Renewable and Sustainable Energy Reviews 81 (2018) 1350–1364

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Overview of research on China's transition to low-carbon development: The role of cities, technologies, industries and the energy system

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ARTICLE INFO

Keywords:
Low-carbon cities
Low-carbon technologies and industries
Low-carbon transition of China's energy system

ABSTRACT

China is experiencing a transition to low-carbon economic development. This paper assesses the current literature on the potentials of and barriers to China's transition to low-carbon development, identifying promising fields of action and suggesting a research agenda that systematically addresses the shortcomings. Through a broad literature review, we select three main research areas of interest: low-carbon cities, low-carbon technologies and industries, and the transition of China's energy system. As an innovative work, we also summarize some specific issues discussed more in Chinese journals but less in English language ones. Some elements of a more comprehensive research agenda that can improve the understanding of China's ability to enter a low-carbon development pathway are suggested.

1. Introduction

China's crucial role as an emitter of greenhouse gases has long been recognized in the debate about global climate change mitigation. Researchers have emphasized both the need for a significant reduction in China's emissions and the potential for accomplishing this if the Chinese government agrees to a fundamental policy shift. More recently, it has become increasingly acknowledged that this policy shift has already started to occur, even though it may be a side effect of China's domestic energy issues rather than a direct result of a global climate agreement. However, the economic, political and institutional preconditions that would enable China to begin a transition to a low-carbon development pathway are still poorly understood. Whereas some researchers have overestimated the steering and implementation capacities of a central government in a planned economy [142], others have underestimated the societal dynamics that might promote such a transition at a rate faster than that in other countries. This paper therefore assesses the current literature on the potentials of and barriers to China's transition to low-carbon development. Through a broad literature review, we selected some of the best covered topics. Although we omitted a number of topics, we believe that we have covered those most relevant to the overall question of low-carbon development in China. The objective of this review paper is to combine existing literature from various disciplines to systematize current knowledge about the most important challenges of low-carbon development in China and to discuss the implications of the findings for finding promising routes to strengthen low-carbon strategies and develop research on this topic further. Obviously the literature covers a wide range of – sometimes incompatible – methodologies. For the sake of transparency, we mention these methodologies, but it is beyond the scope of this review paper to discuss in depth their respective underlying assumptions and epistemological starting points. As this is a review paper in nature, it cannot directly contribute to the reduction of GHG emissions, but we hope to improve the understanding of how such strategies are – or are not – leading to emission reductions in the long run. The paper is organized as follows: in the remainder of this introduction, we explain the preconditions for low-carbon development in China and deduce the three strands of literature on low-carbon development in China that have been most intensely researched in the past years. Chapters 2–4 follow the three themes we have identified: Chapter 2 summarizes the literature on low-carbon cities in China, Chapter 3 focuses on the literature about low-carbon technologies and industries, and Chapter 4 reviews the literature on the transition of China's energy system. While these three chapters focus on research publications in Anglophone mainstream journals, we add a brief fifth chapter on the literature published in Chinese journals. Chapter 6 summarizes our findings and draws some conclusions.

What are the preconditions for low-carbon development in China? Even though China's per capita CO_2 emissions remain below those of other industrialized countries, at 6.7 t (2010–2014), its total CO_2

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http://dx.doi.org/10.1016/j.rser.2017.05.099
Received 10 May 2016; Received in revised form 26 February 2017; Accepted 18 May 2017
Available online 08 July 2017
1364-0321/

emissions have grown enormously in recent decades, thus making China the world's largest single national emitter [108]. China's energy system is mostly based on coal [91], and the majority of its coal-fired power plants operate at relatively low efficiency levels. Energy security has become a pressing issue in terms of both domestic and international strategies [42,43]. Domestic problems connected to energy consumption are becoming increasingly important. At the same time, there is pressure from rural areas because China still suffers from rural energy poverty and from large metropolitan areas, where the population suffers from poor and sometimes dangerous urban air quality. As a reaction to all these pressures and in an attempt to become a more active player in international climate negotiations, China's government has recently made a voluntary commitment to lowering its CO_2 emissions per unit of GDP by 60–65% by 2020 (compared with 2005 levels) and to increasing the share of non-fossil fuels in its primary energy mix (UNFCCC 2015; [81]). Another recently established goal is that the share of non-fossil fuels used in primary energy consumption should be increased to 15% by 2020 [82]. China has also issued a series of national strategies for energy conservation and emission reductions; these are presented in the 12th Five-Year Plan.[1] Policies and measures such as emissions trading have been introduced in several provinces [18,39]. The societal preconditions required for implementing such policies effectively and for achieving ambitious mitigation targets are therefore a pertinent research topic.

This article seeks to contribute to the above-mentioned research area and provides a literature review, on the basis of which research gaps will be identified. Our main focus is on mainstream peer-reviewed journals in English, but we also examine relevant debates in peer-reviewed journals in Chinese. A review of research papers in relevant journals[2] revealed three main research areas of interest: low-carbon cities, low-carbon technologies and industries, and the transition of the national energy system from one based on fossil fuels toward one based on renewable and nuclear energy sources. The three research areas resonate with three important economic and social dynamics currently affecting China: rapid urbanization, rapid technological development and industrialization, and an ongoing increase in energy demand. We assess these three strands of literature consecutively, summarizing recent findings and identifying research gaps. The final chapter therefore identifies what appears from the literature as promising approaches to low-carbon development in the Chinese context and suggests elements of a more comprehensive research agenda that can improve the understanding of China's ability to enter a low-carbon development pathway.

2. Current research on low-carbon cities in China

As densely populated and resource-intensive regions, cities have always been hotspots of innovation. Since the beginning of industrialization, however, cities have been under intense environmental pressure because of their high concentrations of industry, infrastructure and population. They have also been regarded as the world's main sources of greenhouse gas emissions and the primary contributors to global warming and climate change [14]. According to UN Habitat [96], approximately 40–78% of global GHG emissions are estimated to originate in cities. Moreover, the proportion of greenhouse gas emissions from cities is increasing continuously because of ongoing urbanization [65]. In many parts of the world, urban sprawl and energy-intensive development patterns are still seen as pathways to urbanization [1,75]. This phenomenon is particularly true for some developing countries, whose energy consumption and GHG emissions are expected to continue to increase significantly along with rising living standards and material affluence [22,78].

As the world's largest developing country, China is experiencing urbanization on an unprecedented scale. China's urbanization rate has increased from approximately 36% in 2000 to nearly 53% in 2012 [74]. Migration, urban expansion, and the emergence of new cities near existing cities all indicate that urbanization in China will exert continuing acute pressure on infrastructure, economic growth, land development, urban resource demands, and pollution [9]. China's 35 largest cities contain approximately 18% of the country's population and contribute 40% of the country's energy usage and CO_2 emissions [14,44]. This percentage continues to grow along with China's high-speed urbanization.[3] A low-carbon urban development strategy would therefore offer a high GHG emission-reduction potential for China. At the same time, China's cities are extremely vulnerable to the impacts of climate change because of their high population densities, concentrated economic activities and scarce natural resources. Cities in northern and western China tend to experience droughts, dust storms, and smog, which have been particularly serious in recent years, whereas the eastern and southern cities often suffer from floods and extreme rainstorms. Liu and Deng have shown that the mean annual precipitation is expected to decrease by 2–10% in drought-prone northern China but increase by more than 20% in flood-prone southern China [65]. A strong dust storm attacked the northwest provinces in April of 2014, including some important cities such as Lanzhou City in Gansu Province and Wulumuqi City in Xinjiang Province. Some eastern cities, such as Shanghai, and southern cities, such as Guangzhou, suffer from rainstorms almost every summer. It can be assumed that the immense scale of urbanization will increase public pressure and therefore lead to a bolder and more aggressive decarbonization strategy for both national and regional policy makers.

Which low-carbon city initiatives have been started in China, and what can we learn about them from the existing literature? An initial low-carbon city program was implemented by China's Ministry of Construction and the Worldwide Fund for Nature in 2008. In August 2010, China's National Development and Reform Commission (NDRC) launched a low-carbon city experimental project that was implemented in eight cities: Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang, and Baoding[4] [16]. The concept of the low-carbon city, which integrates elements of both a low-carbon economy and a low-carbon society, has been found to be a new path by which China can achieve its goals of sustainable urbanization, ecological civilization and scientific development [106,14]. Therefore, these "low-carbon cities" are intended to develop low-carbon economies and to promote low-carbon lifestyles. Specifically, a low-carbon city is characterized by reduced pollution, low emissions, and high energy efficiency [65].

So far, however, low-carbon cities in other countries have been little more than an inspiring guiding principle for city administrators and citizens. Even if policies promoting low-carbon cities abound, it would

[1] The Five-Year Plans, as an important part of Chinese domestic economic plans, are a series of social and economic development initiatives that mainly focus on carrying out major national construction projects, mapping strategies for economic development, setting growth targets and launching reforms. The first Five-Year Plan began in 1953. The 11th Five-Year Plan covers the period 2006–2010, and the 12th covers 2011–2015.

[2] Using the SCI and SSCI network databases, we searched with the key words "low-carbon" and "China" to identify related articles published during the 2004–2016 period. The total number of articles identified was 16926. Because we are focusing primarily on the effects of low-carbon policies on China's economy and society from the perspectives of management and economics, papers focusing on technologies from purely natural science or technological perspectives were excluded from our list. For similar reasons, papers about low-carbon agriculture were also beyond the scope of our review because that field is another vast and complex research area closely related to chemistry, biology, geology, etc. Moreover, by using Bibexcel software, we also analyzed the frequency of key words appearing in the 6000+ articles we identified. In addition to obvious words such as "China", "carbon dioxide", "low-carbon", and "climate change", key words closely related to content included issues such as "low-carbon economy", "energy consumption", "renewable energy", "energy efficiency", and "low-carbon city". Therefore, our paper is divided into reviews centered on the concepts of "low-carbon city", "low-carbon technologies and industries in China", and "the transition of China's energy system".

[3] By 2014, China's urban population had grown to 54% of the country's total population (World Bank: http://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS).

[4] Source: http://www.worldbank.org/en/news/feature/2012/05/03/sustainable-low-carbon-city-development-in-china.

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Table 1
Definition of scope 1, 2, and 3 GHG emissions.
(Source: [41,2])

	Definition of scope
Scope 1: Direct GHG emissions	Direct GHG emissions occur from stationary combustion, mobile combustion, process emissions and fugitive emissions.
Scope 2: Indirect GHG emissions from electricity	These are emissions from the generation of purchased electricity consumption, steam and heating consumption.
Scope 3: Other indirect emissions	Emissions in this optional reporting capacity are a consequence of other life-cycle emissions excluded from scopes 1 and 2 (for example, GHG emissions generated during the process of raw materials production within district boundaries of the city)

be overly optimistic to expect that local governments have sufficient legal and political leeway and steering capacity to achieve such ambitious goals easily [3,4]. Financial limitations are also common, e.g., the lack of resources to invest in low-carbon technologies [71].

What can be learned from the available research on the current status of low-carbon cities in China? Current research mainly focuses on the following topics: first, the challenges of establishing GHG emissions inventories; second, the identification of factors influencing GHG emissions in China's cities; and, third, the exploration of paths by which China's cities can achieve low-carbon development.

2.1. Establishing a GHG emissions inventory of China's cities

Some authors have suggested that developing benchmarks and a more comprehensive GHG emissions inventory is a necessary first step in the context of global efforts to mitigate climate change [24]. Establishing a local carbon emissions accounting system is a prerequisite to and the first priority in realizing a low-carbon transition [71]. The research on establishing a GHG emissions inventory has important theoretical and practical implications for China's efforts in energy conservation, emissions reduction, and low-carbon city construction. On the one hand, transparent and robust quantification is the basis against which the effects of mitigation efforts can be measured. GHG inventories should therefore be conducted regularly to track progress and indicate areas for further improvement [90]. On the other hand, a GHG emissions inventory that is in line with up-to-date international GHG inventory standards can help to facilitate comparison and analysis with other cities in the world, which is important in providing central and local policy makers with a clear understanding of their city's GHG emissions status.

A comprehensive GHG emissions inventory requires two important components: a standard inventory methodology and up-to-date activity data. Kennedy et al. [41] have elaborated on the methodology of GHG emissions inventories in detail. In general, the methodology can be divided into two categories: the top-down approach and the demand-centered, bottom-up approach. Moreover, three scopes have been suggested for GHG inventories at the city level (Table 1).

Although there are several studies of GHG emissions in Chinese cities, so far, most have been based on the city's aggregate energy consumption by using a top-down methodology [2], in line with IPCC guidelines and the WRI/WBCSD model.[5] Some authors have discussed conceptual problems and problems of data availability that arise when applying this methodology. Dhakal [14] has described a further methodological problem that has to do with differences between official *city* populations and *urban* populations: cities and towns are politico-administrative units. Designating a place as a “City” has historical, political, resource distribution, and other implications in China. Generally, the statistical data of a certain city cover both urban and rural areas in that city. The best method for estimating China's urban energy consumption would be to determine the energy consumption of each city and town and then divide these figures into urban and rural energy uses. However, the energy use information that would be required for this approach is available for only a few large cities. Therefore, so far, most studies on urban energy use in China rely on an aggregated and top-down methodology. In this sense, Sugar et al. [90] have provided comprehensive and detailed emissions inventories for Shanghai, Beijing, and Tianjin and have compared the results with those for ten other cities around the globe. The results show that the majority of emissions in the three Chinese cities were from electricity production, heating and industrial fuel use, and ground transportation. When compared with other cities around the world, these three cities are among the highest per capita emitters. The authors have also examined similarities and differences in GHG emissions among cities in China and cities located in other countries. The results provide a benchmark for discussions of the effectiveness of strategies designed to reduce carbon emissions.

Inventories using a bottom-up methodology are still rare. The study of Bi et al. [2] is the first comprehensive accounting system for GHG emission inventories at the city scale in China; it is based on a bottom-up methodology and includes six sectors. This study focuses on scope 1 and 2 emissions (see Table 1) in Nanjing City. The results show that the three largest GHG contributors are industrial energy consumption, industrial processes, and transportation. In contrast to a top-down methodology, the bottom-up approach results in lower per capita and per GDP carbon emissions values (in this particular study, such values were comparable to or even lower than the world average). Wang et al. [106] have suggested that although the GHG inventories calculated by a top-down approach can provide proxies of total GHG emissions, they do not provide sufficient information for local governments to define operable measures to reduce carbon emissions. Analyzing the GHG emissions characteristics of China's mega-cities based on the study of Bi et al. [2], Wang et al. have developed inventories for 12 of the most developed cities in China by using bottom-up approaches (similarly to Bi et al. [2]). The results show that although average per capita emissions in these cities are lower than those in many large cities in developed countries (London, Los Angeles, New York, etc.), the total carbon emissions of Chinese cities can still be well above those of their Western counterparts. Tong et al. [95] have quantified GHG emissions associated with four different-sized cities in China by a method called community-wide infrastructure GHG footprint. This method can represent the life cycle and trans-boundary impacts of infrastructure use. The research has analyzed the GHG emissions in Yixing, Qinhuangdao, Xiamen and Beijing by calculating the carbon footprints of seven of their most essential infrastructures, i.e., electricity, non-electricity energy, water supply and wastewater treatment, transportation, municipal waste management, construction materials, and food. The results show that industrial energy use is the dominant contributor to GHG emissions in the four cities [95].

GHG emissions inventories in China's cities often cover scopes 1 and 2, whereas scope 3 emissions are rarely included (see Table 1). For example, Li et al. [50] have outlined a detailed inventory of CO_2

[5] The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* provides detailed instructions on how to model this. See http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. The WRI/WBCSI model is the *Greenhouse Gas Protocol* (GHGP) developed by the World Resources Institute and World Business Council on Sustainable Development (WBCSD). See http://www.wri.org/our-work/project/greenhouse-gas-protocol/online-courses#project-tabs.

emissions and future trends as a basis on which Shanghai might determine actions to help mitigate climate change. This paper estimates the inventory of CO_2 emissions from energy uses (including industrial activities) but excludes other indirect emissions. A study by Song et al. [88] is among the few studies that have extended beyond this limited scope, although the research focused on only the community level (the smallest official social unit in a particular area or place, often consisting of only 4000–15,000 inhabitants). Through life-cycle analysis, the authors have presented a three-scope accounting framework for community carbon emissions, including emissions from direct fossil fuel combustion, purchased energy (electricity, heat, and water), and supply chain emissions embodied in the consumption of goods. A typical high-quality community in Beijing is used as a case study to elaborate on the CO_2 emission inventory in detail. The results show that emissions from different elements in the supply chain embodied in the consumption of goods are too significant to be ignored. The top three emission items are transport and communication (41.36%), buildings (14.11%), and education and recreation (10.41%). The emissions stemming from buildings are a conservative estimation because this study considered only major material consumption owing to a lack of data. Moreover, this study shows that energy consumption tends to increase along with increases in income [88].

In summary, the GHG inventories conducted in China to date remain at the initial stages and are very limited in scope:

First, because of differences in the concepts, scopes, data availabilities and statistical methods between Chinese and Western cities, it is difficult for China's cities to directly use the common international methodology to establish GHG inventories. China would have to establish GHG inventories in line with international standards to improve comparability.

Second, the GHG inventories carried out to date lack continuity. Most of the research has focused on one or only a few cities in a given year. Few of these studies have established a basis for long-term monitoring of GHG emissions, which is important in analyzing changes.

Third, China's GHG inventories seldom cover scope 3 emissions [88]. This is partly because life-cycle analysis is often used to add scope 3 emissions, but it is difficult to obtain related data in China. Publication of more emissions data will require long-term adjustments by the government, enterprises, and other organizations.

Overall, there seems to be a research gap concerning the use of inventories in the policy process and in other aspects of governance, although Sugar et al. [90] have at least mentioned governance as a topic. Some inventories include policy implications, but their actual role in the policy process is poorly understood. Here, one can draw insights from a series of recent studies on the challenges of local governance, e.g., the study by de Jong et al. [13], which explains the substantial implementation gap by a top-down technocratic planning mode that fails to acknowledge the close interrelations between local government actors and land and real estate developers. A comparison of Chinese and Swedish eco-cities emphasizes the need to overcome typical cross-sector barriers for local governance attempts to achieve environmental goals [117]. Recent debates on urban governance in Chinese megacities have also revealed a shift in governance from clientelistic to more corporatist modes. Although this shift has also included more transparent policy making and a stronger role for the district government, the central government often interferes in unforeseeable ways [145,146]. The complex interactions between the central government and the local government remain an important precondition for developing low-carbon strategies at the city level. Although the central government issues far-reaching decarbonization targets, it often remains unclear how city governments can actually contribute to achieving these goals and how local development goals can be reconciled with low-carbon development pathways.

2.2. Identification of factors influencing GHG emissions in China's cities

Developing an understanding of the factors influencing GHG emissions in cities is a crucial prerequisite for mitigating China's anthropogenic emissions, as policies can then better prioritize and identify the most important leverage points. Quantifying the magnitude of each factor that drives emission changes in cities is necessary so that a potential bottom-up climate mitigation policy at the city and sectoral levels can be designed and initiated. Li et al. [54] have used Wuhan City as an example and have studied the driving factors of GHG emissions. In this paper, they reveal the dynamic relationships between the city's carbon footprint and the factors influencing it. The results show that population growth and economic development are the main influencing factors for GHGs in Wuhan City. Wang et al. [106] have empirically studied the influences of urbanization processes, economic factors, industry structure, and energy intensity on GHG emissions. Notably, they have also considered the share of tertiary industry and R & D output as influencing factors. The results show that both influence GHG emissions negatively, leading the authors to conclude that the city administration of Beijing should pay more attention to the typically underestimated tertiary sector. Li et al. [44] have selected Tianjin in northern China as a case study to identify the factors driving CO_2 emissions during the 1996–2012 period. In addition to basic factors such as energy intensity, population, and income, they have also considered the effect of foreign direct investment (FDI). The results show that the influx of foreign capital harms the local environment. As an economic center and as the largest coastal city in northern China, Tianjin is an important investment hotspot for foreign capital. FDI has had an important effect on economic and technological development in Tianjin City, but this goes hand in hand with accelerated deterioration of the local environment. Investors see relocating their polluting industries to Tianjin City as a way of avoiding more stringent environmental regulations elsewhere [44]. However, this result is inconclusive, as Wang et al. found no significant influence of foreign direct investment on China's carbon intensity.

Many scholars have studied the factors influencing cities' GHGs from a purely economic perspective. The factors usually include carbon/energy intensity, power mixture, industrial structure, and population. Wang et al. [99] have analyzed the main drivers of increasing GHGs in Suzhou City during the 2005–2010 period. Chong et al. [9] have investigated the key drivers affecting emission increases in six Chinese megacities: Beijing, Shanghai, Tianjin, Chongqing, Guangzhou, and Hong Kong. In all cities, economic and energy intensity effects have long been the two dominant factors contributing to changes in carbon emissions.

Some scholars have also studied this issue from a broader perspective by taking urban development intensity into consideration. Urban development intensity can be defined as comprising the multiple impacts that human development activities exert on urban areas, including land use, population, economic intensity, the spatial distribution of infrastructure, and public service facilities. Wang et al. [102] have qualified the relationship between urban development intensity and carbon dioxide emissions. They have suggested that improved urban planning and spatial optimization may be effective means of reducing GHG emissions in China's cities because factors such as land-use intensity, economic intensity, population intensity, infrastructure intensity, and public service intensity are all drivers of GHG emissions. Land use intensity is an index for measuring the spatial pattern of land use. It is often reflected by indicators such as the ratio of built district to urban areas, the ratio of living land use to built district areas, the ratio of production land use to built district areas, and the ratio of infrastructure land use to built district areas. Higher land use intensity refers to a larger proportion of built-up areas. With relatively higher populations and levels of construction, large built-up areas have exerted more pressure on both the environment and the economy, resulting in further emissions growth. This study concludes that, when pursuing low-carbon strategies, policy makers should consider the effects of urban development intensity, for example, by controlling land-use intensity. It might be debatable that tighter population and construction will cause environmental pressure because higher intensity also leads to less spatial demand; moreover, densely populated cities are often thought to be environmentally preferable, at least compared with suburban sprawl developments, because of their higher intensity. However, in China's cities, there are certainly some cases of inefficient land use. One example would be the so-called “ghost cities”, which consist of residential high-rise buildings without anyone living in them. Even though these cities do not have high energy demand because of the lack of population, the emissions stemming from the construction process would still have to be taken into account. Wang et al. [102] also mention that China's continued family planning policy contributes to reducing population intensity; this also controls the scale of urban populations and helps to avoid increases in CO_2 emissions. Without delving into ethical considerations of forced birth control, it should be mentioned that this policy has recently been changed for demographic reasons to allow two children per family. Zhao et al. [130] have estimated the carbon emissions of different land use types in Nanjing City. By establishing matching relationships between different land use types and GHGs, the carbon emission intensity of regional land use in this city was analyzed. The results suggest that to decrease the carbon emission intensity of land use, it is important to consider spatial expansion, intensity, and structure in future land use and urban development. Carbon emission effects should also be introduced into land use planning.

Among all studies of the factors influencing GHGs in cities, the STIRPAT model is a particularly popular method. STIRPAT is an acronym for Stochastic Impacts by Regression on Population, Affluence, and Technology. It refers to a statistical and conceptual model for assessing human impacts on the environment. It has been adopted as an analytic strategy to identify the primary drivers of environmental harm and to uncover leverage points for ameliorating that harm. For example, Li et al. have used this model to study the driving factors of GHGs in Wuhan City [54]. From this model, Wang et al. have developed an improved STIRPAT model to explore the influence of the level of urbanization, level of economic development, proportion of industry, and energy intensity on GHG emissions [106]. Also using the STIRPAT model, Li et al. [44] have used Tianjin City as an example to identify factors influencing GHGs. Many other researchers have used the index decomposition analysis method to study this issue. This method is an analytical tool originating from energy studies and has been extended to areas other than energy and emissions. For example, Wang et al. [99] have decomposed GHGs into impact factors, including population, per capita GDP, carbon emission per unit of energy consumption, carbon intensity, and energy intensity, to study the roles of these factors in GHG changes. This method has also been used in a study by Chong et al. [9].

Other methodologies have also been applied to analyzing the drivers of GHG emissions. In managing the dynamical evolution and the intrinsic stochastic behavior of vital elements inside urban energy systems, Feng et al. [20] have used system dynamics (SD) to describe the inner interactions and structures affecting urban developments and to identify both desirable and undesirable interventions.

In summary, for the methodologies used to explore the factors influencing GHGs, the STIRPAT model and the index decomposition method are often applied. The distinctions among studies lie in the differences of sample cities, the uniqueness of factors, and data accuracy. The factors influencing GHGs can be summarized into four categories: the economic level, industry zoning, energy system development, and city layout. First, the GHG emissions are considered to increase along with economic growth, which makes strong policies to control emissions at the city level less attractive for local governments. However, the exact relation between economic level and GHG emission can be further studied by decoupling research, which has already attracted some researchers' attention. In a few of China's cities, especially the large ones, strong decoupling effects between economic development and GHG emissions have already appeared, but because of strong economic imbalances among China's cities, this cannot easily be generalized. Second, industry zoning has a few more factors such as industrial structure, the proportion of tertiary industry, investment, etc. Researchers often advocate the adjustment of industrial structure. However, for many cities, the rapid increase of GHG emissions is caused by the development of the tertiary sector instead of the industrial sector. Researching emissions from the tertiary and household sector perspective may be a new approach to controlling GHG emissions in cities. Third, the energy system and energy intensity are crucial to emissions and are discussed in Section 4 of our paper. For the last point, the city layout is very important, but there is still a lack of detailed academic discussion, and improved city designs are particularly difficult to achieve in already existing cities.

2.3. Exploring paths to building low-carbon cities

The establishment of low-carbon cities has been promoted worldwide because cities are key drivers of energy usage and associated carbon emissions. The concept of the low-carbon city, which integrates elements of both a low-carbon economy and a low-carbon society, provides a new model of sustainable urbanization for China, a model directed toward ecological civilization[6] and scientific development [127]. However, even if governments develop a basic understanding about the most important features of a low-carbon city, the most difficult question is the transition: how to switch from a traditional development path to a low-carbon development path.

Zhang et al. [127] have presented a scenario analysis of Beijing's future energy consumption and GHG emissions. They have used the Long-range Energy Alternatives Planning (LEAP) model to simulate a range of pathways and analyze how these would change energy consumption and carbon emissions from 2007 to 2030. They have suggested that although regulation and technological improvements will play an important role in mitigating GHG emissions in Beijing, these factors would not be sufficient to cause larger reductions. Larger reductions would require a transformation of the city's economic and social development pattern, including clean energy policies to accelerate change in its energy structure.

Also through scenario analysis, Guan and Barker [28] have used CO_2 emissions as an environmental indicator to investigate Guangyuan's future carbon performance and an alternative low-carbon development path. Technological improvements and production structure changes, which are interdependent, have been identified as the key determining factors likely to affect both carbon intensity and CO_2 emissions in the future. The paper concludes that governmental policies should include appropriate guidelines to address both factors, but with strong emphasis on the decarbonization of the production structure to avoid the mistake of ‘pollute first and address the pollution later’, which occurs during the emission-intensive industrialization processes that many Western countries and China's coastal regions have followed.

It is not easy to conceive of viable ways for China' cities to achieve cleaner and ecologically sustainable economic growth. Therefore, low-carbon city development is often combined with the goal of developing knowledge cities. Because green/clean technologies are often believed to boost both the environment and economic development, importing

[6] Ecological civilization is a concept proposed by Hu Jintao in his report to the concluded 17th National Congress of the Communist Party of China (in 2007). The concept recognizes the importance of harmonious development among humans, nature, and society, rather than solely focusing on economic growth as the core of development. Although it is unclear to what extent this concept guides policy processes, it signals a discursive shift in the official party line.

knowledge, expertise, science, and technology from foreign countries is considered to be a key component of developing low-carbon cities. Some researchers have suggested that it is useful, in terms of the low-carbon development of China's cities, to learn from and collaborate with successful low-carbon cities in developed countries. Aiming to identify conditions for robust Sino-foreign partnerships in eco-cities, de Jong et al. [12] have examined how Sino-foreign initiatives are organized (including their strengths and weaknesses) and have constructed a typology of Sino-foreign initiatives that have focused on ecological knowledge related to cities. They have identified conditions for robust Sino-foreign partnerships in low-carbon cities. They found three types of collaboration between China and foreign partners. The first one is the least intense. It resembles a client-provider/designer relationship and offers very limited project success. The second type offers a more structured basis for interaction through an intergovernmental agreement-based collaboration. The third type goes much further and includes a large-scale joint venture in which both sides monitor the progress and quality of the project. Jakutyte-Walangitang and Page [36] have described a low-carbon city action plan for China's low-carbon pilot cities. It is a Sino-Austrian cooperation that has been initiated between the Development and Reform Commission of Nanchang, one of the eight selected Low-Carbon Pilot Cities, and the Austrian Institute of Technology to develop a comprehensive set of Low-Carbon City Measures and a Low-Carbon City Action Plan, proposing specific technological and non-technological measures and concrete actions. The plan is capable of introducing important changes targeting improved energy efficiency and the reduction of CO_2 emissions in Nanchang. A team of experts has developed an integrated Low-Carbon City Action Plan, including sectors such as buildings, energy supply and consumption, industries, transportation, agriculture, and urban planning. Dienst et al. [15] have presented some outcomes of the Sino-German Low-Carbon Future Cities (LCFC) project, including analysis of the status quo and an assessment of the likely future development of Wuxi City.

These studies have demonstrated that, similar to cities throughout the world, China's cities face a dilemma between economic growth and decarbonization. Researchers are therefore looking for new ways to coordinate industry and eco-efficiency so that the low-carbon city strategy can be realized. Currently, some researchers believe that industrial symbiosis (IS) provides a way to achieve system-level innovation useful in pursuing sustainable urban development. IS is a system-level innovation designed to share service, utility, and by-product resources among diverse industrial processes or actors to add value, reduce costs and improve the environment [125,144]. IS can change the traditional linear structure of resource utilization by closing loops (in terms of material/waste recycling, heat exchange, etc.); thus, the environmental efficiency of the entire system or network is enhanced. According to the philosophy of IS, the linkage between industries and urban communities may enhance the eco-efficiency of both [16]. Dong et al. are the main advocates of this idea. They have used Liuzhou and Jinan as case studies to calculate the CO_2 emissions reduction potential under IS projects [16,17]. Moreover, by using scenario analysis, Wang et al. [98] have accounted for the industrial park of Suzhou City and analyzed future trends.

Broadly speaking, after the questions of the status of cities' emissions and what factors cause them, many researchers have begun to discuss which path can lead China's cities to achieve a low-carbon mode. Policies need to be implemented in practice, and much research can still be done on implementation processes. We clearly identify a lack of studies addressing feasible ways of switching to a new path, given the challenges of governance and the messy reality of most city development processes in the real world. Summarizing the literature, there is a visible need for all-encompassing systemic change, which cannot easily be generated through incremental policy measures, regulation, and technological improvements. The goal of a low-carbon city implies system-level innovation, as suggested by some studies on Sino-foreign partnership projects in this area. Among the required systemic changes, the energy policies and production technology improvements offer many ways for practical improvements. Finally, the city layout plays an important role in the entire establishment process of low-carbon cities. Although it is impossible to change the layout of an existing city in the short term, some changes of urban forms and functional areas can help to ease the urban pressure and lead to a lower carbon city. For example, Beijing has begun to explore the idea of polycentric city development by building Tongzhou District as a sub-civic center. This measure shifts some administrative and financial activities away from the central zones and reduces the stress of housing, traffic, and energy supply, making Beijing closer to a low-carbon city [69].

3. Current research on low-carbon technologies and industries in China

Technological innovations for industry processes and structural changes in energy- and carbon-intensive industries are additional research topics in the context of low-carbon development in China that have attracted much attention in recent years.

Low-carbon development of industries is an important concept within programs for developing low-carbon cities (see above); however, it deserves special treatment as an issue of importance for the national economy as a whole. One line of reasoning emphasizes that industrial production is the core of Chinese economic development and that it contributes the most to China's emissions. Many energy-saving and carbon reduction policies are targeted at industrial production and certain energy intensive industrial sectors. For example, in 2013, China's *Ministry of Industry and Information Technology* published a report that compared the CO_2 emissions of the iron and steel industrial sector, nonferrous metal industrial sector, petrochemical industrial sector, chemical industrial sector, machinery industrial sector, and textile industrial sector with those in 2010. The report indicated that CO_2 emissions per unit of industrial added value should be reduced by approximately 17–22% by the end of 2015. Improving energy efficiency is critical to the low-carbon development of industrial production. China is also on its way to building carbon emissions trading systems (ETS). In seven ETS pilots, the targets have mainly focused on the important energy-intensive industrial sectors. As a developing country, China is facing the dual pressures of economic output and carbon reduction. Balancing this relationship is critical to China's industrial low-carbon transition. We will examine both issues, industry development and technological innovations, independently and then draw conclusions.

3.1. Low-carbon development of Chinese industries

China's industries are extremely energy intensive and are primarily responsible for the country's GHG emissions. The phrase “made in China” is familiar to the residents of the United States and Europe. China is the largest exporter in the world. Exported goods include new electronics, clothing, fashion accessories, and even medical equipment. One reason for the rapid growth of China's CO_2 emissions in recent decades is Western consumption patterns. Liu et al. [66] have analyzed changes in the GHG emissions of 36 industries in China during the 1998–2005 period. They have also explored the main factors of industrial GHG emissions. The changes in industrial CO_2 emissions have been described by carbon emissions coefficients of heat and electricity, energy intensity, industrial structural shift, industrial activity, and final fuel shift. The authors have found that industrial activity and energy intensity contributed the most to the industrial sectors' GHG emissions during the study period. Raw chemical or chemical material products, nonmetal mineral products, and smelting or pressing of ferrous metals should be among the top priorities for enhancing energy efficiency because they are the most energy intensive among

China's 36 industries. The factors contributing to industrial CO_2 emissions have been studied by many researchers. In summarizing the relevant research, we find similar results: not only for the entire industrial sector but also for some separate sub-sectors, industrial output is the main factor causing CO_2 emissions to increase. In addition to the study by Liu et al. mentioned above, research by Li et al. [52], Ouyang and Lin [83], and Shao et al. [85] has also suggested that the level of industrial activity is the largest contributor to the CO_2 emissions of the industrial sector and that the energy intensity effect is the most important factor in emissions reduction. Studies by Fan et al. [19], Lin et al. [58], and [100,107] have explored the determinants of increased CO_2 emissions in the petrochemical industry, food industry, and iron and steel industries, respectively. For these industries, the level of industrial activity, that is, economic output, is the major determinant of CO_2 emissions.

According to these results, we can deduce that there has not been an obvious decoupling of industrial output and GHG emissions because industrial output is by far the most important factor. This is further supported by Li et al. [52], who have tested the decoupling relationship between CO_2 emissions and economic growth in China, suggesting that there is only a weak decoupling between the two. Zhang and Da's [126] research also proves the weak decoupling relationship from 1996 to 2010, indicating that the economy grew with increased carbon emissions. Similarly, the results of Zhao et al. [131] show that the industrial emissions from 1993 to 2013 experienced weak decoupling with economic growth.

Thus, reduction policies in China are all based on carbon intensity instead of total emission amounts. Liu B et al. (2015) have analyzed the factors influencing carbon intensity in industrial production and indicate that the energy intensity effect is most important compared with the emission coefficient effect and the structural effect. This result suggests that low-carbon industrial development will still depend on energy efficiency improvements; as studies have shown, energy intensity is the main factor contributing to emission reductions. Lin and Long [59] have made an interesting innovation, finding that the output per worker (OW) is an important factor that causes the increase of GHG emissions. The OW is formulated as industrial outputs for every worker. With the development of advanced technologies, labor has been gradually replaced by equipment and capital. The larger output per worker means more energy consumed by more equipment, leading to more GHG emissions [59].

So far, we have summarized findings about industry in general. What can we see if we differentiate between different industry sectors?

The *iron and steel industry* is one of the major industrial sectors contributing to energy consumption and CO_2 emissions in China. The GHG emissions of this industry mainly come from coal combustion, and thus, the increase in energy demand has exerted great pressure on the availability of energy resources and the goal of GHG emissions reductions. Sun et al. [92] have described the total CO_2 emissions change from 1980 to 2008 using four factors: emission coefficient, energy structure, energy consumption, and steel production output. The results show that production output is the major factor responsible for the increase in CO_2 emissions. In addition, shorter time series (1995–2007) have been used to analyze the influencing factors of energy-related CO_2 emissions in the iron and steel industries [93]. Lin and Wang [60] have conducted an intensive analysis of CO_2 emissions efficiency and carbon mitigation potential, suggesting that the iron and steel industry should put more effort into adopting energy-saving techniques and enhancing cooperation. However, from a long-term perspective, the fundamental solution to low-carbon development lies in energy substitution. Regarding the low-carbon development of the iron and steel industry, much work has been conducted from the macro perspective. Zhang et al., however, have conducted an empirical analysis of 85 questionnaires regarding various companies in the iron and steel industry to explore the determinants (regulatory pressures, pressures from the supply chain, environmental practices of competitors, financial cost, etc.) that drive or hinder the implementation of low-carbon practices [124]. The results suggest that regulatory policies promote the development of CO_2 reduction strategies at the management level but have no significant influence on energy-saving practices and CO_2 reduction in the actual production processes. Because most regulations imply only voluntary commitments to reducing carbon emissions, they fail to have significant effects on detailed practices. However, regulations do direct companies to start analyzing their CO_2 emission problems. Pressure from the supply chain may also produce positive effects on CO_2 reduction practices, whereas the lack of financing for implementing CO_2 reduction strategies through technological changes is a strong barrier.

Another important industry is the *building industry*. In China, the building industry has become an increasingly important energy-demand sector, accounting for more than 20% of final energy consumption [49]. The design and construction of urban infrastructure with a long lifespan - of buildings in particular - has the potential to shape energy perspectives for the coming decades. Therefore, reducing the GHG emissions of the building industry is very important not only for the development of a low-carbon economy but also for the construction of low-carbon cities. Li has conducted a review of the literature regarding the forecasting of GHG emissions to investigate the energy-saving and GHG emission mitigation potential offered by the implementation of energy efficiency policies in the building sector [48]. Later, Li and Colombier assessed the role of energy efficiency in buildings for addressing climate change mitigation [49]. These two works provide a comprehensive overview of the characteristics, energy consumption status and development trends of this industry. They also outline economic and institutional barriers to large-scale deployment of sustainable, low-carbon, and carbon-free construction techniques, including high information costs, the persistence of carbon-intensive building techniques, the lack of appropriate incentives for landlords, and limited access to financing and energy subsidies. Furthermore, they cite as institutional barriers the fragmentation of the building industry and of the design process into many professions, trades, work stages, and industries. Although China issued a comprehensive multi-sectoral energy conservation plan over the 2006–2010 period, the authors note the resistance of actors in the building sector to this plan and its low enforcement and implementation rate in many medium and small cities because of inadequate technical and institutional capacities. In their opinion, cost effectiveness and policy relevance should be considered as the primary criteria in assessing mitigation programs in the building sector [49]. Zhang and Zhou [128] have analyzed the relationship among emission reduction regulations of governments, emission reduction awareness of companies, and their practical behaviors. The findings reveal that the related regulations, including direct regulations and economic carbon instruments, can increase companies' real improvement in emission reduction awareness and behaviors, indicating that for policy makers, adopting carbon reduction regulations is an effective way to encourage companies to consider more advanced carbon management [128]. Chen et al. [6] have presented a low-carbon building evaluation framework that can be used to monitor the effects of such regulations. They have accounted for the GHG emissions of buildings by dividing the life cycle of buildings into nine stages: building construction, fitment, outdoor facility construction, transportation, operation, waste treatment, property management, demolition, and disposal. It is argued that some economic and policy instruments can be used to foster the transition of this life cycle to low-carbon development. These instruments could include energy labeling and certification, establishing internal carbon markets, and encouraging energy pricing reforms.

Wang et al. [103] and Hu et al. [32] have analyzed low-carbon production in the Chinese *cement industry* at the macro and micro levels. Wang Y et al. have presented a GHG emission inventory of the cement industry in China and identified the main driving factors influencing GHG emission changes in the cement industry. Hu and colleagues selected two cement companies with different production processes to investigate material/energy use as well as emissions. The shaft kiln and the NSP (New Suspension Preheater) kiln are the two most common production processes in China. The two plants investigated in this paper have either a shaft kiln production line or an NSP kiln line. The study results show that the efficiency of energy consumption (including electric power consumption and overall energy consumption) is lower for the shaft kiln than for the NSP kiln. As for environmental emissions, the shaft kiln emits more SO_2, $CO2_2$, NO_x, and dust per unit of product than the NSP kiln and has higher eco-environmental impacts. Shen et al. [86] have also quantified the CO_2 emissions of China's cement industry based on the Life Cycle Assessment method.

Others have looked at energy efficiency in various Chinese industries comparatively. Xia et al. have conducted an integrative assessment of the energy efficiency of 38 industries in China [111] and found that the industries with the lowest energy efficiency are smelting and pressing of ferrous metals, manufacture of raw chemical materials and chemical products, and manufacture of non-metallic mineral products. In 2012, Wu et al. constructed both static and dynamic energy efficiency performance indexes for measuring industrial energy efficiency performance with CO_2 emissions [109]. Their study shows that the most important potential for energy efficiency improvements in China's industrial sector mainly comes from technological improvements.

In summary, industrial production is a major GHG emitter in China. Of all industries, the steel and iron industry is among the most important for its high energy intensity. The main drivers of industrial GHG emissions are industrial output and energy intensity. There are effective ways for industries to enhance their energy efficiency from a short-term perspective, including adopting energy-saving techniques and importing advanced technologies from developed countries. Consequently, their energy intensity can be reduced, but so far, no real decoupling between output growth and carbon emissions has been achieved. Therefore, carbon reduction policies based on total emission amounts will still be in conflict with the growth targets of the industries: as long as industrial output is the most important factor, output cannot be increased without also increasing carbon emissions. Therefore, the most important option lies in eliminating inefficient production technology and improving energy efficiency by widely applying energy-efficient technologies in the secondary industry, while from a long-term perspective, a shift in the energy mix is an even more important step toward low-carbon development. Achieving real low-carbon development will be difficult unless China ends the highly coal-dependent development mode of its industries.

3.2. Development of low-carbon technologies in China

It is generally acknowledged that the Chinese economy is coal dependent. Coal, the most abundant energy resource, is expected to dominate China's energy scheme for a very long time [8]. Thus, the development of clean coal technologies is crucial to China meeting its low-carbon targets. In 2005, Glomsrød and Wei [25] analyzed the question of whether using clean coal technologies is a viable strategy for reducing carbon emissions and improving China's environmental quality. Using a computable general equilibrium (CGE) of the Chinese economy, this work assesses the multiple benefits and costs of coal cleaning. Currently, the clean coal technologies being developed in China mainly include high efficiency combustion and advanced power generation technologies, carbon capture and storage (CCS) technologies, and integrated gasification combined cycle (IGCC) technologies. However, the development of low-carbon technologies in China is still at the initial stage. Chen and Xu have described the role of coal in the Chinese energy system and the recent achievements of Chinese clean coal technologies [8]. CCS may have been seen as a solution for resolving environmental dilemmas, addressing energy security issues, and meeting low-carbon development targets. To date, CCS – including demonstration sites – has been a focus of research, but it has not been commercialized, and it is unlikely, given current trends, that this technology will find large-scale application either in China or elsewhere before 2030 [129]. Liu and Gallagher [64] have explored opportunities in Chinese CCS technology and have identified critical CCS-enabling technologies. Based on their results, they have proposed a roadmap for China that includes four steps [64], suggesting that in each step, major government support would be needed to implement a CCS strategy and achieve widespread commercialization of this technology.

Other studies have focused on low-carbon technologies in individual industries. For example, focusing on the coal chemical industry, Xie et al. have considered certain key technologies, including direct and indirect coal liquefaction, large-scale and high-efficiency coal gasification technology, the exploitation of coal poly-generation systems, and large-scale production of methanol and dimethyl ether (DME) technology using coal and COG [113]. Fischer [21] has analyzed the barriers to and challenges of low-carbon technology diffusion in China's photovoltaic industry. When developing low-carbon technologies, the role of companies and their R & D activities are also important. Liu and Gao [73] also discuss the issue of low-carbon technology diffusion but focus on the iron and steel industry. Using data from 60 sample companies in the iron and steel industry, the study argues that a moderate carbon price may generate a relatively more significant impact on the diffusion of low-carbon technologies compared to non-price related policies. A carbon price may drive companies to improve their carbon management, leading to a wider use of low-carbon technologies [73].

Zhou et al. [139] have discussed the role of joint R & D in enhancing companies' innovation capacity. The findings indicate that joint R & D has improved Chinese companies' technological capacities, human resources, and financial growth potential. Lin and Yang [61] have studied the role of investment in achieving efficiency gains in China's power industry. The results show that there exists a relatively vast space in which to promote the efficiency of the power industry. Furthermore, the investment structure reform of the power industry has the potential to provide significant impetus to improve efficiency. The authors conclude that foreign capital should be positively introduced while the proportion of state-owned assets is lowered to break the state's monopoly. To summarize, many technological options currently under discussion center around providing cleaner coal, as coal is expected to stay dominant in the Chinese energy structure for some time. While several technologies are available, the research reveals a low level investment in these technologies and a lack of incentives through carbon pricing as major challenges.

4. Current research on the transition of China's energy system

Cities and the industrial production sector are two major sites where low-carbon developments can be fostered. However, a look at China's total energy demand and at the structure of the entire energy system can provide more comprehensive insights. Which changes in the Chinese energy demand are expected in the coming decades, how much does the structure of the current energy system contribute to carbon emissions, and what are the prospects of switching to a low-carbon energy system in China?

Many studies concerning the forecasting of energy consumption and GHG emissions in China from both short-term (until 2020) and mid- to long-term (2030, 2050) perspectives exist. Scenario analysis is a popular method for forecasting and typically includes low-carbon electricity scenarios, implementation of low-carbon policies, and technological development. At the mid- and long-term levels, Chai and Zhang [5] and Zhou et al. [135] have forecasted primary energy consumption trends for 2020, 2030, and 2050 and have made comparisons among them. Similar research included the predictions of energy consumption until 2030 [33] and of energy consumption,

CO_2 emissions, and carbon intensity until 2050 [138,7]. The outcome of these scenarios is that in the long term, the economic structure will have been well adjusted, with much improved efficiency, leading to a decrease in the growth rate of carbon emissions. After 2030, along with a population stabilization scenario and an optimization of the industrial and energy structures, the amount of GHG emissions will start to decrease in absolute terms. Moreover, if more low-carbon technologies such as CCS can be applied, the peak time may occur earlier.

The scenarios differ in their assumptions about how much and how fast low-carbon changes can be achieved in the short term. On the one hand, some projections are based on scenario analysis in which both energy structure and economic structure will be readjusted toward a sharp decline in carbon intensity. However, the results show that even if the CO_2 intensity of GDP can be reduced by 50%, total CO_2 emissions in 2020 would still be the same as in 2005 [112,29]. The energy demand has also been forecasted by taking energy/economic structure improvement as variables [38], which shows that China's energy demand will maintain high growth until 2020, and the higher the economy grows, the larger the energy demand becomes. On the other hand, some researchers argue that in the short term, it is difficult to change China's energy-intensive economic structure. Moreover, the capacity for improving energy efficiency is limited [136,47]. Such studies suggest that encouraging the use of non-fossil energy or low-carbon energy, especially the use of hydro-, wind, and nuclear power, is necessary for the Chinese government to achieve the emission reduction targets. Liu et al. [68] indicate that the mitigation potentials of renewable energy are much larger than those of energy efficiency and CCS. A strategy toward non-fossil-based energy sources could also have the much-wanted side effect of increased energy security, as it would ease the pressure to import oil to China [43,79]. We will now look in more depth at the two specific issues of changes in the energy demand (4.1) and the switch of the Chinese energy system toward non-fossil energy sources (4.2).

4.1. Changes in the energy demand

Some authors have analyzed the structure and development of Chinese energy demand at a systemic level and how these relate to carbon emissions. He et al. [29] have identified the main features of GHG emissions from fossil energy combustion in China as a whole, showing large annual CO_2 emissions with rapid increases, low levels of per capita CO_2 emissions, high energy intensity, and a large CO_2 emissions factor due to China's coal-dominated energy structure. In a recent study, Lin and Ouyang [63] have not only analyzed the characteristics of energy demand in China but also compared these characteristics with the situation in the United States. They have shown that economic growth, urbanization, and industrialization are the leading forces contributing to the increase in energy demand, whereas improved energy intensity, advances in technology and increased energy prices contribute to a decline in energy consumption. The energy consumption of both the United States and China increased significantly during their urbanization stages. For energy consumption per capita, there are similarities and differences between the two countries. The common feature is that the energy consumption per capita of each country showed an upward trend in the rapid urbanization stage, with the difference that the energy demand per capita of China was far below that of the United States. Finally, for the energy consumption structure, coal was dominant in the energy structure during urbanization in both countries. However, coal has gradually been replaced by petroleum and natural gas in the United States, whereas China's coal-dominant energy structure has not yet shown any signs of shrinking. China's high energy consumption and GHG emissions are comprehensive results of its rapid urbanization and industrial output growth. For many years, the stable long-term correlations between population growth, economic growth, the urbanization process, and energy consumption remained unbroken [119,38,75], but the system is now under stress for various reasons, including fast-growing demand and structural change, growing environmental awareness and policies, and the rising costs of generation, transition, and distribution [40].

Following this observation, one important question would be at which level of decision-making, and how, the energy demand can be managed effectively: at the level of the central government and planning, at the provincial or lower levels, at the household levels, or within individual companies. Kahrl et al. [40] have argued that in the Chinese electricity system, the processes of planning, project approval and rate setting (i.e., determining the price of electricity) are still performed by the central government. The authors discuss two different ways to approach these problems: a top-down and a bottom-up approach. The top-down process would establish a legal framework for electricity sector jurisdiction and decision-making. In this case, electricity-generating companies would passively react to the legal framework. In contrast, the bottom-up process would rely on active management decisions at the company level. This would require the build-up of planning capacities and the development of analytical tools that could support a more cost-reflective electricity system and improve regional management. The authors emphasize the importance of management decisions at the company level and thus argue for strengthening the bottom-up approach, which would help to maximize benefits and minimize costs, both systematically and transparently. In their study on an optimal CO_2 mitigation strategy, Liu et al. [76] have also taken into consideration certain management issues in energy systems, e.g., how to cope with uncertainties and complexities related to carbon emissions. Under the assumption of stochastic power generation demand under specific GHG emission reduction targets, uncertainties will stem from the levels of power demand influenced by weather changes, population growth, and economic growth. According to the authors, current thinking about allocation strategies for CO_2 emission permits does not reflect these fluctuations and tendencies. Decision alternatives, including expanding generator capacity, switching to a more energy-efficient facility, coal selection, and coal blending, could be identified as desired strategies under environmental constraints. Li et al. [45] have studied energy system management to address interactions among energy supply, processing and demand activities, and associated GHG emissions, in particular the interactions with changes in the energy demand at the household level.

The household level has become a hot topic in recent years and includes both direct energy consumption and GHG emissions [26,27] and indirect types of material consumption and emissions [105,118,141,143]. In a more systematic reflection, the household sector can be divided into urban households [116,133,27] and rural households [118,57,70]. The indirect carbon emissions from "indirect energy requirements" are defined as the carbon emissions from the production of goods that are ultimately consumed by households. The indirect energy demand is usually not obvious, as it has a complicated relationship with the process of producing goods. The results from most studies have indicated that the material consumption level, emission intensity of consumed products, urbanization level, industrial structure (as discussed above), population, and consumption structure (the proportion of low-carbon products to the total consumed products) are the main factors influencing the energy consumption and GHG emissions of the household sector [104,105,10,67]. Among these factors, the material consumption level, which is usually measured by household consumption per capita, plays a dominant role in energy consumption and GHG emissions growth, whereas declining carbon intensity of the consumed products may mitigate such growth [105,118,67]. According to the forecast of Dai et al. [10], as incomes increase in the coming decades, energy consumption and GHG emissions in China's household sector will continue to rise dramatically. Therefore, changing patterns of material consumption to less carbon-intensive products and to service-oriented goods may be a strategy for saving energy and reducing emissions at the household level [10,67].

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To summarize, many studies note the complex causal linkages between different levels of the production and consumption of goods and services in the development of the total energy demand, and most studies do not expect the energy demand to decrease any time soon.

4.2. Switching to non-fossil energy sources

Switching from an economy based on fossil fuels to an economy (at least partially) based on renewable and low-carbon (cleaner) energy sources has been identified as the key to a low-carbon energy transition [79]. So far, China is heavily dependent on high-carbon fossil fuels. The long-standing dominance of coal in the energy mix has caused severe air pollution, water pollution, and loss of land resources and has thus been a major threat to China's environmental sustainability [5]. Researching issues of GHG emissions reduction and low-carbon transitions within energy systems, especially the Chinese electricity system, is critical. From the perspective of domestic low-carbon development, the Chinese electricity system has characteristics of high energy consumption, high carbon emissions, and high pollution. The low-carbon transition and clean production of power may play an important role in China's sustainable development. However, being predominantly coal based, the Chinese electricity system is also the world's single largest source of CO_2 emissions [35]. Coal-fired power accounts for approximately 80% of total electricity generation, and emissions from coal-fired power plants account for approximately 40% of total emissions in China [114,134]. Therefore, from a global perspective, the transition to a low-carbon electricity system in China is critical to global efforts to combat climate change [40].

The Chinese government has designed a series of fundamental strategies for energy development that promote a partial replacement of fossil fuels but remain far from a substantial switch in the foreseeable future. These strategies include low-carbon or clean energy development, favoring energy conservation over further expansion, exploiting hydropower in accordance with local conditions, and developing nuclear and renewable energy [37]. For China, a country with abundant renewable energy resources, development of these resources may not only ensure energy security, improve the energy structure, and reduce negative effects on the environment but also alleviate rural energy poverty. Energy poverty in China, characterized by fuel poverty and power shortages, occurs at the household level and is worse in rural households. Over 75% of rural households use solid fuel such as wood or weed, whereas these figures are much lower in urban areas and townships, i.e., 8% and 36%, respectively [94]. The large amount of solid fuel usage in rural areas is closely tied to low household incomes [101], thus explaining why it is considered to be more important to develop non-fossil energy in China compared with some developed countries.

Some studies have summarized the current situation of renewable energy development in China. They have detailed the characteristics of China's energy structure and analyzed current issues in energy systems. For example, Shi [87] has provided an overview of the policy measures implemented over the past decade to support renewable energy development and has analyzed the current characteristics and conditions of renewable energy development. The implementation results of development goals and policy measures are also considered. Jiang et al. [37] have analyzed the pressure and challenge of energy development, focusing on the status of Chinese hydro-, wind, and nuclear power.

The potential contribution of renewable energies to achieving the goal of GHG emissions reduction has also been studied. Zhou et al. [136] have explored the development of non-fossil energy in China until 2020 and examined the role of renewable energy in achieving mitigation targets. Aiming to provide a scientific basis on which governments can set countermeasures against climate change and establish low-carbon energy development strategies, Hu et al. [33] have concentrated on the potential and contribution of low-carbon energy for achieving China's carbon intensity reduction goals. Ren and Sovacool [84] have assessed the effect of renewable energies by determining the relative performance of hydropower, wind energy, solar energy, biomass energy, and nuclear power with respect to the energy security dimensions of availability, affordability, accessibility, and acceptability. They conclude that hydropower and wind power are the most promising low-carbon energy sources for enhancing China's energy security, whereas nuclear power and solar energy have the least potential. Liu et al. [68] have looked at the actual development status of renewable energy. Moreover, an analysis of CO_2 mitigation costs, mitigation potential, and the fossil energy conservation capacity of renewable energy has been conducted, resulting in a high mitigation potential of renewable energy. According to the authors, among the renewable energy resources, hydropower and wind should be prioritized because of their relatively more mature technologies and lower prices. Electricity from renewable energy will save a substantial amount of traditional fossil fuels, and its cost tends to decrease gradually. Lin et al. [62] have investigated the factors influencing the share of renewable electricity in the energy consumption structure. The results indicate that economic development and financial development have positive impacts, while foreign direct investment has negative impacts. This would suggest a more strategic approach to foreign direct towards the development of renewable electricity [62].

Some research has focused on individual renewable energy sources in China. For example, Huang and Yan [34] have examined the development status of *hydropower* in China, as well as factors restricting hydropower development. For *wind power*, Liu and Kokko [77] have discussed the recent development of the wind power industry, focusing on pricing policies, transmission capacity and the structure of the equipment manufacturing industry. They have also considered policies and challenges related to the wind power business environment.

The development of *nuclear power* may be more complicated. Because of rapid growth in electricity demand, and adjustment of its power structure, China has accelerated construction of nuclear power plants. Considering the increasing cost of oil and natural gas, and the enormous environmental pressure resulting from coal consumption, nuclear energy is considered to be an inevitable strategic option for China [137]. Nuclear energy is regarded as a sustainable option in the Chinese context because it can replace fossil energy on a large scale. Studies have suggested the possibility of technological improvements for nuclear safety and for substantial cost reductions. The unsolved problem of long-term nuclear waste treatment and storage is sometimes also discussed [137] but does not play a prominent role in current policy developments. China's government has announced its intention to speed up nuclear energy development. The Medium- and Long-term Nuclear Power Development Plan was first released in 2007. Thereafter, the successive plans associated with the nuclear power development were made. China's nuclear generation capacity is planned to increase to 40 GW by 2020, with a further 18 GW under construction, which means that nuclear power construction has entered a stage of accelerated development [80]. After the Fukushima accident in 2011, the Chinese government has increased its attention to nuclear safety. The related laws and policies are applied to each stage of nuclear power development, including site selection, construction, commissioning, operation and decommissioning [122,80]. The accident also had negative impacts on the public acceptance of nuclear energy. Zhu et al. [140] tested the public acceptance change by using the data of land price near nuclear power plants in China. The results show that the land prices have dropped within areas 40 km outside nuclear power plants, especially, the price dropped by an average of 18% in the first month after the Fukushima accident. This reflects the people's repulsion of living near nuclear power plants, indicating a decrease of public acceptance.

After decades of effort, China has managed to establish a comprehensive energy industry system. Moreover, efforts have been made to enhance energy efficiency, improve industry as well as energy structure, and promote a low-carbon energy transition. However, there are still several issues remaining to be solved. China's current total energy efficiency is still 10% lower than that of developed countries [37]. This is mainly because of China's lack of effective energy management. Consequently, the percentage of energy consumption in China from low-efficiency equipment is almost three times greater than the average level in developed countries. The development and application of renewable energy requires not only political and institutional support, but economic and market incentives. Early research pointed out that both private and state-owned renewable energy production companies are overly reliant on support from the government. Although many strategies have been designed to promote the development of renewable energy, what is lacking are policies that consider the market mechanism and provide financing [87]. Until now, these problems are still being lively discussed. Authors identify a lack of legal framework in support of renewable energy [123], defining the rights, responsibilities and obligations for each actor in the renewable energy industry, in order to avoid “passing the back” phenomenon caused by confused or overlapped responsibility. Technology standards are another element which needs to be developed to support renewable energy development [121]. Moreover, many authors raise the issue of commercialization mechanisms. At the current stage, the development of the renewable energy industry in China depends heavily on government support, subsidies, and funds from Clean Development Mechanism (CDM) projects. Once these financial supports are withdrawn, the renewable energy industry is expected to shrink again. Authors thus suggest the gradual replacement of government programs by the market mechanism [110,132,46].

5. Research regarding low-carbon development in Chinese journals

This paper is based mostly on research published in mainstream English-language journals. However, there is also a debate on low-carbon strategies in Chinese journals, which is difficult for Western observers to follow. Before we come to the concluding chapter, we therefore offer a brief summary of our findings of the literature in Chinese journals. A review of this research has shown that very similar topics have been discussed and that there are no systematic differences between these bodies of literature. However, a few points are emphasized in Chinese journals that rarely appear in English journals. Taking low-carbon cities as an example, there is less dominance of mathematical modeling and analysis in Chinese journals compared to English journals. First, Chinese articles treat in more detail the concept of low-carbon cities (definitions, main features, and significance) [115,11,23,51,55,56,89]. According to this literature, low-carbon cities can be defined by five features. The first is economic, meaning that minimum input should be used to produce maximum output. Second, low-carbon cities should be secure, including economic security, ecological security, and social security. Next is systematic construction, meaning that the establishment of low-carbon cities should be a systematic and comprehensive project. Moreover, building low-carbon cities should be a dynamic and continuous process. Finally, low-carbon cities should have regional characteristics, meaning that the construction plan should take local features into consideration.

Another specific feature is the more detailed assessment of the practice of developing low-carbon cities, including comparing China's low-carbon cities with foreign cities. In a study by Liu and Wang, China's development model is compared with those of London, Tokyo, Copenhagen, and others. China's cities have not established a clear method of low-carbon development. In contrast, mature low-carbon cities have sufficient experience building low-carbon industries, which in turn support the development of the entire city in a low-carbon way. On the basis of the practice of Masdar (United Arab Emirates) and Malmö (Sweden), some Chinese cities, such as Shanghai, Chongqing, and Beijing, are trying to build low-carbon pilot zones to explore effective ways of building low-carbon cities [72]. Some researchers have tried to establish an evaluation indicator system to assess low-carbon cities in China [141,143,30,31].

Many parties are involved in low-carbon city construction, including governments, enterprises, research centers or universities, and citizens, but this is seldom discussed in English journals. In contrast, some studies in Chinese journals provide a normative suggestion of the respective roles of these different parties [55,56]. The most important task of governments is thus to establish a scientific plan for the city's development. They are also responsible for the diffusion of the low-carbon concept and the promotion of low-carbon awareness. At the same time, governments must build an assessment index system and incentive mechanisms. Enterprises should encourage low-carbon production to provide low-carbon products to the market. The role of research centers is to focus on low-carbon technologies so that they can provide technological support for the development of low-carbon cities. Citizens should develop awareness of low-carbon consumption and lead low-carbon lifestyles [11,120].

Specific issues that arise during the development of low-carbon cities have also been identified in Chinese publications [115,72,89]. The development of a low-carbon city should not occur at the expense of the city's other development goals. This means that the low-carbon target is not the only indicator that should be evaluated. The establishment of low-carbon cities cannot be treated as simply an investment in power generation or other infrastructure. It is always a long-term project. Low-carbon establishments should be designed that take local features into consideration. Problems with the current construction of low-carbon cities are also analyzed by studies in Chinese journals. For example, the goals of governments in building low-carbon cities are not sufficiently clear. Some projects are carried out only to demonstrate the achievements of local officials. Furthermore, practices and studies mainly focus on large cities, whereas medium-sized or small cities are seldom mentioned [53]. Finally, actual housing demand is often overestimated, resulting in an unreasonable investment scale.

Some analyses of Chinese publications also refer to low-carbon technologies and industries. The government's role in the development of low-carbon technologies and industries is discussed extensively. Li has suggested that governments have the responsibility to support low-carbon developments. First, governments should design laws and regulations to provide legal insurance for the development of low-carbon industries. Second, governments are thought to have the responsibility to raise the environmental awareness of the public to promote the successful implementation of low-carbon practices. Third, governments should set comprehensive and scientific environmental targets to measure and assess emission reduction achievements. Fourth, governments should encourage enterprises to focus on innovative low-carbon technologies. Fifth, governments should aim to improve industrial structures and energy structures. Sixth, governments should guide cooperation with developed countries [51].

To summarize, even though there are broad similarities between the publications in Chinese and in English, there seems to be more debate in Chinese journals about the role of different parties in the various implementation processes, in particular the role of the government.

6. Identifying fields of action and research gaps

China has taken important steps toward reducing future carbon emissions, and a lively academic debate regarding how the country can achieve low-carbon development exists. In this paper, we summarize the most important findings and identify research gaps in the current literature on low-carbon development in China. The final chapter will first present some overall comments and then summarize findings and research gaps for the three topics of low-carbon cities, low-carbon technologies and industries, and the transition of China's energy system individually.

Overall, the most important finding repeated in all chapters with some variation is that, so far, no effective decoupling between industrial output and carbon emissions has been achieved. Despite all gains in energy and carbon efficiency and despite the massive expansion of renewable energies, economic growth so far still unavoidably means rising GHG emissions. Therefore, for China, carbon reduction policies are more likely to be based on carbon intensity instead of total emission amounts. This is in line with the Chinese official climate policy goal to achieve a peak in its absolute carbon emissions only in 2030.

Some of the debates about the most promising ways to achieve low-carbon development address the role of the state and the effects of pricing and market mechanisms. Several studies have emphasized that the diffusion of low-carbon technologies or a further increase of renewable energies would depend on cost-avoiding behavior on the side of emitters and on new investments independent of the state. Typically, authors suggest market mechanisms and a (moderate) prize for carbon emissions. This resonates with the current trends in economic thinking about mitigation policies. However, the question of how market mechanisms work in the context of the current Chinese economic system, still heavily influenced by state funding and central planning, deserves more attention.

Our overview reveals the need for deep structural change if low-carbon development is the short- and long-term goal. We find evidence in the literature that a shift in the industry structure and a switch of the energy system away from fossil fuels would be the most important routes to low-carbon development. Against this backdrop, both mainstream Anglophone journals and Chinese journals pay most attention to cities and their role in low-carbon development. Cities bring together many structural aspects for research on low-carbon development, as their industry and energy structures and, in general, the city layout and its major infrastructures greatly influence their carbon emissions and the ways cities can decarbonize. Judging from our literature overview, we conclude that cities have great potential for achieving the switch to a low-carbon development mode. However, low-carbon cities are still in the early phase, and the literature discusses many unresolved problems – e.g., of governance, of cooperation, of planning, and of funding.

A crosscutting issue in all three topics was China in the international context: how do China's strategies toward low-carbon development compare to strategies in different countries, and how can collaboration with foreign partners contribute to implementing the strategies? Comparison with strategies in other countries, e.g., at the city level, was shown to be difficult because of data problems, incoherent methodologies, and a lack of continuous monitoring. The effects of international collaboration always depend on the circumstances in which collaboration occurs: partner projects between cities can be anything from loose client-provider relationships to large-scale joint venture projects with effective long-term engagement on both sides. The effects of FDI were also tested in several studies, with inconclusive results – the potential carbon effects of FDI were shown to be both positive and negative. Studies would need to differentiate better between different types and sectors of FDI to improve our understanding of the potential contributions of international collaboration to low-carbon development.

One other issue became obvious in all preceding chapters: research on low-carbon development is characterized by a large diversity of methodologies, often with incompatible epistemological starting points and underpinnings. Explaining in detail how the methodologies we found would relate to each other, what types of knowledge claims they generate, and what their respective validity and explanatory model is was beyond the scope of our paper. Our overview led us to believe that much could be gained from mapping these methodological approaches systematically to better qualify the implications of each methodology's findings. However, we found very few papers that discuss their findings in light of findings generated by competing or even incompatible approaches. We suggest a more systematic comparison and evaluation in this regard and more comprehensive meta-studies.

After these general and cross-cutting comments, we will as our last point summarize our main suggestions for the three topics on which this paper focused:

- Low-carbon cities

  Few articles have presented a clear strategy or roadmap for establishing a low-carbon city. From a summary of the literature, however, we deduce some useful steps. First, the features of energy consumption and GHG emissions should be analyzed with tools that reflect local characteristics. Related environmental policies or goals set by local governments should also be considered. Moreover, a set of viable or proposed measures should be designed. During this phase, the key sectors should also be identified. Measures can be clustered by sectors or groups in both technological and non-technological categories. However, each of them should be specific and have one clear target focusing on one industry. Next, a clear timeline should be considered. A careful weighing and prioritization of specific measures in each sector is required as part of this timeline. Time points for checking and monitoring should also be determined. Low-carbon cities can be better established through a general shift from multiple isolated measures (addressing individual technologies or sectors) to a more integrated approach (combining key carbon activities together). During the establishment process, the relationship between the local government and foreign partners must be carefully considered. A solid framework of bi-national political support, active public and private investment, and effective advice and communication between the two sides can contribute to successful collaboration initiatives [12]. Further research could address the following topics:

  (1) Continuous inventory research for a city: not just for one year, but for the long term (continuous observation of emission changes in the city);
  (2) Assessment of low-carbon practices in a city, especially in China's low-carbon city pilot projects, focusing on how low-carbon development goals are actually implemented;
  (3) The role of governments and issues of governance during the construction of low-carbon cities;
  (4) A more elaborate social science analysis of local governance and urban planning. Most papers, especially papers in English journals, are mainly based on formal mathematical modeling. The societal and institutional preconditions of low-carbon city development in China are substantially under-researched.

- Industry

  There is very little current literature on how management strategies can improve energy efficiency, promote the shift of the energy mix and generate more green investments. More in-depth studies of individual industries are required to complement the broad overviews and to identify at a more concrete level the technologies that can promote low-carbon production pathways under the conditions of specific industries. Identifying how management strategies can support the transition over the short and long terms is also critical. In addition, studies have shown that almost no decoupling of industrial activity and CO_2 emissions has been achieved so far and that enormous potential from technological improvements remains. Further research may address the following topics:

  (1) The role of governments/enterprises/citizens in the development of low-carbon industries;
  (2) The relevance of management methods or public environmental awareness as drivers of the development of low-carbon industries;
  (3) Quantitative sector and multi-sector analyses that could be complemented by case studies adopting a micro perspective:

which low-carbon technologies have been used, what are the effects, and which organizational features have fostered or hindered their implementation?
(4) Cost analyses of low-carbon production processes for companies in different sectors;
(5) Development of a roadmap or specific steps for improving the industrial structure, and an analysis of benefits and losses produced by such adjustment.

- Transition of the energy system

In summary, clean coal technologies are considered to be an appropriate way to balance CO_2 reduction and economic development in China. Of these technologies, CCS has attracted much attention from both researchers and enterprises, although it is still at the demonstration stage and has not been applied at a large scale. Studies suggest that an improved investment structure must also be enhanced by increasing the proportion of foreign investment instead of state-owned investment, but other studies show ambivalent results. Further research may address the following topics:
(1) The drivers and hindering factors in the diffusion of renewable energy application in China;
(2) Deeper discussions of management strategies for technologies, including issues of selection, ways of updating current systems, and cost estimations, to better promote low-carbon production;
(3) Study of the collaboration mechanisms among governments, enterprises and research centers;
(4) A broader discussion about the long-term costs and the risks of nuclear energy, including the problem of nuclear waste management, which might support a balanced assessment of all long-term non-fossil options for the Chinese energy mix.

Acknowledgement

This study is supported by the Program National Natural Science Foundation of China (Reference No. 71173017, 71573016, 71521002); the Cluster of Excellence Integrated Climate System Analysis and Prediction (CliSAP; Reference No. DFG EXC 177) provided institutional support in Hamburg.

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