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# The evolution of inter-sectoral linkages in China's energy-related $CO_2$ emissions from 1997 to 2012

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ABSTRACT

Energy-related $CO_2$ emissions in China have been extensively investigated. However, the mechanisms of how energy-related emissions are driven by inter-sectoral linkages remains unexplored. In this paper, a subsystem input-output model was developed to investigate the temporal and sectoral changes of emissions in China from 1997 to 2012. We decomposed total emissions into internal, spillover, feedback, and direct components. Our results show that the equipment manufacturing, construction and services sectors are the main sources of emissions during the whole period, which have a larger spillover component, primarily through indirect upstream emissions in the heavy-manufacturing, transportation, and power sectors. The emissions from the power and transportation sectors are dominated by direct rather than the spillover emissions. The shares of the feedback and internal components in the heavy manufacturing sectors were significantly higher than those of other sectors. Our results suggest that further addressing carbon emissions along the supply chain of equipment manufacturing, construction and services sectors, and improving technologies in the heavy manufacturing and power sectors holds important future opportunities for curbing the rapid growth of carbon emissions in China.



## 1. Introduction

Accompanying extraordinarily rapid economic growth, China became the leading $CO_2$ emitter in the world in 2006. In 2014 Chinese emissions already accounted for 30% of the world total, twice as much as the second-largest, the United States, at 15% (Liu, 2015). In response, China has committed to cut emission intensity (kg CO2eq/Yuan) by 40–45% in 2020, and by 60–65% in 2030, both figures relative to a 2005 baseline (Xinhua net, 2009; NDRCC, 2015). Furthermore, the government has a goal to peak absolute $CO_2$ emissions by 2030 and increase the share of non-fossil fuel energy to 20% in the same year (CDNDRC, 2014). In order to meet these national goals in an efficient and cost-effective manner, specific policies targeting the economic sectors with more opportunities to reduce carbon emissions will have to be developed. As such, further information on sectoral emissions is of the utmost importance.

Several sectors already have their own reduction targets. For instance, the energy sector has a standing commitment to reduce coal consumption to 65% of total primary energy consumption by 2017 (The State Council, 2013). Within the Energy Development Strategy Action Plan (2014–2020), the installations of wind and solar power in 2020 are expected to reach 200GW and 100GW, respectively (The People's Republic of China, 2014; Yang et al., 2016). The refining, coking, non-metallic mineral, and chemical sectors have goals in terms of energy consumption per unit of value added (The State Council, 2011). The allocation of sectoral emission reduction targets has focused to a great extent on traditional, energy-intensive sectors. There is still a widespread under-appreciation of the importance of reductions in non-energy intensive sectors (Zhang et al., 2015). However, the achievement of national targets will depend on how emissions from each sector will interact with those from the rest of the economy (Zhao et al., 2016). Accordingly, understanding how embodied carbon emissions are driven throughout the economy is both important and urgent for developing differentiated and practical emission reduction targets.

Previous research has analyzed carbon emissions in China from both single-sectoral and multi-sectoral perspective. Single sector studies include, Li et al. (2016), focused on the cement sector and developed

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an integrated assessment model to estimate the reduction potentials through different carbon mitigation pathways. Lin and Zhang (2016), also focusing on cement, applied the logarithmic mean Divisia index (LMDI) method to examine carbon intensity, energy intensity, energy structure, sector scale, and labor productivity. In the mining sector, Shao et al. (2016) adopted the generalized Divisia index method (GDIM) to investigate drivers of $CO_2$ emissions changes, and conducted a scenario analysis to identify mitigation pathways. In the power sector, Khanna et al. (2016) used an energy end-use model to evaluate energy and carbon emissions reduction potential to 2050, and Su et al. (2016) calculated provincial $CO_2$ emissions considering the fuel mix of exported electricity. In the iron and steel sector, Xu et al. (2016b) developed a Material Flow Analysis to estimate the $CO_2$ emissions; Peng et al. (2016) used global, multi-regional input-output (MRIO) and structural path analysis to single out important supply chain paths; and, Lin and Wang (2015) used stochastic frontier analysis to evaluate $CO_2$ emission reduction potential. Finally, in the freight sector, Hao et al. (2015) established a bottom-up model to forecast trends of energy consumption and GHG emissions. Such single-sectoral analyses are very valuable in themselves but they do not take into account the possibility of synergistic effects, with emissions occurring elsewhere in the economic landscape, when a policy targets a specific sector.

Multi-sectoral studies have focused on cross-sectoral comparisons among various industries or sectors, usually with a continuous time series. For example, Yu et al. (2016) proposed a multivariable, environmental learning curve panel model to estimate the emission abatement potential of 43 sectors. There have been a number of studies employing the LMDI method to break down sectoral contributions to GHG emissions. For example, Wang and Zhao (2016) studied the changes of carbon emissions in high, mid, and low energy-consumption sectors for 1996–2012. Xu et al. (2016a) explored emissions during different periods and from different sectors. Liu et al. (2015a) extended the LMDI methodology to analyze the changes in carbon intensity in 12 sub-sectors in China's industrial sector. Yan and Fang (2015) investigated the impact of emissions in 42 sub-sectors of the Chinese manufacturing industry for 1993–2011. Xu et al. (2014) analyzed the variations in sectoral emissions from 1996 to 2012. Many studies have focused on $CO_2$ emissions in China's sectors, but previous work does not examine the inter-sectoral linkages of $CO_2$ emissions from the perspective of supply chains (Ouyang and Lin, 2015; Kang et al., 2014; Ren et al., 2014). Thus, they may over-estimate the responsibility of the energy-intensive sectors and under-estimate the responsibility of non-energy intensive sectors (e.g., services) when the full effect of their supply chain is considered. In other words, although significant efforts for emission reduction in the energy-intensive sectors has been made, the non-energy intensive sectors' demand for energy-intensive products may indirectly cause substantial $CO_2$ emissions in the upstream energy-intensive sectors. We therefore believe a complete analysis of sectoral $CO_2$ emissions propagating throughout the whole supply chain is required.

The trade linkages in different regions that influence China's emissions have been investigated. The regional linkage effect is divided into the spillover and feedback effect (Round, 2001). The spillover effect measures the indirect effect of final demand changes in a specific region on the $CO_2$ emissions of other regions. The feedback effect then measures the increase in emissions occurring in the original region resulting from spillovers from other regions. Some studies have examined spillover and feedback effects of carbon emissions occur in multiple regions of China (Zhang and Zhao, 2005; Meng et al., 2013; Tang et al., 2015), but we are not aware of any comparative analysis of spillover and feedback effects of Chinese sectoral emissions. It is then fruitful to examine sectoral linkages in China with more detail.

Several studies have applied a subsystem input-output methodology to investigate sectoral emissions, taking into account the structure and sectoral linkages of different national economies. Subsystem models consider an individual sector, or group of sectors, as a subsystem and then study its production relations with the rest of the economy, while remaining embedded in the fulal production system. Previous studies are focused on the carbon emissions embodied in a group of sectors (Alcantara and Padilla, 2009; Butnar and Llop, 2011; Rachel, 2014; Matias and Thomas, 2014; Yuan and Zhao, 2016; Yuan et al., 2017). Llop and Tol (2013) expanded the approach to sectoral based emissions for the whole Irish economy, but did not investigate feedback mechanisms of emissions in detail. Alcantara et al. (2017) extended the model in a different way to uncover the different components of total consumption-based emissions in the different sectors in Spain. They clarified the relationship between inter-sectoral spillover of $CO_2$ emissions and the whole supply chain and addressed inter-sectoral feedback of $CO_2$ emissions but only for a single year. Here, we use the method from Alcantara et al. (2017) and extend this approach to a time-series analysis.

Final consumption of one sector leads to both its own carbon emissions and to emissions in other sectors (Liu et al., 2012; Alcantara and Padilla, 2009) and, according to Alcantara et al. (2017), the sum of these emissions can be decomposed in four components: direct, internal, spillover and feedback, which we now briefly review. Direct emissions are the corresponding change in the emissions caused by a small, exogenous change in the final consumption. For example, an increase in the final consumption of chemical products will generate extra $CO_2$ emissions in the chemical sector simply because the increase causes a direct effect of the same amount on the output of the chemical sector. Internal emissions are defined as carbon emissions arising only from the intermediate consumption of own inputs for the final consumption itself. For example, to satisfy the final demand of chemical sector, the chemical sector buy its own inputs for intermediate consumption, which will generate new carbon emissions in the fabrication of chemicals. However, for the fabrication of chemicals, the chemical sector requires inputs from other sectors along a supply chain, leading to extra $CO_2$ emissions in the production processes of other sectors: these are inter-sectoral spillover effects. Spillover effects are defined as the indirect impacts of the final consumption of one sector on the emissions occurring in the production processes of other sectors arising from additional inputs requirements. If a specific sector has greater spillover effects than others, then this sector has a strong pulling effect on the total carbon emissions in China by stimulating production in other sectors and should therefore be taken into account when designing an emission reduction policy. Additionally, there might exist a loop in the economic network in which the chemical sector providing inputs to a sector further upstream in its own supply chain. If that is the case, there will be further $CO_2$ emissions taking place in the chemical sector: these are inter-sectoral feedback effects. Feedback effects are defined as further emissions generated in the intermediate consumption of one sector caused by an additional input stimulus arising in the other sectors. For example, if the chemical sector requires additional inputs from the other sectors, in turn, the additional production in the other sectors will be reflected in the intermediate consumption of the chemical sector through the further demand for additional inputs. Therefore, if a specific sector has greater feedback effects than others, then emission changes in this sector depend more strongly on its own demand.

Given the existence of a knowledge gap in the current understanding of inter-sectoral carbon linkages in the Chinese economy, and the importance this presents to policy making, here we use subsystem input-output modelling to conduct a time-series analysis (1997–2012) of multi-sectoral emissions in China. For the purpose of the study we investigate the four emission components outlined above: direct, internal, spillover, and feedback. Our study differs from those reviewed above as we explore how sectoral linkages of a given sector with the rest of the economy change over time, and compare the changes in inter-sectoral spillover and feedback emissions. Such analyses can not only clarify how emissions are created and distributed across sectors, but