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Chapter 1

General introduction

This chapter introduces China’s carbon emission problem, with a focus on the decarbonization of China’s electricity sector through the development of low-carbon electricity (LE) technologies. It also introduces the research questions which are addressed in this thesis.

1.1. The importance of decarbonization of China’s electricity sector

With rapid economic growth in China, its carbon emissions have been growing rapidly. Since joining the World Trade Organization (WTO) in 2002, China’s carbon emissions increased from 3472 to 9265 million tonnes (Mt) during the period 2002-2015, at an annual rate of 13% (Shan et al., 2017). China’s total carbon emissions overtook the United States in 2006 (BP Statistical Review of World Energy 2017). At present, China is the largest emitter of carbon in the world (Zhao et al., 2018). China’s emissions accounted for about 27.5% of the world’s total in 2014 (Du and Lin, 2018). The International Energy Agency (2013) forecast that by 2035, China’s percentage of the world’s total carbon emissions will be approximately 33% (Hao et al., 2016). China is also a net emission exporter through trade (Kanemoto et al., 2014). During 2002-2011, the accumulated emissions embodied in exports accounted for approximately 30% of the total carbon emissions in China (Liu et al., 2017). From 1990 to 2008, 75% of the growth in consumption-based emissions of Annex B countries were from China’s export-embodied emissions (Peters et al., 2011). The emission savings in carbon abating countries have been partly compensated by net emission transfers from China, leading to the so-called carbon leakage effect (Paroussos et al., 2015, Chang, 2016).

China has been under pressure from the international community to reduce its carbon emissions. To reduce emissions, in 2009, China set a 2020 target to reduce CO₂ emissions per unit of Gross Domestic Product (GDP) by 40-45% from the 2005 level (NDRC, 2014). In November 2014, in the U.S.-China Joint Announcement on Climate Change, China guaranteed that the carbon emissions per unit of GDP will reduce even further by 2030, by 60%-65% compared to the 2005 level, and that the total emissions will peak around 2030 (Shao et al, 2016). In the 13th Five-Year Plan (2016-2020), China formulated mitigation targets for reducing aggregated energy intensity and aggregated carbon emission intensity by 15% and 18% by 2020, respectively (NDRC, 2016). Given these developments, and the future international targets, studies on China’s carbon emissions are both important and relevant.

The electricity sector is an important area of focus, since it is a large contributor to the total emissions. The CO₂ emissions from electricity generation in China increased from 588 to 3631 Mt during the 1991-2014 period, with an increasing share from 24.94% of the total energy-related carbon emissions in 1991 to 36.88% in 2014 (Hou and Hou, 2018). China’s generation capacity per capita reached 1 KW at the beginning of 2015, which happens to be the global average (CEC, 2015). From 2002 to 2016, China’s electricity consumption increased from 1639 TWh to 5920 TWh (NEA, 2017). CEC (2015) reports that the total electricity consumption is expected to reach 7700 TWh by 2020, corresponding to a consumption per capita of 5570 KWh by 2020. In 2016, the energy
consumption of the electricity sector reached 1303 million tonnes of oil equivalent, accounting for about 43.34% of the total energy consumption (IEA, 2017). Coal is the dominant energy in China’s electricity sector and accounted for 79.97% of the total in 2016 (IEA, 2017). Since the main source of emissions results from the burning of fossil fuels, the increase in electricity consumption will unavoidably lead to the growth of China’s carbon emissions. The carbon emissions from China’s electricity sector increased by 277.42% from 1995 to 2014 (Wang et al., 2018). Since the relevance of the electricity sector with respect to carbon emission mitigation is so obvious, the decarbonization of China’s electricity sector is crucial to realizing China’s emission reduction targets.

1.2. The development of low-carbon electricity

Since the electricity sector comprises the most important sector of emissions, it continues to be a major focus of attention for national policy makers. A key part of this attention has been on the development of LE technologies. In September 2007, the government of China announced a target to double the share of renewable energy in the total primary energy consumption, from 8% in 2006 to 15% in 2020 (NDRC, 2007). The 13th Five-Year Plan (2015-2020), goes even further, with a target to increase non-fossil energy to 20% of the total primary energy consumption by 2020 (Zhang et al., 2017). Targets for mid-century were set in the 2016, China’s Energy Production and Consumption Revolution Strategy (2016-2030), stipulating that the share of non-fossil energy should be higher than 50% of total primary energy consumption by 2050.

China’s energy policy has resulted in the rapid growth of LE generation in recent years. The proportion of non-fossil energy in total primary energy consumption reached 11.2% in 2014 (He, 2015). Since 2000, China’s hydropower saw a rapid development. In 2004, the installed capacity of China’s hydropower surpassed 100 GW, and China possessed the world’s largest number of dams. Apart from having the world’s largest installed capacity for hydropower, China also became a crucial player on innovation in hydropower technology in 2015 (Li et al., 2018). Due to the implementation of China’s Renewable Energy Law after 1 January 2006, wind and solar power have witnessed tremendous growth in both installed capacity and generation. The cumulative installed capacity for wind power increased from 1 GW in 2005 to 149 GW in 2016, with an increasing share of the total electricity generation from 0.07% in 2005 to 4.02% in 2016 (CEC, 2017). The cumulative installed capacity for solar power grew from 70 MW in 2005 to 77 GW in 2016, with an increasing proportion from almost 0% of the total electricity generation to 1% in 2016 (CEC, 2017). Clearly, there are carbon benefits from increasing LE deployment. However, there is much to do in terms of understanding the magnitude and distribution of these benefits across China spatially, and through the economy.

Research on the carbon impact of Chinese LE development has been a fast-growing area of attention in recent years. Several attempts have been made to explore the impact of LE development on future emissions. For instance, Zhao et al., (2017) deployed Life Cycle Assessment (LCA) methods to investigate the impact of the substitution of wind power for coal-fired power. Wu et al., (2017) used CGE models to predict the impact of national LE development policies on the existing carbon market and economy. Song et al., (2015a, b) combined a dynamic simulation model with an input-output (IO) framework to assess the contribution of LE development to achieving emission reduction targets. There are also a few ex-post studies observing the relationship between LE development and the trend of emissions using econometric analysis techniques (Li and Yang, 2016, Wang and
Li, 2016) and decomposition methods (Dong et al., 2016, Lima et al., 2016, Tian and Yang, 2016). These studies have provided empirical evidence showing that LE development has played a key role in reducing China’s carbon emissions. However, there is a significant variation of LE impacts between China’s different provinces due to significant differences in resource endowments. Currently, some studies have compared effects of LE development across regions. For example, Li et al., (2017) introduced a multi-region Computable general equilibrium (CGE) model, which incorporated three regions of China (eastern, central and western regions), to investigate regional effects of LE policies in China. However, they did not describe the detailed effects of various types of LE technologies. Moreover, they did not explore the pattern of LE impacts, that is, how LE development affects carbon emissions across regions in China. The carbon impact of LE development can be ascribed by many modes. For example, inter-regional electricity transmission represents a flexibility mechanism that allows regions to more efficiently share LE resources (Abrell and Rausch, 2016). Therefore, there is a clear need for research which assesses the carbon impact of LE development through a multi-regional analysis that can identify the pattern of carbon impacts of China’s LE development.

1.3. The relation to carbon emissions embodied in exports

There have been several studies evaluating the carbon emission impacts from LE developments in China. For example, Zhou et al., (2012) analyzed the contribution of non-fossil energy to achieving China’s energy and climate targets for 2020. The result showed that the use of non-fossil energy contributes to 17-19% of the total emissions reduction target in 2020. Duan (2017) evaluated the climate change benefits of the substitution of wind for coal-fired electricity, and investigated the long-term emission mitigation potential of wind power expansion. The result showed that emission reductions associated with the substitution of wind power for coal-fired power increase with the expansion of wind power market. Li et al., (2017) explored the regional effects of promoting non-fossil fuels on the carbon emissions in China, showing that all regions demonstrate declining trends in carbon intensity with increasing share of non-fossil fuels. There is general agreement that the development of LE could reduce China’s carbon emissions. However, most of these studies assessed the impact of LE development on the total national carbon emissions in China, but did not provide a clear conclusion about the historical impact of LE development on the carbon emissions embodied in China’s exports. Therefore, in this thesis, the impact of LE development on China’s export-embodied carbon emissions are explored.

Previous literature on China’s export-embodied emissions mainly focused on the balance of carbon emissions embodied in trade (Dong et al., 2017, Li et al., 2017, Zhang et al., 2017), and analyzed the driving forces of emissions embodied in China’s international trade using Multi Regional Input-Output (MRIO) models (Duan and Jiang, 2017, Wu et al., 2016, Zhao et al., 2016). Liu et al., (2015) ascertained that adjusting the energy structure in a few number of provinces could reduce the total emissions embodied in China’s exports. These studies have enhanced the understanding of the drivers of export-embodied carbon emissions. However, they only relate their findings to the carbon impact of the change of the share of fossil fuel in the total primary energy consumption, but did not identify the difference in the carbon impacts of various LE technologies. Moreover, limited work has been undertaken to assess the impact of LE development on China’s export-embodied emissions at the provincial level.
Chapter 1

China shows a great deal of regional variety, both in terms of LE resource endowments and the share of exports in the total GDP. Exports are concentrated in the developed provinces, such as Guangdong, Shanghai, Jiangsu and Zhejiang. However, the levels of LE penetration in these provinces are lower than those of inland provinces (e.g. Sichuan, Guangxi and Yunnan) (see Chapter 3). In order to optimally develop LE in appropriate regions, China has enhanced the inter-regional electricity transmission such that the regions with little LE resources can unitize the LE transmitted from the regions with abundant LE resources (Wang et al., 2016). In 2014, inter-regional electricity transmission was up to 391.2 billion kWh, an annual increase of 10.89% (Zeng et al., 2016). Since inter-regional electricity transmission is critical, an analysis of carbon impacts of LE development at the regional level needs to consider inter-regional electricity transmission capacity. Moreover, since the development of LE in one region could affect carbon emissions embodied in other regions’ exports via inter-regional economic linkages (Feng et al., 2013), it is necessary to estimate inter-regional spillover effects of LE development on carbon emissions embodied in exports.

1.4. Carbon impact of expansion of low-carbon electricity infrastructure

The carbon impact of LE development has been extensively examined, with a consensus on the carbon benefit of LE operation. However, LE technologies consume more energy and materials and induce more carbon emissions in installation processes compared to fossil-fuel electricity technologies (Hu et al., Wiedmann et al, 2010, 2011, Phel et al., 2017). Thus, the carbon impact of LE development relates not only to the operational impact of LE expansion, but also to the carbon impact of the expansion in LE infrastructure. Moreover, given China’s regional diversity, there are significant differences in the carbon impact of LE infrastructure across China. Therefore, an analysis of the characteristics of carbon impacts of LE investments in different provinces can provide implications for regional energy management.

Inter-regional economic linkages are also an important factor for tracing the carbon impact of LE investments, as inter-regional carbon flows pinpoint regions in which the supply chain of LE investments can be improved. For example, considering that the western and central regions are major suppliers of intermediate inputs for the eastern region (Hong et al., 2016), the improvement of manufacturing technologies in the western and central regions could reduce the carbon impact of LE investment in the eastern region through providing low-carbon intermediate products (see Chapter 4). Therefore, recognizing the hidden linkages and carbon flows embodied in the inter-regional trade is of great importance to exploring carbon impacts of LE investments.

Finally, China’s mitigation scenarios as developed by the International Energy Agency have shown that switching from fossil-fuel electricity technologies to LE technologies is a key element of decarbonization strategies (IEA, 2017). Yet, they do not provide estimations of the “carbon overhead” related to creating a LE infrastructure. Since China will need to build a large amount of low-carbon electricity infrastructure to hit climate targets, and because this infrastructure can be more carbon intensive to build (not to use), China will need to plan for a certain amount of the remaining carbon budget to be taken up with this expansion. This can be called “carbon overhead” of LE infrastructure. In other words, the “carbon overhead” refers to the additional environmental cost in the investment stage of LE, while LE development could bring carbon emission mitigations
in the operation stage through increasing the share of LE in the total primary energy consumption. Since electricity supply will undergo a transformation towards LE technologies in the future, the carbon impact of LE investments is expected to continue to increase. This means that the “carbon overhead” from LE infrastructure might be a constraint on LE development in the future. Moreover, the impact of LE investments on carbon emissions cannot be assessed statically, since for such relatively new technologies learning curves can be expected to drive down the carbon impact of LE investments (Aste et al, 2016).

1.5. Methods for analyzing the carbon impact of low-carbon electricity development

Single-region IO models provide an approach to modeling a regional economy within IO framework, however, they do not identify inter-regional connections. In order to capture the various economic linkages among several regions in a multi-regional economy, MRIO models were suggested by Chenery (1953) and Moses (1955). Leontief and Strout (1963) developed the gravity-model method to calculate the inter-regional flows in a connected-region MRIO model, containing counterparts to the intra-regional technical coefficients matrices and the inter-regional technical coefficients matrices. Many studies have shown that a Multi-Regional Input Output (MRIO) approach is useful in analyzing China’s carbon emissions at the regional level (Feng et al., 2013, Tian et al., 2014). A major advantage of MRIO is that it takes into account regional production and emission characteristics. Particularly, MRIO analysis can be used to identify how production in one region drives production and carbon emissions in other regions via supply chains (Wiedmann et al., 2010, Meng et al., 2013).

In terms of assessing the carbon impact of LE development in China, an MRIO model is a comprehensive approach in which the entire carbon footprint of LE development can be considered. This means that not only the intra-regional carbon impact of LE development can be taken into account, but also the indirect carbon impact of LE development in other regions. Therefore, the results of MRIO analysis can provide holistic insights into the regional and sectoral interactions through the whole supply chain of LE sectors, which is beneficial for policy makers to understand the inter-regional carbon flows induced by LE activities. In principle, China’s National Bureau of Statistics only publish official IO tables for individual provinces in China, and thus a problem is the estimation of the transactions between regions. However, some researchers have complied MRIO tables by constructing cross-regional and cross-sectoral matrices. Currently, China’s MRIO tables for 2002, 2007 and 2010 are available with all 30 Chinese provinces. However, different researchers compiled these MRIO tables at different sector details based on the availability of data. The MRIO table for 2002 is for 21 Chinese sectors (Shi and Zhang, 2012), while the MRIO tables for 2007 and 2010 are for 30 sectors (Liu et al., 2012; 2014). Thus, the sectors in the three MRIO tables are often aggregated into 21 sectors. Moreover, the carbon emissions by sector can be estimated based on China Energy Statistical Yearbooks (CESY) (NBS, 2003, 2008, 2010, 2012, 2015). This thesis introduces MRIO models and more details are in Chapters 3, 4, and 5.

There have been few studies analyzing the carbon impacts of region-specific LE implementation scenarios for China with MRIO models. One of the main reasons is that the available Chinese MRIO only has one, average electricity generation sector by region. For assessments on LE, different types of electricity production sectors must be discerned
in an MRIO table. Some researchers disaggregated the MRIO table itself to obtain disaggregated electricity sub-sectors (Lindner et al., 2012), however, this will induce parametric and systematic error (Wiedmenn et al., 2011). This can be solved by expanding the existing Chinese MRIO into a multi-regional economic-energy hybrid model which links energy data in physical units to a Leontief matrix in monetary units (Guevara and Rodrigues, 2016) (see Chapter 3). Through this approach, energy types can be disaggregated according to the amount of electricity generation in energy units, while the aggregated electricity sector in the MRIO table still remains in monetary units. The hybrid model not only has the characteristic of the comprehensiveness of IO models, but also provides the accuracy from energy data of inter-regional electricity generation and transmission. Furthermore, within the IO framework, Hedi, (2017) provided a final-demand approach to assess the impact associated with an exogenous demand stimulus in an electricity sub-sector (e.g. an investment activity in wind power). Using this approach, a demand stimulus of an electricity sub-sector can be introduced into the MRIO table by constructing a demand vector that reflects the changes of the inputs in the existing sectors of the MRIO table. Therefore, MRIO tables do not need to be disaggregated even for the estimation of the impact of new demand stimulus of the LE sector. These two approaches combined help to overcome a major limitation of previous MRIO analyses on this topic (see Chapter 4).

1.6. Research questions

From the above, we can deduce a number of issues. First, as many authors have shown, the structure of China’s energy system has enormous implications on the carbon embodied in the products and services produced and used in and exported by China. So, a study of the impact Chinese LE development on export-embodied carbon emissions should contribute to providing fundamental information for investigating export-embodied emission reduction potentials in China. Yet, few authors have taken into account LE developments from a regional perspective in China. A main reason for this is lack of detail in the electricity production sector in the available Chinese MRIO tables. However, this problem can be solved by a hybrid unit MRIO mode (see Chapter 3) and a final demand approach (see Chapter 4), as described above. At the same time a regional perspective is highly relevant, since the implementation of LE and the production of products and services for use in China and for exports are not at evenly distributed over the various Chinese regions. It is also appreciated that LE investments are usually more carbon intensive than investments in traditional electricity generation. As indicated, most scenarios do not take this factor into account (e.g. IEA, (2017)), let alone from a region-specific perspective. Against this background, this thesis aims to answer the following research questions:

1. How are carbon emissions distributed across sectors from the perspective of inter-sectoral linkages? What spillovers occur via supply chains, particularly between the electricity sector and other production sectors?

2. How will the development of low-carbon energy across regions impact carbon emissions embodied in China’s exports? What is the role of electricity transmission and supply chains in regional emission reductions?

3. How do the carbon emissions from investments in LE infrastructure compare to the reduction of carbon emissions during the use of LE? How are the carbon impacts of
this infrastructure distributed within China?

4. How will the carbon impact from the expansion of LE infrastructure evolve in the future?

1.7. Outline of thesis

As described above, an MRIO approach has many advantages in analyzing the linkage effects between regions in China. However, few studies have applied an MRIO approach to the carbon impacts of LE development in China at the regional level, because no sector captures LE generation in the existing Chinese MRIO table. To solve this problem, in this thesis, the MRIO model is improved by developing a multi-regional economic-energy hybrid model, such that LE generation in energy units can be added to the Chinese MRIO tables in monetary units. Moreover, to investigate the carbon impacts of installing LE generation system, this thesis also presents a demand-driven MRIO approach in which the inputs for LE investments are allocated among the sectors existing in the MRIO tables based on the LE investment structure. Using these approaches, the carbon impact associated the LE expansion in the operational and investment stages are separately estimated and the research questions can be addressed.

The thesis consists of 6 chapters. This chapters, Chapter 1, is a general introduction, providing a background on the general status of China’s carbon emissions. The importance of developing LE electricity technologies is highlighted. After reviewing most relevant studies on the carbon impact of LE development, the research questions and outline of the thesis are discussed.

Chapter 2 answers research question 1. It provides an overview of China’s carbon emissions from a multi-sectoral perspective, focusing on the temporal variations of carbon emissions and the contributions of various sectors. By treating each sector as a subsystem, the different emission components (internal, feedback, spillover and direct) of different sectors are assessed to explore the carbon linkages of each sector with the rest of the economy. The investigation of the carbon linkages between China’s sectors provides decision makers a comprehensive picture for formulating feasible emission mitigation policies.

Chapter 3 answers research question 2. It analyzes the impact of LE development on carbon emissions embodied in the exports of China’s 30 provinces during 2002-2014. A multi-regional economic-energy hybrid model is developed, such that the carbon impact of LE electricity can be categorized into the intra-regional effect, electricity transmission effect and supply-chain effect. The historical, export-embodied emissions in China is compared against a counterfactual in which the LE expansion of 2002-2014 did not take place. The results are used to better understand the patterns of carbon impacts of LE development across provinces and over the years, given the dynamic nature of China’s economic development and the heterogeneity of China’s regions.

Chapter 4 answers research question 3. It focuses on the carbon impact of LE infrastructure expansion using a demand-driven MRIO model. Historical emissions induced by LE investments are compared with a counterfactual scenario without LE investments to gain insight into the carbon impact of LE investments at the provincial level. The estimated carbon impact of LE investments is compared with the operational impact of LE. Moreover, in order to summarize the patterns of regional carbon impacts of
Chapter 1

LE investments, the intra-regional and inter-regional impacts of LE investments are separately assessed.

Chapter 5 answers research question 4. It projects the carbon impact of LE investments during 2015-2040. Based on the declining trend of historical carbon intensity of LE installation, experience curves are constructed to project the carbon intensity of LE installation up to 2040. By combining predicted carbon intensity of LE installation with the predicted cumulative installed capacity under well-known scenarios from national and international bodies, the carbon impact of LE investments during 2015-2040 is projected. The results provide indications on the carbon performance of LE investments in the future.

Chapter 6 summarizes the answers to the research questions posed above and develops a general discussion focusing on the directions of future research.
References


Chapter 1


