts a review on the related work, and Section 3 displays the research methods and materials, including the emission accounting model and emission decomposition model. Section 4 displays and analyzes the historical emissions and structural change in the cement industry, while Section 5 provides a detailed discussion on the impacts brought by structural change and low-carbon technologies diffusion. Section 6 summarizes the core findings and the limitations of this study.

2. Related work

2.1 CO_2 emission accounting for cement industry

CO_2 emissions from cement production are categorized into process-related emissions (mainly due to the carbonate decarbonization) and energy-related emissions, which can be further

[1] Analogous to the energy intensity in decomposition analysis (B.W. Ang & Zhang, 2000), aggregate emission intensity here refers to the amount of CO2 emissions released by the production of a given unit of output at the sectoral level.

subdivided into emissions from fuel burning and indirect emissions for electricity consumption (Ali et al., 2011). Emission accounting mainly adopts the emission factor method, that means the total emissions are estimated by multiplying the activity data with the emission factor for per unit of activity. At present, there are several mature international guidelines governing emission accounting for cement production at the national, sector, and factory level, such as the three-tier methods in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories , and the CO_2 emission accounting standard of Cement Sustainability Initiative (CSI, 2011). Besides the accounting methods, the process-related emission factor for clinker production should be carefully estimated, as the default one recommended by IPCC may over or under-estimate the total emissions of the Chinese cement industry. According to the main chemical reactions during calcination, i.e., $\mathrm{CaCO_3 \rightarrow CaO + CO_2}$ and $\mathrm{MgCO_3 \rightarrow MgO + CO_2}$, this emission factor can be derived based on the stoichiometric compositions of the reaction as follows.

$$\mathrm{EF_{clinker}} = \mathrm{Content_{CaO}} \times 44/56 + \mathrm{Content_{MgO}} \times 40 \tag{1}$$

where $\mathrm{Content_{CaO}}$ and $\mathrm{Content_{MgO}}$ represent the CaO and MgO contents of clinker which should be calculated based on plant-level surveys. The National Development and Reform Commission of China (NDRC), which was previously responsible for the country's climate change affairs, estimated the process-related emission factors for clinker production based on specific data collected from 128 plants in 2005, when compiled the national inventories (Department of Climate Change, 2012). L. Shen et al. (2014) surveyed the raw material, raw meal, clinker, cement and fuel of 289 production lines across the 18 provinces of China by 2012, and estimated the process emission factors by kiln types, which is lower than the default values found in the IPCC Guidelines by 1.4-3.4%. Cai et al. (2016) estimated the overall process emission factor at 0.504 t CO_2/t clinker based on the detailed information of 1,574 cement enterprises in 2013, but without claiming the specific content of CaO and MgO. The emission factors from other sources are also included for comparison as below.

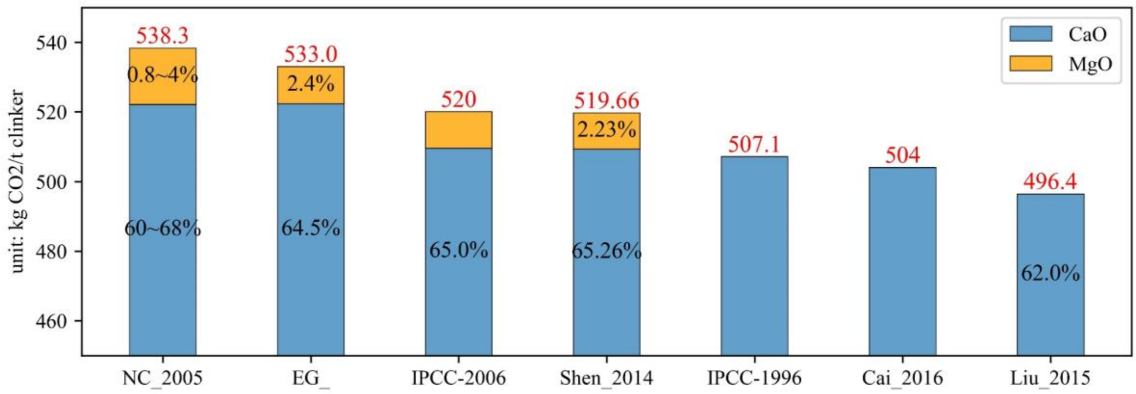

Fig. 2 Comparison of process-related emission factors for clinker production.

NDRC estimated the process-related emissions at 157.8 Mt CO_2 and 411.7 Mt CO_2 in 1994 and 2005 respectively in its twice communication reports submitted to UNFCCC (NDRC, 2004, 2012). Another issue is the high variations and uncertainty in energy consumption, as the amount of coal used for heating the kiln was not directly available in the official statistics but rather being estimated by different reported coal intensity (J. Liu et al., 2021).

2.2 Decomposition analysis on CO_2 emissions from cement sector

Decomposition analysis aims to identify and assess the drivers of observed changes over time of energy and environmental impacts indicators of nations or sectors (de Boer & Rodrigues, 2019). There are two techniques for decomposing indicator changes at the sector level, i.e., structural decomposition analysis (SDA) and index decomposition analysis (IDA) (Hoekestr & van der Bergh, 2003). SDA uses input-output tables (IOT) and models as a basis to explore the link between environmental impacts and consumption activities. IDA begins with defining a governing function relating the aggregate to be decomposed to a number of ‘indices’ (singular ‘index’), i.e., pre-defined factors of interest, then with the defined function, various quantitative methods can be formulated to gauge the impacts of changes of these factors on the aggregate (B. W. Ang, 2004). According to their definitions, SDA requires much more data as it relies on IOTs, while IDA only requires sector level data (Hoekestr & van der Bergh, 2003). Notably, IDA and SDA have different emphasis, as de Boer and Rodrigues (2019) pointed out that the former explores the link between environmental impact and production level while the latter explores the link between impact and consumption activities. Moreover, SDA may not support the long-term continuous monitoring on the structural change in cement sector, as IOTs are released almost every five years in China. Therefore, given the research emphasis and data availability, previous literature often adopted IDA to analyze the structural change over years (e.g., change in product mix change, decrease in sectoral energy intensity) in the cement sector of China.

Nevertheless, there are several shortcomings in these studies pertinent to China's cement sector, such as subjective selection of driving factors and unreasonable decomposition. J. Xu et al. (2012) decomposed the total carbon dioxide emissions from cement production based on the production procedures. Despite their analysis could quantify the mitigation effect from the structural shift, the significant impacts from demand change of downstream sectors were overlooked. Y. Wang et al. (2013) divided the total emissions into energy-related and process-related emissions and decomposed the former into the energy emission factors, energy structure, energy intensity, and total production, which could not lead to specific improvement as they mixed clinker production and cement grinding together. Lin and Zhang (2016) decomposed the total emissions into five effects from the productivity perspective, i.e., total employees, unit industrial added value per employee, energy consumption per unit added value, energy structure, and carbon intensity of energies. But this decomposition is unreasonable as it omitted a large part of non-energy emissions (i.e., process-related emissions). Shan et al. (2019) decomposed the total emissions to the structure of the construction industry, emission intensity, input efficiency, and fixed asset investment from an economic perspective. However, the fixed asset investment may not significantly relate to cement production as cement costs only account for a small part of it. While Zheng et al. (2021) decomposed emission intensity reasonably according to the components of accounting formulas, their analysis on total emissions just added a scale effect (i.e., total production), which could not reflect the effects resulting in production change.

Based on the above review, we can summarize that the emission drivers of the cement industry should be categorized into the socio-economic and technical factors. The former mainly reflects the demand change of downstream sectors, which is related to population growth and economic development, while the latter reflects the intra-industry structural change and technology improvements. Thus, this study adopts the Kaya identity to systematically decompose the emission drivers for the cement industry, of which the aggregate emission intensity can reflect the intra-industry mitigation effects whereas other drivers reflect the socio-economic effects which are outside the industry. Besides, the emission intensity is decomposed based on its constitutions to further investigate the historical intra-industrial mitigation effects.

3. Method

This study aims to retrospect the historical socio-economic drivers on total CO_2 emissions and the recent structural changes on emission intensity of cement production in China. As shown in Fig. 3, a three-step framework is proposed in this study. First, the updated activity data from multiple sources are collected to develop the China Cement Industry Dataset (CCID) for emission accounting. Second, this study estimates the CO_2 emission intensities and the total emissions from cement production in China from 1990 to 2020, based on the defined system boundary and available statistics. Third, this study adopts and extends the Kaya identity to decompose the total emissions to the socio-economic drivers and emission intensity, which is further decomposed to investigate the industrial structural change. After that, the impacts from the decomposed factors are quantified by the LMDI approach. Finally, a decoupling analysis is conducted to check whether the total emissions have been decoupled with the economic development, based on the categorization proposed by Tapio (2005).

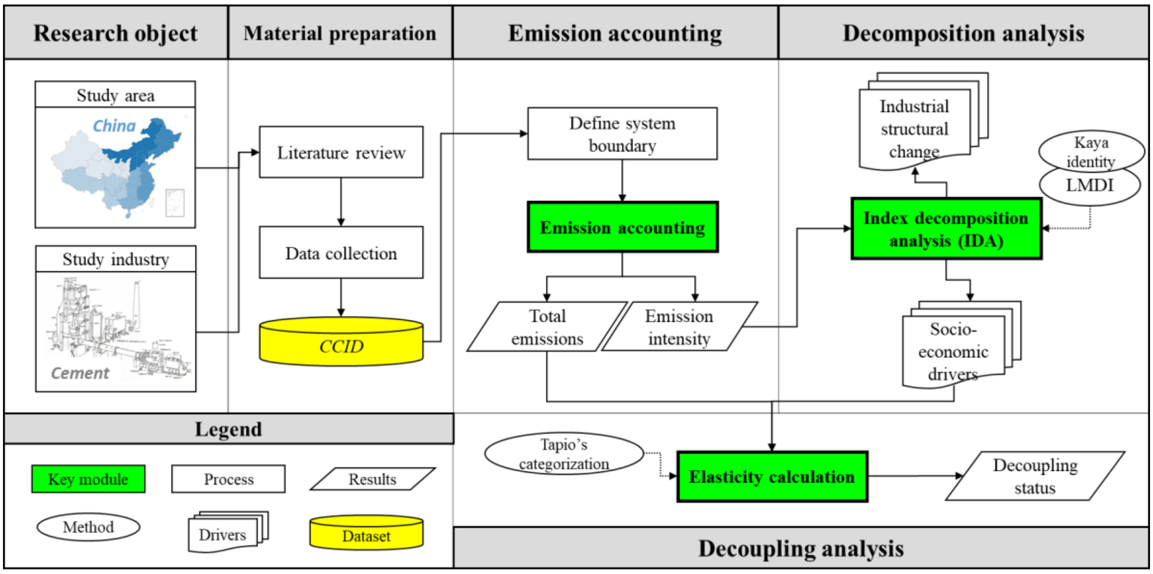

Fig. 3. Research framework of this study.

3.1 Emission accounting

In this study, we adopt the emission factor method recommended by the IPCC Guidelines to estimate the CO_2 emissions from the cement sector in China, through multiplying the production activity data by the aggregate emission intensity to obtain the total emissions. Here the aggregate emission intensity is the amount of CO_2 emissions released by the production of a given unit of specific output (cement or clinker) at the sectoral level. We consider both direct emissions released from the cement plants, i.e., process-related and fossil fuel-related emissions, and the indirect emissions from purchased electricity and re-divide them into emissions from clinker and cement production respectively. Thus, the total emissions can be calculated as below:

$$C = O_{\text{cement}} \times EI_{\text{cement}} \tag{2}$$

$$C_{\text{clinker}} = O_{\text{clinker}} \times EI_{\text{clinker}} \tag{3}$$

where O denotes the annual output of cement and clinker and EI denotes emission intensity. Then, we can define the system boundary for estimating the emission intensities of cement production based on the accounting methods in previous studies and the IPCC Guidelines (Fig. 4). Herein, we merge the production activities to three main processes, i.e., raw meal preparation (including crushing the raw materials and grinding the raw meal), kiln calcination, and cement grinding, for the consistency with the available statistics. The activity level data are collected from both official and industrial sources (i.e., *CCID*).

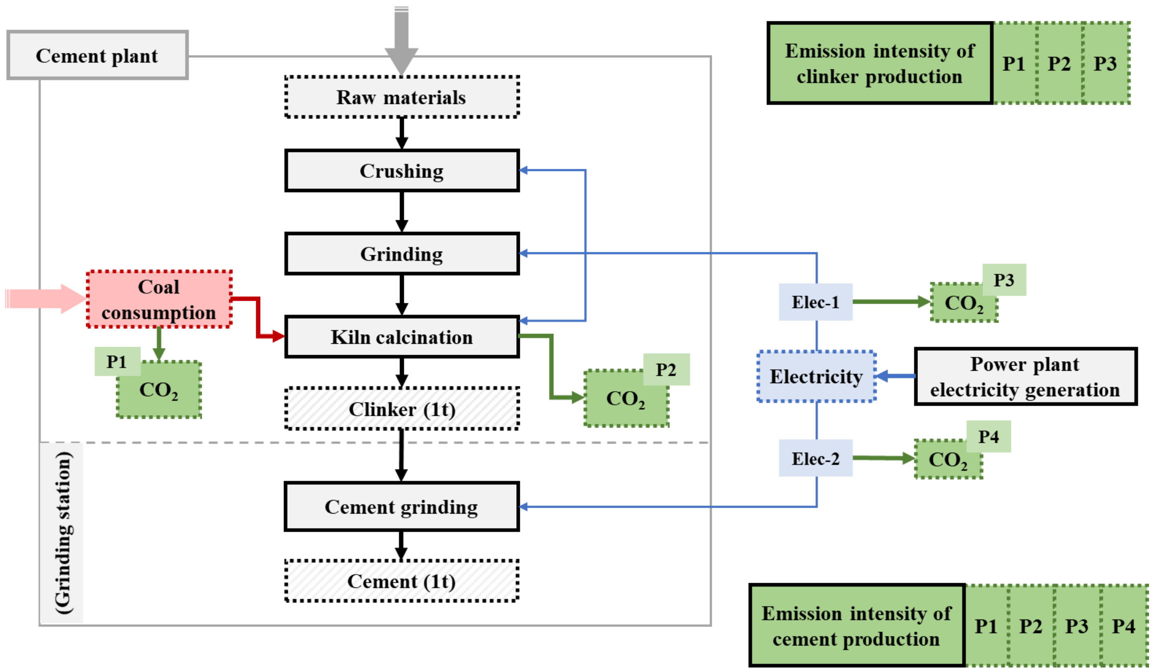

Fig. 4. System boundary for estimating aggregate emission intensities.

As shown in Fig. 4, the CO_2 emissions from clinker production originate from coal burning, carbonate decomposition during kiln calcination and purchased electricity (i.e., subparts P1-P3 in Fig. 4), while those of cement production include both the above emissions and the electricity consumed for cement grinding (P1-P4 in Fig. 4). According to the evolution of past decades, the cement kilns in China are groups into three main types, i.e., rotary kilns with pre-calciner (NSP), shaft kilns (SK) and other types of rotary kilns (OR) (T. Gao et al., 2017). Thus, the carbon emissions from clinker production are differentiated to represent each kiln types (Eq. (4)). These intensities can be developed as below:

$$EI_{\text{clinker}} = \sum_i w_i \cdot EI_{\text{clinker},\, i} \tag{4}$$

$$EI_{\text{clinker},\, i} = EI_{\text{process},\, i} + EI_{\text{coal},\, i} + EI_{\text{elec\_1},\, i} \tag{5}$$

$$EI_{\text{cement}} = CCR \times EI_{\text{clinker}} + EI_{\text{elec\_2}} \tag{6}$$

where EI represents the emission intensity, and the superscript t and subscript i in the above equations refer to the certain year and kiln type respectively. The w_i represents the share of a specific kiln type in the whole sector, while CCR is the clinker-to-cement ratio which represents the required content of clinker to produce per unit of cement. For the process emission intensity (i.e., P2), we adopt the data from field surveys on over 200 production lines across the whole country conducted by L. Shen et al. (2014). Moreover, the emission intensities of sub-parts P1, P3 and P4 are shown below:

$$EI_{\text{coal},\, i} = e_{\text{coal},\, i} \times EF_{\text{coal}} \tag{7}$$

$$EI_{\text{elec\_1},\, i} = e_{\text{elec\_1},\, i} \times EF_{\text{elec}} \tag{8}$$

$$EI_{\text{elec\_2}} = e_{\text{elec\_2}} \times EF_{\text{elec}} \tag{9}$$

where e_{coal} and $e_{\text{elec\_1}}$ refer to the coal consumption required for kiln calcination and electricity consumption (mainly for crushers and grinders) to produce the unit clinker product, and $e_{\text{elec\_2}}$ denotes the electricity consumption for grinding clinker with additives to produce per unit of cement product. Besides, EF_{coal} and EF_{elec} represent the emission factor of coal burning and coal-fired electricity generation respectively. We adopt J. Liu et al. (2021)'s method to estimate

e_{coal} , $e_{\text{elec\_1}}$, and $e_{\text{elec\_2}}$ based on the data collected from literature, official and industrial reports (see Appendix A). The conversion factor of bituminous coal is adopted for EF_{coal} as it is the main use for heating the kilns, while EF_{elec} is calculated by the methods recommended by NDRC (also shown in Appendix). The symbols, definitions, and units of all the variables are listed in the Table 1.

Table 1 List of variables.

Variable	Definition	Unit
t	The superscript *t* denotes a certain year.	-
i	The subscript *i* refers to the type of cement kiln.	-
C	Total annual carbon-dioxide emissions from cement production.	Mt CO_2
C_{clinker}	Total annual carbon-dioxide emissions from clinker production.	Mt CO_2
O_{cement}	The annual cement output.	Mt
O_{clinker}	The annual clinker output.	Mt
EI_{cement}	Aggregate annual emission intensity of cement production.	t CO_2 /t
EI_{clinker}	Aggregate annual emission intensity of clinker production.	t CO_2 /t
EI_{process}	Emission intensity of carbonate decomposition during the kiln calcination.	t CO_2 /t
EI_{coal}	Emission intensity of carbonate decomposition during the kiln calcination.	t CO_2 /t
$EI_{\text{elec\_1}}$	Emission intensity of raw meal preparation to produce unit clinker.	t CO_2 /t
$EI_{\text{elec\_2}}$	Emission intensity for grinding unit cement product.	t CO_2 /t
e_{coal}	Coal consumption intensity for heating the cement kilns.	kg ce / t
$e_{\text{elec\_1}}$	Electricity consumption intensity for raw meal preparation to produce unit clinker.	kWh / t
$e_{\text{elec\_2}}$	Electricity consumption intensity for grinding unit cement product.	kWh / t
EF_{coal}	Emission factor of fuel burning for heating in the cement kilns (Mainly of bituminous coal).	kg CO_2 / t
EF_{elec}	Emission factor of coal-fired power generation.	kg CO_2 / kWh
w_i	The weight of each kiln type.	%
CCR	The clinker-to-cement ratio for cement production.	%
POP	Population scale.	10^4
GDP	Gross domestic product at constant price in 1990.	10^8 yuan
Con	Annual output value of construction industry at constant price in 1990.	10^8 yuan
o_{cement}	Annual cement production per capita.	T

3.2 Decomposition analysis on total emissions and emission intensity

After emission accounting for the cement sector, we decompose both the total emissions and emission intensities of cement and clinker production, and the Fig. 5 displays the analytical process and related factors.

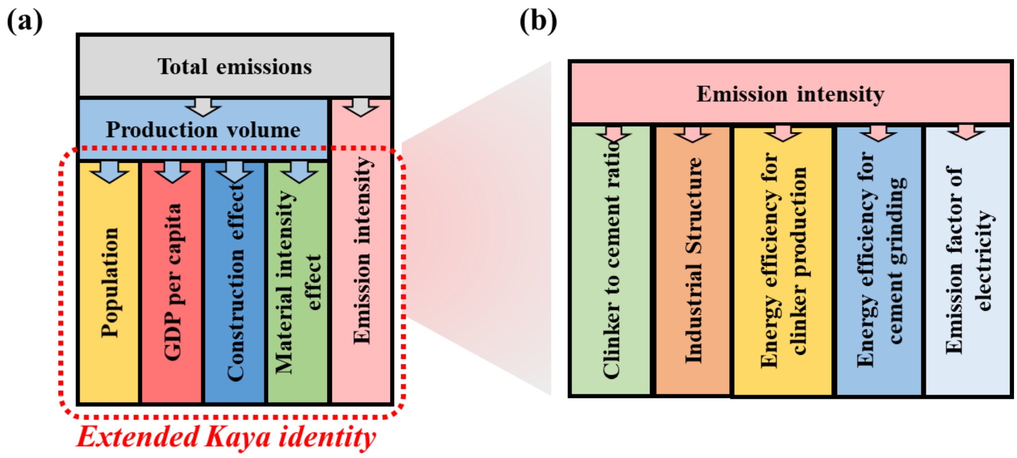

Fig. 5. Decomposition on total emissions and emission intensity.

Initially, the apparent change on total emissions originates from the production volume and the aggregate emission intensity according to the accounting equation. To investigate the impacts from the socio-economic factors, we adopt the Kaya identity to further decompose the emissions with two improvements, as it has the concise form and a powerful interpretation on the drivers of CO_2 emissions (Kaya, 1989). Besides analyze the socio-economic drivers of carbon emissions at country or regional level, recently Kaya identity was more applied to the analysis on drivers of carbon emissions at the sectoral level, as it can relate the sectoral emission dynamics with the socio-economic change reasonably (Ma et al., 2019; X. Wang et al., 2020; X. Zhang et al., 2017). However, we made two improvements on this identity to avoid bias and obtain further insights, when we focus on the cement sector. First, compared with the original Kaya identity, the energy consumption is substituted by the cement production volume, as it is improper to decompose the total emissions with energy consumption given that nearly two-thirds of CO_2 is emitted from carbonate decomposition rather than only from fuel burning. Second, we add the output of the construction sector into this identity. It is meaningful to consider the impact of construction sector, when we analyze socio-economic drivers here, as all the output of cement sector will eventually flow into the construction sector as construction materials. Thus, the extended identity can consider not only two common drivers, i.e., population and affluence level (Cao et al., 2016; Ma et al., 2017; Yokoi et al., 2022), but also the impacts from cement sector's downstream – the construction industry- namely construction activity level and material consumption intensity (as shown in Eq. (10)).

$$C = POP \times \frac{GDP}{POP} \times \frac{Con}{GDP} \times \frac{O_{cement}}{Con} \times \frac{C}{O_{cement}} = POP \times EG \times CON \times MI \times EI \qquad (10)$$

where POP denotes the population, EG denotes the GDP per capita (at 1990 constant price), CON denotes the ratio of construction industry output (in monetary form) to GDP, and MI denotes the cement product per construction output (i.e., material intensity). Thus, the arithmetical change in total CO_2 emissions associated with cement production $\Delta C^{0\rightarrow \mathrm{T}}$ from the base year to year T is decomposed into five factors, i.e., population growth effect (ΔC_{POP}), economic growth effect (ΔC_{EG}), construction effect (ΔC_{CON}), material intensity effect (ΔC_{MI}), and emission intensity effect (ΔC_{EI}).

$$\Delta C_{tot} = C^{\mathrm{T}} - C^{0} = \Delta C_{\mathrm{POP}} + \Delta C_{\mathrm{EG}} + \Delta C_{\mathrm{CON}} + \Delta C_{\mathrm{MI}} + \Delta C_{\mathrm{EI}} \qquad (11)$$

According to Eqs. (4)-(9), the changes on aggregate emission intensity can be decomposed and merged to the clinker-to-cement ratio (ΔEI_{CCR}), industrial structure (ΔEI_{IS}), energy efficiency for clinker production ($\Delta EI_{\mathrm{eff\_1}}$), energy efficiency for cement grinding ($\Delta EI_{\mathrm{eff\_2}}$), and emission factor of electricity ($\Delta EI_{\mathrm{EF\_elec}}$). Thus, the addictive decomposition equation can be shown below, and the detailed process is displayed in the supplementary information (SI.2).

$$\Delta EI_{tot} = EI^{\mathrm{T}} - EI^{0} = \Delta EI_{\mathrm{CCR}} + \Delta EI_{\mathrm{IS}} + \Delta EI_{\mathrm{eff\_1}} + \Delta EI_{\mathrm{eff\_2}} + \Delta EI_{\mathrm{EF\_elec}} \qquad (12)$$

Given the advantages of the theoretical foundation, adaptability, ease of use and result interpretation, and perfect decomposition, Logarithmic Mean Divisia Index (LMDI) decomposition is adopted to quantify the impact from the underlying factors on the total emissions and the aggregate emission intensity (B. W. Ang, 2004). LMDI-I is adopted for the decomposition in Eq. (11), while LMDI-II is used for Eq. (12) as it contains both the additive and multiplicative forms (B. W. Ang et al., 2003). The formulas for the additive LMDI-I and LMDI-II decomposition are shown in Eqs. (13) and (14) respectively:

$$\Delta C_x = L(C^T,\ C^0)\ln(\frac{x^T}{x^0}) \tag{13}$$

$$\Delta EI_x = \frac{L(\omega_x^T,\ \omega_x^0)}{\sum_j L(\omega_j^T,\ \omega_j^0)} L(EI^T, EI^0)\ln(\frac{x^T}{x^0}) \tag{14}$$

where x refers to a certain effect or driver, and $\omega_x = EI_x / \sum_i EI_i$ is the weight of x in the aggregate, and the function $L(a,\ b)$ is the logarithmic average of two positive numbers given by:

$$L(a,b) = \begin{cases} \dfrac{a-b}{\ln a - \ln b}, & (a \neq b) \\ a & , (a = b) \end{cases} \tag{15}$$

3.3 Decoupling method

In this study, the elasticity of carbon emissions from cement production on GDP, i.e., $e(C, GDP)$, is defined and quantified as we aim at investigating its decoupling status of cement production with economic development. Causal-chain decomposition was applied to analyze the causes of total decoupling state variation based on the logical causal relationships among different quantitative impact factors (X. Wang et al., 2020). Thus, the elasticity $e(C, GDP)$ can be further subdivided into $e(C,O)$, $e(O,Con)$, and $e(Con,GDP)$ as follows:

$$\begin{aligned} e(C,GDP) = \frac{\Delta C / C}{\Delta GDP / GDP} &= \frac{\Delta C / C}{\Delta O_{cement} / O_{cement}} \times \frac{\Delta O_{cement} / O_{cement}}{\Delta Con / Con} \times \frac{\Delta Con / Con}{\Delta GDP / GDP} \\ &= e(C,O) \times e(O,Con) \times e(Con,GDP) \end{aligned} \tag{16}$$

where $e(C,O)$, $e(O,Con)$, and $e(Con,GDP)$ echo the above emission intensity, material intensity and construction effect in the decomposition analysis respectively. According to the framework proposed by Tapio (2005), eight logical possibilities of decoupling status can be distinguished as below, according to both the elasticity and sign of variables.

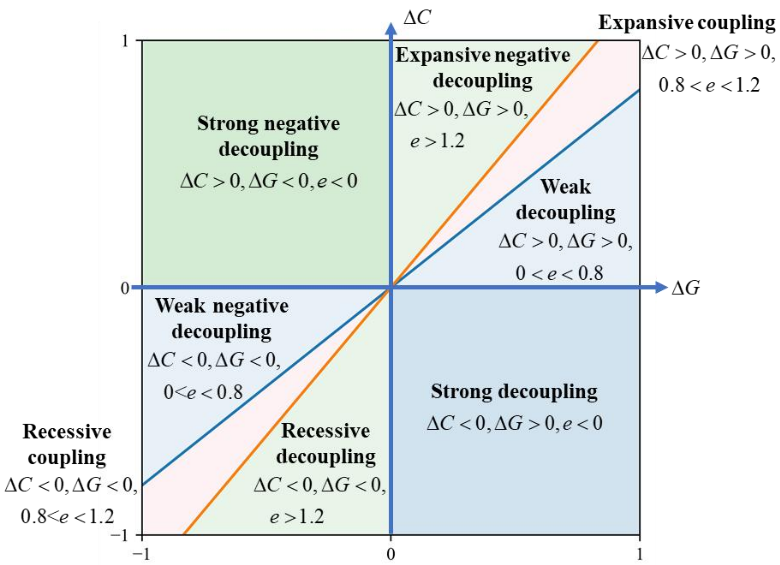

Fig. 6. Schematic of decoupling categories. (Note: ΔG refers to ΔGDP)

3.4 Uncertainty analysis

In this study, a Monte Carlo approach is adopted to assess the uncertainty distribution range of the estimated emissions. The simulation will run 10,000 times, of which each run randomly select the values of those variables with uncertainty with equal probabilities from their uncertain range to calculate the aggregate emissions. Finally, the uncertainty range is presented as the intervals with lower and upper bounds of 95% confidence around the central calculation results (Y. S. Wang et al., 2020). Herein, we assume the values sampled from the uncertain interval of variables are normally distributed and set the different values of coefficient of variation (CV) corresponding to differentiate data quality for the Monte Carlo simulations. The CV of clinker and cement production statistics is set to 5%. The CV of energy intensities obtained by regressions on a large amount of data is also set to 5%, while that of those with poor data quality is set to 10%. As for the data with better quality, such as process emission factors from field survey, CV of them is set to 1%.

3.5 Data source

Except for the annual cement production published by the National Bureau of Statistics in China, other indicators of activity level are seldom released from official sources, such as clinker production. To fully reflect the activity level of the cement sector, we compiled the *China Cement Industry Dataset (CCID)* from multiple sources with long time series and comprehensive spatial coverage. Important industrial yearbooks published by industry association, i.e., *China Cement Almanac* (2005-2015) and *Almanac of China Building Materials Industry* (1981-2020), are fully referenced when developing this dataset (China Building Materials Federation, 2020; China Cement Association, 2015). Besides, both official and industrial reports, as well as survey literature published in other years, are also made referenced to. This dataset is introduced in detail in the supplementary information (SI). As for the socio-economic factors, population and national gross domestic product (GDP) from 1990 to 2020, they are retrieved from the China Statistical Yearbook of the latest year, while the latter is transferred to the values at the 1990 constant price (National Bureau of Statistics, 2021). Output values of the construction industry (1990-2020) are retrieved from the China Statistical Yearbook on Construction (NBS, 2021b).

4. Results

4.1 Historical CO_2 emissions from cement industry

The total CO_2 emissions from cement production in China have increased from 152.3 million metric tons (Mt) in 1990 to 1,215.9 Mt in 2014, at an average growth rate of 9.0% y^{-1}. The emissions dropped by 5.8% for the first time in 2015, due to the slump in cement demand throughout the whole country, after that the emissions climbed gradually back to above 1,200 Mt and accelerated again to a new peak of 1,313.7 Mt in 2020 (Fig. 7a). Obviously, clinker production rather than cement production dominates the total emissions from the cement industry, as nearly 95% of total emissions is from clinker production. Meanwhile, there is a controversy on whether the emissions from the cement industry have peaked. Although a few studies with the accounting periods covered up to 2015 claimed that the carbon-dioxide emissions from the cement industry in China had peaked in 2014 (J. Liu et al., 2021; Shan et al., 2019), we find that the total emissions grew again after 2015 and had exceeded the former peak in 2019. The proportion of process emissions from carbonates decomposition has risen from nearly 50% in 1990 to 65.9% in 2020, while that of fossil fuel burning has dropped to 26% with the energy efficiency improvement (Fig. 7b). At the same time, we can see a significant structural change in total emissions due to the rapid and large-scale penetration of NSP kilns especially in 2000-2015 (Fig. 7c). The emissions from NSP kilns jumped from 42.1 to 1,230.7

Mt CO_2 at a high average rate of 18.4% per year between 2000 and 2020. In contrast, the emissions from shaft kilns dropped rapidly from 2003 to null in 2015 when these outdated kilns were almost eliminated (MIIT and NBE, 2011, 2012, 2013, 2015, 2016).

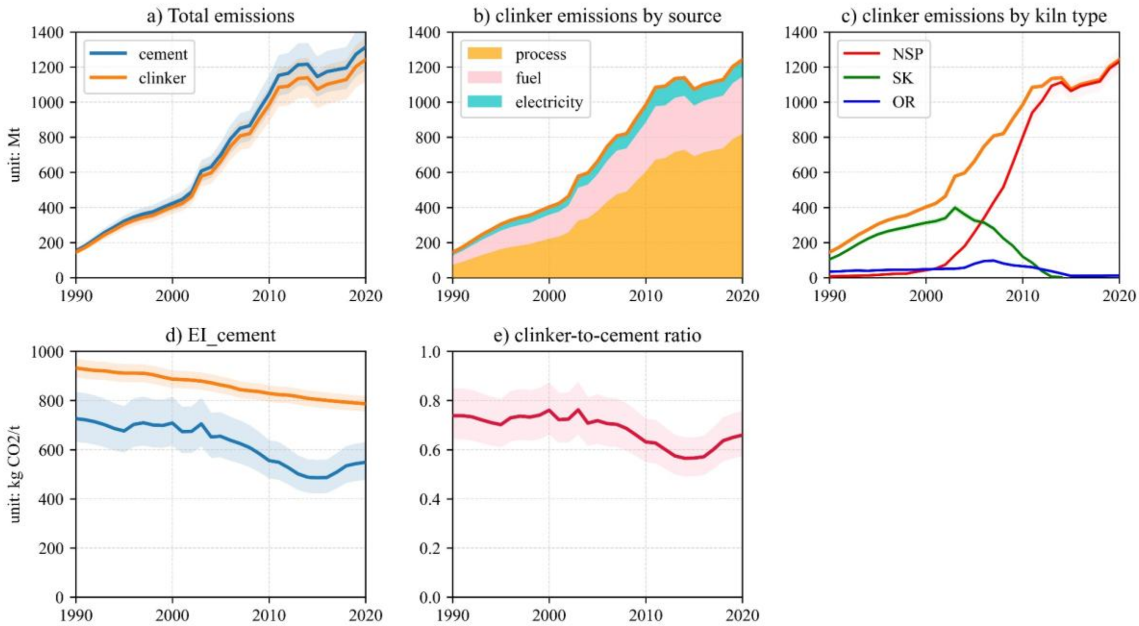

Fig. 7. CO_2 emissions and emission intensity of cement production in China. (Notes: The shaded area around the lines represents the 95% uncertainty interval of carbon emissions calculated by this study)

While the total emissions in rising trends, the aggregate emission intensities of cement and clinker production have declined, due to the penetration of NSP kilns and continuous technology improvement. Notably, the clinker-to-cement ratio (CCR) dominates the evolution trend of emission intensity of cement production because the intensity of clinker production is monotonically decreasing (Figs. 7d and 7e). The emission intensity of cement production fluctuated around 700 kg CO_2/t in the 1990's. Since the accelerated promotion of pre-calciner kilns, it dropped to 485.3 kg CO_2/t cement in 2015, averaging 2.9% per year. However, it rebounded back to 548.6 kg CO_2/t cement in the recent five years, mainly due to the rising clinker-to-cement ratio. As for the emission intensities of clinker production, the emission intensity of pre-calciner kilns decreased gradually from 918.7 to 787.3 kg CO_2/t clinker between 1990 and 2020 at an average rate of 0.5% per year, while that of shaft kilns has similar reduction. In addition, the emission intensity of other rotary kilns dropped from 938.2 to 725.7 kg CO_2/t clinker during the same period, averaging nearly 1.0% per year. The drivers leading to an evolution of total emissions will be investigated based on decomposition analysis in next sub-section.

4.2 Decomposition on total emissions

Initial decomposition reveals that production volume always dominates the change on total emissions, and its change is also significantly correlated to the latter (Fig. 8). This phenomenon implies that an improvement in emission intensity could not offset the larger emission increment caused by the exponentially expansion in production. Notably, the effect of production volume and emission intensity has reversed since 2015.

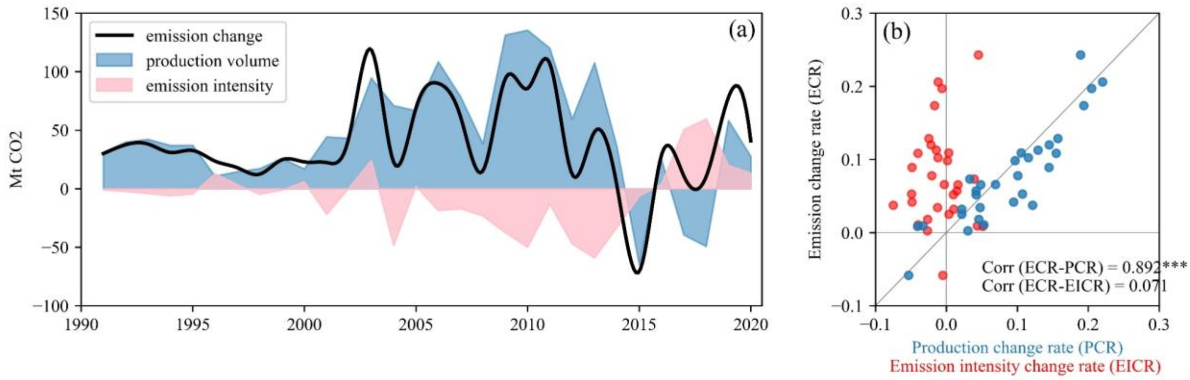

Fig. 8. Total emissions change caused by varying production volume and emission intensity (a), and the correlations between emissions change rate and that of production volume and emission intensity (b). (Note: Blue dots represent annual emission change rate (ECR) versus production change rate (PCR), while red dots represent ECR versus emission intensity change rate (EICR). And Pearson's correlation coefficient between ECR and PCR is significant.)

The impact of the socio-economic drivers in the past three decades can be quantified by further decomposition (Fig. 9), and the three growth drivers are economic growth effect, construction effect and population effect in the order of magnitude. The economic growth as represented by GDP per capita is always the most significant drivers to emission growth, as it gave rise to an increase in emissions by 154.7%, 154%, and 68.5% in the past three decades, respectively. The construction effect can reflect the impact of construction activities on carbon emissions from cement production which made a significant contribution to the emission growth by 101.8% during 2000-2010. This is mainly because the construction sector gradually became a pillar of economic growth during the rapid urbanization process, with massive investment in real estate development and infrastructure construction in China during this period. The population effect diminished from 17.9% to 5.8%, as its growth has gradually slowed down in China. Compared with the relatively stable necessary housing demand caused by population growth, economic development could result in much more construction, not least newly built commercial buildings and various infrastructure facilities, and thus the driver of GDP per capita was much larger than that of population. In contrast, the material intensity effect, which reflects the material efficiency of the construction industry, significantly contributed to the emission mitigation by -78.2% and -59.4% in 2000-2010 and 2010-2020, respectively. This is always a mitigation factor as material efficiency is improving in the construction sector of China. Besides, the emission intensity effect also contributed to emission reduction, despite its contribution diminished from -39.6% to -1.4% during the same period.

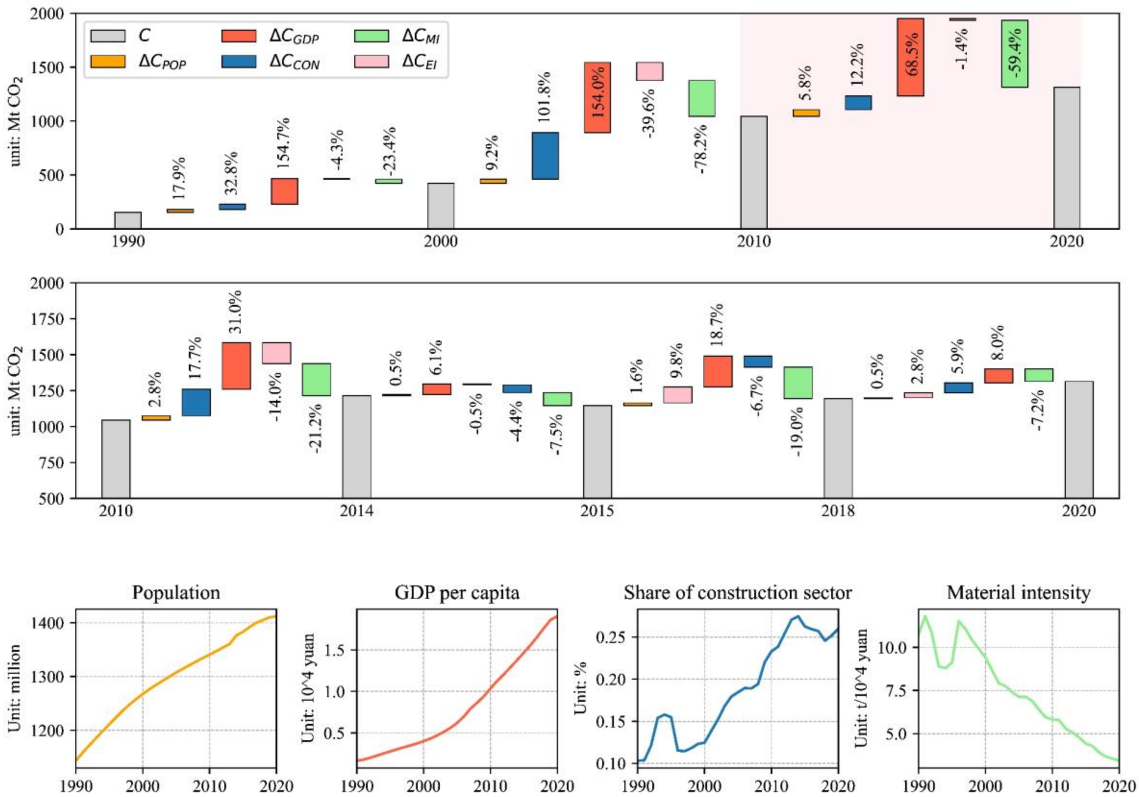

Fig. 9. Decomposition on total emissions.

A reversal of the construction effect and emission intensity effect can be seen from a further detailed decomposition analysis of the last ten years, while the relationship on size between the drivers remains basically unchanged in the decadal analysis (Fig. 9b). Notably, since the "12th

Five-year Plan" (2011-2015) of the mainland China, its government decided to adjust the economic structure, implying that the economy development would not depend primarily on fixed asset investment (mostly in real estate and infrastructure development). Thus, the construction effect resulted in a decrease in emissions by 4.4% in 2015 for the first time, leading to a so-called peak in 2014. This was mainly because of the sudden decline in demand for cement product in 2015 originated from the drastic fall in real estate investment (from 10.5% to 1.0% in 2015). This mitigation effect was further expanded to -6.7% during 2015-2018 despite it rebounded back to +5.9% in the recent two years with the adjustment having gradually completed. As for the emission intensity effect, it was consistently a significant factor to curb the total emissions before 2015, especially during the large-scale promotion for the PC kilns (i.e., 2000-2015). Nevertheless, its abatement effect fell to 0.5% between 2014 and 2015, with the saturation of the PC kilns across the country. Despite it has reversed to become a driving factor in the recent five years (contributed to the emissions growth by 9.8% and 2.8% respectively), mainly due to the rising clinker-to-cement ratio in this period (Figs. 7d and 7e).

4.3 Decomposition on emission intensity

Fig. 10 presents the decomposition analysis on the aggregate emission intensity to analyze its structural change and periodic fluctuations in the last 20 years. Once again, the results show that the clinker-to-cement ratio (i.e., CCR) dominates the fluctuations in aggregate emission intensity. This effect mitigated the emission intensity by 5.2%, 11.2%, and 9.6% every five years during 2000-2015, with the CCR gradually dropped from 0.76 to 0.56. The decline in CCR was attributed to the better clinker quality caused by the newly-built advanced NSP kilns compared to the outdated low-automated shaft kiln (J. Xu et al., 2012). Specifically, the cement mix requires less clinker with good quality than for that with worse quality when producing the low-grade cement product, leading to the clinker savings. However, the emission intensity has rebounded by about 15% since 2015, mainly due to the CCR (15.3%) due to the increasing requirement for clinker content in the cement mix for producing higher-grade cement product in recent years, with the phasing out of the low-grade cement product in the modified concrete specifications in China.

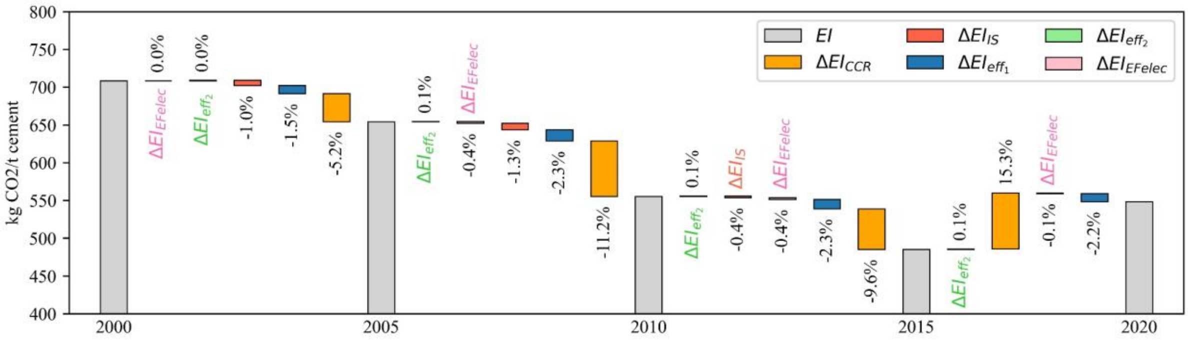

Fig. 10. Decomposition on the aggregate emission intensity of cement production in China.

Beyond the CCR, the energy efficiency for clinker production is always the second most significant mitigation factor, as it mitigated the emission intensity by 1.5-2.3% during this period. As for the industrial structure, it decreased the emission intensity by 1.0%, 1.3%, and 0.4% respectively during 2000-2015, due to the penetration of the NSP kilns and the phasing out of the shaft kilns during this period (MIIT and NBE, 2011, 2012, 2013, 2015, 2016). But the IS effect diminished with the saturation of the NSP kilns. Notwithstanding an improvement in electricity efficiency for cement grinding, its mitigation effect is insignificant. As for the emission factors for coal-fired power generation, it has gradually decreased from 1.15 to 0.85 kg CO_2/kWh in the past three decades with the continuous improvement, leading to a slight decline in the aggregate emission intensity (up to -0.4%).

4.4 Decoupling analysis

The decoupling analysis is displayed in the Fig. 11. The GDP elasticity of CO_2 emissions from cement production $e(C,GDP)$ fluctuated during the past three decades. The $e(C,GDP)$ was often seen an expansive coupling status when China increased the investment in construction, such as the post-financial crisis period (2009-2011) with a stimulus investment package of 4 trillion Chinese yuan. Notably, there was only once strong decoupling that occurred in 2015, mainly due to the strong decoupling in its sub-elasticity $e(O,Con)$. Nevertheless, $e(C,GDP)$ rebounded from the weak decoupling status to expansive coupling and expansive negative decoupling in 2019 and 2020 respectively, which means the emissions would still increase no matter an decrease in production scale. Also, the three decomposed elasticities also show diversified traces, which means the net decoupling status of the overall indicator depends on the offsetting or enhancement between these fluctuated elasticities. $e(C,O)$ was often at or around the expansive coupling status and even exhibited recessive decoupling and strong negative decoupling in recent years, which shows that the carbon emissions was often coupled with the production scale and confirms again that the past efficiency improvement could not offset the emissions growth from scale effect. $e(O, Con)$ is always at the status of weak decoupling, while even at the strong decoupling for three times in recent five years, mainly because of the abovementioned improvement on material efficiency. Moreover, $e(Con, GDP)$ is in an expansive negative decoupling in most years. Overall, we could not assert that carbon emissions from cement production are decoupled with economic growth.

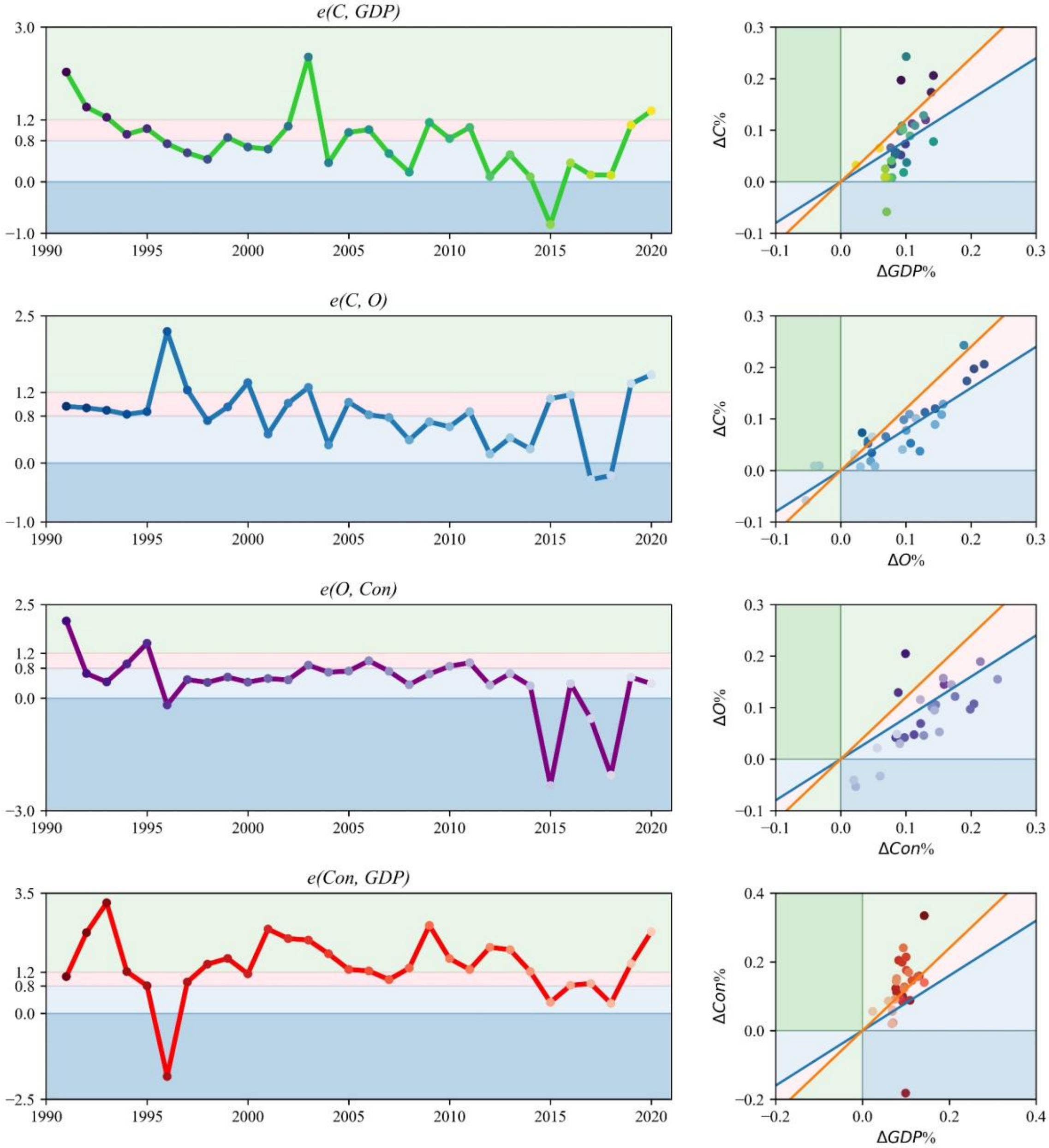

Fig. 11 Decoupling analysis of CO_2 emissions from cement production on economic growth. (Note: The color of dots becomes lighter year over year.)

5. Discussion

5.1 Inter-sector impacts outweigh intra-sector mitigation effort

Decomposition analysis compares the impact of the socio-economic factors and the intra-sectoral emission intensity on the total carbon emissions from a macro perspective and it reveals that the inter-sector impacts significantly outweigh the intra-sector mitigation efforts in the past decades. For instance, the most significant intra-sectoral transition was the penetration and saturation of the NSP kilns during 2000-2015, which has a proficient energy efficiency compared with the outdated shaft kilns (Fig. 12). During the same period, a large number of outdated cement plants with shaft kilns were eliminated under the guidance of the government's relevant policies (MIIT, 2011; State Council, 2013). The step-improved national efficiency regulations of China also urged for an improvement on energy efficiency of cement kilns. However, the mitigation effect from emission intensity never dominated the emission abatement, as it just decreased the total emissions by 4.3%, 39.6%, and 1.4% during the past three decades. In contrast, material efficiency of the construction sector contributed much more abatement, i.e., -23.4%, -78.2%, and -59.4% during the same period. Further decoupling analysis reveals that the total CO_2 emissions from cement production have yet been decoupled with GDP, which means that economic growth would continue to drive the emissions in the short-term. If we aim at a carbon-neutral cement sector in the middle of this century, something should be reversed compared with the present situations. It means that the mitigation effect of EI should expand to offset the emission growth from the production scale, and even lead to much more mitigation.

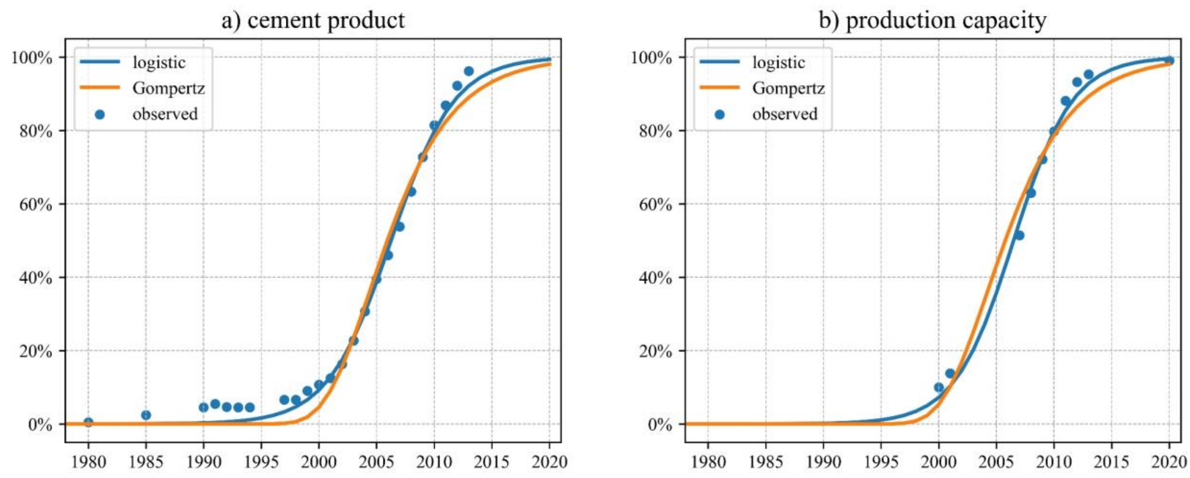

Fig. 12. Historical development of NSP kilns in China. (Notes: The share of product produced by NSP kilns and production capacity are fitted by logistic curve and Gompertz curve, both of which are growth functions. And data were retrieved CCID.)

5.2 What leads to recent rebound in emission intensity?

Apparently, decomposition analysis reveals that the rebound clinker-to-cement ratio (CCR) would drive the rebound in emission intensity of cement production (Fig. 8). This indicator reflects the average content of clinker mixed and ground with SCMs and additives to produce cement, and it implies the impact of the demand structure. Before the discussion on the rebound, we should go through the significant drop in CCR during 2000-2015 which has been attributed to the penetration and saturation of the modern NSP kilns in China (J. Xu et al., 2012). Specifically, low-grade product dominated the market in the past, as grade 32.5 cement accounted for up to 68% in the total product of China during 2014-2015, while this figure is only 8%, 11%, and 21.5% in the U.S., U.K., and Germany respectively during the same period (C. Gao, 2017). The CCR for the above four countries are 0.566, 0.83, 0.80, and 0.69 in 2015, respectively (C. Gao, 2017). Provincial surveys also confirmed the share of grade 32.5 cement was over 70% in 2016 in Xinjiang, China (Sun, 2017). Furthermore, it is estimated that over half of grade 32.5 cement is composite cement (C. Gao, 2014), which the substitution of clinker is allowed up to 50% (see Table A2). Given the basically unchanged product structure, less clinker with better quality produced by the newly built NSP kilns can meet the strengthened requirement than that produced by the shaft kilns, when producing similar low-grade cement.

However, despite a debate on whether to phase out the grade 32.5 cement, it is clear that China has moved to reduce the use of low-quality cements which tend to have very low clinker ratios (Andrew, 2019). Since small cement plants produce low-grade composite cement often mixed with non-compliant admixtures to reduce the costs, which is detrimental to the cement quality, large cement producers appealed to the Chinese government for the cessation of grade 32.5 cement given that it is difficult to supervise fully. The State Council of China initially decided to abolish the Grade 32.5 Composite Cement as soon as possible and planned to promote the usage of higher-grade products (State Council, 2013, 2016). After that, the second and third modifications of the National Regulations on Common Portland Cement (GB175-2007) in China were conducted to abolish the grade 32.5 and 32.5R composite cement respectively, which were effective from 1 December 2015 and 1 October 2019 respectively (NSMC, 2014, 2018). Furthermore, some regional governments were even more aggressive on the cessation of grade 32.5 cement. For instance, Qinghai, Xinjiang Province of China have totally prohibited the production, sales, transportation, and usage of grade 32.5 cement (DII of Qinghai, 2019; Sun, 2017). Consequently, more clinker is required to produce the higher-grade cement after these adjustments, leading to a climb back in CCR to 0.66 since 2016. Despite the current CCR is still much lower than that of developed countries, the recent rebound and resulting emissions growth deserve our attention as the adjustment does not seem to have finished.

5.3 Policy implications

More and more people are envisioning a net zero-carbon cement sector and outline its emission pathway around the world to achieve the 1.5°C and 2°C climate goal (GCCA, 2021). Given the net-zero carbon cement industry is defined as the industry with net-zero emission intensity, the proposed technological roadmap and policy suggestions always focus on how to optimally adopt the four common types of measures to reduce the emission intensity as much as possible, i.e., improving energy efficiency; switching to alternative fuels; using alternative materials; and implementing carbon capture, utilization and storage (CCUS) (J. Xu et al., 2016; C.-Y. Zhang et al., 2021). However, the effects of these intra-sectoral measures should be carefully evaluated and examined when formulating future low-carbon policies, given that the aggregate emission intensity only declined by 177.4 kg CO_2/t cement in the past three decades. The cement sector of China could realize carbon neutrality by 2060 only in the most ambitious scenario with the emission abatement contributed by future carbonation in the concrete structure (Dinga & Wen, 2022). Their analysis may be over-optimistic as their roadmap was portrayed without the consideration of the required investment and any feasibility evaluation. Although a series of demonstration CCUS projects have been conducted around the world (GCCA, 2021), only the *Baimashan Cement Plant* in Anhui Province of China has retrofitted a 5000/t clinker production line with the post-combustion carbon capture equipment up to now (Cai et al., 2021). Its annual capture volume is limited to 50,000 tons, which is not significant compared to up to 1 Mt total emissions released by the entire plant. Also, regional disparity, transportation cost, and the feasible pipeline layout should be carefully considered when evaluating the capture potential, rather than merely envisioning a national deployment rate when developing the industrial policies (Tang et al., 2021). Despite the overall capacity of co-processing solid waste across 111 production lines in China was up to 6 Mt/year (S. Liu et al., 2021), most of co-processed hazardous wastes are inorganic waste with low or even no calorific value, such as electroplating sludge and cyanide-containing waste residue, rather than waste tires which is frequently used for alternative fuels in Europe and the U.S. (Peng et al., 2016).

In contrast, inter-sectoral policy options may be more efficient and cost-effective to decarbonize the cement sector. Habert et al. (2020) demonstrated that the combined effect of marginal gains from interventions at various stages along the cement and concrete value chain can reduce the GHG emissions by up to 50% if all stakeholders are engaged. Miller et al. (2021) proposed an inverted-pyramid hierarchy to measure the resource-efficiency of cementitious materials used within a circular economy context, i.e. reduce, re-use, re-cycle, recover and disposal. We can refer to this framework when formulating any future low-carbon policies. The results of this study also confirm that the construction effect and material efficiency of the construction sector could significantly mitigate the carbon emissions, and this echoes with the 'reduce' measures such as less construction and material efficiency in this framework. Since there is currently no feasible mass-scale commercial route to supply cement-based materials with zero or negative emissions, the most resource-efficient option may be to reduce the demand and production volume of cementitious materials (Miller et al., 2021).

Finally, severe overcapacity should be concerned as it will reduce the profit of cement companies and weaken the initiative and financial capacity for decarbonization. For instance, the utilization rate of production lines in Xinjiang, China was only 39% in 2015 when the market demand sharply declined, resulting in a total loss of 1.5 billion Chinese yuan for the local companies. Thus, it is necessary to shrink the cement sector to a reasonable scale in China, which means that the outdated and small cement plants should be eliminated gradually from now, because of their lower efficiency and poor-quality products. Such adjustment can benefit the low-carbon transition through increasing the utilization rate of cement kilns, reducing the excessive market competition, and increasing the profits.

5.4 Comparison with previous studies

We compared our estimates of total CO_2 emissions from China's cement sector and its two parts (i.e., process emissions and fuel emissions) with a number of previous studies, which also conduct a similar sectoral emissions accounting (Fig. 13). As shown in Fig. 13a, our estimates of total emissions are highly consistent with previous studies, except for estimates of S. Zhang et al. (2015) and Shan et al. (2019). It is reasonable that process emissions of different studies have a highly consistent trend (Fig. 13b), as they adopted similar production activity data and emission intensities. Thus, the variations among different estimations can be mainly attributed to the variations in the estimates of fuel emissions (Fig. 13c). These high variations result from the uncertainty in energy consumption data, as the amount of coal used for heating the cement kilns was not directly available in the official statistics but rather being estimated by different reported coal intensity (J. Liu et al., 2021). Our results also performed well when we compared them to official estimates in National Communication Reports (NCR) submitted to UNFCCC in specific years (NDRC, 2004, 2012). Total emissions differed from the corresponding estimates from NCR by 3.8% in 2005, while process emissions differed by -8.0% and -7.8% in 1994 and 2005 respectively.

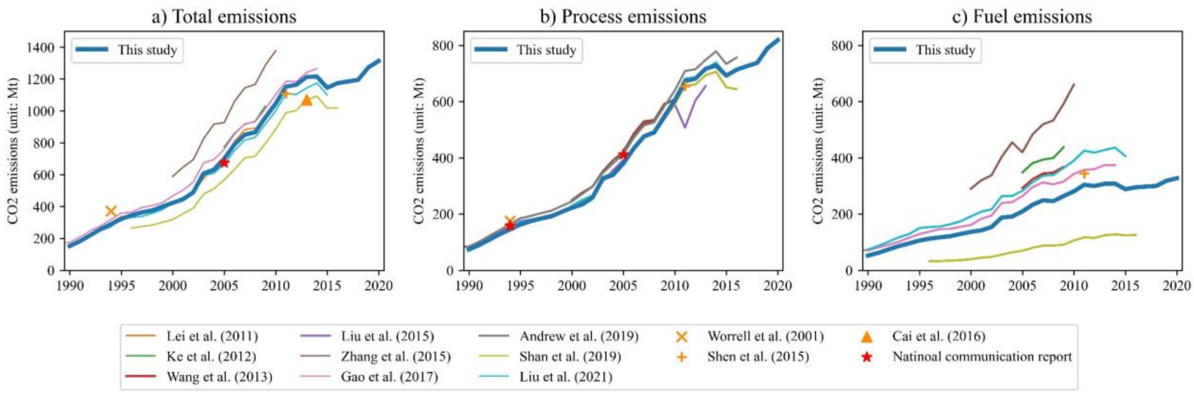

Fig. 13 Comparison of total CO2 emissions (a), process emissions, and fuel emissions (c) of China's cement sector with previous studies and official reports. *(Note: Continuous annual emissions accounting results from Lei et al. (2011), Ke et al. (2012), Y. Wang et al. (2013), Liu et al. (2015), S. Zhang et al. (2015), T. Gao et al. (2017), Andrew (2019), Shan et al. (2019), and J. Liu et al. (2021), are collected for comparison. Some results in specific years, i.e., Worrell et al. (2001), W. Shen et al. (2015), and Cai et al. (2016), were also retrieved for comparison. Moreover, emissions accounting from official department are included in this comparison, i.e., two national communication reports submitted to UNFCCC (NDRC, 2004, 2012).)*

6. Conclusions

This study proposed a three-step framework to estimate CO_2 emissions; investigate the socio-economic drivers and industrial structural change, and decoupling status of the cement sector in China; and assess the emission-mitigation potential for cement industry in China. Specifically, the CO_2 emissions and emission intensity of cement and clinker production are estimated during 1990-2020, based on the updated activity data and emission factors. Extended Kaya identity and LMDI are adopted to decompose the socio-economic drivers on total emissions, while the intra-industrial structural change on the emission intensity also be investigated. Finally, the definition of Tapio (2005) is adopted to check the decoupling status of total emissions on economic development. Through this study, several key findings can be drawn:

(1) CO_2 emissions from cement production have yet peaked in China. The total emissions have re-increased to 1,313.7 Mt in 2020 since the sharp decline in 2015, which is above the 2014 peak of 1,215.9 Mt. The aggregate emission intensity of cement production significantly decreased from 708.5 to 485.3 kg CO_2/t during 2000-2015 with the penetration of the NSP kilns, but after that it rebounded to 548.6 kg CO_2/t.

(2) The decomposition analysis reveals that the inter-sector impacts outweighed the intra-sectoral mitigation effects in the past three decades. Economic growth and the support construction activities contributed significantly to the emission growth, and the mitigation effects from the decreased emission intensity are much less than that from material efficiency of the construction sector. Further decoupling analysis also reveals that the total emissions have yet been decoupled with the economic development.

(3) Apparently, the rebound in aggregate emission intensity could be attributed to the rebound in the clinker-to-cement ratio (CCR). Furthermore, the re-increased CCR is related to the recent modifications of National Regulations on Common Portland Cement in China to totally abolish the low-grade (i.e., 32.5 and 32.5R) composite cement which allows the much substitution for clinker. Thus, the large share of them was re-occupied by the higher-grade cement which requires more clinker for production, leading to a significant increase in the overall CCR.

(4) Given that limited effect of intra-sectoral mitigation in the past, a 'reduce' approach may be a much more efficient and cost-effective policy option for short to medium term, such

as reduction in construction activities and improvement in material efficiency. At the same time, the overcapacity should be further addressed for better low-carbon transition.

To conclude, this study has explored the historical trends of CO_2 emissions and revealed the recent structural change in the cement sector of China. However, some limitations still exist. For example, the provincial disparities have yet been fully considered when formulating the policies to decarbonize the cement sector. Besides socio-economic drivers, other factors, such as climate zones and architectural preference, are temporally not considered in the analytical framework of this study. In future, more impact factors would be considered and integrated into our analytical framework for further studies. Also, the regional disparity should be carefully considered during policy formulation, as the capacity and potential for conducting ambitious low-carbon transitions may vary under different regional contexts, such as local carbon storage capacity.

Data availability

Part of data used for analysis in this study are available in a repository online in accordance with funder data retention policies (Tongyuan Wu, Thomas S.T. Ng, and Ji Chen. "Data for Deciphering-the-CO2-emissions-and-emission-intensity-of-cement-sector-in-China-through-decomposition-analysis." Zenodo. Accessed March 2, 2022. https://doi.org/10.5281/zenodo.6321438).

Supplementary Information

Components of China Cement Industry Dataset (CCID) and some other information are available in the supplementary information.

Acknowledgements

This study was supported by …

Appendix A.

Table A1. Abbreviations

Abbreviation	Definition
NSP	New suspension preheater cement kilns.
SK	Shaft cement kilns.
OR	Other rotary cement kilns.

Table A2. Composition requirement for common Portland Cement (State Administration for Market Regulation and National Standardization Management Committee of PRC, 2020).

<table>
<tr><th rowspan="3">Type</th><th rowspan="3">Sub-type</th><th colspan="7">Composition (mass ratio) /%</th></tr>
<tr><th colspan="6">Main component</th><th rowspan="2">Substitution</th></tr>
<tr><th>Clinker + Gypsum</th><th>Granulated blast furnace slag</th><th>Fly ash</th><th>Pozzolanic mixed material</th><th>Limestone</th><th>Sandstone</th></tr>
<tr><td rowspan="3">Portland Cement</td><td>P.I</td><td>100</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">P.II</td><td rowspan="2">95~100</td><td>0~5</td><td>-</td><td>-</td><td>-</td><td>-</td><td rowspan="2">-</td></tr>
<tr><td>-</td><td>-</td><td>-</td><td>0~5</td><td>-</td></tr>
<tr><td>Ordinary Portland Cement</td><td>P.O.</td><td>80~95</td><td colspan="3">5~20</td><td>-</td><td>-</td><td>0~5</td></tr>
<tr><td rowspan="2">Portland slag cement</td><td>P.S.A</td><td>50~80</td><td>20~50</td><td>-</td><td>-</td><td>-</td><td>-</td><td>0~8</td></tr>
<tr><td>P.S.B</td><td>30~50</td><td>50~70</td><td>-</td><td>-</td><td>-</td><td>-</td><td>0~8</td></tr>
<tr><td>Fly Ash Portland Cement</td><td>P.F</td><td>60~80</td><td>-</td><td>20~40</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Pozzolanic Portland Cement</td><td>P.P</td><td>60~80</td><td>-</td><td>-</td><td>20~40</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Composite Portland Cement</td><td>P.C</td><td>50~80</td><td colspan="5">20~50</td><td>0~8</td></tr>
</table>

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