China’s industrial carbon emissions : historical drivers at the regional and sectoral levels and projections in light of policy targets

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Chapter 1

General introduction

1.1. Background

The Paris Agreement of 2015 aims to hold the global average temperature increase to well below 2 °C above pre-industrial levels and pursue efforts to limit this to 1.5 °C (UNFCCC, 2015). The cumulative CO_2 emissions have been identified to be near-linear with global mean temperature change by several studies (Allen et al., 2009; Matthews et al., 2009; Meinshausen et al., 2009). Even though the global CO_2 emissions from fossil fuels remained stable from 2013 to 2016 with values of 32.29-32.32 $GtCO_2$/yr, the cumulative emissions still keep increasing. In order to meet the goals of Paris Agreement, the emissions should be reduced rapidly until zero emissions (Peters et al., 2017). China has a crucial role to play in realizing such climate ambitions. Since the reform and opening up in 1978, China's economy has developed rapidly, exhibiting strong rates of urbanization and industrialization. China's economic development depends strongly on energy consumption, especially fossil energy. The fossil energy consumption accounted for 88.9% of national energy consumption in 2016, generating a large amount of CO_2 emissions (IEA, 2018). China's CO_2 emissions experienced rapid growth since 2002, surpassing the USA to become the largest CO_2 emitter in the world in 2007 (IEA, 2017). In response to climate change, China made a commitment at the Copenhagen Conference, in 2009, that carbon intensity should decrease by 40-45% in 2020 when compared to the 2005 level (NDRC, 2010). Further targets were then made for intermediate steps towards 2020, and further reductions by 2030, achieving 60-65% reductions by 2030 over a 2005 baseline and reaching the emissions peak by 2030 or even earlier (INDCs, 2015). From 2013 to 2016, the CO_2 emissions of China decreased from 9.53 $GtCO_2$/yr to 9.2 $GtCO_2$/yr, which was caused by a shift in economic structure, a change in the energy mix, and improvement of energy efficiency (Guan et al., 2018).

The industrial sector is the pillar of China's economic development. The share of industrial value added (IVA) in China's GDP is around 40% (NBSC, 2001-2016b). Industrial energy consumption increased from 707 Mtce/yr (million tons of coal equivalent) in 2000 to 2196 Mtce/yr in 2015, accounting for almost 68% of national energy consumption (NBSC, 2001-2016a). This energy consumption is largely coal-based and led to a large amount of CO_2 emissions, with coal-based emissions representing up to about 84% of national CO_2 emissions in 2015 (Shan et al., 2018). This large share of industrial emissions has led policy makers to enact industry-specific policy targets, in addition to setting targets for emissions reduction at national level: 34% decrease in industrial energy intensity from 2015 to 2025; 40% decrease in industrial carbon intensity from 2015 to 2025; 3% increase (from 12% to 15%) in low-carbon energy consumption from 2015 to 2020; 2.8% decrease (from 27.8% to 25%) in the share of IVA of six energy-intensive industries in total IVA; 4.7% increase (increase from 5.3% to 10%) in share of green manufacturing output (SC, 2015; MIIT, 2016). Given the large share of China in global carbon emissions, and the dominant role of the industrial sector in China's emissions reduction efforts, studying industrial energy consumption and CO_2 emissions is crucial to understand how to achieve the emissions reduction of China and whether China can achieve the emission targets set at national and international levels.

1.2. Approaches to account for CO_2 emissions

There are two commonly used methods to estimate CO_2 emissions, namely production-based and consumption-based approaches (Peters, 2008). The production-based accounting (PBA) calculates CO_2 emissions considering the direct energy consumption by the producer (including exports), so PBA can identify the key emitters (e.g., nations or industries) who generate the emissions directly and find the ways to reduce emissions from the production side, such as improve the energy efficiency using clean production technologies. Compared to PBA, the consumption-based accounting (CBA) estimates the CO_2 emissions of products consumed including imports, where the indirect emissions embodied in the trade can be revealed and consumers' responsibilities for environmental burdens can be identified (Mi et al., 2019; Liang et al., 2017b). CBA can support policy decisions related to consumption behaviors and international collaboration. Therefore, the PBA focuses on the direct emitters while CBA focus on the final consumers. Usually, it will make a difference in emissions when using different approaches (Liang et al., 2017a). In order to better enable producers and consumers to shoulder the responsibilities of emissions reduction in addressing the climate change, studies have been conducted from both production and consumption perspectives for policy supports (Liang et al., 2017a; Liang et al., 2017b).

Globally, the United Nations Framework Convention on Climate Change (UNFCCC) used PBA approach to assess the impact of each country on climate change caused by greenhouse gas (GHG) emissions, so that the emissions reduction targets can be developed (Gavrilova and Vilu, 2012). Additionally, the current UN emissions allocation system for greenhouse gases attributes emissions to countries in which emissions physically generated during production (Steininger et al., 2015). Against this background, the commitment of China's emissions reduction targets to the Copenhagen conference and Paris Agreement were based on PBA. In order to address the emissions reduction of China's critical industry and make a connection with China's emission goals, the CO_2 emissions in this thesis refer to the production-based emissions.

1.3. Historical evolution of industrial energy consumption and CO_2 emissions

Energy consumption is one of the major sources for CO_2 emissions and has been causally linked to economic development in China (Mi et al., 2018). China's industrial output grew rapidly from 2000 to 2015, exhibiting a fivefold increase. Along with this, there was a substantial increase in industrial energy consumption, with an average annual growth rate of 9.9% since 2000 (NBSC, 2001-2016a). The fraction of coal consumption in China's energy mix increased from 56.68% in 2000 to 65.24% in 2010 and decreased thereafter to 59.32% in 2015. The industrial energy consumption exhibited growth before 2013 and declined in 2014 and 2015. However, the industrial energy intensity decreased from 0.18 Mtce/billion yuan in 2000 to 0.13 Mtce/billion yuan in 2015 (in 2000 constant prices). Along with the rise in energy consumption, China's industrial CO_2 emissions increased with an annual growth rate of 9.7% during the period of 2000-2013 (from 2.5 $GtCO_2$/yr to 8.2 $GtCO_2$/yr). They declined by 1.7% and 3.2% in 2014 and 2015, respectively. The industrial carbon intensity experienced a decrease from 0.61 Mt/billion yuan in 2000 to 0.45 Mt/billion yuan in 2015 (in 2000 constant prices). The significant changes in energy consumption/intensity and CO_2 emissions/intensity prompts important questions about what factors caused such changes.

Considerable progress has been made in developing a better understanding of how economic activities and their development are related to changes in carbon emissions (Rosa and Dietz, 2012). A crucial area in this research field is to analyze the driving forces that influence the evolution of energy consumption or CO_2 emissions. A better understanding of these driving drivers is critical to formulate policies for emissions reduction and targets achievement (Wang et al., 2017). The examination of the drivers of CO_2 emissions has been conducted by scholars from various perspectives, such as economics, political science and sociology (Rosa and Dietz, 2012). Next to studies analyzing historical drivers of carbon emissions, studies that analyze future trends in emissions are also important in assessing if existing carbon reduction policies are sufficient to realize emissions pledges such as INDCs (Intended Nationally Determined Contributions) and global emission targets.

1.4. Drivers of changes in carbon/energy intensity

As discussed in section 1.2, the driving forces of industrial CO_2 emissions and energy use are of great importance. China covers a vast geographical territory with significant regional differences in natural resource endowments and levels of industrialization and economic development. This suggests that there may be important regional differences in the factors driving the industrial CO_2 emissions. Furthermore, according to China's Industrial Classification for National Economic Activities in 2017, the industrial sector can be divided into 42 sub-sectors. The contribution to the aggregated industrial carbon emissions may vary across sub-sectors. So, when conducting the studies on energy consumption and CO_2 emissions at the national level of China, the differences at provincial and sectoral levels should be taken into account. In the following sections, therefore the regional heterogeneities in carbon/energy intensity and sectoral heterogeneities in carbon/energy intensity will be addressed.

1.4.1 Regional heterogeneity in carbon intensity

China's manufacturing is concentrated in eastern China in industrial clusters near coastal cities, which are thriving centers of industrial production for the export of goods. Simultaneously, the inland provinces have developed metallurgy, mining, and other resource-intensive industries (IEA, 2017). For example, Guangdong is a province which mainly focuses on clothing, electronics, toys and food. Hebei has abundant iron ore and oil resources. Jiangsu, Shanghai and Zhejiang are three important comprehensive industry provinces in China. Xinjiang, Shanxi and Inner Mongolia are the most important provinces extracting primary energy carriers such as coal. Thus, given such crucial differences in industry structure, the industrial CO_2 emissions are likely to vary significantly across provinces. In 2015, the top three provinces by absolute CO_2 emissions were Shandong, Jiangsu and Hebei, with values 173.5%, 159.6% and 145.8% higher than the national average. Conversely, the industrial absolute CO_2 emissions in Hainan, Beijing and Qinghai were 11.7%, 14.4% and 15.5% of the national average level (CEADs, 2018).

In 2015, industrial carbon intensity varied from 0.1 Mt/billion yuan in Beijing to 2.1 Mt/billion yuan in Xinjiang (CEADs, 2018; NBSC, 2016b). The provinces in the central and northwest regions had higher emission intensities, whereas the provinces in the eastern coastal areas had lower intensities. Shandong, Jiangsu, Guangdong and Zhejiang are the provinces which had absolute CO_2 emissions higher than the national average level while their carbon intensity (Mt/billion yuan) was lower than the average level. On the other hand, the carbon intensity also changed over time for all provinces. From 2000 to 2015, the industrial carbon intensity decreased by 83% in Beijing while it increased by 53% in Xinjiang. Against this background, it is important to compare the industrial carbon intensity as well as the driving forces that influence industrial carbon intensity over time across provinces.

Several studies have explored the driving forces of industrial CO_2 emissions/intensity in a time series of multiple provinces (Zhou et al., 2017; Wang and Feng, 2017; Wang et al., 2018a). However, in those studies changes in CO_2 emissions/intensity are obtained on the basis of the emissions/intensity in the observed year and previous year, which can only address the temporal characteristics for each province. In view of the regional heterogeneities in carbon intensity, the spatial comparison is also worth investigating. Therefore, an additional study that can simultaneously capture the spatial and temporal differences in carbon intensity and its driving forces is of great importance (Chapter 2).

1.4.2 Sectoral heterogeneity in energy intensity

Rapid economic growth allowed for very high rates of capital stock improvement and renewal, and the installation of modern and energy-efficient equipment for capacity additions has also increased over the past few years. The industrial aggregate energy intensity of China has improved significantly from 2000 to 2015: it is half of what it was in 2000. The energy intensity of the steel sector, for example, was reduced by 74.7% between 2000 and 2015 (NBSC, 2001-2016a; NBSC, 2001-2016b). The diversity of manufacturing processes, ranging from the very energy-intensive electricity, steel, cement and chemicals sub-sectors to non-energy-intensive sub-sectors such as electronics fabrication, presents a substantial variation in an assessment of the energy intensity of the industrial sector. For example, in 2015 the energy intensity varied from 0.51Mtce/billion yuan in the *petroleum* sector to 0.002 Mtce/billion yuan in the *tobacco* sector (in 2000 constant prices) (NBSC, 2001-2016a; NBSC, 2001-2016b).

Heavy capital investment has been the main driver for the rapid economic growth of China over the past few decades, with the R&D expenditure and fixed asset investment in industrial sector increasing almost tenfold (NBSC, 2001-2016b). Energy intensity has been identified as the most important factor causing the decline of industrial carbon intensity (Wang et al., 2018a; Wang and Feng, 2017; Zhou et al., 2017). The R&D expenditure and fixed asset investment always go hand in hand with the commercial scale and technology progress, and are identified as factors that may affect the energy efficiency/intensity. (Shao et al., 2016; Zhang et al., 2017). However, it is unclear what role the investment played in industrial energy intensity with each sub-sector although Guan et al. (2014) pointed out that the intensive investment may lead to an increase in national carbon intensity. Therefore, it is important to conduct an analysis exploring the driving forces of industrial aggregate energy intensity, especially the factors related to the R&D expenditure and investment. If a sectoral perspective is taken, more details can be provided for policy makers. Several previous studies have conducted studies on the drivers of industrial CO_2 emissions from a sectoral perspective (i.e., Wu and Huo, 2014; Liu et al., 2015), but they failed to consider the technological factors. It will help us to further improve the energy efficiency and avoid over-investment when the technological factors and the contribution of each industrial sub-sector to the industrial aggregate indicator are taken into account.

1.4.3 Methods for identifying the drivers of CO_2 emissions

Decomposition analysis is one of the most commonly used method to analyze the drivers for changes in carbon emissions (Ang and Choi, 1997). A decomposition analysis essentially assigns changes in an aggregate metrics into components related to several candidate drivers, and the results are usually used to explain the contribution of the candidate drivers to the observed changes in the aggregate indicator. The most popular decomposition methods are IDA (index decomposition analysis) and

SDA (structural decomposition analysis) (Hoekstra and van den Bergh, 2003). Although both IDA and SDA are used to understand the determinants of the CO_2 emissions/intensity, their origins and methodological foundations are different. IDA is usually based on the activity and emissions data, which usually can be easily obtained and employed in both historical and future analyses. Studies in continuous time series has always been common since the continuous data for these indicators are usually available. However, the SDA is often based on input-output (IO) tables and has relatively high data requirements (Wang et al., 2017). Data for continuous years is usually not available because benchmark IO tables are published with gaps of several years (Su and Ang, 2012). As far as the study objective is concerned, if the focus is the energy end-use sector or a national level, IDA is a good choice. The data set on end-use energy and output both in the aggregate level and its components can be derived. This is an advantage of IDA analysis since energy policy implications always aim at end-use sectors. However, if the supply and demand relationships of an economy or the embodied energy/emissions are of interest, SDA should be a priority since it could model the whole economic system (Wang et al., 2017).

Another commonly used method to identify the drivers of environmental indicators is the IPAT formula, where the environmental impacts (I) can be presented as: I= Population (P) × Affluence (A) × Technology (T) (Ehrlich and Holdren, 1971). Using the IPAT formula as the theoretical basis, the STIRPAT (Stochastic Impacts by Regression on Population, Affluence and Technology) model was proposed (Dietz and Rosa, 1994), which is a stochastic model and can be used to identify the non-proportionate impacts of factors or variables on environment (Shao et al., 2011). In empirical studies, the STIRPAT is always used combining with econometric techniques (Lin et al., 2017). The results of a decomposition analysis can be used to reflect the observed changes in CO_2 emissions caused by a certain driver, while the results of STIRPAT can only identify the elasticity coefficients between CO_2 emissions and the drivers for the study period.

In this thesis, the index decomposition analysis was used because the end-use sector (industrial sector), the yearly change of industrial carbon/energy intensity and the contribution of the drivers are the subjects of interest.

1.5. Debate on whether China can achieve the emissions goals

China set the goal to reduce her carbon intensity by 40-45% in 2020 and 60-65% in 2030 compared to 2005, and to achieve a peak in carbon emissions by 2030 or before (NDRC, 2010; INDCs, 2015). In recent years, a large number of studies have discussed whether China can achieve these 2020 and 2030 emissions goals. Some of them pointed out that China can achieve the reduction targets of carbon intensity with current policies (Xu et al., 2017; Zhang et al., 2017), while others pointed out that the ongoing policy framework is not sufficient to meet the goals (Yuan et al., 2012; Elzen et al., 2016). Besides, some studies suggested that China cannot reach the emissions peak in 2030 in the business as usual scenario (Yu et al., 2018) while others thought that the emissions peak can be achieved in 2030 or even earlier (Hao and Wei, 2015; den Elzen et al., 2016; Niu et al., 2016).

Previous studies were mainly based on the major drivers of CO_2 emissions, such as economic output, energy structure, energy intensity (efficiency) and industrial structure, to project the CO_2 emissions for China as a whole, a specific region or a specific industry (e.g., Zhu et al., 2018; Zhang et al., 2017; Wu and Peng, 2016). However such studies paid little attention to regional heterogeneities or convergence. At the same time, several studies showed that the CO_2 emissions per capita tend to converge across different provinces (Wang and Zhang 2014; Zhao et al., 2015). Indeed, for a specific industrial sub-sector, since technological features are similar, one can expect that regional convergence will take place over time due to technology adoption and diffusion (Gries et al., 2018). As discussed before, the industrial sector played a crucial role in China's the economic development but also in the rise of China's carbon emissions. Energy-intensive industries accounted for almost 90% of industrial emissions. Therefore, regional convergence of energy efficiency and carbon emissions in China's energy-intensive industries will be of great significance for China's future CO_2 emissions and related emissions goals.

As discussed before, the driving forces of the historical evolution of industrial energy consumption and CO_2 emissions in China have been studied extensively (see section 1.3). Besides, there are many studies that focused on the projections of CO_2 emissions in the industrial sector and its major sub-sectors (e.g., energy-intensive industries) using different scenario assumptions, to investigate future trajectories and whether the emissions peak can be realized in 2030 (e.g., Wang et al., 2016; Zhao et al., 2018; An et al., 2018; Gao et al., 2017). Research on the driving forces can help us understand which factors contributed to decrease in CO_2 emissions in the past while the projections of CO_2 emissions can tell us the possible way to achieve the emissions goals. There are many strong and frequent policies in China, connecting with which can help us to better understand the historical drivers and scenario assumptions in projections. Therefore, a more systematic summary of previous studies is urgently required to investigate the changes in patterns of drivers, the possible range of the industrial CO_2 emissions and policy goals. The lessons learned from the efforts on industrial emissions reduction of China can indicate how China can contribute to the emission reductions agreed upon in Paris Agreement.

1.6. Research questions

As discussed above, the industrial sector accounted for about 84% of national emissions in 2015, so the industrial CO_2 emissions play a crucial role if China is to achieve its national and internationally pledged carbon reduction goals. The main research question posed in this thesis is hence: *Has the industrial sector in China effectively been decarbonizing in recent years, across different regions and subsectors, and is it plausible that it will reduce its CO_2 emissions in conformity with national and internationally pledged emission goals?*

Tracking the progress of decarbonization in China's industrial sector towards emissions targets requires studies from different perspectives, related to more specific research questions outlined below.

First, unsurprisingly for a country of the size like China, there are major differences in economic development, demographic trends and resource availability across provinces, which result in the uneven distribution of specific industrial activities across the various provinces. Thus, shaping provincial policies for emissions reduction will be an important component for national policies. In view of heterogeneities across provinces the first specific research question is:

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?*

When answering this first question, the energy intensity appeared to be the determining factor explaining the industrial carbon intensity for all the provinces in China. Therefore the factors driving the industrial energy intensity was of high relevance. At the same time, the industrial sector can be split into various sub-sectors in relation to the different manufacturing processes. It is hence important to capture the characteristics of the different industrial sub-sectors, to provide sector-specific policy recommendations. Against this background, the second specific research question can be formulated:

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?*

To answer the question if China can achieve the 2020 and 2030 carbon emissions goals, the future trajectory of CO_2 emissions should be further addressed. Here, the fact that different provinces show different carbon intensities by sector is of interest. A convergence of carbon intensity within similar sectors can be expected: worse performers who have relatively higher carbon intensity in due time are likely to catch up with the better performers (with lower carbon intensity), which can be achieved by technology adoption and diffusion. There are six energy-intensive sub-sectors in the industrial sector that play a very important role in industrial energy consumption and emissions. Motivated by this, the third specific research question is formulated as follows:

SQ3. *What is the contribution of regional convergence in energy-intensive industries to* CO_2 *emissions reduction and to the emissions goals of China?*

Finally, a large number of studies have been done into the historical development and future developments into the industrial CO_2 emissions of China. One important research stream consists of studies analyzing the driving forces of historical changes in emissions. Another research focus concerns the projections of CO_2 emissions in industrial sector and its major sub-sectors. Furthermore, China has developed a large number and strong policy initiatives to reduce industrial CO_2 emissions. However, there exist no systematic review that relates historical drivers, future projections, and policy interventions focused on industrial CO_2 emissions in China. Against this background, the last specific research question can be formulated:

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?*

In sum, the overall objective of this dissertation is to study the industrial CO_2 emissions of China, especially in the driving forces of their historical changes, as well as projections of the contribution of industrial sector to China's 2020 and 2030 emissions goals. Through the systematic analysis of the historical data and the existing literature on this topic, policy recommendations can be proposed for China to mitigate global climate change.

1.7. Guide to this thesis

This thesis consists of 6 chapters. This first chapter gives a general introduction, in which the motivation, the research questions and the outline of this thesis are provided.

Chapter 2 discusses the first research question. It identifies the driving forces of industrial carbon intensity using a spatiotemporal logarithmic Divisia index decomposition analysis which integrates spatial and temporal analyses together. By comparing the carbon intensity and its determinants (energy intensity, energy structure and emission coefficient) in different provinces to the national average over time, it can be used to analyze how important different determinants were by province. Besides, spatial autocorrelation is used to aggregate the thirty provinces into four clusters, which are used to address the question of how the presence of neighbors with different (or the same) level of economic development (and its evolution) affects the industrial aggregate carbon intensity.

Chapter 3 sheds light on the impacts of both macro and technological factors on the industrial aggregate energy intensity, and hence discusses the 2nd research question. The macro factors are sectoral energy intensity and industrial structure, while the technological factors refer to R&D efficiency, R&D intensity and investment intensity. Based on the decomposition results, an attribution analysis is conducted to identify the detailed relationship between the influencing factors and sub-sectors, which is significant to assist policymaking since the sensitivity and adaptability of industrial sub-sectors to energy and environmental policies are different. The results thus obtained can be used to test the effectiveness of energy-related policies specified for certain sub-sectors.

Chapter 4 focuses on research question 3, and answers how regional convergence in each energy-intensive sub-sector will impact CO_2 emissions and contribute to meeting the 2020 and 2030 emissions targets. Three scenarios are developed: a business-as-usual (BAU) scenario, which is used to reflect the historical regional convergence; a frontier scenario, which is obtained from the DEA (data envelopment analysis) results and reflects a weak form of regional convergence; and a best available scenario, which refers to a strong form of regional convergence. The CO_2 emissions of each energy-intensive sub-sector are predicted based on the Kaya identity within these three scenarios. By comparing the results in three scenarios, the contribution of regional convergence to the emissions goals can be obtained.

Chapter 5 answers research question 4. It conducts a systematic literature review, focusing on the historical drivers, projections and policy goals of CO_2 emissions in the industrial sector and its major sub-sectors. The drivers of historical emissions, the possible ranges of CO_2 emissions until 2050 in different studies and the policy targets in recent policies are discussed.

Chapter 6 presents a synthesis of the answers to the research questions, followed by a general discussion and outlook for future work.

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