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How the transitions in iron and steel and construction material industries impact China's CO_2 emissions: Comprehensive analysis from an inter-sector linked perspective

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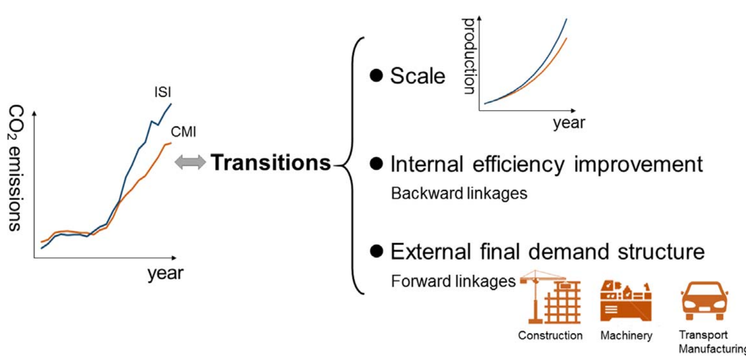
HIGHLIGHTS

- An integrated framework for inter-sector linkage analysis was developed.
- ISI and CMI CO_2 emissions experienced a rapid growth after 2002.
- Production efficiency was improved substantially in ISI and CMI in recent years.
- The construction sector induced huge CO_2 emissions though forward linkages.
- Machinery and transport manufacturing become significant sources of CO_2 emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

CO_2 emissions mitigation in iron and steel industry (ISI) and construction material industry (CMI), including cement, glass, and ceramics materials, is crucial for the realization of CO_2 emission peak targets in China, given their great contributions to China's emission structure. Great transitions have occurred in the two industries recently, including scale expansion, efficiency improvement, and changes in production and demand structures. By developing an integrated framework for inter-sector linkage analysis, we investigated the impact of recent transitions in the ISI and CMI on China's CO_2 emissions between 1992 and 2012. Results show that the CO_2 emissions from ISI and CMI increased by 4.2 and 6.8 times over two decades, respectively, and the two key sectors have significantly higher backward and forward linkages than average in terms of CO_2 emissions. The internal efficiency improvement of the ISI and CMI are crucial factors curbing the rising CO_2 emissions in these two sectors. The total CO_2 intensity of the ISI and CMI have declined by 78% and 68%, separately, cumulatively reducing 517 Mt and 704 Mt CO_2 emissions during the studied period. The external final demand growth and its structure changes of the ISI and CMI have had a significant impact on their CO_2 emissions. The construction sector is the greatest consumer, responsible for 53% and 86% emissions increase of ISI and CMI during 2002–2012, respectively. Emerging manufacturing and machinery also became substantial emissions sources,

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generating 536 Mt CO_2 emissions in 2012 by consuming iron and steel products. Based on these findings, policy recommendations for CO_2 emissions mitigation in the two key sectors and their related sectors are also discussed.

1. Introduction

Curbing the growth of CO_2 emissions to hold the global average temperature rise below 2 °C above pre-industrial levels has been recognized as a worldwide challenge after the Paris Climate Change Conference [1]. The sectoral approach is considered to be a practicable and manageable tool to realize CO_2 emission mitigation targets [2]. Since a few key sectors are responsible for the majority of CO_2 emissions, mitigation policies that are focused on crucial industries are significant and effective. The iron and steel industry (ISI) and the construction material industry (CMI), mainly including cement, gypsum, brick, stone, glass, ceramics, and refractory materials, are the typical carbon-intensive industries as well as major sources of CO_2 emissions in many countries [3–5].

Mitigating CO_2 emissions of the ISI and CMI is extraordinarily significant for China considering their substantial share of China's emissions. Since China has experienced rapid economic growth along with soaring CO_2 emissions and become the World's top emitter [6], China is now facing mounting international pressure to make advances in CO_2 abatement in a changing economy and society to deliver on its commitment to peak China's carbon emissions by 2030 [7]. Therefore, investigating the features and sources of ISI and CMI CO_2 emissions is important and urged for China's CO_2 emission sectoral mitigation in the two industries. Moreover, China's ISI and CMI are experiencing a great transition period. First, rapid urbanization and massive investment, especially in construction, boosted the Chinese economy and the expansion of the ISI and CMI, similar to the boom of ISI in Japan during the 1960s [8]. Crude steel production in China has grown by 8 times and cement by 6 times during 1992–2014 (see Supporting Information (SI), Fig. S1). Second, since the growing consumption of iron and steel and construction materials has also led to high pollution levels and heavy CO_2 emissions, China has been making great efforts to improve the production and organizational efficiency of the two industries. For instance, China attempted to shut down many high-emission small enterprises to improve industrial concentration degree [9] and adopt many new technologies for cleaner production [10,11]. Similar transitions also occurred in some upstream industries of the ISI and CMI, such as mining. Furthermore, with the promotion of strategic emerging industries that are important consumers of the outputs of the two industries, the demand structure of the two industries, especially for the ISI, has changed significantly. Such transitions in China, including the scale expansion, technological progress, and changes in the production and demand structure, have also induced great changes in their CO_2 emissions. Understanding how the great internal and external transitions impact China's CO_2 emissions can help find the key focus and refine the mitigation policies.

Intensive studies focusing on ISI and CMI CO_2 emissions have been done in recent years from different perspectives. Focusing on the CO_2 emissions trend and features of ISI and CMI, Hasanbeigi et al. [12] compared the CO_2 intensity of steel production in four countries, China, Germany, Mexico, and the United States, and found that China had a highest carbon intensity in its steel production due to its smallest share of electric arc furnace (EAF) production. Tian et al. [13] studied energy-related greenhouse gas (GHG) emission trajectories in China's ISI during 2001–2010 and concluded that the rapid emission growth was mainly attributed to the production scale effect, and construction was the largest downstream sector of embodied emissions. Cai et al. [14] investigated the CO_2 emissions of China's cement industries based on informative factory-level data and discussed the policies' implication on companies of different ownership and size. The potential of CO_2 emission reduction in the ISI and CMI is another crucial issue and many scholars have investigated the production process and technological improvement in the ISI and CMI to calculate the potentials in different countries and regions, such as China [15–20], the U.S. [21], Japan [22,23], EU [24], the United Kingdom [25], Germany [26,27] Thailand [28]. Moreover, many scholars studied the main drivers of CO_2 emission growth by decomposition analysis. By using the Logarithmic Mean Divisia Index (LMDI), Wang et al. [29] and Lin et al. [30] investigated the main drivers of the growth of CO_2 emissions in China's cement industry and found that the production activity effect and the labor productivity effect were major drivers of the increase in emissions, while the energy intensity effect played a positive role in curbing the CO_2 emission increase. Lin and Ouyang [31] examined the driver of growing emissions in China's non-metallic mineral products industry using the LMDI method during 1986–2010 and explored the reduction potential in non-metallic mineral industries.

These previous studies recognized the importance of ISI and CMI CO_2 emissions and provided valuable insight into CO_2 emission mitigation in the two industries; however, they only focused on the internal features and changes within the two sectors, and few of them investigated the ISI and CMI with a consideration of inter sectoral linkages in the context of the entire economic system. Internal optimization in the ISI and CMI cannot address the growing emissions successfully; their linkages with upstream and downstream industries have great effects on CO_2 emissions of the ISI and CMI. Therefore, it is necessary to understand their CO_2 emissions impacts from the inter-sector linked view given that the ISI and CMI are the key nodes in the economic network.

In fact, many studies have been done to explore the environmental impact of economic activities from the inter-sector linked perspective. Backward and forward linkage analysis, focusing on the independency of sectors in an economic network, is widely used to explore the inter-sector linked economic system and its environmental impacts [32,33]. For example, Nagashima et al. [34] studied the linkage effects of the Japanese wind power system and evaluated its economic and environmental impacts based on a hybrid input-output method. Zuhdi [35] compared the leading and key sectors in the Indonesian and Japanese economies and concluded that the manufacturing industry played a crucial role in Indonesia and that transport is the key to the Japanese economy by using backward and forward linkage analysis. Beidari et al. [36] investigated the linkage and multiplier impact on direct and indirect energy consumption and CO_2 emissions of growing South Africa's economy. Chang et al. [37,38] calculated the backward and forward linkage of different Chinese sectors in consideration of CO_2 emissions and examined the key emission industries. Wang et al. [39] and Zhao et al. [40] integrated input-output analysis with the hypothetical extraction method to uncover inter-industrial CO_2 emission linkages in the economic system. Structural Path Analysis (SPA) is another broadly embraced method for exploring the significant industrial chains with respect to environmental impact. For instance, Meng et al. [41] conducted a detailed structural path analysis to examine the PM2.5 emission generation and accumulation though China's supply chains and concluded that there were different patterns of industrial chains with respect to PM2.5 emissions. Zhang et al. [42] investigated China's energy consumption though industrial paths and further identified the crucial sectors and paths in China's energy system. Oshita [43] examined the key supply chains in consideration of CO_2 emissions associated with Japan's overall demand and found that the paths from electricity to the services sector contributed the most in Japanese CO_2 emissions during 1990–2000. Peng et al. [44] focused on the