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Chapter 6

Conclusions and Discussion

This thesis studied in depth the energy use and CO\textsubscript{2} emissions of the industrial sector in China. Being responsible for about 84% of the Chinese CO\textsubscript{2} emissions in 2015, the industrial sector plays a vital role in achieving the emission goals for China. A main research question was proposed as illustrated in Chapter 1: 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\textsubscript{2} emissions in conformity with national and internationally pledged emission goals?

Due to the different energy-source mixes, uses and economic development needs, the comparisons among industrial sectors in 30 provinces will identify the key components for each province that should be improved in order to achieve the reduction of overall industrial CO\textsubscript{2} emissions. This can provide policymakers with a basis of formulating policies from a provincial/regional perspective. Chapter 2 addressed this question by ranking the carbon intensity of industrial sector in each province and identifying its drivers (energy intensity, energy mix and emission coefficient). From another perspective, the industrial sector is an integration of many sub-sectors, and the CO\textsubscript{2} emissions reduction of overall industrial sector will be dependent on the performance of each sub-sector. Due to the disparities in products and technologies among different industrial sub-sectors, differentiated policies at sector-level are necessary. Chapter 3 answered this question, where the driving forces of industrial aggregate energy intensity (IAEI) and the contribution of each industrial sub-sector to the IAEI were investigated. Chapter 2 showed that there were significant differences in carbon intensities and their driving forces among provinces. Chapter 3 indicated that the energy-intensive industries played important roles in shaping the IAEI. Based on the answers obtained from Chapters 2 and 3, we want to know what will happen to the CO\textsubscript{2} emissions and carbon intensity of energy-intensive industries if regional differences disappeared (regional convergence was achieved). Therefore, Chapter 4 studied to what extent convergence of performance of energy-intensive industries across provinces can contribute to CO\textsubscript{2} emission reductions and emission goals. After studying the historical drivers from regional and sector perspectives as well as the contribution of energy-intensive industries to the emissions goals, a systematic understanding of industrial CO\textsubscript{2} emissions is of great interest. Thus, Chapter 5 was born. Chapter 5 provided a critical literature review on the driving forces for the historical industrial CO\textsubscript{2} emissions and the projected ranges for future emissions, against the backdrop of policy goals, both for the industrial sector as a whole, and for the major industrial sub-sectors (electricity generation, cement production, steel production, chemicals, petroleum and non-ferrous metals). In combination, Chapter 2-5 presented a series of studies that aimed to answer the main research question.

Section 6.1 will now discuss the answers on the specific research questions and then come back on this main research question. This is followed by a discussion in section 6.2, followed by an outlook and suggestions for further research in section 6.3.
6.1 Conclusions

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?

Using spatiotemporal decomposition analysis, the carbon intensity of industrial sectors in different provinces was decomposed reflecting the changes in energy intensity, energy mix and emission coefficients. The industrial aggregate carbon intensity (IACI) and its drivers within each province were compared to the national average level, allowing to rank provinces in terms of IACI from a spatial perspective and in terms of the changes in IACI over time from a temporal perspective. From a spatial perspective, the results show that Beijing, Tianjin, Shanghai and Guangzhou performed best, exhibiting an IACI well below the national average. In contrast, the IACI of Hebei, Shanxi, Inner Mongolia, Ningxia and Xinjiang was much higher than the national average during the study period. Changes in the energy mix of Heilongjiang performed the best and contributed most to the decrease in IACI, but in contrast led to a high increase in IACI of Ningxia. By comparing to the national average level, changes in emission coefficients contributed the most to the reduction of IACI in Qinghai, Hubei, Yunnan and Sichuan while this factor contributed the most to the increase IACI in Heilongjiang, Inner Mongolia and Jilin. From a temporal perspective, the IACI declined in 28 provinces (i.e. all 30 Chinese provinces, except Ningxia and Xinjiang). Changes in the energy mix and emission coefficients had relatively small impacts on IACI. In Hainan changes in the energy mix had the highest contribution to IACI reductions (-25.15%) while Sichuan showed the highest contributions from reduced emission coefficients (-24.81%). The patterns of energy intensity effect played a decisive role in shaping the IACI both from the spatial and temporal perspectives.

Taking GDP per capita and geographic location into consideration, the 30 provinces were divided into four clusters: provinces with high (H) or low (L) levels of economic development (GDP per capita), which are surrounded by provinces with high (H) or low (L) levels of economic development, are abbreviated as HH, HL, LH and LL. By decomposing the IACI of these four clusters, it could be shown that provinces with high levels of economic development reduced their IACI most and if their adjacent provinces were less-developed, they reduced it even more.

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?

An extended decomposition analysis was conducted at the sectoral level to study the impacts on industrial aggregate energy intensity (IAEI) by various macroeconomic and technological factors. Such factors included sectoral energy intensity, industry structure, R&D efficiency, R&D intensity and investment intensity. Unlike earlier studies, this study found that the R&D efficiency (-76%) was the dominant factor contributing to the decrease in IAEI. This was followed by the effects of sectoral energy intensity (-27.2%) and industry structure (-16%). Conversely, the investment intensity and R&D intensity largely contributed to an increase in IAEI, with values of 174.1% and 52.1%, respectively. However, the effects of investment intensity and R&D intensity are more than offset by the effects of R&D efficiency, sectoral energy intensity and industrial structure. Their combined effects led to an overall decrease in IAEI by 38.3% from 2003 to 2015.
To identify the adaptability and sensitivity of various industrial sub-sectors, the effects of sectoral energy intensity, industrial structure, R&D efficiency, R&D intensity and investment intensity were attributed to 36 industrial sub-sectors. The results showed that 35 sub-sectors (excluding gas production and supply) contributed to the decrease in IAEI through R&D efficiency, of which the sub-sectors of ferrous metals (-14.9%) and non-metallic mineral products (-13.4%) contributed the most. The energy intensity of five sub-sectors went up, especially plastic products and non-metallic mineral products while the sub-sectors of ferrous metals (-16%) and non-ferrous metals (-5.7%) contributed the most to the decrease in IAEI though sectoral energy intensity effect. The industrial structure effect was largely attributed to the sub-sectors of petroleum, coking and nuclear fuel (-5.6%) and ferrous metals (-4.7%). 29 industrial sub-sectors contributed to the increase in IAEI through investment intensity, of which non-metallic mineral products (40.8%) and chemical materials (28.5%) were the largest contributors. The sub-sectors of non-metallic mineral products and ferrous metals saw an increase in IAEI by 17.8% and 10.5%, respectively, through R&D intensity.

In sum, the findings indicate that the IAEI decreased from 2003 to 2015 with 38.3%, but also that different sub-sectors in the Chinese energy-intensive industry play a different role in this overall reduction. Therefore, different policies and measures should be put forward in different sub-sectors due to their varying degrees of adaptability and policy sensitivity.

**SQ3. What is the contribution of regional convergence in energy-intensive industries to CO₂ emissions reduction and to the emissions goals of China?**

In order to address this research question, three scenarios were developed to reflect different levels of regional convergence: (1) a business as usual (BAU) scenario, in which the historical regional convergence will continue; (2) a frontier scenario, which is established based on the DDF (directional distance function) method, and is used to reflect a weak form of regional convergence, in which provinces approach an efficiency frontier, where the provinces perform well in emissions abatement while keep the industrial output growth; and (3) a best available technology (BAT) scenario, in which all provinces will realize the emission levels per unit of output of the best-in-class province, representing a strong form of regional convergence.

The CO₂ emissions in the three scenarios are predicted based on the Kaya identity. By comparing the CO₂ emissions and the carbon intensity under the frontier and BAT scenarios to those in BAU, the potential contribution of regional convergence to CO₂ emissions and emissions goals can be calculated. The results show that the CO₂ emissions in energy-intensive industries can be reduced with about 43% if the frontier scenario can be realized in 2030. The reduction potential will be more than 80% if the BAT scenario is reached. The reduction potentials of the electricity and ferrous metals sectors are the most significant due to their high absolute emissions and the heterogeneities across provinces. For the COP21 in Paris, China has pledged in its INDCs (Intended Nationally Determined Contributions) to peak its CO₂ emissions by 2030. The results indicate that the CO₂ emissions of energy-intensive industries cannot reach the peak before 2030 under a BAU scenario. The emissions however could peak in 2025 if there was regional convergence, either in the weak or strong forms. With the energy-intensive industries being responsible for 79% of China’s total emissions in 2015, realizing their peak emissions before 2030 is crucial for realizing the aforementioned INDCs. China also pledged to reduce its carbon intensity by 40-45% in 2020 and 60-65% in 2030. The energy-intensive industries can achieve these reduction goals 2020 and 2030 even
in the BAU scenario. If regional convergence occurs, more ambitious reductions in carbon intensity can be obtained. For energy-intensive sub-sectors, the *electricity* sector cannot achieve the reduction goals of 40-45% by 2020 and 60-65% by 2030 in the BAU scenario, while the goals can be realized under the frontier and BAT scenarios.

**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?

To answer this research question, first 65 studies were collected that analyzed the historical drivers for industrial CO\(_2\) emissions in China. These studies explored many drivers of industrial CO\(_2\) emissions, including industrial activity, energy intensity, energy mix, emission coefficients and industry structure. In general, increase in industrial activity was identified as the most important factor driving the increase in industrial CO\(_2\) emissions after 2000. Improvement of emissions coefficients had a marginal influence on the reduction of industrial CO\(_2\) emissions. However, various other factors contributed to relative emission reductions since 2013. The most important factor was a reduction in energy intensity. Also a change in the energy mix contributed to the decrease in industrial emissions, particularly after 2012. Since China has policy targets to increase low-carbon energy use until 2020, changes in the energy mix will lead to further emission reductions in the future. Changes in the industry structure had both positive and negative effects on emissions before 2007. After 2007, changes in industry structure contributed to a reduction of carbon emissions. Since China embarks on ambitious efforts to restrict energy-intensive industries and promote green manufacturing as well as high value-added industries, further shifts in the industrial structure will support further emission reductions in the future.

Next, 70 papers were collected that discussed projections of CO\(_2\) emissions in China’s industrial sector and its major sub-sectors. From the highest projections per sub-sector across studies, a BAU scenario was constructed. From the lowest projections per sub-sector across studies, an optimistic scenario was constructed. A medium scenario was constructed as the median projection over all other scenarios (so excluding the BAU and optimistic scenarios) reported in the literature collected if there were more than two remaining scenarios in one study. This analysis did not compare projections of the carbon intensity with national or international intensity reduction goals. The reason for this is that the carbon intensity in different industrial sub-sectors is measured in different ways, which are not always consistent definitions in national targets or international pledges (CO\(_2\) emissions per unit of IVA for the industrial sector). The assessment did show however that the median CO\(_2\) emissions of industrial sector will likely peak in 2030 in the BAU and medium scenarios. This is in line with China’s INDCs as committed to the COP21 in Paris in 2015. If the optimistic scenario is realized, the peak of industrial emissions already took place in the past, i.e. 2013. Zooming in on industrial sub-sectors, the following picture arises. For the *electricity* sector, the median CO\(_2\) emissions will increase until 2030 in the three scenarios, indicating that it is less likely for the *electricity* sector to reach the emissions peak before 2030. For the *ferrous metals* and *nonmetallic product* sectors, the median CO\(_2\) emissions in three scenarios will decline until 2050, even the maximum emissions also will decline except for 2020, meaning that their emissions peak will be reached in 2020 or even in 2013. Policies and regulations as laid down in e.g. plans like the *13th FYP (Five-Year-Plan)*, *China Industrial Green*
Development (2016-2020) and Made in China 2025 will further ensure that national and international carbon reduction commitments will be met.

Based on the answers to the sub-questions, now a positive answer can be given to the overall research question: 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 CO₂ emissions in conformity with national and internationally pledged emission goals? After a rapid growth over the past decade, the China’s industrial CO₂ emissions decreased since 2013, while the industrial aggregate carbon intensity showed a sustained decline, indicating that the decarbonization measures helped. Chapter 2 (answering SQ1) suggested that the measures for improving energy efficiency were the most important steps to reduce the industrial aggregate carbon intensities as energy intensity was the most important factor in shaping the industrial aggregate carbon intensity for all provinces. Herein, the energy intensity in Xinjiang, Ningxia and Shanxi should be greatly improved. As a complement to Chapter 2, Chapter 3 (answering SQ2) showed that the sensitivity and adaptability of each industrial sub-sector to the policies were different, and the energy intensity in petroleum, plastic products and non-metallic products sectors should be the focus of improvement. In Chapter 4 (answering RQ3) it could be shown that under a frontier scenario and a BAT scenario, where sectors in different provinces converge in terms of carbon-intensity, overall CO₂ emission reductions of 43% and 80% for energy-intensive industries could be realized, respectively, in 2030. This result indicated that the regional convergence should be encouraged in energy-intensive industries, where the regional convergence can be achieved by technological diffusion from advanced provinces to backward provinces. Also the meta-review conducted in Chapter 5 (answering RQ4) on historical drivers and future projections give reasons for careful optimism. Even in the BAU scenario, which is the most pessimistic across all forecasts, the Chinese industrial sector is likely to peak its CO₂ emissions by 2030. When the median emissions of the optimistic projections across studies are taken, China’s industrial emission peak is likely already have taken place in the past. The assumptions behind the optimistic scenarios mainly focused on the important historical drivers obtained in Chapter 2 and Chapter 3, such as improvement of energy efficiency (intensity), shifts in energy structure (encouragement of renewables) and industrial structure (from energy-intensive industrial sub-sectors towards high value added industrial sub-sectors). What should be emphasized was that these policies should be implemented considering the disparities of provinces and sub-sectors, thus it will be more conducive to the achievement of overall industrial emissions targets.

6.2 Discussion

A spatiotemporal decomposition analysis was used to compare the IACI and its driving forces of the industrial sector in 30 provinces in China. In this method, a reference province should be constructed. The choice can be made to use an existing province or a hypothetical one. If the gaps between the best performing province and the remaining provinces are of interest, the best performing province can be used as reference. If only a general ranking of provinces is desired, then the national average (arithmetic or weighted average) can be regarded as the benchmark. A spatiotemporal decomposition can rank provinces in terms of the IACI, energy intensity, industrial structure or energy mix, information that can provide a basis for policy recommendations. For example, China’s overall emissions goals should be the sum of the provincial ones. The provincial targets could take into account their current CO₂ emissions, but also their carbon intensity. For instance, for developed provinces or municipalities, such as Beijing, Tianjin and Shanghai an emissions cap could be set. At
the same time, less developed provinces with high carbon intensities, such as Shanxi, Ningxia and Xinjiang, could be allowed to reach their emissions peak later. Such provinces then can reduce their emission intensity and at the same time still grow economic output significantly. By differentiating targets by province in this way, national emission goals can be realized easier.

Regional convergence can contribute significantly to a reduction in CO₂ emissions of China’s energy-intensive industries, and can support the realization of an emission peak around 2025. However, there might be some reasons, such as resource endowments and the remaining economic life-time of industrial installations, that may prevent the realization of regional convergence. The electricity sector can be regarded as an example. There are different technologies for power generation, such as thermal power, hydropower, nuclear power, wind power and solar power. The potential deployment of low-carbon energy technologies depend however strongly on geographical and weather conditions. Their deployment hence shows a clear regional distribution. Hydropower is concentrated mainly in southwest region and Hubei province; nuclear power is mainly located in Zhejiang, Fujian and Guangdong; wind power is based in the north of China; and solar power is mainly deployed in the Yangtze River Delta, Bohai Rim and western regions. Thus, it is difficult for all provinces to converge the same optimal power mix due to differences in local resource endowments. However, it has to be noted too thermal power generation is still dominant in most provinces and the efficiency of these thermal power plants varies across provinces. For example, emission factors (CO₂ emissions per unit of power generation) of thermal power plants in Inner Mongolia are 20% higher than that in Guangdong (Liu et al., 2018). This means that there exists room for regional convergence though low-carbon technology diffusion across provinces for a specific sector, where the regional convergence could result in emissions reduction.

China’s industrial CO₂ emissions grew from 2.5 Gt/yr in 2000 to 8.2 Gt/yr in 2013 with an annual growth rate of 9.7%, and decreased thereafter to 7.8 Gt/yr in 2015 (7.1 Gt/yr from energy consumption and 0.7 Gt/yr from cement production) (CEADs, 2018). Continuous decrease in energy intensity, a lower use of coal and shifts in industrial structure towards high-value added industries were the three major factors for this decrease. If this decrease in industrial CO₂ emissions could be maintained, China’s commitment to the Paris Agreement is likely to be achieved, because the industrial sector accounted for 84% of national emissions in 2015. However, industrial emissions may fluctuate in the coming years. Chapter 5 shows that the industrial emissions are likely to peak in 2030. The emissions of the electricity sector may still increase afterwards, but this is compensated by reductions in e.g. the ferrous metals and nonmetallic products sectors. In addition to the factors studied in this thesis (e.g., energy efficiency, energy mix, industrial structure, industrial activity and pollutant reduction) which are subject to clear targets set in Chinese policy plans, additional decarbonization measures can be been deployed. Examples are carbon capture storage (CCS) and the deployment of a national emissions trading system (ETS) (ADB, 2015; Springer et al., 2019). The most important target sectors for CCS are fossil-fuel intensive industries, such as petrochemicals, ferrous metals and thermal power plants. China has produced a roadmap for CCS deployment. This roadmap assumed an emission reduction by CCS of 10 Mt/yr in 2020, 40Mt/yr in 2030, 440 Mt/yr in 2040 and 2400 Mt/yr in 2050 (ADB, 2015). China has also established a national ETS at the end of 2017. The electricity sector is at this point the only sector covered. The deployment of CCS and the ETS may result in an earlier emissions peak of China’s industrial sector as suggested in this thesis.
6.3 Outlook

This study explored the driving forces of the evolution in historical industrial energy use and carbon emissions in China from a regional and sectoral perspective. Next to this, how the industrial sector and its sub-sectors could contribute to China’s CO₂ emissions goals in 2020 and 2030 was investigated. However, there are still several topics that can be studied in further work.

In recent years, industry relocation, especially in manufacturing, has become an important topic of research (Chen et al., 2017). Industry relocation is in principle an effective way to optimize the spatial distribution of the production system. Yet, it often results in shifting production from relatively developed countries (regions) to the relatively less developed countries (regions) (Chen et al., 2017). Historically, such ‘offshoring’ resulted in production being moved to countries (regions) with higher emission intensities, leading to an overall decrease in domestic carbon emissions per unit of output (Michel, 2013). Hence, if a more evenly distributed pattern of production will lead to a higher utilization efficiency of equipment and a reduction of transport, all potentially causing a decrease in CO₂ emissions, should be studied further. Even though Chen et al. (2017), Chen et al. (2018) and Pappaset et al. (2018) have discussed the impacts of industry transfer (relocation) and industrial agglomeration on CO₂ emissions, little details about the industry transfer (relocation) have been given. Therefore, future research could give more insights into the impacts of industry relocation on CO₂ emissions.

Another important area of research concerns aligning basic statistics. Both the IPCC and National Development and Reform Commission of China (NDRC) provide information on basic factors related to energy and emissions, such as the net caloric value of different energy carriers, and CO₂ emission factors per unit of caloric value per type of carriers. For China, such basic statistical information differs highly between these two data sources (Shan et al., 2018). The IPCC default emission factors are almost 40% higher than those provided by the NDRC (Liu et al., 2015). Such differences in emission coefficients will lead to huge over- or underestimations of China’s CO₂ emissions and large uncertainties in estimates of global emissions. For example, the national CO₂ emissions from fossil fuels is 9.1 Gt/yr in 2015 by IEA while it is 8.6 Gt/yr by Shan et al. (2018). Obviously whether China will realize its emission goals is highly influenced by which data set used. Future work should be done to reduce the discrepancies in such basic data on the caloric value of energy carriers and emission factors.

Finally, studies providing projections of industrial CO₂ emissions should be updated. Most previous studies were not based on the latest data of the energy consumption, which implies that previous studies are not taking into account the declining trend of CO₂ emissions in 2014 and 2015. Additionally, previous studies may have underestimated future shifts in industrial structure. Recent policy plans such as “13th FYP”, “China Industrial Green Development Plan 2016–2020” and “Made in China 2025” restrict emissions of the energy-intensive industries by precise targets, and foresee a strong expansion of green manufacturing. Finally, in existing studies the substitution of low-carbon energy on fossil energy may also be underestimated. In the 13th FYP from 2016 to 2020 poses clear limits on the use of coal for energy production. Simultaneously, the 13th FYP for Electricity and Energy was issued in fall 2016, which included a number of capacity targets for different power generation technologies for 2020. Therefore, these recent policies should be taken into account in future studies that make projections of the carbon emissions of the industry sector in China.
References


