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Summary

Introduction

The Paris Agreement set a long-term temperature goal of holding the global average temperature increase to well below 2 °C and pursuing efforts to limit this to 1.5 °C above pre-industrial levels. Many previous researchers have identified that the relationship between global mean temperature change and cumulative CO$_2$ emissions is near-linear. Achieving a reduction in CO$_2$ emissions or even negative emissions is the main way to achieve the targets of Paris Agreement. Currently, China is the largest CO$_2$ emitter, accounting for 28.2% of the global emissions in 2015. In China, the industrial sector is the pillar of economic development and the most important sector of CO$_2$ emissions, making up about 40% of national GDP and 84% of national CO$_2$ emissions. Therefore, the CO$_2$ emissions of the industrial sector are important for China to achieve a lower growth or reduction in total emissions. As a prerequisite for carbon reduction, investigating the driving forces of CO$_2$ emissions is of significant importance. In view of the heterogeneities across regions and industrial sub-sectors, the driving forces should be studied from different perspectives. Besides, China promised that its carbon intensity will be reduced by 40-45% and 60-65% in 2020 and 2030, respectively, compared with the 2005 level, as well as that emissions will peak no later than 2030. Regarding whether China can achieve these emissions targets, the industrial sector plays a decisive role. Therefore, the future trajectories of carbon intensity and CO$_2$ emissions of industrial sector and its major sub-sectors are worth exploring.

Research questions

According to the abovementioned discussion, a main question and several key research questions can be extracted. These pertain to the driving force of historical industrial energy use and CO$_2$ emissions from regional and sectoral perspectives, as well as future CO$_2$ emissions/intensity. The main question is: Has the industrial sector in China effectively been decarbonizing in recent years, across different regions and sub-sectors, and is it plausible that it will reduce its CO$_2$ emissions in conformity with national and internationally pledged emission goals? The following four research questions are addressed:

**SQ1.** What are the spatial differences in carbon intensity across the provinces in China? What are the differences in driving forces across provinces? What patterns will emerge in the spatial clusters formed when provinces are grouped using spatial autocorrelation?

**SQ2.** What factors drive the changes in aggregate energy intensity of the industrial sector? What is the contribution of industrial sub-sectors to the changes in aggregate energy intensity?

**SQ3.** What is the contribution of regional convergence in energy-intensive industries to CO$_2$ emissions reduction and to the emissions goals of China?

**SQ4.** What are the patterns of historical drivers for the changes in industrial CO$_2$ emissions in China as identified in the existing scientific literature? What projections for future CO$_2$ emissions of industrial sector and its major sub-sectors are provided in the scientific literature? And how will policy goals affect the industrial emissions in the future?
Answers to research questions

**Answers to SQ1.** Chapter 2 presented a study on driving forces of industrial aggregate carbon intensity (IACI) from a regional perspective. Using a spatiotemporal decomposition analysis, the IACI was decomposed into three factors: energy intensity, energy structure and industrial structure. The IACI of each province was compared against the national average level, allowing us to capture both the rankings of provinces from a spatial and temporal perspectives. The results showed that Beijing, Tianjin, Shanghai and Guangdong were the best performers, and their IACI were 90.42%, 80.61%, 80.26% and 78.6% lower than the national average, respectively. From the temporal perspective, the IACI of Beijing, Chongqing, Tianjin and Hubei decreased the most with values of 88.11%, 76.73%, 75.35% and 74.71% from 1999 to 2015, respectively. Energy intensity was the decisive factor determining the patterns of carbon intensity. Based on spatial autocorrelation, we found that provinces with high levels of economic development performed well and if their adjacent provinces were less-developed, they performed even better.

**Answers to SQ2.** Chapter 3 developed a study considering the impacts of both macro and technological factors on the industrial aggregate energy intensity (IAEI). As a first step, the IAEI was decomposed into the factors of sectoral energy intensity, industrial structure, R&D efficiency, R&D intensity and investment intensity. Then, the contribution of industrial sub-sectors to the IAEI through each driver was explored. The results showed that the IAEI decreased by 38.26% from 2003 to 2015, of which the R&D efficiency, sectoral energy intensity and industrial structure contributed to -76.01%, -27.19% and -15.06%. However, the investment intensity and R&D intensity largely contributed to the increase in IAEI, with values of 174.09% and 52.06%, respectively. For each driving force, energy-intensive industries contributed the most, indicating that energy-intensive industries play an important role in the industrial sector as a whole.

**Answers to SQ3.** Chapter 3 established three scenarios, BAU (business as usual), frontier and BAT (best available technology) scenarios, to investigate the contribution of regional convergence in energy-intensive industries to CO₂ emissions and emissions goals, with each scenario reflecting a different form of regional convergence. The results showed that the CO₂ emissions of energy-intensive industries cannot reach the emissions peak before 2030 in BAU scenario, while the emissions peak will be achieved around 2025 in the frontier and BAT scenarios. As for carbon intensity, the 40-45% and 60-65% reduction targets can be realized by energy-intensive industries even in the BAU scenario, and the reduction proportions will be larger in the frontier and BAT scenarios. For energy-intensive sub-sectors, the reduction potentials of the electricity sector in both CO₂ emissions and carbon intensity were the most significant.

**Answers to SQ4.** Chapter 4 conducts a systematic literature review related to two major research streams, on is driving forces of CO₂ emissions and the other is the future trajectory of CO₂ emissions in industrial sector and its major sub-sectors. We found that a reduction in energy intensity was responsible for the decrease in industrial CO₂ emissions since 2000 while a rise in industrial activity was the dominant factor leading to an increase in CO₂ emissions. The effects of industrial structure and energy structure were mixed in the early years of the analysis, but the industrial structure turned to be a factor decreasing the CO₂ emissions after 2007 and the energy structure started to contributed the decrease in industrial CO₂ emissions after 2012. Based on the results of extensive studies, it can be found that the median CO₂ emissions of industrial sector will likely peak in 2030 (earlier in 2013
in the optimistic scenario), which is aligned with China’s commitment to Paris Agreement. For industrial sub-sectors, the median emissions of electricity sector will increase until 2030 in three scenarios, while the median emissions of ferrous metals and nonmetallic product sectors will decline until 2050. The recent published policies are increasingly consistent with the Paris Agreement. If the targets of carbon intensity can be achieved, the industrial emissions in 2020 will be close to the median emissions in medium scenario and in 2030 will be within the median emissions between medium and optimistic scenarios.

**Outlook**

Industry relocation frequently occurs between China’s provinces, especially the manufacturing industry shifting from developed provinces to the relatively underdeveloped provinces. This phenomenon is a byproduct of economic development, which could optimize the spatial layout of productivity and form a reasonable industrial division system. Therefore, the impact of industry relocation on the CO$_2$ emissions of the industrial sector as a whole is worth studying in the future.

Currently, there is no consistent emission coefficient (net caloric value and CO$_2$ emissions per net caloric value) for China’s fossil fuels, where both IPCC and National Development and Reform Commission published the related data sets. Because the coefficient is a major component when estimating CO$_2$ emissions, its choice will lead to over- or under-estimation of CO$_2$ emissions. Thus, the assessment of whether China can achieve its emission goals will be affected. Therefore, this matter should be discussed in future work.

The projections of industrial CO$_2$ emissions should be updated. Most previous studies were not based on the latest data of the energy consumption, so the decline trend of CO$_2$ emissions in 2014 and 2015 is hardly captured. Several policy documents were issued in recent two years, such that industrial energy intensity, industrial structure and energy structure are now more strictly regulated. Therefore, the projections of industrial CO$_2$ emissions should be updated considering both the latest data set of energy consumption and the newest policies.