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Carbon Emission Reduction Characteristics for China's Manufacturing Firms: Implications for formulating carbon policies

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Abstract: The rapid development of China's manufacturing industry since China's accession to WTO in 2001 has dramatically increased China's carbon emissions. To inform the carbon policy development of China's manufacturing industry, this study constructed a DEA-GS (data envelopment analysis and grid search) model from a cost perspective to understand the their emission reduction characteristics. Using a large sample of manufacturing firms from 2008 to 2011, the carbon pricing and reduction potential of China's manufacturing firms was explored by analyzing the firms' marginal abatement costs. The results showed that: (a) with increasing marginal abatement costs, the growth rates of both cumulative emission

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reduction activities and emission reduction of these firms gradually slowed down. When the marginal abatement cost exceeds 200 Yuan/ton, neither the number of reduction activities nor the amount of reduced emissions increase. (b) The impact of marginal abatement costs on the numbers of reduction activities and firms in each sub-sector is heterogeneous. (c) The emission reduction behaviors of manufacturting firms, determined by carbon pricing, are mostly concentrated in developed areas or around large cities. In contrast, areas with substantial emission reductions are more scattered. The results suggest that The emission reduction characteristics of sub-sectors should be fully considered when formulating carbon policies for China's manufacturing industry. The carbon price for the China's manufacturing industry should not exceed 200 Yuan/ton. Furthermore, the carbon policy of China's manufacturing industry should have broader coverage, rather than merely covering developed areas.

Keywords: manufacturing industry; marginal abatement cost; carbon policy; China

1 Introduction

China plays a vital role in the control of global warming and China’s manufacturing industry (CMI) is critical for achieving the defined carbon emission reduction goals. The rapid development of China's manufacturing industry since China’s accession to WTO in 2001 has dramatically increased China's carbon emissions (Yu et al., 2021). As the world's factory and the world's largest carbon emitter, China contributed 28.8% to the global emissions in 2019, and still remains the main driver of the growth of global carbon emissions (BP, 2020). CMI has contributed 29.3% to the national GDP and accounted for more than 50% of the national total carbon emissions currently (Yang et al., 2020). Therefore, CMI is not only an important economic sector but also a major source of carbon emissions. Establishing a corresponding CMI carbon emission reduction policy is not only important for achieving China peak emission before 2030 and carbon neutrality by 2060 in a cost-effective way, it is also important to the world.

Studying the characteristics of carbon emissions, including the emission reduction potential and reduction activities, is a prerequisite for formulating an optimal carbon policy. The characteristics are linked to the marginal abatement cost (MAC) of CMI. MAC is an essential indicator for the formulation of carbon policies and is also a standard policy tool with which to assess options to mitigate climate change (Zhou et al., 2014). When the government issues a carbon policy, the key focus needs to be the matching of the resulting carbon price with the MAC of firms. When the carbon price formulated by the carbon policy is lower than the MAC of firms, the economic emission reduction potential cannot be achieved; however, if the carbon price is too high, this may increase the burden on firms and weaken their competitiveness (Zhang and Baranzini, 2004). Therefore, accurate measurement of MAC is particularly important for the rational formulation of governmental carbon policies.

The existing studies on MAC for CMI mainly focused on aggregated levels per industry or province, thus limiting their value for the formulation of carbon policies that target firms. Furthermore, the significant divergence of MAC value across regions and sub-sectors undermines its role in supporting carbon policy making. Among the few studies of MAC at the firm level, e.g., Wei et al. (2013), Du et al., (2016), and Wang et al. (2017), sectors were chosen ad hoc, and comparison across different sub-sectors of CMI are missing. A MAC calculated through a large sample of firms will be closer to the true value, and is therefore more suitable as a reference for carbon policies. However, so far, MAC of all CMI sub-sectors from the firm perspective has still not been reported. By using a large sample of CMI firm-level data, this paper investigates the MAC of CMI and its associated carbon emission reduction potential and activities from a cost perspective. The obtained results provide detailed information for the formulation of CMI carbon policies. An optimization model of manufacturing production costs for individual firms is developed. Furthermore, a framework for calculating MAC using the grid search (GS) method is proposed, which is applied to the data of 66308 manufacturing companies from 2008 to 2011.

The contributions of this study are three-fold: first, it introduces the GS method into the MAC analysis. By combining data envelopment analysis (DEA) and GS methods to discover multiple MACs that may exist in a firm based on the non-parameter method. Second, a large sample at the firm level was used to analyze the MAC of CMI in more detail from the micro-level. Third, based on the results of the calculated MAC, a reference for the formulation of carbon policies is provided from the three dimensions of overall, sub-sectors, and spatial distribution.

The remainder of this paper is organized as follows: Section 2 briefly reviews the relevant literature. Section 3 descripts the methodology and data. Section 4 presents the empirical results and a brief discussion. Section 5 concludes the paper.

2 Literature review

Among the numerous studies on MAC of CMI, the significant difference in the MAC value undermines its value for policy formulation. The MAC of the Chinese industries was estimated from different regional scopes, time horizons, and sectors; significant differences were found in the obtained MAC values. Using the Chinese provincial data for 2008, Peng et al. (2012) calculated the MAC of 24 industrial sectors, which ranged from 200 to 120,300 Yuan/ton. The MAC values of both the heavy industry and the chemical industry were lower than that of the light industry and the high-tech industry. Using the same level data for 2015, Duan et al. (2018) showed that the MAC should range between 598 and 753 Yuan/ton, which can be a reference for the formulation of a carbon policy. Furthermore, Zhou et al. (2015) calculated the MAC of 10 industrial sectors in Shanghai for 2011 and showed that these should range between 394.5 and 1906.1 Yuan/ton. Moreover, they also found that MAC and carbon intensity are negatively correlated. As a single sector, the iron and steel industry has attracted much attention because of its high energy consumption. From a provincial perspective, Che (2017) found that in 2012, the MAC of China's iron and steel industry ranged from 1981.76 to 4268.89 Yuan/ton, suggesting that encouraging the emissions trading scheme (ETS) could help to realize the emission reduction tasks. Below this value, Duan et al. (2017) showed that the average value of the MAC in 2011-2014 ranged between 121.12 and 1020.82 Yuan/ton. The authors suggested that the government should fully consider the differences between regions and available emission reduction technologies when formulating carbon policies. Using China's petroleum processing and coking (PPC) industrial data in 30 provinces and a hybrid estimation method combining both bottom-up engineering methods and top-down economy-wide methods, Wang at al. (2020) finds that the MAC of China's petroleum industry would change from 9821 to 16,307 yuan/ton when the abatement level change from 1 to 50%. In contrast, using firm-level data, Wang (2017) concluded that the MAC of China's iron and steel industry in 2014 ranged from 407 to 6058 Yuan/ton. The MAC of the provincial thermal power industry was also investigated. Peng et al. (2018) reported that the national weighted average MAC of CO_2 emissions was 316.51 Yuan/ton, which was higher than the carbon price in the current ETS. Xian et al. (2019) pointed out that the MAC for the provincial power sector ranged from 0.15 to 1285 Yuan/ton, indicating that MAC savings from trading had affected most of China's provinces.

Most of these existing studies on the MAC of CMI were focused at the provincial or municipal level. These aggregated MACs can guide China's carbon policy formulation from an overall perspective. However, they cannot reflect the actual MAC firms face. However, the implementation of the policy ultimately depends on firms. Thus, the MAC from the macro perspective is difficult to apply to carbon policy making of micro firms.

Estimation of the MAC of CMI through firm-level data can help to accurately match carbon policy with carbon price; however, this alone is insufficient. The more micro-data is available, the closer the shadow price is to the real MAC. Unfortunately, the current MAC research for CMI at the firm-level is insufficient. Although several studies investigated the firm-level, e.g., Wei et al. (2013), Du et al., (2016), and Wang et al. (2017), the sectors involved were not comprehensive.

The distance function approach can reflect the evolution of MAC, which is more suitable for the designing of a carbon policy (Ji and Zhou, 2020). At present, the common methods for MAC estimation are mainly expert-based, model-derived, based on the cost function, and based on a distance function approach (Ji and Zhou, 2020). An expert-based approach, which Jackson (1991) applied to carbon emissions, was derived from expert assumptions for the baseline development of emissions and its abatement potential and cost. Model-derived MAC is mainly either calculated by bottom-up engineering or by a top-down economic model, such as the Computable General Equilibrium (CGE) model or the Targets IMage Energy Regional (TIMER) model (Kesicki, 2010). The cost function approach directly calculates the MAC by only constructing a cost if the relevant data is available (Du et al., 2015). The distance function approach estimates MAC by calculating the shadow price. Because of the distance function approach used in the empirical data, future economic and technological scenarios do not need to be assumed.

Compared with a parametric method, a non-parametric method does not need to set the function form in advance and has a relatively low data requirement; therefore, non-parametric methods are widely used (Sheng et al., 2015; Boussemart et al., 2017; Wang and He, 2017).

In summary, further studying the MAC of CMI from firm-level data can add value to the literature and can improve real carbon policy formulation. Moreover, the application of the non-parametric approach has several benefits and is thus appropriate for such studies.

3 Methodology

3.1 Model

The manufacturer is defined as DMU_j, with $j = 1, 2, \cdots, N$. In the t period, the manufacturer j_n inputs the three main production costs into its production activities, including labor cost $l_{j_n}^t$, depreciation of fixed assets $k_{j_n}^t$, and non-fixed asset goods materials cost $c_{j_n}^t$. The production process must ensure that the total amount of energy $e_{j_n}^t$ is sufficient. At the end of the production process, the products obtained through the production process are defined as desired output ($y_{j_n}^t$), and the produced carbon emissions are defined as undesired output ($b_{j_n}^t$).

The production technology of the manufacturer j_n in T ($T = 1, 2, \cdots, t$) periods can be described as a production possibility set (PPS) (Lim and Zhu, 2019; Lozano et al., 2019), as Eq. (1):

$$TE_{j_n}^t = \left\{ (k_{j_n}^t, l_{j_n}^t, c_{j_n}^t, e_{j_n}^t, y_{j_n}^t, b_{j_n}^t) \left| \begin{array}{l} \sum_{T=1}^{t} \lambda_{j_n}^T k_{j_n}^T \le k_{j_n}^t, \sum_{T=1}^{t} \lambda_{j_n}^T l_{j_n}^T \le l_{j_n}^t, \sum_{T=1}^{t} \lambda_{j_n}^T c_{j_n}^T \le c_{j_n}^t, \\ \sum_{T=1}^{t} \lambda_{j_n}^T e_{j_n}^T \le e_{j_n}^t, \sum_{T=1}^{t} \lambda_{j_n}^T y_{j_n}^T \ge y_{j_n}^t, \sum_{T=1}^{t} \lambda_{j_n}^T b_{j_n}^T \le b_{j_n}^t \end{array} \right. \right\} \quad (1)$$

where $\lambda \in R_n^+$ denotes the PPS with the CRS.

The manufacturers complete production at their own minimum cost within their PPS range. When carbon emissions do not incur costs, the optimal production decision model of manufacturer j_n can be expressed as:

$$\min \overline{l_{j_n}^t} + \overline{c_{j_n}^t} + \overline{e_{j_n}^t} + \overline{k_{j_n}^t}$$

$$\text{s.t.} \begin{cases} \sum_{T=1}^{t} \lambda_{j_n}^T k_{j_n}^T \le \overline{k_{j_n}^t} \\ \sum_{T=1}^{t} \lambda_{j_n}^T l_{j_n}^T \le \overline{l_{j_n}^t} \\ \sum_{T=1}^{t} \lambda_{j_n}^T c_{j_n}^T \le \overline{c_{j_n}^t} \\ \sum_{T=1}^{t} \lambda_{j_n}^T e_{j_n}^T \le \overline{e_{j_n}^t} \\ \sum_{T=1}^{t} \lambda_{j_n}^T y_{j_n}^T \ge y_{j_n}^* \\ \sum_{T=1}^{t} \lambda_{j_n}^T b_{j_n}^T \le \overline{b_{j_n}^t} \\ \lambda_{j_n}^T \ge 0 \end{cases} \quad (2)$$

Model (2) shows that manufacturer j_n uses the lowest production cost (as available under its existing technology) when producing output $y_{j_n}^*$. When a carbon emission restriction policy is in place, manufacturer j_n increases the emission reduction costs. The optimal production decision model of manufacturer j_n can be expressed as:

$$\min \overline{\overline{l_{j_n}^t}} + \overline{\overline{c_{j_n}^t}} + \overline{\overline{e_{j_n}^t}} + \overline{\overline{k_{j_n}^t}} + \tau_i \overline{\overline{b_{j_n}^t}}$$

$$\text{s.t.} \begin{cases} \sum_{T=1}^{t} \lambda_{j_n}^T k_{j_n}^T \le \overline{\overline{k_{j_n}^t}} \\ \sum_{T=1}^{t} \lambda_{j_n}^T l_{j_n}^T \le \overline{\overline{l_{j_n}^t}} \\ \sum_{T=1}^{t} \lambda_{j_n}^T c_{j_n}^T \le \overline{\overline{c_{j_n}^t}} \\ \sum_{T=1}^{t} \lambda_{j_n}^T e_{j_n}^T \le \overline{\overline{e_{j_n}^t}} \\ \sum_{T=1}^{t} \lambda_{j_n}^T y_{j_n}^T \ge y_{j_n}^* \\ \sum_{T=1}^{t} \lambda_{j_n}^T b_{j_n}^T \le \overline{\overline{b_{j_n}^t}} \\ \lambda_{j_n}^T \ge 0 \end{cases} \qquad (3)$$

where τ_i represents the cost of per unit carbon emission, $\tau_i > 0$, $\tau_i \in \mathrm{R}$.

In general, when the unit carbon emission cost exceeds the manufacturer's MAC, manufacturer j_n will choose energy saving and emission reduction to decrease the carbon emissions from production. Therefore, the MAC of manufacturer j_n can be defined as: there are two unit carbon emission costs τ_m and τ_n, $\tau_m < \tau_n$, for every real number $a > 0$, that satisfy $\tau_n - \tau_m < a$ and $\overline{\overline{b_{j_n}^t}}_{n} - \overline{\overline{b_{j_n}^t}}_{m} < 0$. Then, τ_n is defined as a MAC point, which represents a reduction activity of the manufacturer j_n when the market carbon price exceeds τ_n. The denotations $\overline{\overline{b_{j_n}^t}}_{m}$ and $\overline{\overline{b_{j_n}^t}}_{n}$ are the solutions of model (3) when $\tau_i = \tau_m$ and $\tau_i = \tau_\mathrm{n}$, respectively.

Model (3) is not differentiable using the DEA technique (Färe et al., 2005; Tang et al., 2016). Moreover, multiple MAC points may exist for an individual firm. To get more comprehensive results, the MAC points τ_n of the manufacturers as defined can be searched by the GS method (Wang et al., 2019; Beltrami and da Silva, 2020). The emission reduction corresponding to each MAC point can also be solved. In addition, the search range of MAC values can also be set to avoid extreme individual MAC from interfering with the overall results.

3.2 Data description

This study used a sample of manufacturing firms from China's tax database for 2008-2011, obtained by random sampling, at a sampling ratio of 50% of the total. The sample firms were screened and 66,308 firms were selected that had operated smoothly during these four years as the final sample. Smooth operation means that their operating indicators all exceed zero, including labor cost, depreciation of fixed assets, materials costs of non-fixed asset goods, output, and the carbon emissions; see Model 1. According to the amount of energy used, the carbon emissions of each firm could be calculated according to the IPCC (2006) method (Zhang et al., 2013). All other variables are obtained directly from the database. Based on the average growth rate of the manufacturing industry in China, this study assumed an output value growth of 8% for each manufacturing firm in 2011 as target output.

To understand the MAC characteristics of CMI in more detail, according to the Chinese Industry Classification (CIC) code, the manufacturing industry was divided into 31 sub-sectors (see Appendix A). Moreover, the sample firms were classified into 342 cities in mainland China and the MAC characteristics of CMI were analyzed from a spatial perspective. Since the data of Southern Tibet and Taiwan were unavailable, both regions were excluded.

The GS method was used to search the MAC points of each sample manufacturer. For each firm, the parameters to be searched include the two unit carbon emission costs τ_m and τ_n. During the search calculation, $\tau_n+1=\tau_m$ was set, which means that the calculation error of the marginal abatement cost remains within 1 Yuan/ton. According to this accuracy and considering the feasibility of this low amount, the search step size was set to 1 Yuan/ton before calculating the data with the model. Based on the calculation results of MAC, the reduction characteristics of CMI were analyzed.

4 Results and discussion

4.1 Overall carbon reduction characteristics of firms of CMI

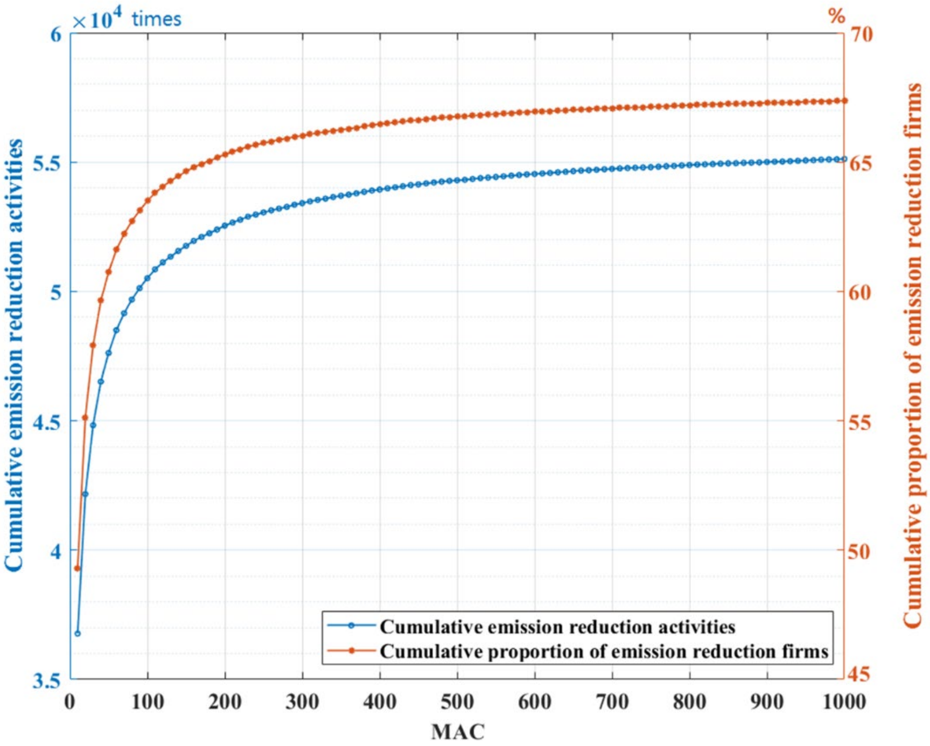


Fig. 1 Overall distribution characteristics of marginal abatement cost (MAC) for firms in China's manufacturing industry (CMI)

Through the model presented in Section 2, the MACs of 66,308 manufacturing firms were calculated in the sample. The characteristic of a firm's MACs were analyzed from the perspective of the number of emission reduction activities and the amount of emission reduction. Among them, the former can reflect the frequency of the firms' response to carbon policies, while the latter can reflect the intensity of carbon policies for firms.

Fig. 1 shows the relationship between emission reduction and MAC of CMI firms, including the cumulative number of activities for emission reduction and the cumulative ratio of firms with emission reduction. With increasing MAC, cumulative emission reduction activities will increase, indicating that the CMI is progressively affected by carbon policies. From the point of view of specific distribution, there are 36,772 reduction activities in the MAC interval range of 0-10 Yuan/ton. The cumulative number of reduction activities has a faster initial growth rate. However, since the MAC continues to increase, this growth rate is consistently slowing down. If the MAC exceeds 700 Yuan/ton, the additional number of reduction activities for each additional 10 Yuan/ton of MAC is less than 20. Since the curve in Fig. 1 is almost flat where MAC exceed 1000 Yuan/ton, the range where the MAC exceeds 1000 Yuan/ton has been excluded. This also means that an excessively high carbon emission price formulated by a policy does not help firms to reduce their emissions.

The cumulative number of firms with reduction activities in different MAC ranges is shown in Fig. 1. Similar to the trend of the cumulative emission reduction activities curve, the cumulative proportion of firms with emission reduction increases but its rate gradually slows down with increasing MAC. When MAC is at 10 Yuan/ton, 49.3% of firms will implement emission reduction activities. When the MAC increases to 200 Yuan/ton, this ratio will increase to 65.3%. Then, as the MAC continues to grow, this ratio almost remains fixed.

In contrast to the previous studies presented in Section 2, the overall weighted average MAC of CMI is 80 Yuan/ton, which implies that the MAC value that was previously calculated from a macro perspective may be too high, and it is therefore not advisable to use it as a reference for the formulation of reduction policies. It should be pointed out that the MACs of the firms are rarely distributed within this high range. This suggests that while excessive carbon prices (or taxes) may be unaffordable for firms, their effect on emission reduction is small. To prevent such cases from affecting the overall results, only a MAC interval that does not exceed 1000 Yuan/ton was studied.

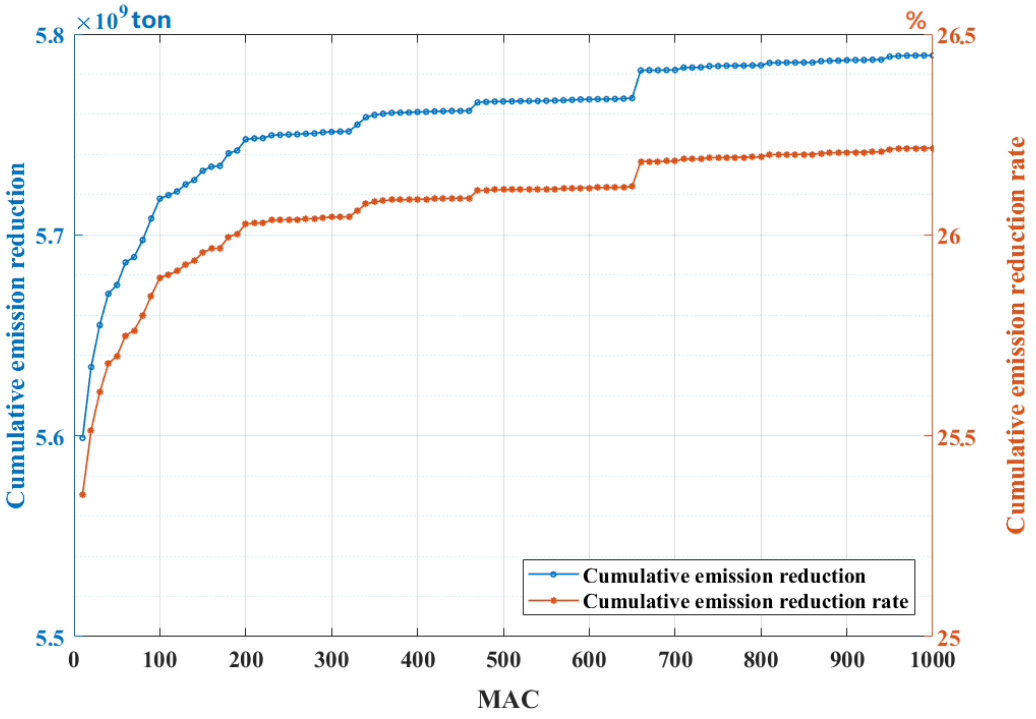


Fig. 2 Cumulative distribution of manufacturers' emission reduction

Fig. 2 shows both the cumulative emission reduction and cumulative emission reduction rate corresponding to different MAC across the sampled firms from CMI. Similar to the curves in Fig. 1, the curves in Fig. 2 generally follow an increasing trend and the rate of change decreases with increasing MAC. The cumulative emission reduction and its rate should be consistent with the cumulative number of firms that engage in emission reduction and their activities. However, because of the differences among firms and their emission reduction activities, the trend of curves in Fig. 2 is more tortuous. When the MAC is 10 Yuan/ton, CMI can achieve an emission reduction of 25.35%. While this MAC is low, it is consistent with the planned MAC in 2010 by the National Development and Reform Commission of China’s Energy Research Institute (ERI) (Wang and Chen, 2015). This low MAC was defined according to unrestrained energy consumption and carbon emissions at the time of issue (World Bank, 2020). With a further increase in MAC to 200 Yuan/ton, the additional cumulative emission reduction rate is only 0.65%. Beyond 200 Yuan/ton, when the MAC increased, the emission reduction rate no longer increased considerably.

From the relationship between the MAC and emission reduction as shown in Fig. 1 and Fig. 2, the MACs of CMI firms mostly remain below 200 Yuan/ton. Therefore, within a 200 Yuan/ton MAC range, the emission reduction potential of most firms can be realized. By considering affordability and effectiveness, when setting the ETS or carbon tax of CMI, an excessively high carbon emission price does not promote firms' emission reduction, and is therefore meaningless. Consequently, the price formulated by a policy should not exceed 200 Yuan/ton.

4.2 Firm carbon reduction characteristics by sub-sector

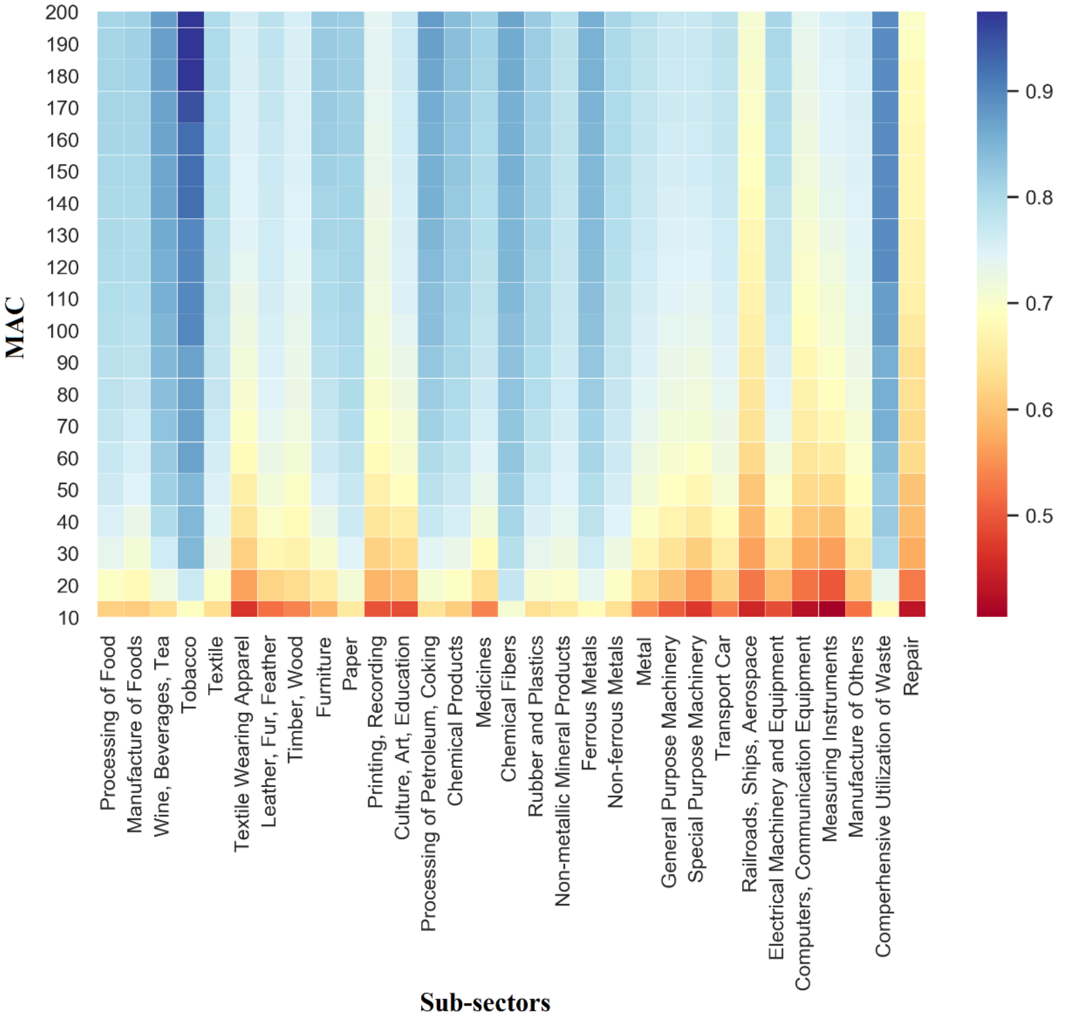


Fig. 3 Average reduction activities of CMI for each sub-sector

To explore the characteristics of the emission reduction activities of different sub-sectors of the CMI, Fig. 3 describes the average number of emission reduction activities of firms for each sub-sector within the MAC range. These reduction activities reflect the possibility of firms in various sub-sectors of CMI to implement emission reduction because in response to the carbon regulation policy. To reflect these characteristics, the interval where emissions reductions are more concentrated is analyzed (i.e., where MAC does not exceed 200 Yuan/ton).

From the sub-sector perspective, the average number of emission reduction activities of firms varies significantly with the distribution of the carbon MAC. The average number of emission reduction activities of 16 sub-sectors is lower than the average of CMI (i.e., C18, Textile Wearing Apparel; C19, Leather, Fur, Feather; C20, Timber, Wood; C23, Printing, Recording; C24, Culture, Art, Education; C27, Medicines; C33, Metal; C34, General Purpose Machinery; C35, Special Purpose Machinery; C36, Transport Car; C37, Railroads, Ships, Aerospace; C38, Electrical Machinery, and Equipment; C39, Computers, Communication Equipment; C40, Measuring Instruments; C41, Manufacture of Others; C43, Repair. See Appendix A for detail). Investigating the sample data showed that the average carbon emissions of firms in these sub-sectors are generally lower compared with those of other sub-sectors. Therefore, when the government implements carbon policies, the costs of carbon emissions in these firms remain relatively low, making them less sensitive to carbon prices than the firms of high-carbon sub-sectors. However, as the MAC continues to increase, the average number of emissions reductions of companies in these sub-sectors is increasing faster than the average level of CMI, except for C20 (i.e., Timber, Wood,). This means that these sub-sectors are less price-sensitive than others. When the government implements a carbon regulation policy, firms in these sub-sectors be only be motivated to reduce emissions by specifying a correspondingly higher carbon price or taxes than the CMI average. The low initial value and low growth rate of the C20 sub-sector indicate that the impact of a carbon price or associated taxes on emissions reduction activities is lower in this sub-sector than in other sub-sectors.

In contrast, the remaining 15 sub-sectors (i.e., C13, Processing of Food; C14, Manufacture of Foods; C15, Wine, Beverages, Tea; C16, Tobacco; C17, Textile; C21, Furniture; C22, Paper; C25, Processing of Petroleum, Coking; C26, Raw Chemical Products; C28, Chemical Fibers; C29, Rubber, and Plastics; C30, Non-metallic Mineral Products; C31, Ferrous Metals; C32, Non-ferrous Metals; C42, Comprehensive Utilization of Waste) have higher average emission reduction activities than the average of CMI. The average carbon emissions of firms in these sub-sectors generally exceed those of other sub-sectors. However, their growth rate is lower, except for C15 and C16. This shows that most firms in these specific sub-sectors are price sensitive and may already be affected by relatively low carbon prices or taxes. The initial and high growth rates of the two sub-sectors C15 and C16 indicate that the emission reduction of both sectors is more affected by the carbon price or taxes.

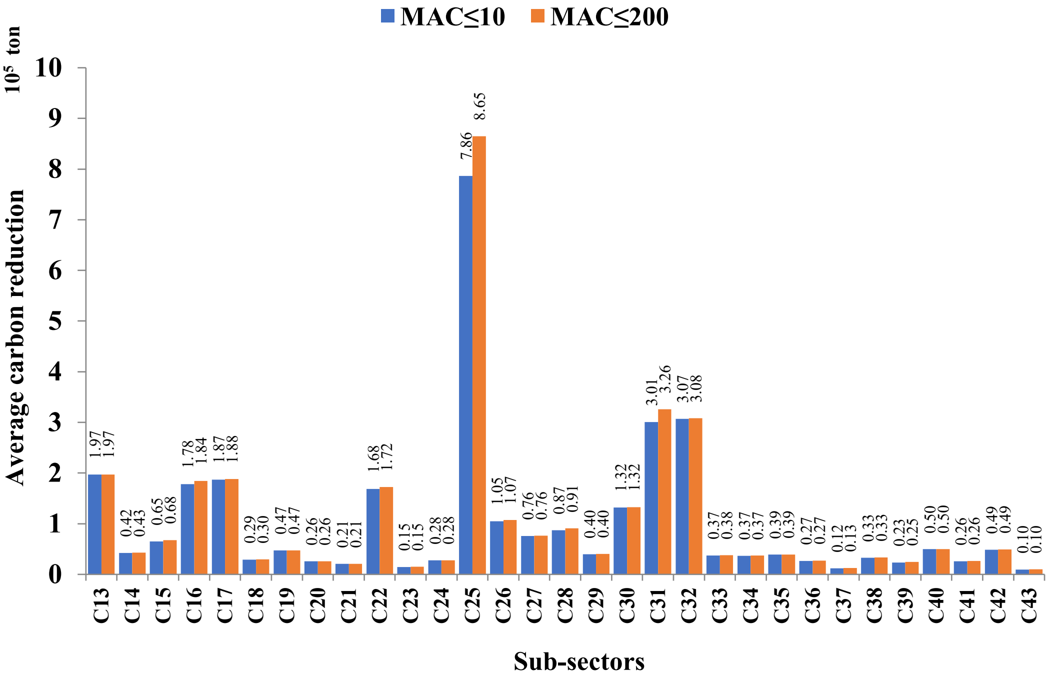


Fig. 4 Average emission reductions for CMI sub-sectors

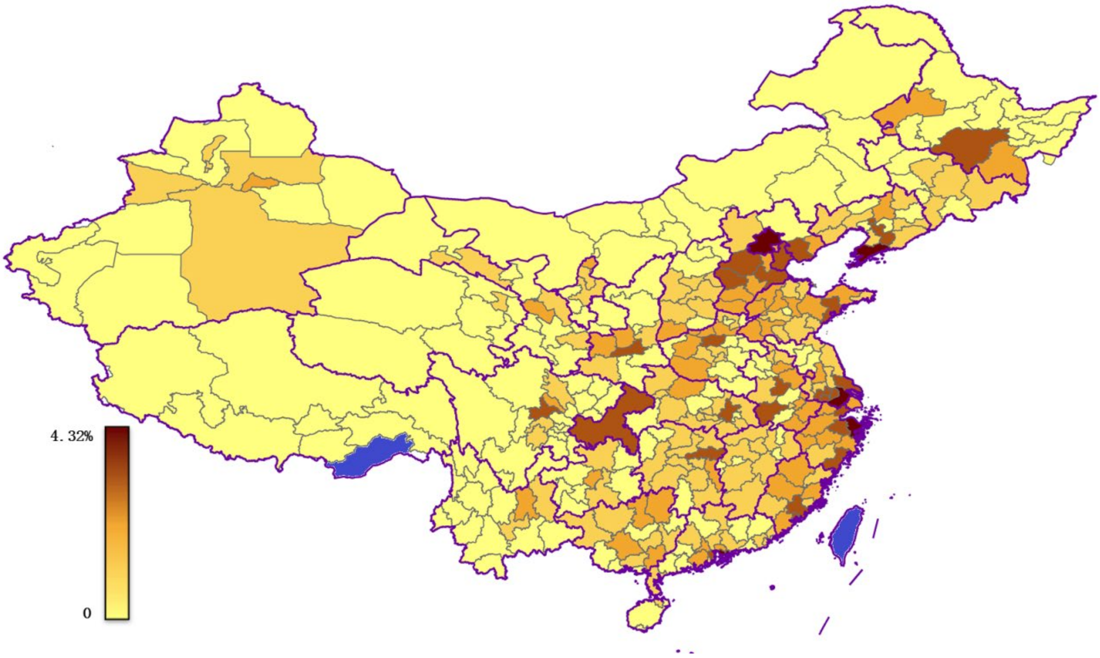
Fig. 4 shows the average reduction potential of firms in various manufacturing sub-sectors within the MAC. This potential represents the average emission reductions firms for each sub-sector will achieve when the market's carbon price is not lower than the two possible prices. C25, which represents the processing of petroleum and coking, can produce more emission reduction effects than other sub-sectors. Moreover, sub-sectors C13, C16, C17, C22, C26, C27, C28, C30, C31, and C32 have higher average emissions reductions than others. These are key sub-sectors for reducing emissions in the CMI (Zhang et al., 2017). When formulating carbon emission regulation policies, such sub-sectors with higher carbon reduction potential should be fully considered as focus. By imposing appropriate carbon emission costs, the firms of these sub-sectors can reduce even more carbon emissions on average.

Comparing the two intervals of the MAC in 10 Yuan/ton and 200 Yuan/ton showed that there are apparent differences between the two sub-sectors of C25 and C31. The difference between the remaining sub-sectors is not apparent. This shows that CMI can achieve most of the emission reduction potential when the cost of carbon emissions is as low as 10 Yuan/ton. For the sub-sectors C25 and C31, the carbon price (formulated by ETS or carbon tax policies) should be higher than that of other sub-sectors to stimulate the emission reduction potential of most firms. To solve problems like this, Felder and Schleiniger (2002) proposed a differentiated carbon tax that considers the characteristics of different sub-sectors. This differentiated carbon tax pricing framework has been considered to be more efficient than uniform pricing (Boeters, 2014). Because of the significant differences in the MACs in CMI, different sub-sectors are affected differently by a carbon price. When formulating a carbon emission regulation policy, to improve the efficiency of the carbon policy, a differentiated carbon price should be defined according to the MAC characteristics of different sub-sectors. The European carbon tax policy applies extensive exemptions and different rates (Ekins and Speck, 1999), and the Chinese government can refer to such differentiated carbon tax pricing in different sectors, e.g., Norway's carbon policy (Bruvoll and Larsen, 2004). Categorizing similar sub-sectors and setting different carbon prices for each category is effective to arrive at more efficient carbon emissions policies for CMI.

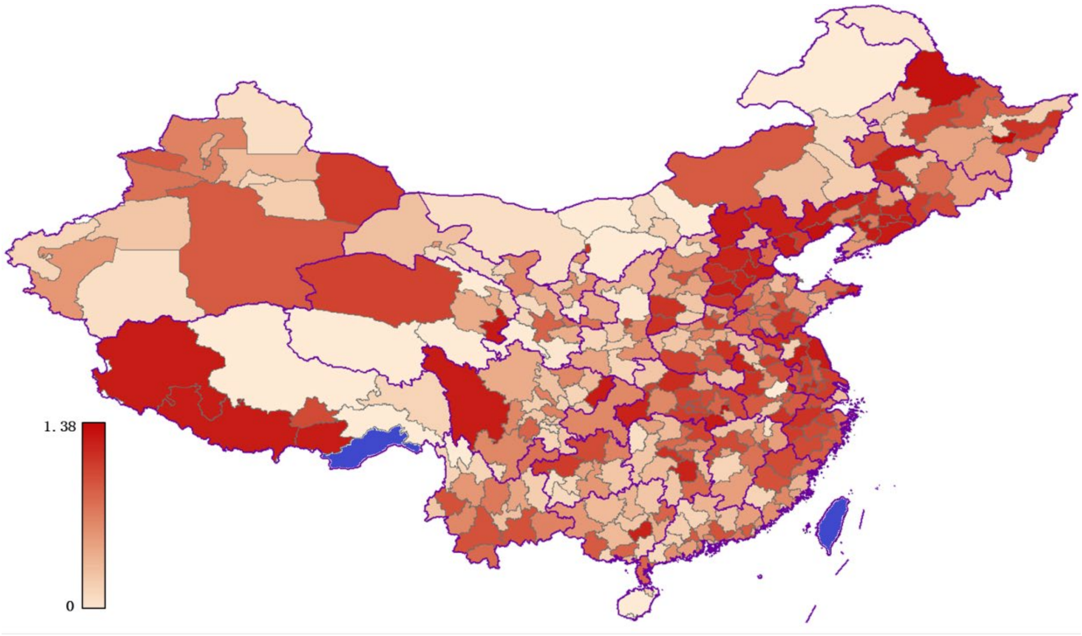
This subsection showed that the impact of MACs on the number of reduction activities and the amount reduced by firms in each sub-sector are quite different. When the average carbon emissions of sub-sector firms are high, the firms in these sub-sectors will be more sensitive to the carbon price as formulated by carbon regulation policies, and their reduction potential is generally higher. These results indicate that the government should differentiate between sub-sectors when formulating carbon policies. High-carbon-producing sub-sectors should be a significant target of policy formulation.

4.3 Firm carbon reduction characteristics from the spatial perspective

Similar to the previous subsection, the spatial distribution characteristics of CMI firms' emission reductions are explored within a carbon policy that applies a carbon price of 200 Yuan/ton.



(a) Cumulative proportion of national emission reduction activities of CMI firms

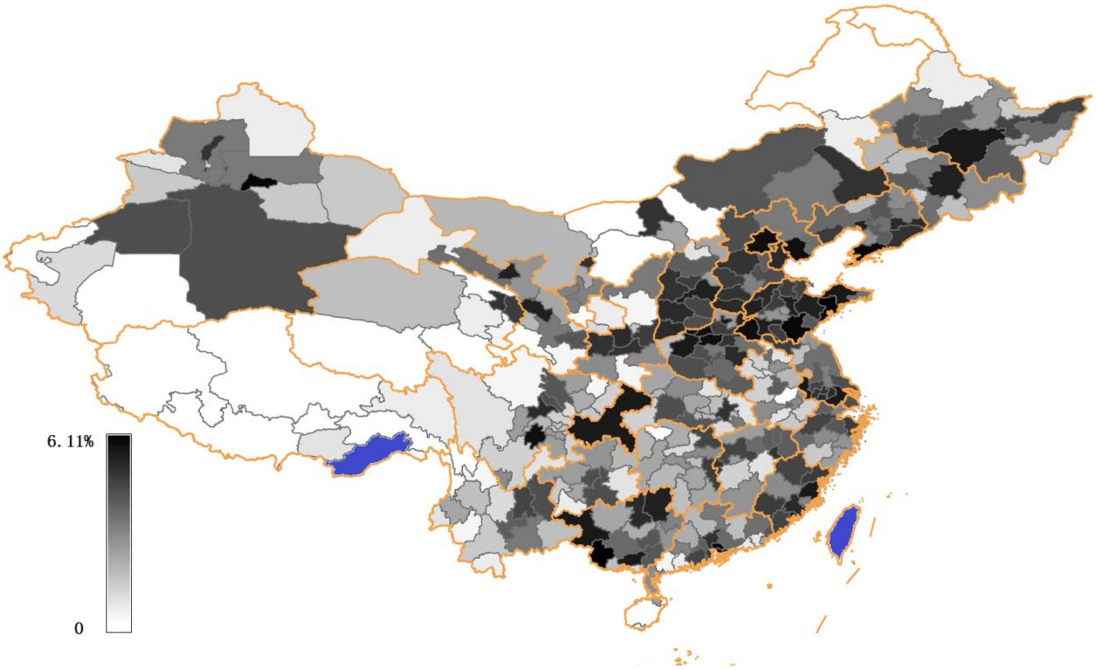


(b) Average emission reduction activities of CMI firms for each city

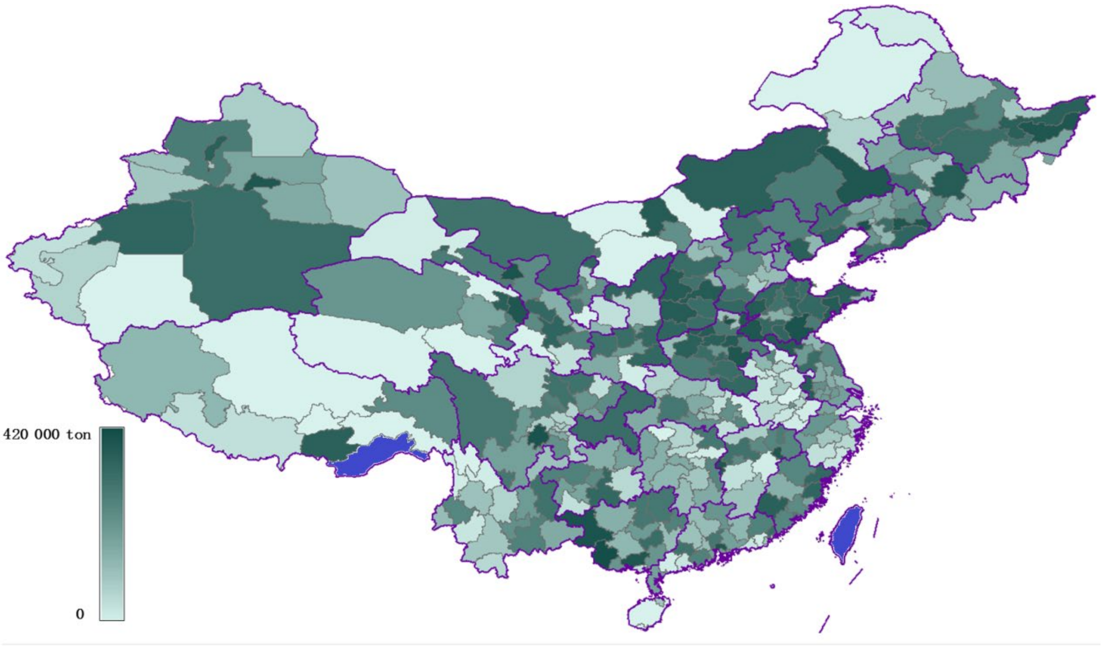
Fig. 5 Spatial distribution map of reduction activities of cities (the carbon price formulated by carbon policy is 200 Yuan/ton)

Fig. 5(a) shows the distribution of the potential emission reduction activities of CMI firms in the cities across China when the carbon price remains within 200 Yuan/ton. Affected by carbon policies, the emission reduction activities of the firms of CMI are mainly concentrated in eastern and southeastern coastal cities in China, which also encompasses the most developed regions. The Beijing-Tianjin-Hebei area and the Yangtze River Delta area show the highest concentration. Moreover, Shenzhen, Qingdao, and Dalian also show higher concentration. From the southeast to the northwest of mainland China, the agglomeration of emission reduction activities gradually decreases. Furthermore, the number of reduction activities shows an inland dispersion, mostly in large cities (capital cities), such as Chengdu, Chongqing, Changsha, Zhengzhou, Wuhan, and Harbin, which also have a disproportionally large number of firms. With these large cities at the center, the intensity of emission reduction activities diverges to the surroundings. The northwestern part of mainland China shows less distribution. This distribution characteristic is highly consistent with the geographical distribution of manufacturing agglomeration zones (Liu et al., 2017).

To support the exploration of the sensitivity of CMI firms to MAC, the average emission reduction activities of firms in each city are shown in Fig. 5(b). Overall, CMI firms in China's northeastern and eastern coastal provinces are more sensitive to the carbon price. Furthermore, inland cities, where the firms are sensitive to the carbon price, are dispersive. However, in the southern region of Xinjiang, where manufacturing is less prevalent, CMI firms are sensitive to carbon prices. Comparing Fig. 5(a) and Fig. 5(b), high-value regions are mostly different except for the Beijing-Tianjin-Hebei area. Many cities with more cumulative emission reduction activities than others, but their CMI firms are not sensitive to the carbon price. This indicates that the main reason for the stronger emission reduction activities in these regions is the concentration of firms. In contrast, not only is the number of CMI firms in the Beijing-Tianjin-Hebei area large, the firms in this area are also sensitive to the carbon price. This has led to more emission reduction activities in these regions compared with other areas. The geographical distribution of emission reduction activities reflects the heterogeneous impact of carbon emission regulations on manufacturing firms in various regions. Since the eastern coastal cities and the large inland capital cities in the southeast of China are more developed, the reduction activities are relatively concentrated (Wang and Mao, 2017). Therefore, when carbon emission reduction policies are introduced, more manufacturing firms will be affected in these areas. However, most of these developed areas have many reduction activities because of the large number of CMI firms, rather than the firms' sensitivity to the carbon price. In contrast, in most small cities, CMI firms are more sensitive to the carbon price.



(a) Cumulative proportion of national emission reduction of CMI firms in each city



(b) Average emission reduction of CMI firms for each city

Fig. 6 Spatial distribution map of the proportion of national emission reduction for cities (the carbon price formulated by carbon policy is 200 Yuan/ton)

Furthermore, the total reduction potential of all manufacturing firms was calculated for each city, as shown in Fig. 6(a). In general, the more reduction activities exist, the more emission reduction will be implemented. However, differences exist between the distribution of emission reductions and reduction activities. Identical to the large number of cumulative reduction activities, the Beijing-Tianjin-Hebei area also shows strong cumulative emission reduction. However, exceeding the reduction activities, the Beijing-Tianjin-Hebei area plus Shandong and northern Henan constitute China’s largest area with huge emission reduction. In contrast, although the Yangtze River Delta area has a large number of emission reduction activities, the cumulative emission reductions by manufacturing firms are not particularly large. This may be due to the relatively low emissions firms in the Yangtze River Delta area produce, as shown in Fig. 6(b). Compared with the northern region of China, the southern region is more developed, and the technological content of CMI is also higher. Areas with CMI firms that have high average emission reductions are mostly concentrated in the north, especially north of the Yellow River.

Moreover, large cities such as Shenzhen, Qingdao, and Dalian also hold great potential for reducing emissions because of their high number of reduction activities. In contrast, although a number of inland cities and regions have fewer emission reduction activities, they hold a large reduction potential. Examples for these cities are Chongzuo and Qinzhou in the Northern Gulf Economic Zone and neighboring Baise City in Guangxi Province, Jilin and Panjin in the Northeast Industrial Zone, Urumqi and Karamay in Xinjiang Province, Leshan in Sichuan Province, Jiaozuo Luoyang and Hebi in northern Henan Province, Yantai, Linyi, Heze, and Liaocheng in Shandong Province, as well as Jinzhong in Shanxi Province. These cities are mostly resource-dependent, most of which have the characteristics of rich mineral resources and developed heavy industries (Wang et al., 2019). High-energy-consuming industries have a greater potential for emission reductions, despite fewer implemented reduction activities. As shown in Fig. 6(b), in most of these small cities, CMI firms show a large average emission reduction amount within a carbon regulation policy. This means that the higher total emission reductions in these cities are caused by the large emission reductions by CMI firms, not by a large number of firms.

From a spatial perspective, when formulating manufacturing carbon regulatory policies, most of the affected firms are concentrated around large cities. However, high-polluting manufacturing firms gradually left large and densely populated cities and moved to smaller cities. Therefore, compared with the spatial distribution of the number of emission reduction activities, cities with higher total carbon emission reductions are more dispersed. Therefore, when formulating a CMI carbon regulation policy, the government should not only rely on the number of regional firms. Because a number of small cities with fewer reduction activities will also have larger total emission reductions, the geographical scope of policy implementation should be wide. Small cities with high carbon emissions should receive priority treatment because of their huge reduction potential.

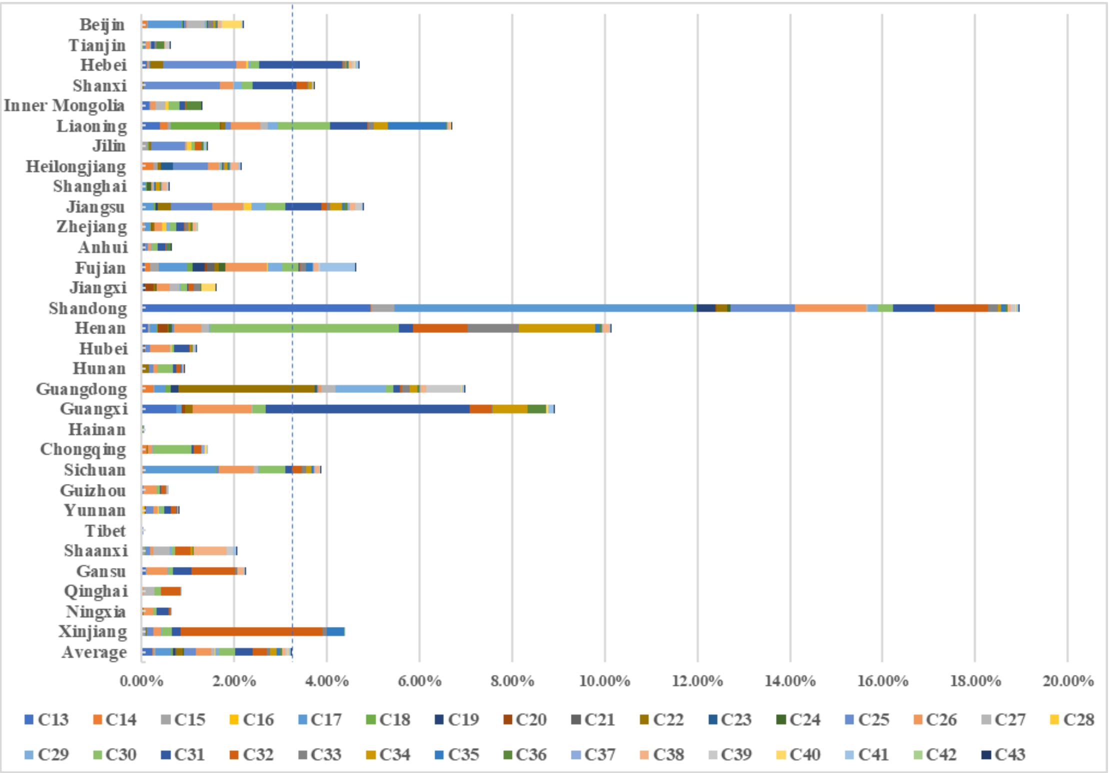


Fig. 7 Provincial-level sectoral structure showing the emission reduction potential for CMI

Judging from the carbon emission reduction potential of CMI in each province, Hebei, Shanxi, Liaoning, Jiangsu, Fujian, Shandong, Henan, Guangdong, Guangxi, Sichuan, and Xinjiang have a higher reduction potential than the national average (Fig. 7). Among them, the reduction potential of Shandong is much higher than that of other provinces. Shandong Province is the largest contributor to the total CO_2

emissions of China (Xu et al., 2016) because it has a high total energy consumption, and its energy mix is dominated by fossil fuels (Li and Yang, 2020).

Furthermore, several provincial sub-sectors have high emission reduction potential and need to receive priority treatment by carbon policies. These are C17 in Shandong and Sichuan; C25 in Hebei, Shanxi, Jiangsu, and Shandong; C26 in Fujian, Shandong, and Guangxi; C30 in Liaoning, Henan, and Chongqing; C31 in Hebei, Shanxi, Liaoning, Shandong, and Guangxi; C32 in Shandong, Henan, Gansu, and Xinjiang; C33 and C34 in Henan; C18 and C35 in Liaoning; C22 and C29 in Guangdong; C13 in Shandong. These sub-sectors of specific provinces are the main contributors to the emission reduction potential of CMI, which can be used as the key control target of the emission reduction policies targeting manufacturing firms.

Formulating a national carbon policy can help CMI to reduce carbon emissions. However, differences in structure and scale are important factors that affect the effectiveness of such a policy. Therefore, the policy should be flexibly adjusted according to specific circumstances. Both different provinces and different sub-sectors should be treated differently. The efficiency of the policy can be improved by implementing specific regional carbon tax policies for sub-sectors with high emission reduction potential in corresponding provinces.

5 Conclusions

CMI has played a key role in China's economic development, but it has also caused notable carbon emissions. However, formulating apporpaote carbon policies needs to understanding the carbon reduction characteristics of the CMI. Using a DEA-GS model and a large sample of CMI firms from 2008 to 2011, the MACs of CMI firms and their associated emission reduction potential and activities were calculated. Based on the obtained results, the emission reduction characteristics of CMI were analyzed from three aspects: overall, sub-sectors, and regions. Several insights for firm-level carbon policies are presented.

This study reaches the following conclusions: First, the cumulative number of emission reduction activities and cumulative emission reductions of CMI increase with the MAC; however, the growth rate has gradually slowed. If MAC exceeds 200 Yuan/ton, both the number of reduction activities and the amount of reduced emissions rarely increase. Specifically, when the MAC ranges within 0-10 Yuan/ton, CMI firms implement the most emission reduction activities. The distribution is lower when the MAC exceeds 200 Yuan/ton, and within this MAC, CMI can reduce carbon emissions by 26%.

Second, the impact of MACs on the number of reduction activities and the reduction amount of firms in each sub-sector differ strongly. There are 13 sub-sectors (including the manufacture of textile wearing apparel, leather, fur, feather, timber, printing, recording, culture equipment, medicines, metal, machinery, transport car, railroads, ships, aerospace, electrical equipment, measuring instruments, others, and repair). Most of the firms can implement emission reduction activities at low MACs. In contrast, for the 15 other sub-sectors (including the manufacture of foods and drink, tobacco, textile, furniture, paper, petroleum, chemical products, and fibers, rubber and plastics, mineral, metals, and comprehensive utilization of waste), most firms can also implement emission reduction activities at higher MACs. Under the same MACs, firms in the sub-sector C20 (i.e., Timber, Wood) will require fewer measures than others. Furthermore, there are 10 sub-sectors (including the processing of food, tobacco, textile, petroleum and coking, raw chemical products, medicines, chemical fibers, non-metallic mineral products, ferrous metals, and non-ferrous metals) that have higher average emissions reductions than others. Furthermore, the potential for sub-sectors C25 (i.e., petroleum and coking) and C31 (i.e., ferrous metals) can only be achieved with high MACs.

Third, a large number of CMI emission reduction activities are concentrated around developed regions and large cities, while many small remote regions can also contribute large amounts of carbon emission reduction. When implementing manufacturing emission reduction policies, most of the reduction activities implemented by CMI firms are mostly concentrated in the Beijing-Tianjin-Hebei area, the Yangtze River Delta area, as well as large inland cities and their surrounding areas. However, regions with high total emission reductions are relatively scattered, and the manufacturing industry in some small cities far from large cities are also affected by the carbon regulation policy and can achieve larger emission reductions. Although manufacturing firms are subject to a geographical agglomeration effect in developed regions, the distribution of manufacturing firms with notable potential for emission reduction is relatively scattered.

Based on this analysis, the following policy implications are suggested: First, the maximum amount of carbon cost for CMI should not exceed 200 Yuan/ton,. Second, when formulating carbon policies for CMI, heterogeneity should be considered in emission reductions among sub-sectors. For example, sub-sectors with large emission reduction potentials should receive less free allowances, a practice that has been implemented in China's pilot ETS (Sun et al., 2019). Third, when formulating carbon policies for CMI, the Chinese government should emphasize both large urban areas with a large number of firms and remote areas with firms that cause high emissions.

Furthermore, a number of policy implications and suggestions for other countries can also be drawn. First, Because of large differences between production processes and technologies, the formulation and implementation of carbon policies should differentiate between sub-sectors. Second, within the same sub-sector, different marginal carbon prices need to be set according to emission scales. Within a sub-sector, large firms generally have large carbon emissions, which indicates that they are more sensitive to carbon prices and have greater emission reduction potential than smaller firms. A policy with multiple marginal carbon prices, such as an increasing block carbon tax, can be considered as a reference for policymakers (Zhou et al., 2019; An and Zhai, 2020). Moreover, the national carbon policy should cover all regions, and the carbon policy across the world should be unified as much as possible; otherwise, the local carbon policy will only achieve partial carbon reduction because of carbon leakage.

A number of limitations may be associated with this study. First, this study assumed that firms only aims to maximize their profits in a competitive market. A more sophisticated market environment has not been considered. Second, this paper does not consider technological advancements. This study specifically investigated the MAC of a static technology manufacturing industry in 2008-2011. However, these limitations suggest the directions of future research. Despite these limitations, this study presents a highly condensed reflection of reality and has strong a guiding significance for policymakers.

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Appendix A Chinese Industry Classification code

Index	**Sub-sectors**

C13	Processing of Food from Agricultural Products
C14	Manufacture of Foods
C15	Manufacture of Wine, Beverages and Refined Tea
C16	Manufacture of Tobacco
C17	Manufacture of Textile
C18	Manufacture of Textile Wearing Apparel
C19	Manufacture of Leather, Fur, Feather and Related Products Footwear
C20	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm and Straw Products
C21	Manufacture of Furniture
C22	Manufacture of Paper and Paper Products
C23	Printing, Reproduction of Recording Media
C24	Manufacture of Articles For Culture, Art, Education Sport Activities and Entertainment Products
C25	Processing of Petroleum, Coking
C26	Manufacture of Raw Chemical Materials and Chemical Products
C27	Manufacture of Medicines
C28	Manufacture of Chemical Fibers
C29	Manufacture of Rubber and Plastics
C30	Manufacture of Non-metallic Mineral Products
C31	Smelting and Pressing of Ferrous Metals
C32	Smelting and Pressing of Non-ferrous Metals
C33	Manufacture of Metal Products
C34	Manufacture of General Purpose Machinery
C35	Manufacture of Special Purpose Machinery
C36	Manufacture of Transport Car making.
C37	Manufacture of Railroads, Ships, Aerospace and Other Transportation Equipment
C38	Manufacture of Electrical Machinery and Equipment
C39	Manufacture of Computers, Communication Equipment and Other Electronic Equipment
C40	Manufacture of Measuring Instruments
C41	Manufacture of Others
C42	Comprehensive Utilization of Waste
C43	Repair of Metal Products, Machinery and Equipment