Science of the Total Environment 699 (2020) 134386

Contents lists available at ScienceDirect

Science of the Total Environment

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

CO_2 emission characteristics and reduction responsibility of industrial subsectors in China

Xinru Lin [a], Yiting Zhang [b], Chenyi Zou [a], Lihong Peng [a,*]

[a] College of the Environment & Ecology, Xiamen University, Xiang'an South Road, Xiang'an District, Xiamen 361102, China
[b] Policy Research Center, Hubei Academy of Environmental Science, Bayi Road, Hongshan District, Wuhan 430072, China

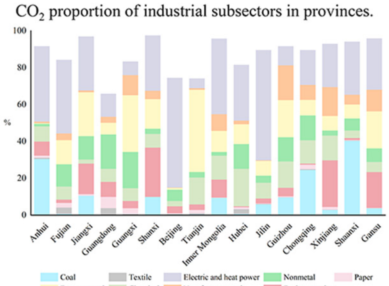
HIGHLIGHTS

- This paper calculates the CO_2 emissions of industrial subsectors in China's provinces.
- This paper analyzes the CO_2 emission characteristics of selected subsectors in provinces and economic regions.
- This paper identifies the industrial subsectors that each province should focus on.
- This paper provides constructive suggestions for policymakers to promote low-carbon economy and sustainable development.

GRAPHICAL ABSTRACT

CO_2 emission characteristics and reduction responsibility of industrial subsectors in China

CO_2 proportion of industrial subsectors in provinces.



Key provinces of each industrial subsector.

Industry	First-level key province	Second-level key province
Coal	Anhui, Chongqing and Shaanxi	Jilin, Xinjiang and Gansu
Textile	/	Anhui and Beijing
Paper	Guangdong	Anhui, Jiangxi, Chongqing and Xinjiang
Fuel processing	Xinjiang	Fujian
Chemical	Xinjiang and Guangdong	/
Nonmetal	/	/
Ferrous metal	Fujian, Inner Mongolia and Xinjiang	/
Non-ferrous metal	Inner Mongolia, Chongqing and Xinjiang	Fujian
Electricity and heat power	Anhui and Fujian	Guangxi

ARTICLE INFO

Article history:
Received 7 July 2019
Received in revised form 8 September 2019
Accepted 8 September 2019
Available online 10 September 2019

Editor: Damia Barcelo

Keywords:
China
CO_2 emission
Decoupling model

ABSTRACT

Industrial subsectors have an important role in reducing China's carbon dioxide (CO_2) emissions. The present study analyzes the CO_2 emission characteristics of selected subsectors. Results show that the electric and heat power sector is the major industrial CO_2 emitter, and CO_2 emissions of most sectors present huge inter-provincial and inter-regional differences. Then, the CO_2 emission reduction responsibility of provincial-level industrial subsectors is confirmed by the decoupling model. Results show that the development of a low-carbon economy in the nonmetal sector is ideal, and the economic growth in Shanxi and Guizhou is moving toward a low-carbon and energy-saving mode. Moreover, the subsectors that each province should focus on are identified. Finally, constructive suggestions for policymakers to promote low-carbon economy and sustainable development are provided.

1. Introduction

Global warming, which is mainly caused by an increase of carbon dioxide (CO_2) concentration in the atmosphere (IPCC, 2007; Letcher, 2019), is a serious environmental challenge. China is the world's largest CO_2 emitter (Le Quéré et al., 2017) and promises to reduce its CO_2 emission per unit of GDP by 18% from the 2015 level, according to the country's "13th Five-Year Plan". China has a vast territory. To achieve the national goal, provincial administrative regions (hereafter called provinces) need to work together. Industry, as a dominant factor of the national economy, is a major energy consumer and source of CO_2 emissions (Shan et al., 2018; Wang et al., 2019). Therefore, studying the CO_2 emission characteristics of the industrial subsectors of each province, as well as their responsibility to reduce these emissions, is a matter of urgency.

Correct CO_2 emission accounting is not only the basis of analyzing CO_2 emission characteristics, but supports identification,

* Corresponding author at: Room A119, College of the Environment & Ecology, Xiamen University, Xiang'an South Road, Xiang'an District, Xiamen 361102, China.
E-mail addresses: xrlin@stu.xmu.edu.cn (X. Lin), zhangyt@lanhit.com (Y. Zhang), 33120182202178@stu.xmu.edu.cn (C. Zou), lhpeng@xmu.edu.cn (L. Peng).

https://doi.org/10.1016/j.scitotenv.2019.134386
0048-9697/

selection, introduction, and implementation of CO_2 emission reduction plans and measures (Schaltegger and Csutora, 2012). The main accounting methods used by existing studies are life cycle assessment (LCA; Ji and Chen, 2016; Wang and Chen, 2018; Kennelly et al., 2019), input–output model (Wang et al., 2018c; Liu and Fan, 2017; Zhang, 2018; Li et al., 2018), and emission factor approach (Zhao and Wu, 2018; Fan et al., 2013; Lin and Nelson, 2019; Du et al., 2019a). As a widely used method to quantify the environmental impact of a given product throughout its entire life cycle (ISO, 2006), LCA is considered as a promising tool to obtain potential CO_2 emissions (Antón and Díaz, 2014). However, LCA always leads to truncation errors (Ward et al., 2018) and provides limited functions in macro-analysis (Antón and Díaz, 2014). Input–output model is well described, consistent, and can be applied in direct and indirect CO_2 emissions accounting. However, this model has a high data requirement (Kennelly et al., 2019). Unfortunately, the input–output tables of China's provinces have not been updated for many years. Emission factor approach, which is supported by the Intergovernmental Panel on Climate Change (IPCC) and adopted in "Guidelines for National Greenhouse Gas Inventories," is an authoritative, reliable and convenient method for measuring CO_2 emissions from energy activities (Ma et al., 2019). For instance, Yang and Liu (2017) applied emission factor approach to calculate China's urban household CO_2 emissions from commercial energy, such as coal, liquefied petroleum gas (LPG), and gasoline in 2015. Wang et al. (2018a) employed emission factor approach to estimate CO_2 emissions generated by transportation in China from 1990 to 2015. Wang and Jiang (2019) used emission factor approach to calculate the energy-related CO_2 emissions in China from 2000 to 2014. In summary, emission factor approach meets the requirements of our study.

Responsibility sharing in CO_2 emission reduction is the key to achieve the national reduction goal at the minimum cost. Some scholars allocate the total CO_2 emission allowances to provinces (Dong et al., 2018; Yu et al., 2019; Xie et al., 2019) or industrial sectors (Yang et al., 2017; Zhang and Hao, 2017; Zhu et al., 2018) to clarify their responsibility to reduce CO_2 emissions. Others identify the responsibility by concerning the nexus between economic growth and CO_2 emissions. Environmental Kuznets curve (EKC; Wang et al., 2017b; Riti et al., 2017) and decoupling model (Luo et al., 2017; Zhao et al., 2017) are the two general methods (Wu et al., 2018). Compared with EKC, decoupling model is easier to understand and operate (Wang et al., 2017a), and provides a real-time dynamic relationship between economic growth and pollutant emission (Wang and Yang, 2015). Thus, decoupling model has received increasing attention in the field of sustainable development. Wang et al. (2017b) adopted the Tapio model to analyze the decoupling relationship between economic growth and CO_2 emission of the transportation industry in Jiangsu Province from 1995 to 2012. Jiang et al. (2018) employed Tapio model to quantify the decoupling effects of CO_2 emissions in China's six major sectors from 2000 to 2014. Du et al. (2019b) applied Tapio decoupling model to investigate the relationship between economic growth and CO_2 emission from the construction industry of China's 30 provinces for the 2005–2015 period. Additionally, several studies also explored the driving forces of decoupling combined with decomposition method (Zhao et al., 2017; Wang et al., 2018b).

Numerous province-level decoupling studies have been completed in China, but evidently, most of them have focused on a specific industry or a certain province, and systematic comparative analyses involving multiple provinces and industries are lacking. Furthermore, existing studies have often targeted major sectors, such as industry, construction, and manufacturing, and lack in-depth exploration of other industrial subsectors. This study attempts to fill certaining gaps identified the literature. According to the CO_2 emissions of industrial subsectors in China's provinces calculated by the emission factor approach, the CO_2 emission characteristics of selected subsectors are discussed from the perspective of provincial and economic region. The decoupling model confirmed the responsibility to reduce emissions of provincial-level industrial subsectors. We aim to produce an efficient guidance and reference to promote the low-carbon economy and sustainable development.

2. Methods and data

2.1. Calculation of CO_2 emissions

We used the emission factor approach to calculate CO_2 emissions of industrial subsectors in China's provinces. The function is shown in Eq. (1):

$$C_i^t = \sum_{j=1}^{n} E_{ij}^t F_j \tag{1}$$

where C_i^t represents the CO_2 emissions from the i-th sector in t year, E_{ij}^t represents the j-th energy consumption of the i-th sector in t year, and F_j represents the CO_2 emission factor of the j-th energy.

According to the China Energy Statistical Yearbook, the types of energy used to calculate CO_2 emissions are raw coal, cleaned coal, other washed coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, LPG, refinery gas, natural gas, heat and electricity. Their CO_2 emission factors come from the "Guidelines for Provincial Greenhouse Gas Inventories" (Climate Division, National Development and Reform Commission, China, 2011).

2.2. Determining responsibility to reduce CO_2 emissions

2.2.1. Decoupling model

Decoupling theory was first proposed by the Organization for Economic Co-operation and Development (OECD) in 2002 (OECD, 2002), but the original decoupling model has led to poor stability of the calculated results due to high sensitivity in the choice of benchmark years (Zhao et al., 2016; Wu et al., 2018). Tapio decoupling model (Tapio, 2005) overcomes the problem with its flexible incremental analysis. The decoupling elasticity ε of CO_2 emission (C) and economic growth (output values, denoted as V) in a certain industrial subsector of a province can be measured as follows:

$$\varepsilon = \frac{\delta C}{C_0} \Big/ \frac{\delta V}{V_0} \tag{2}$$

where subscript 0 denotes the base year, and δC and δV represent the increments of CO_2 emissions and output values, respectively, between the base and target years.

We adopt the judgment presented by Zheng and Zhang (2013) considering that the output value of China's industrial subsectors increased from 2005 to 2014. The decoupling states can be classified into two categories: decoupling ($\varepsilon \le 0.5$) and coupling ($\varepsilon > 0.5$). Strong decoupling with $\varepsilon < 0$ is the most ideal state because of the implication that the low-carbon economy has been achieved. By contrast, the greater the value of ε, the more CO_2 is emitted per unit of output, which means that the industrial subsectors in coupling state should undertake additional responsibility to reduce CO_2 emissions.

2.2.2. Selection of key industrial subsectors

We count the energy consumption by industrial subsectors from 2000 to 2014. As shown in Fig. 1, the following 8 sectors consume 80% of the total energy consumption in industry: smelting and pressing of ferrous metals (hereafter called ferrous metal); manufacture of raw chemical materials and chemical products

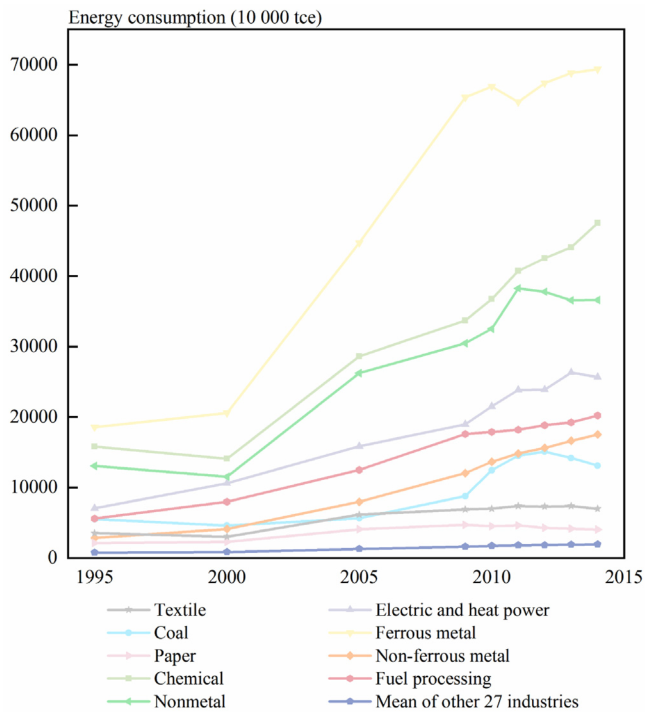


Fig. 1. Energy consumption of industrial subsectors in 2000–2014.

Table 1
Industrial subsectors covered by carbon trading pilot areas.

Area	Sub-industry
Beijing	Electric and heat power, cement, petrochemical, other industrial enterprises, service, urban rail transit, bus passenger transport
Shanghai	Steel, petrochemical, chemical, non-ferrous metal, electric power, building material, textile, paper, rubber, chemical fiber, etc.
Tianjin	Steel, chemical, electric and heat power, petrochemical, oil and gas production, etc.
Chongqing	Industrial enterprises with emissions of $\geq$20,000 tons of CO_2 in any year from 2008 to 2012
Hubei	Steel, chemical, cement, automobile making, electric power, non-ferrous metal, glass, paper, etc.
Shenzhen	Enterprises with emissions of $\geq$3000 tons of CO_2 in any year
Guangdong	Electric power, steel, petrochemical, cement, civil aviation, paper

(chemical); manufacture of non-metallic mineral products (nonmetal); production and supply of electric power and heat power (electric and heat power); processing of petroleum, coking and processing of nuclear fuel (fuel processing); smelting and pressing of non-ferrous metals (non-ferrous metal); mining and washing of coal (coal); and manufacture of textile (textile).

The industrial subsectors covered by carbon trading pilot areas are shown in Table 1. Aside from the eight sectors mentioned, manufacture of paper and paper products (paper) has received wide attention.

In summary, we finally select 9 industrial subsectors as the objects of the study. They are ferrous metal, chemical, nonmetal, electric and heat power, fuel processing, non-ferrous metal, coal, textile, and paper.

2.3. Data sources

The output values and energy consumption of industrial subsectors are collected from China Energy Statistical Yearbook 2006–2015. The study includes 16 provinces in China, namely, Guangdong, Anhui, Fujian, Jiangxi, Guangxi, Shanxi, Beijing, Tianjin, Inner Mongolia, Hubei, Jilin, Guizhou, Chongqing, Xinjiang, Shaanxi, and Gansu. Others are excluded because of the unavailability of data.

3. Results and discussion

3.1. CO_2 emission characteristics in provinces

Fig. 2 shows the proportion of CO_2 emissions from 9 key industrial subsectors in each province to its total industrial CO_2 emissions. In addition to Guangdong, the 9 key sectors in the remaining provinces have a cumulative proportion of $\geq$75%. This proportion exceeds 90% in 10 provinces, which fully illustrates the representativeness of the 9 industrial subsectors.

CO_2 emissions from the electric and heat power sector are the highest. As an important livelihood support, the sector contributes nearly 60% of total industrial CO_2 emissions in Beijing and Jilin; >40% in Anhui and Inner Mongolia; about 20% in most provinces; and only 7.44% and 5.23% in Guangxi and Tianjin, respectively.

The ferrous metal sector, which mainly includes ironmaking, steelmaking and ferroalloy smelting, is one of the important raw material industrial subsectors in China. The sector accounts for 45% of total industrial CO_2 emissions in Tianjin; between 20% and 30% in Gansu Guizhou, Jiangxi, and Guangxi; approximately 10% in most provinces; and <1% in Beijing and Anhui.

The proportion of CO_2 emissions from coal sector to total industrial CO_2 emissions shows large inter-provincial differences: $\geq$30% in Shaanxi and Anhui, and <1% in Guangdong, Beijing and Fujian. These results are closely related to coal resource endowment. A similar situation occurs in the fuel processing sector, which contributes 25% of the total industrial CO_2 emissions in Shanxi and Xinjiang but only <1% in Hubei and Chongqing. The same is true for the non-ferrous metal sector.

The chemical sector has a relatively balanced proportion (10%) of CO_2 emissions in all provinces. The textile sector and the paper

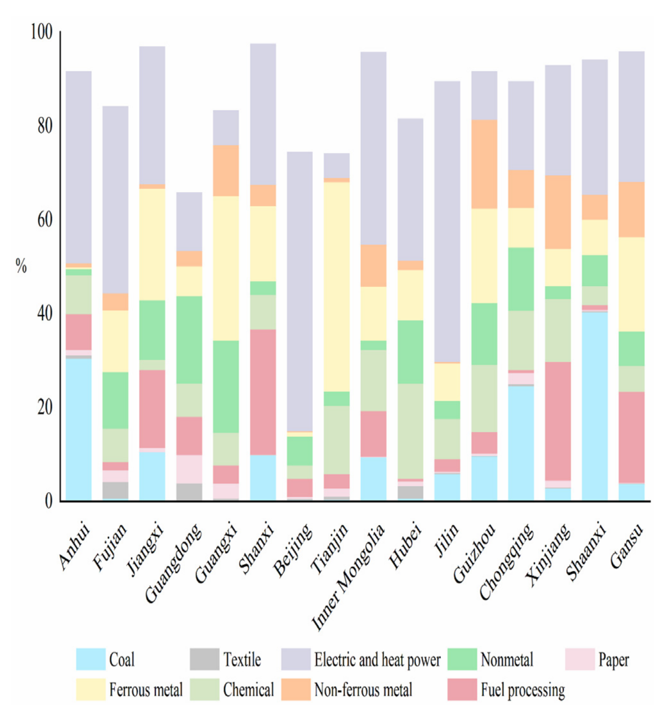


Fig. 2. CO_2 proportion of 9 industrial subsectors in 16 provinces.

sector have the least contribution to total industrial CO_2 emissions, but they still have a place in Guangdong and Fujian.

3.2. CO_2 emission characteristics in economic regions

According to the division of China's four economic regions, Inner Mongolia and Jilin are in Northeast China; Anhui, Jiangxi, Shanxi, and Hubei are in Central China; Fujian, Guangdong, Beijing, and Tianjin are in East China; and Guangxi, Guizhou, Chongqing, Xinjiang, Shaanxi, and Gansu are in West China. Fig. 3 shows the proportion of CO_2 emissions from 9 key industrial subsectors in each economic region to its total industrial CO_2 emissions.

The CO_2 emission characteristics of industrial subsectors differ from one region to another. The textile and paper sectors are classified as light industries. They have great technical and resource advantages in East China. As a result, they contribute more CO_2 emissions in East China than in other regions. With rich coal reserves in West and Central China, the coal sector contributes nearly 13% of total industrial CO_2 emissions in these two regions, but only 0.29% in East China. Owing to the low dependence on fixed resources, the proportions of CO_2 emissions from the chemical, nonmetal and fuel processing sector to total industrial CO_2 emissions vary minimally among the four economic regions. The electric and heat power sector plays a pivotal role in all economic zones. The sector contributes half of industrial CO_2 emissions in Northeast China and up to 20% in West China. The CO_2 emissions by the non-ferrous metal sector are mainly emitted in West China, and the ferrous metal sector emits more CO_2 in East and West China.

3.3. Responsibility to reduce CO_2 emissions

The decoupling elasticity of industrial subsectors in each province and the proportion of their CO_2 emissions to total industrial CO_2 emissions in 2014 (hereafter referred to as CO_2 proportion) are shown in Fig. 4. In this study, the industrial subsectors that are in coupling state and have high CO_2 proportion are required to shoulder additional responsibility.

The coal sector presents coupling in Anhui, Fujian, Tianjin, Hubei, Jilin, Gansu, Chongqing, Xinjiang and Shaanxi. In Fujian,

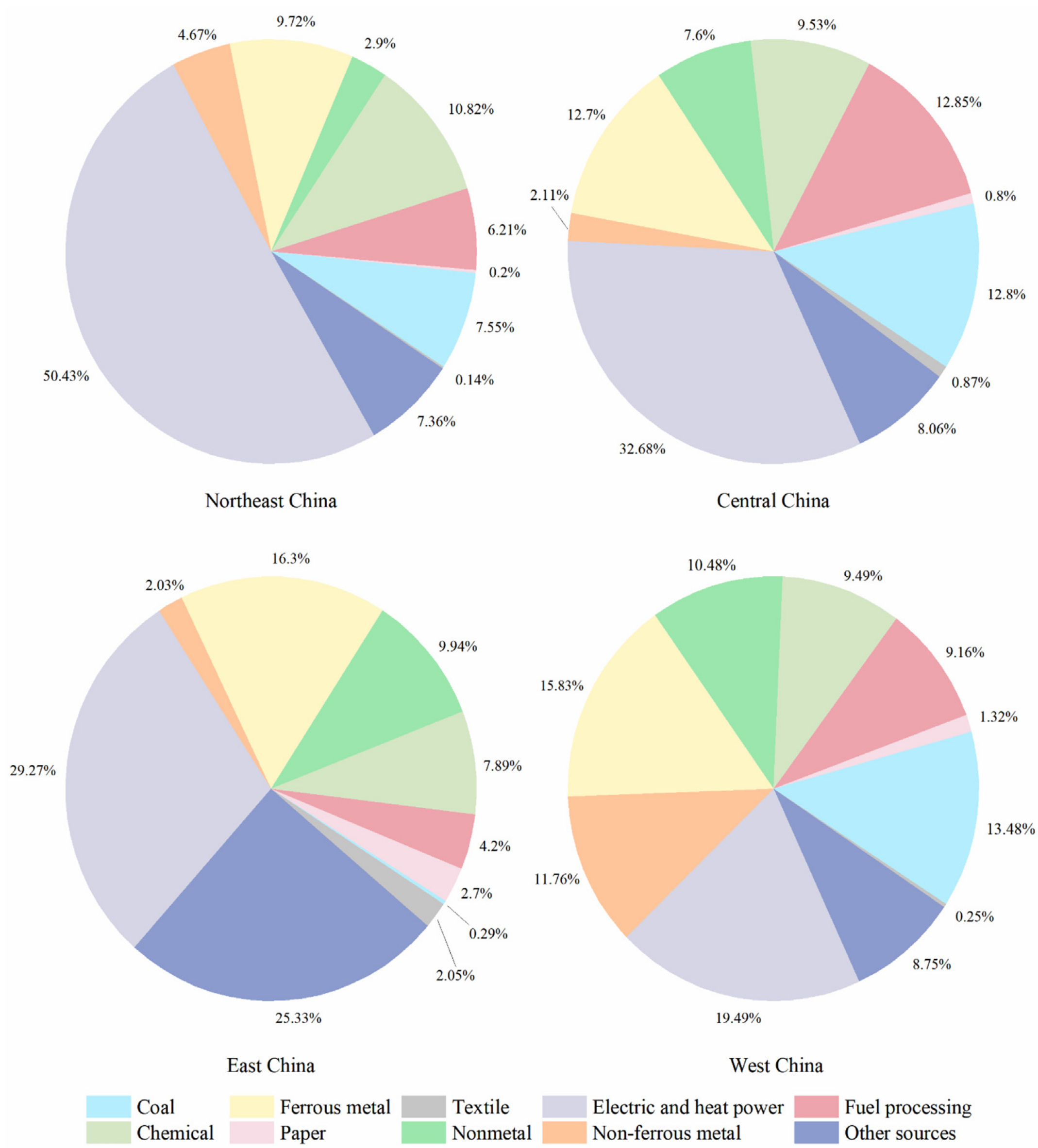


Fig. 3. CO_2 proportion of 9 industrial subsectors in 4 economic regions.

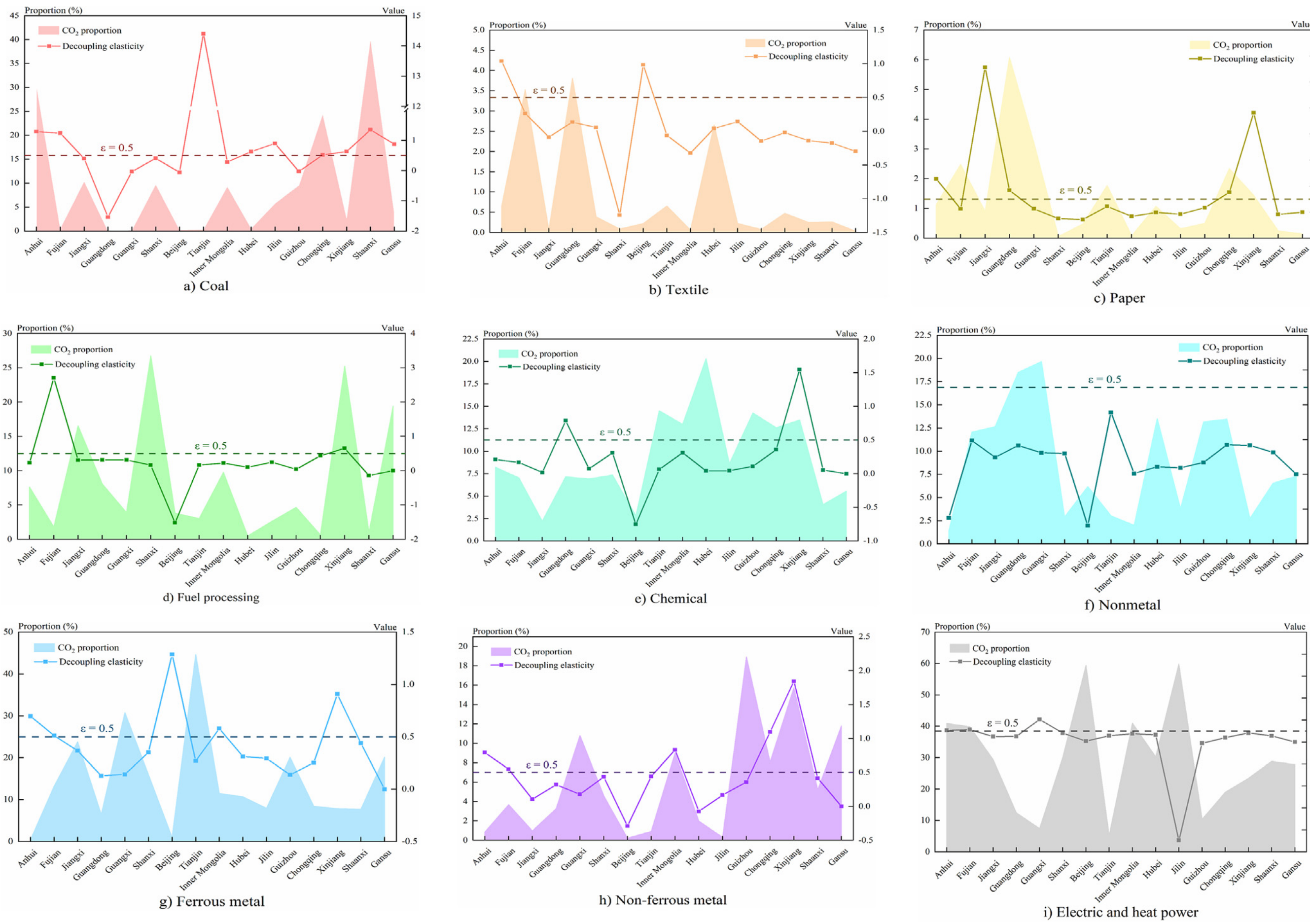


Fig. 4. Decoupling elasticity and CO_2 proportion of industrial subsectors in provinces.

Tianjin and Hubei, the CO_2 proportion of the coal sector is <1%, far below 30%, 24%, and 40% in Anhui, Chongqing, and Shaanxi, respectively. The rates are 5.8% in Jilin, 2.7% in Xinjiang, and 3.7% in Gansu. Therefore, Anhui, Chongqing, and Shaanxi are selected as the first-level key provinces for CO_2 emission reduction in coal sector, and Jilin, Xinjiang, and Gansu are its second-level key provinces.

The coupling state of the textile sector occurs in Anhui and Beijing. As their CO_2 proportion is not high, the two provinces are selected as the second-level key provinces to strengthen low carbon construction in the textile sector.

The paper sector of Jiangxi, Anhui, Guangdong, Chongqing, and Xinjiang is in a coupling state. Among them, the decoupling elasticity in Jiangxi is particularly high at 5.56. The CO_2 proportion in Guangdong (6.08%) is several times more than the other four provinces (1.14% in Anhui, 0.91% in Jiangxi, 2.35% in Chongqing, and 1.44% in Xinjiang). After comprehensive consideration, Guangdong is selected to be the first-level key province to assume a major CO_2 reduction responsibility in the paper sector, and Jiangxi, Anhui, Chongqing, and Xinjiang are the second-level key provinces.

The fuel processing sector presents coupling in Fujian and Xinjiang. The decoupling elasticity in Fujian (2.70) is much greater than that in other provinces, but the CO_2 proportion is only 1.8% in Fujian while that in Xinjiang is as high as 25%. As a result, Xinjiang is selected as the first-level key province for CO_2 emission reduction in the fuel processing sector, and Fujian is the second-level key province.

The coupling state of the chemical sector occurs in Guangdong and Xinjiang. With the high CO_2 proportion in Guangdong (7.2%) and Xinjiang (13.5%), these provinces are both selected as the first-level key provinces to reduce CO_2 emissions in the chemical sector.

The nonmetal sector shows a unique behavior. It can be observed from Fig. 4 that all provinces are in a decoupling state, indicating that the development of the sector is relatively ideal. Anhui and Beijing present the best decoupling performance with decoupling elasticity below zero. The nonmetal sector in Anhui and Beijing achieved economic growth along with the decrease of CO_2 emissions. All industrial subsectors should strive to move toward such a state.

The ferrous metal sector of Anhui, Fujian, Beijing, Inner Mongolia, and Xinjiang is in coupling state. In Anhui and Beijing, the CO_2 proportion of ferrous metal sector is <1% whereas that in Fujian, Inner Mongolia, and Xinjiang is about 10%. Thus, Fujian, Inner Mongolia, and Xinjiang are selected as the first-level key provinces to strengthen low carbon construction in the ferrous metal sector.

The non-ferrous metal sector presents coupling in Anhui, Fujian, Inner Mongolia, Chongqing, and Xinjiang. Considering the high CO_2 proportion of the non-ferrous metal sector in Inner Mongolia (9.01%), Chongqing (8.07%), and Xinjiang (15.75%), these three provinces are selected as the first-level key provinces for CO_2 emission reduction in non-ferrous metal sector. The CO_2 proportion in Fujian is relatively low (3.68%), so Fujian is selected as the second-level key province of the sector. Anhui is not considered because of its extremely low CO_2 proportion (only 0.86%).

The coupling state of the electric and heat power sector occurs in Anhui, Fujian, and Guangxi. The CO_2 proportion of the sector in these three provinces is 41%, 40%, and 7.4%, respectively. As a

Table 2
Key provinces of each industrial subsector.

Industry	First-level key province	Second-level key province
Coal	Anhui, Chongqing and Shaanxi	Jilin, Xinjiang and Gansu
Textile	/	Anhui and Beijing
Paper	Guangdong	Anhui, Jiangxi, Chongqing and Xinjiang
Fuel processing	Xinjiang	Fujian
Chemical	Xinjiang and Guangdong	/
Nonmetal	/	/
Ferrous metal	Fujian, Inner Mongolia and Xinjiang	/
Non-ferrous metal	Inner Mongolia, Chongqing and Xinjiang	Fujian
Electricity and heat power	Anhui and Fujian	Guangxi

result, Anhui and Fujian are selected as the first-level key provinces to reduce CO_2 emissions from the electric and heat power sector, and Guangxi is the second-level key province.

Table 2 provides a summary.

Only the industrial subsectors of Shanxi and Guizhou are in a decoupling state, which means that the overall low-carbon development capacity of the two provinces is strong, and their mode of economic growth is moving toward low-carbon and energy-saving. Although Shanxi is a major energy consumer, since 2008, it has undergone large-scale restructuring and shut down many coal enterprises, thereby resulting in a negative growth of CO_2 emissions in recent years. Guizhou is rich in mineral resources, but its exploitation and utilization are limited by the presence of mountains. Thus, the CO_2 emissions in Guizhou increase slowly, which is why subsectors in Shanxi and Guizhou exhibit decoupling.

Anhui, Fujian, and Xinjiang have the largest number of industrial subsectors in coupling state. In the past decade, Xinjiang has developed rapidly supported by the West Development Strategy in China. Inevitably, the development of high energy-consuming industries has brought high emissions. Following Shanghai, Zhejiang and Jiangsu, Anhui and Fujian have become the key provinces with economic growth in East China. As a result, energy consumption is significantly faster, and CO_2 emissions increase sharply, thereby promoting coupling.

We are pleased to find that other provinces have only one or two industrial subsectors in coupling state, which means that most of the provincial industrial subsectors are on the road to a low-carbon economy.

4. Conclusions and policy suggestions

Industrial subsectors are the focus of energy conservation and emission reduction in China. We apply the emission factor approach to calculate the CO_2 emissions of industrial subsectors in China's provinces during the 2005–2014 period. The conclusions on CO_2 emission characteristics are as follows: (1) The sum of CO_2 emissions from these nine industrial subsectors (including ferrous metal, chemical, nonmetal, electric and heat power, fuel processing, non-ferrous metal, coal, textile, and paper) accounts for an average of 87.5% of the total industrial CO_2 emissions in the provinces. (2) The electric and heat power sector has the largest average contribution to the total industrial CO_2 emissions of provinces, at 29.1%, while the textile sector has the smallest, only 0.8%. (3) From the perspective of economic regions, the electric and heat power sector remains the major CO_2 emitter, but the sector with the least CO_2 emissions is different in each region, such as the textile sector in Northeast and West China, the paper sector in Central China, and the coal sector in East China. (4) The CO_2 proportion of most industrial subsectors presents huge inter-provincial and inter-regional differences.

To promote a low-carbon economy and achieve the goal of national CO_2 emission reduction, we identified the reduction responsibility of industrial subsectors in provinces by considering the nexus between their economic growth and CO_2 emissions. The decoupling model was employed and the conclusions are as follows: (1) The development of the low-carbon economy in the nonmetal sector is ideal. (2) The CO_2 emission reduction pressure of textile, fuel processing, and chemical is mainly concentrated in 2 provinces. And CO_2 reduction in the coal, paper, ferrous metal, and electric and heat power sector needs the joint efforts of 3–5 provinces. (3) The economic growth in Shanxi and Guizhou is moving toward low-carbon and energy-saving mode. Other provinces can properly refer to their experience to achieve continuous improvement in decoupling. (4) Anhui, Fujian, Xinjiang and Chongqing need to undertake the major CO_2 emission reduction responsibility of 3–5 industrial subsectors. The economic growth of these four provinces is achieved at the cost of excessive CO_2 emission, and the various CO_2 reduction plans have not achieved their designated goals. (5) The other 10 provinces (Guangdong, Jiangxi, Guangxi, Beijing, Tianjin, Inner Mongolia, Jilin, Hubei, Shaanxi, and Gansu) need to focus on CO_2 reduction in 1 or 2 sectors.

Given the preceding conclusions, we propose the following policy recommendations.

At the national level, attention must be paid to reducing CO_2 emissions in the electric and heat power sector, which is proved to be the major industrial CO_2 emitter. Promoting the development and deployment of new nuclear technologies is an effective way to reduce CO_2. Setting mechanisms and incentives to support large-scale dissemination of centralized solar thermal power generation and photovoltaic technologies is critical (Grande-Acosta and Islas-Samperio, 2017). In management, the implementation of large and seasonal storage capacity also makes sense (Lamont, 2019). Note that the national carbon emission trading system, with the electric and heat power sector as a breakthrough, was officially launched in 2017. We recommend that the energy trading system that focuses on source control be included in the agenda for good cooperation.

At the provincial level, Shanxi and Guizhou need to maintain the continuous and strong policy enforcement in developing a low-carbon economy. Other provinces have to propose the specific emission reduction plans and phase-in targets for the industrial subsectors selected by our study, and formulate appropriate CO_2 emission reduction measures according to the characteristics of various sectors. For energy-dependent sectors, such as coal processing, optimizing the energy structure has only a slight positive effect on the reduction of CO_2 emissions because the dominant position of coal will not change in the short term. Therefore, the focus should be on technical innovation. For light sectors, such as paper manufacturing, the recovery of the energy from biomass loss will help reduce net CO_2 emissions (Wang et al., 2016), and the advanced technology and scientific management can minimize CO_2 emissions in the production process.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Acknowledgments

The authors would like to thank National Bureau of Statistics for the data accessibility. And we also acknowledge the anonymous reviewers for their helpful and constructive comments.

References

Antón, Lá, Díaz, J., 2014. Integration of life cycle assessment in a BIM environment. Procedia Engineering 85, 26–32.

Climate Division, National Development and Reform Commission, China, 2011. Guidelines for Provincial Greenhouse Gas Inventories (in Chinese).

Dong, F., Long, R., Yu, B., Wang, Y., Li, J., Wang, Y., et al., 2018. How can China allocate CO_2 reduction targets at the provincial level considering both equity and efficiency? Evidence from its Copenhagen Accord pledge. Resour. Conserv. Recycl. 130, 31–43.

Du, Q., Shao, L., Zhou, J., Huang, N., Bao, T., Hao, C., 2019a. Dynamics and scenarios of carbon emissions in China's construction industry. Sustain. Cities Soc. 48, 101556.

Du, Q., Zhou, J., Pan, T., Sun, Q., Wu, M., 2019b. Relationship of carbon emissions and economic growth in China's construction industry. J. Clean. Prod. 220, 99–109.

Fan, J.-L., Liao, H., Liang, Q.-M., Tatano, H., Liu, C.-F., Wei, Y.-M., 2013. Residential carbon emission evolutions in urban–rural divided China: an end-use and behavior analysis. Appl. Energy 101, 323–332.

Grande-Acosta, G., Islas-Samperio, J., 2017. Towards a low-carbon electric power system in Mexico. Energy for Sustainable Development 37, 99–109.

IPCC, 2007. Intergovernmental Panel on Climate Change. Fourth Assessment Report: Climate Change.

ISO 14044, 2006. Environmental Management-Life Cycle Assessment-Requirements and Guidelines.

Ji, S., Chen, B., 2016. Carbon footprint accounting of a typical wind farm in China. Appl. Energy 180, 416–423.

Jiang, R., Zhou, Y., Li, R., 2018. Moving to a low-carbon economy in China: decoupling and decomposition analysis of emission and economy from a sector perspective. Sustainability 10, 978.

Kennelly, C., Berners-Lee, M., Hewitt, C., 2019. Hybrid life-cycle assessment for robust, best-practice carbon accounting. J. Clean. Prod. 208, 35–43.

Lamont, A.D., 2019. Efficient pathways to reduce carbon emissions in the electric sector. Electr. J. 32, 15–24.

Letcher, T.M., 2019. 1 - Why do we have global warming? In: Letcher, T.M. (Ed.), Managing Global Warming. Academic Press, pp. 3–15.

Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A.C., et al., 2017. Global carbon budget 2017. Earth System Science Data Discussions, 1–79.

Li, Y., Su, B., Dasgupta, S., 2018. Structural path analysis of India's carbon emissions using input-output and social accounting matrix frameworks. Energy Econ. 76, 457–469.

Lin, B., Nelson, B.I., 2019. Determinants of industrial carbon dioxide emissions growth in Shanghai: a quantile analysis. J. Clean. Prod. 217, 776–786.

Liu, H., Fan, X., 2017. Value-added-based accounting of CO_2 emissions: a multi-regional input-output approach. Sustainability 9, 2220.

Luo, Y., Long, X., Wu, C., Zhang, J., 2017. Decoupling CO_2 emissions from economic growth in agricultural sector across 30 Chinese provinces from 1997 to 2014. J. Clean. Prod. 159, 220–228.

Ma, X., Wang, C., Dong, B., Gu, G., Chen, R., Li, Y., et al., 2019. Carbon emissions from energy consumption in China: its measurement and driving factors. Sci. Total Environ. 648, 1411–1420.

OECD, 2002. Indicators to Measure Decoupling of Environmental Pressures from Economic Growth, Paris.

Riti, J.S., Song, D., Shu, Y., Kamah, M., 2017. Decoupling CO_2 emission and economic growth in China: is there consistency in estimation results in analyzing environmental Kuznets curve? J. Clean. Prod. 166, 1448–1461.

Schaltegger, S., Csutora, M., 2012. Carbon accounting for sustainability and management. Status quo and challenges. J. Clean. Prod. 36, 1–16.

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., et al., 2018. China CO_2 Emission Accounts 1997–2015. Scientific Data, vol. 5, p. 170201.

Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transp. Policy 12, 137–151.

Wang, S., Chen, B., 2018. Three-tier carbon accounting model for cities. Appl. Energy 229, 163–175.

Wang, Q., Jiang, R., 2019. Is China's economic growth decoupled from carbon emissions? J. Clean. Prod. 225, 1194–1208.

Wang, Z., Yang, L., 2015. Delinking indicators on regional industry development and carbon emissions: Beijing–Tianjin–Hebei economic band case. Ecol. Indic. 48, 41–48.

Wang, Y., Yang, X., Sun, M., Ma, L., Li, X., Shi, L., 2016. Estimating carbon emissions from the pulp and paper industry: a case study. Appl. Energy 184, 779–789.

Wang, Y., Xie, T., Yang, S., 2017a. Carbon emission and its decoupling research of transportation in Jiangsu Province. J. Clean. Prod. 142, 907–914.

Wang, Y., Zhang, C., Lu, A., Li, L., He, Y., ToJo, J., et al., 2017b. A disaggregated analysis of the environmental Kuznets curve for industrial CO_2 emissions in China. Appl. Energy 190, 172–180.

Wang, B., Sun, Y., Chen, Q., Wang, Z., 2018a. Determinants analysis of carbon dioxide emissions in passenger and freight transportation sectors in China. Struct. Chang. Econ. Dyn. 47, 127–132.

Wang, Q., Zhao, M., Li, R., Su, M., 2018b. Decomposition and decoupling analysis of carbon emissions from economic growth: a comparative study of China and the United States. J. Clean. Prod. 197, 178–184.

Wang, Z., Li, Y., Cai, H., Wang, B., 2018c. Comparative analysis of regional carbon emissions accounting methods in China: production-based versus consumption-based principles. J. Clean. Prod. 194, 12–22.

Wang, J., Hu, M., Tukker, A., Rodrigues, J.F.D., 2019. The impact of regional convergence in energy-intensive industries on China's CO2 emissions and emission goals. Energy Econ. 80, 512–523.

Ward, H., Wenz, L., Steckel, J.C., Minx, J.C., 2018. Truncation error estimates in process life cycle assessment using input-output analysis. J. Ind. Ecol. 22, 1080–1091.

Wu, Y., Chau, K., Lu, W., Shen, L., Shuai, C., Chen, J., 2018. Decoupling relationship between economic output and carbon emission in the Chinese construction industry. Environ. Impact Assess. Rev. 71, 60–69.

Xie, Q., Hu, P., Jiang, A., Li, Y., 2019. Carbon emissions allocation based on satisfaction perspective and data envelopment analysis. Energy Policy 132, 254–264.

Yang, T., Liu, W., 2017. Inequality of household carbon emissions and its influencing factors: case study of urban China. Habitat International 70, 61–71.

Yang, B., Liu, C., Su, Y., Jing, X., 2017. The allocation of carbon intensity reduction target by 2020 among industrial sectors in China. Sustainability 9, 148.

Yu, A., Lin, X., Zhang, Y., Jiang, X., Peng, L., 2019. Analysis of driving factors and allocation of carbon emission allowance in China. Sci. Total Environ. 673, 74–82.

Zhang, Z., 2018. Technology-adjusted national carbon accounting for a greener trade pattern. Energy Econ. 73, 274–285.

Zhang, Y.-J., Hao, J.-F., 2017. Carbon emission quota allocation among China's industrial sectors based on the equity and efficiency principles. Ann. Oper. Res. 255, 117–140.

Zhao, L.D., Dong, W.U., 2018. Carbon emission accounting and spatial heterogeneity pattern of China's energy supply side. China Population Resources & Environment 28, 48–58 (in Chinese).

Zhao, X., Zhang, X., Shao, S., 2016. Decoupling CO_2 emissions and industrial growth in China over 1993–2013: the role of investment. Energy Econ. 60, 275–292.

Zhao, X., Zhang, X., Li, N., Shao, S., Geng, Y., 2017. Decoupling economic growth from carbon dioxide emissions in China: a sectoral factor decomposition analysis. J. Clean. Prod. 142, 3500–3516.

Zheng, L., Zhang, Y., 2013. Research on characteristic and target of low carbon development in China's provinces. Science and Technology Progress and Policy 30, 32–36 (in Chinese).

Zhu, B., Jiang, M., He, K., Chevallier, J., Xie, R., 2018. Allocating CO_2 allowances to emitters in China: a multi-objective decision approach. Energy Policy 121, 441–451.