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Carbon Mitigation for Industrial Sectors in the Jing-Jin-Ji Urban Agglomeration, China

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Abstract: Industrial companies are responsible for most of the energy consumption and carbon emissions in China's urban agglomerations. Some scholars have allocated CO_2 emissions to China's industrial sectors in reaching national reduction targets, yet industrial sectors' burden-sharing problem for carbon mitigation at the provincial level has not been well addressed. Given the goal of realizing China's national carbon mitigation target by 2030, we applied a nonlinear quota allocation model to obtain the optimal allocation of emission reduction quotas among 37 industrial sectors in the Jing-Jin-Ji urban agglomeration in China (comprising Beijing, Tianjin, and Hebei). Compared to Beijing and Tianjin, the secondary industry in Hebei bears the highest reduction responsibilities, given that Hebei will experience the largest carbon emissions, at 0.42 billion tons in 2030, which is 80.04% of the total emissions in the Jing-Jin-Ji urban agglomeration. Energy production and heavy manufacturing sectors serve as the major carbon emitters and have relatively high carbon intensities, which indicates that they have significant potential and major responsibilities for impacting carbon mitigation. Based on differences in urban function and development mode, the same industrial sectors in the three provinces have different obligations for emission reductions. This study is vital to allocate reduction responsibilities among industrial sectors and to discrete key sector categories bearing a higher mitigation burden.

Keywords: carbon intensity; industrial sectors; quota allocation modeling; Jing-Jin-Ji urban agglomeration

1. Introduction

Both developed and developing countries must decrease carbon emissions to alleviate climate change and to ensure global sustainable development [1]. China faces specific challenges in making deep carbon emission reductions given its large population [2], rapidly expanding economy [3], and heavy reliance on coal [4]. The United Nations Framework Convention on Climate Change (UNFCCC) has found that China has surpassed the United States to become the largest carbon emitter in the world since 2009 [5]. The Chinese government has committed that by 2030, China's carbon emissions per unit of gross domestic product (GDP) will be reduced by 60% to 65% relative to the 2005 level. Urban agglomerations, or continuous urban areas, are composed of several urban centers and have been developed as part of an explicit national strategy. These agglomerations contribute 64% to China's energy-related carbon dioxide (CO_2) emissions, playing a vital role in shaping the future of climate change [6]. Carbon reductions in urban agglomerations determine national-level carbon emission reductions and climate change.

The responsibilities and equity rights of different countries, provinces, and regions have been studied using different methods. The Boltzmann distribution (a frequency distribution method) was applied to allocate permits in carbon emission trading among eight countries [7]. Pang et al. improved the Pareto model to allocate global emission quotas using the ZSG-DEA model, an effective method for optimizing comprehensive efficiency under total quantity constraints, which can achieve the optimization of resource allocation efficiency [8]. In China, several studies have allocated carbon emission allowances over different provinces [9–12]. Yu et al. concluded that the western region has the largest potential reduction capability and the lowest marginal cost, and therefore should undertake more emission reductions [11]. Focusing on the Jing-Jin-Ji urban agglomeration, Han et al. applied an integrated weighting approach to calculate the carbon reduction capacity and responsibility, finding that Hebei bears the largest burden of carbon reduction because it undertakes a large number of industrial enterprises from Beijing and Tianjin [13].

The rational allocation of carbon reduction among sectors is the basis for achieving carbon emission reduction targets [14–17]. At the national level, heavy industry sectors are understood to bear the largest share of carbon quotas; however, there are differences between specific sectors. Zhang and Hao predicted the carbon reduction responsibilities for 37 sectors and revealed that six key sectors account for 91.77% of the total quota. These six sectors include the manufacture and processing of the ferrous metals sector; the processing of the petroleum sector; the coking and processing of the nuclear fuel sector; the nonmetal mineral products sector; the chemical raw materials and chemical products manufacturing sector; and the mining and washing of the coal sector [18]. Zhao et al. proposed that the production and distribution of electric power and heat power should bear the largest burden of carbon reduction, with CO_2 emission reductions of 1825.98 million tons and 2673.69 million tons for reduction targets of 60% to 65%, respectively [16]. Those studies were mainly conducted on a country scale. This does not provide specific targets in the allocation of carbon reduction quotas in urban agglomerations and economic zones, such as the Jing-Jin-Ji urban agglomeration.

Located in North China, the Jing-Jin-Ji urban agglomeration is an important core region and center of economic growth in China. It includes Beijing (abbreviated as Jing), Tianjin (abbreviated as Jin), and Hebei (abbreviated as Ji). The synergetic development of Jing-Jin-Ji urban agglomeration was part of an explicit national strategy in the National 12th (2011 to 2015) Five-Year Plan [19]. The GDP of the Jing-Jin-Ji urban agglomeration in 2017 represented 9.74% of the total national GDP [20]; however, economic development remains imbalanced. Beijing plunders abundant resources from its surrounding area, especially Hebei, in order to achieve further economic development [21,22]. Despite its rapid economic development, Jing-Jin-Ji urban agglomeration has been assigned significant energy conservation and emission reduction responsibilities. The regional carbon emissions represented 10.24% of the total national emissions in 2015 [23]. Carbon emissions from secondary industry sectors, such as the nonmetal mineral products sectors and smelting and pressing of the ferrous metals sectors, account for 71.34% of total national emissions, indicating that reducing industrial carbon is an effective approach to conserve energy and to achieve the allocated carbon emission targets in the region.

Addressing carbon mitigation issues for industrial sectors, most researchers concern their carbon emission allocation at the national level. Generally, studies on industrial carbon reduction at the provincial level emphasize a specific industrial sector due to its features and higher emission. However, current studies rarely focus on the industrial sectors' burden-sharing problem for carbon mitigation in the Jing-Jin-Ji urban agglomeration in China, which extends the existing knowledge on the topic. Given this background, the main goals of this study were to (1) estimate the future carbon emissions and intensities of 37 industrial sectors in the Jing-Jin-Ji urban agglomeration, and (2) disaggregate the carbon reduction targets among three provinces and 37 sectors to reduce carbon emissions in the Jing-Jin-Ji urban agglomeration. This study provides meaningful information to help the Jing-Jin-Ji urban agglomeration identify carbon reduction targets, assign emission mitigation responsibilities across 37 sectors, and formulate related policies.

The rest of this paper is organized as follows. Section 2 introduces the historical trends of carbon emissions in the Jing-Jin-Ji urban agglomeration. Section 3 presents the data sources and the nonlinear carbon emission reduction quota allocation model. Section 4 shows the predicted carbon emissions and intensities of different industrial sectors in the Jing-Jin-Ji area in 2030, as well as the optimal allocation of carbon reduction targets. Several policy recommendations are proposed based on the results. The last section includes the study conclusions.

2. Overview of Carbon Emissions in the Jing-Jin-Ji Urban Agglomeration

Figure 1 shows that carbon emissions in the Jing-Jin-Ji urban agglomeration have maintained an upward trend over the long term. Compared to Beijing and Tianjin, carbon emissions were highest in Hebei, representing the major proportion of emissions among the three provinces. The cumulative carbon emissions in Hebei were 11.60 billion tons from 2000 to 2015, accounting for 72.3% of the cumulative carbon emissions in the Jing-Jin-Ji urban agglomeration. In 2005, the annual growth rate of Hebei's carbon emissions reached the highest level of 22.69%, which was near twice the level of Tianjin and four times the level of Beijing in the same year. Due to the carbon-based energy structure in Hebei, carbon emissions increased rapidly before 2005, attracting the attention of the local government. The government proposed a series of policies to control the carbon emission, which accounts for the declining growth trend after 2005. From 2000 to 2006, the carbon emissions in Tianjin were lower compared to Beijing; however, since 2007, carbon emissions in Tianjin have surpassed Beijing, and the gap in emissions between Beijing and Tianjin has widened. Beijing's carbon emission fluctuations have maintained relatively stable levels. Historical emissions data indicate that Hebei, which has had the largest historical emissions, bears the most responsibility for reducing emissions. In contrast, Beijing and Tianjin face a relatively low emission reduction burden.

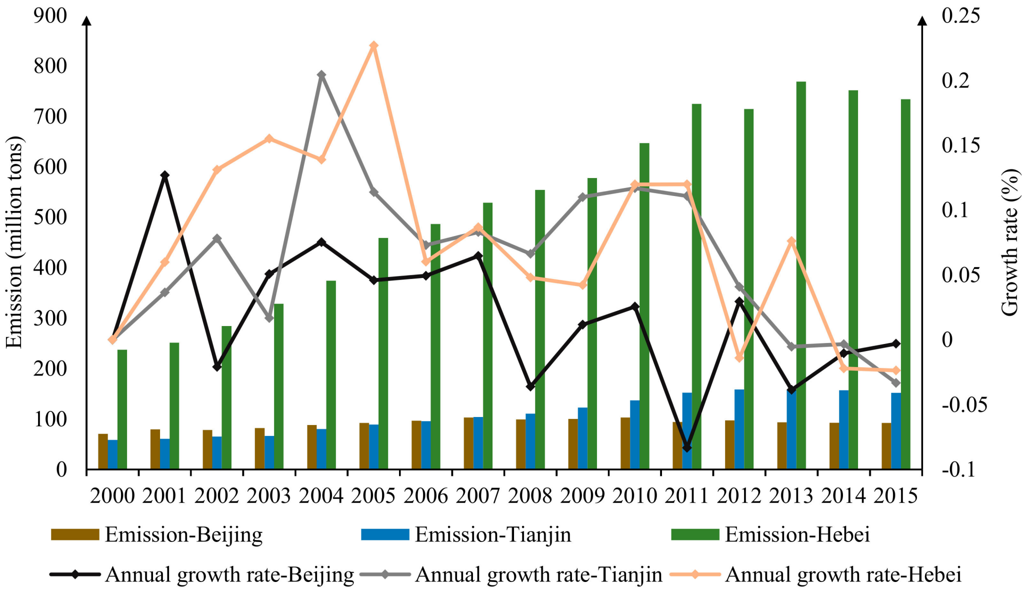

Figure 1. Time series showing carbon emissions and annual growth rate in the Jing-Jin-Ji urban agglomeration.

Figure 2 shows the historical trend of carbon emissions in the primary, secondary, and tertiary industries of the Jing-Jin-Ji urban agglomeration. Industrial sectors are the main force driving economic growth and occupy the dominant position in the three industries. Meanwhile, production processes in the secondary industry generate abundant carbon emissions. In 2015, the average carbon emissions in the secondary industry of Beijing, Tianjin, and Hebei represented 42.58%, 81.86%, and 89.37%, respectively, of total emissions. Carbon emissions generated by the secondary industry consistently remained at a high proportion of total emissions in Hebei and Tianjin. In contrast, Beijing experienced decreases in emissions, from 54.93% to 42.58% of total emissions between 2010 and 2015. To optimize cooperative development in the Jing-Jin-Ji urban agglomeration, Hebei must assume the functional transfer and additional emissions from Beijing and Tianjin [13]. For example, the Shougang Group is a large-scale enterprise group mainly engaged in the iron and steel industry. The group moved to Hebei after 2005 under an arrangement with China's national development and reform commission. This movement led to the secondary industry of Hebei having an average proportion of carbon emissions that was significantly higher compared to Beijing and Tianjin.

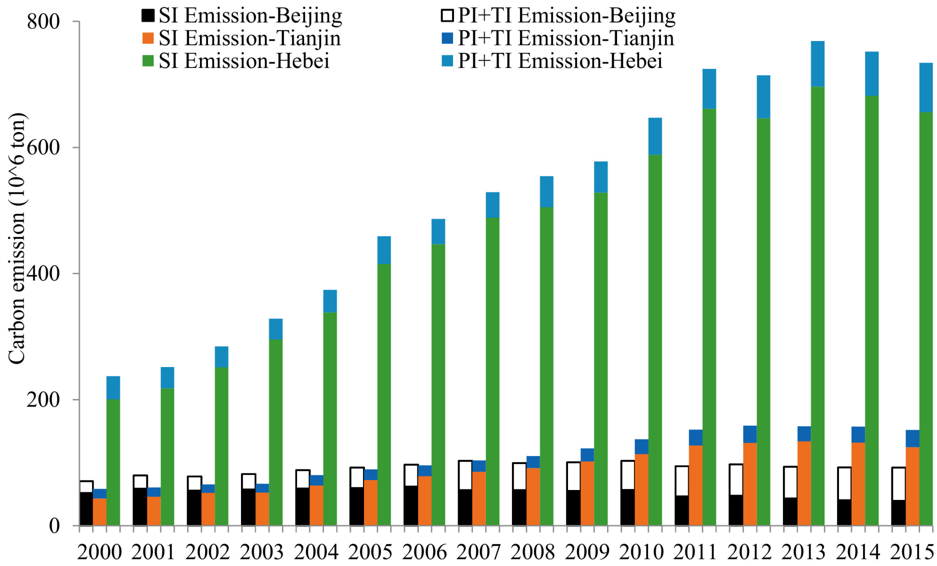

Figure 2. Carbon emission percentages from three industries from 2000 to 2015.

3. Theories and Methodologies

3.1. Data

For this study, we collected historical data, including carbon emissions (2000–2015), from the Jing-Jin-Ji urban agglomeration at the provincial and sectoral levels from China's Emission Accounts and Datasets (CEADs). CEADs regularly publishes the latest carbon emission inventories, which are compiled based on relevant energy data revisions (2015) by the Chinese Statistics Bureau [23]. We reorganized the sectoral-level data and determined the emissions data for 37 industrial sectors. The corresponding GDP and industrial value-added for different sectors were collected from the Chinese Energy Statistical Yearbook for 2000–2015. To eliminate errors driven by price fluctuations, we measured the GDP and the industrial value-added in 2015 using the year 2000 constant prices.

3.2. Carbon Emissions and Intensities in 2030

The carbon emissions and intensities for the three provinces of the Jing-Jin-Ji urban agglomeration in 2030 needed to be determined to identify optimal strategies for the allocation of carbon reduction responsibilities. Carbon intensity refers to a region's carbon emissions per unit of GDP. We selected carbon emissions per unit of industrial value added as the standard to measure carbon intensity at the sectoral level. We applied the growth rate method to forecast carbon emissions, intensities, GDP, and industrial value added. The average annual growth rates for GDP, industrial value-added, and carbon emissions from 2000 to 2015 were recognized as fixed growth rates. The year 2015 was set as the base period for predictions. Then, we generated the GDP and carbon emissions of the three provinces and the industrial value added for 37 sectors in the Jing-Jin-Ji urban agglomeration for 2030 by multiplying the base period by the growth rates. We predicted the sectoral carbon emissions level in 2030 based on the proportions that different sectors contributed to total emissions in 2015. The carbon intensities at the provincial and sectoral level in 2030 were predicted using the future GDP/industrial value-added values, divided by carbon emissions.

Subsequently, we calculated the target carbon intensities of the Jing-Jin-Ji urban agglomeration in 2030, with the goal of achieving China's mitigation targets as submitted to the UNFCCC as part of the Copenhagen Accord. The formula is as follows:

$$EI_{2030} = EI_{2005} \times \eta. \tag{1}$$

In this expression, EI_{2030} refers to the target carbon intensity of the Jing-Jin-Ji urban agglomeration in 2030 (ton/10^4 RMB); EI_{2005} is the carbon emission intensity of 2005 (ton/10^4 RMB); and η represents the national target carbon intensity reduction ratio, which was set at 60%–65% relative to the 2005 level.

The target emission reduction for 2030 was calculated as follows:

$$ER_{2030} = (FEI_{2030}(s) - EI_{2030}) \times FGDP_{2030}(s). \tag{2}$$

In this expression, ER_{2030} refers to the target carbon emission reduction of Jing-Jin-Ji urban agglomeration (ton); $FEI_{\ 2030}$represents the carbon intensities of the three provinces in 2030, which were estimated based on historical data series of carbon emissions and GDP (ton/10^4 RMB); and $FGDP_{2030}$ is the GDP of three provinces in 2030, which was estimated based on the historical GDP data series (10^4 RMB).

3.3. Nonlinear Quota Allocation Modeling

A nonlinear quota allocation model was applied to solve the problem of minimizing abatement costs within the constraint of emission reduction targets. Estimated carbon intensities and the amount of allowable emission were entered into the model to solve the model algorithm. We constructed a marginal abatement cost curve to estimate the abatement cost when realizing carbon emission reduction targets. Previous studies have mainly adopted three forms to investigate abatement costs: the exponential function [24], quadratic function [25], and logarithmic function [26,27]. This study applied the logarithmic function. We generated the formula for the marginal abatement cost curve based on the marginal abatement cost data from the Emissions Prediction and Policy Analysis (EPPA) model [28]. The formula is as follows:

$$MC = -70.9 - 702.6 \times \ln(1 - R). \tag{3}$$

For sector i, we have:

$$r_i = 1 - \frac{e_i}{e_n}. \tag{4}$$

In this expression, e_i refers to the carbon intensity of sector i; and e_n represents the local carbon intensity. When the carbon intensity of sector i is less than the local carbon intensity, then $r_i > 0$. Otherwise, $r_i < 0$. Next, we calculated the marginal abatement cost of sector i with the carbon reduction proportion R_i, as follows:

$$MC_i(R_i) = MC(R_i + r_i) - MC(r_i) = \beta \ln(1 - \frac{R_i}{1 - r_i}). \tag{5}$$

This can be further translated into the formula as follows:

$$MC_i(A_i) = \beta \ln(1 - \frac{A_i}{E_i(1 - r_i)}). \tag{6}$$

In this expression, A_i refers to the emission reductions in sector i, and E_i represents the total predicted emissions from sector i. The total abatement cost for emission reductions in sector i is calculated as follows:

$$C_i(A_i) = \int_0^{A_i} [\beta \ln(1 - \frac{\sigma}{E_i(1 - r_i)})] d\sigma = -\beta[E_i(1 - r_i) - A_i] \ln(1 - \frac{A_i}{E_i(1 - r_i)}) - \beta A_i. \quad (7)$$

The nonlinear quota allocation optimization model can then be formulated as:

$$min\ T\ C = \sum\nolimits_i \left\{ -\beta[E_i(1 - r_i) - A_i] \ln(1 - \frac{A_i}{E_i(1 - r_i)}) - \beta A_i \right\}. \quad (8)$$

This expression is subject to:

$$\sum_i A_i = A; \quad (9)$$

$$A_i \geq 0;. \quad (10)$$

4. Results and Discussion

4.1. Carbon Mitigation at the City Level

Jing-Jin-Ji urban agglomeration's carbon emissions and intensities in 2030 were predicted as shown in Table 1. In general, Jing-Jin-Ji urban agglomeration will witness an increase of 639.24 million tons of carbon emissions in 2030 compared to the 2015 level. There are significant differences among Beijing, Tianjin, and Hebei due to their different energy consumption structures, technological levels, and industrial structures. Hebei is predicted to experience the highest carbon emissions, at 1.21 billion tons in 2030, accounting for approximately 92.14% of the total emissions in the Jing-Jin-Ji urban agglomeration. The carbon intensity in Hebei is estimated to be 2.58 tons per 10^4 RMB in 2030, which is 3.79 times the predicted level for Beijing and 2.55 times the predicted level for Tianjin. Hebei is the home of many energy-consuming industrial enterprises, which have been transferred from Beijing and Tianjin. Extensive development and inefficient industrial structures in Hebei are predicted to create high carbon intensity [29]. The low levels of carbon emissions and intensities in Beijing and Tianjin result from efficient economic development, advanced manufacturing equipment, and mature technology [30].

Table 1. Carbon emissions, intensity, and target reduction for the Jing-Jin-Ji urban agglomeration in 2030.

Regions	Emissions in 2030 (106 ton)	Emission Intensity in 2030 (ton/10^4 RMB)	Target Reduction		Target Reduction for the Secondary Industry	
			60% (10^4 ton)	65% (10^4 ton)	60% (10^4 ton)	65% (10^4 ton)
Beijing	152.41	0.68	482.59	1046.75	229.42	497.63
Tianjin	251.19	1.01	1184.67	2569.58	986.40	2139.52
Hebei	1213.86	2.58	14,605.65	31,680.13	13,257.59	28,756.14

Beijing, Tianjin, and Hebei are predicted to undertake varying emission reduction responsibilities to achieve China's total carbon intensity reduction targets in 2030 (Table 1). The differentiated reduction quotas are consistent with the Common but Different Responsibilities (CBDR) proposed by the Chinese government [13]. Hebei will bear the greatest emission reduction obligations, given its status as a gathering place of heavy industrial enterprises. A total of 146.05 and 316.80 million tons should be reduced in Hebei to achieve reduction targets of 60% and 65%, respectively. However, carbon reduction requirements significantly conflict with local economic development goals [31]. Reduction quotas for Tianjin are 11.85 and 25.70 million tons to achieve 60% and 65% reduction targets, respectively. Beijing has completed the early stages of industrialization, and the current energy consumption by its industrial sectors is assumed to be highly efficient. Therefore, Beijing has the lowest reduction responsibility among the three regions.

Table 2 compared the composition of the secondary industry in developed countries and the Jing-Jin-Ji urban agglomeration in China. The secondary industry only dominates 20.7%, 16.8%, and 26.9% of the total industry in the United States, the United Kingdom, and Japan, respectively. The secondary industry dominates approximately 89.4%, 81.9%, and 42.6% of the total mitigation responsibility of Hebei, Tianjin, and Beijing, respectively. It is known that a structural bonus (economic benefits arising from the rationalization of economic structure) benefits energy intensity, meaning that optimization and adjustments to the industrial structure could support decreased emissions [32–34]. For example, the rise in the proportion of the tertiary industry plays a positive role in reducing carbon emissions [35]. In consequence, Jing-Jin-Ji urban agglomeration still has great potential to further upgrade the industrial structure and develop a low-carbon economy.

Table 2. The composition of secondary industry in developed countries and in China's Jing-Jin-Ji urban agglomeration (%).

Year	United States	United Kingdom	Japan	Beijing	Tianjin	Hebei
2005	22.00	26.20	30.20	64.70	80.90	90.40
2010	21.40	21.10	28.00	54.90	82.70	90.90
2015	20.70	16.80	26.90	42.60	81.90	89.40

4.2. Industrial Sectors' Carbon Emissions in 2030

Reducing carbon emissions requires joint efforts from different industrial sectors (listed in Table 3). In this study, we predicted the carbon emissions and intensities of 37 sectors in the secondary industry in 2030 (shown in Figure 3). All 37 industrial sectors are predicted to emit a total of 21.02, 94.70, and 419.86 million tons of carbon dioxide in Beijing, Tianjin, and Hebei, respectively. The major carbon emitters include energy production sectors and heavy manufacturing sectors. For example, S35 (Production and Supply of Electric Power, Steam, and Hot Water) is a typical energy production sector, generating approximately 50% of the total carbon emissions at the national scale [36]. In this study, S35 is forecasted to discharge carbon emissions of 17.31, 46.99, and 142.61 million tons in Beijing, Tianjin, and Hebei, respectively; the corresponding carbon intensities are predicted to be 0.99, 6.31, and 4.92 tons/10^4 RMB, respectively. S24 (Smelting and Pressing of Ferrous Metals) is one of the four most energy-intensive industries, with a high potential to support energy conservation and decrease emissions [37]. S24 is expected to discharge carbon emissions of 0.14, 35.80, and 208.74 million tons in Beijing, Tianjin, and Hebei, respectively, accounting for 0.68%, 37.80%, and 49.70% of the total emissions from the secondary industry in the three respective provinces.

Table 3. Industrial sectors and their abbreviations.

Industrial Sectors	Abbreviation	Classification
Coal Mining and Dressing	S1	Energy production
Petroleum and Natural Gas Extraction	S2	Energy production
Ferrous Metals Mining and Dressing	S3	Heavy manufacturing
Nonmetal Minerals Mining and Dressing	S4	Heavy manufacturing
Food Processing	S5	Light manufacturing
Food Production	S6	Light manufacturing
Beverage Production	S7	Light manufacturing
Tobacco Processing	S8	Light manufacturing
Textile Industry	S9	Light manufacturing
Garments and Other Fiber Products	S10	Light manufacturing
Leather, Furs, Down, and Related Products	S11	Light manufacturing

Table 3. *Cont.*

Industrial Sectors	Abbreviation	Classification
Timber Processing, Bamboo, Cane, Palm Fiber, and Straw Products	S12	Light manufacturing
Furniture Manufacturing	S13	Light manufacturing
Papermaking and Paper Products	S14	Light manufacturing
Printing and Record Medium Reproduction	S15	Light manufacturing
Cultural, Educational, and Sports Articles	S16	Light manufacturing
Petroleum Processing and Coking	S17	Energy production
Raw Chemical Materials and Chemical Products	S18	Heavy manufacturing
Medical and Pharmaceutical Products	S19	Light manufacturing
Chemical Fiber	S20	Heavy manufacturing
Rubber Products	S21	Heavy manufacturing
Plastic Products	S22	Heavy manufacturing
Nonmetal Mineral Products	S23	Heavy manufacturing
Smelting and Pressing of Ferrous Metals	S24	Heavy manufacturing
Smelting and Pressing of Nonferrous Metals	S25	Heavy manufacturing
Metal Products	S26	Heavy manufacturing
Ordinary Machinery	S27	Heavy manufacturing
Equipment for Special Purposes	S28	Heavy manufacturing
Transportation Equipment	S29	Heavy manufacturing
Electric Equipment and Machinery	S30	High-tech industry
Electronic and Telecommunications Equipment	S31	High-tech industry
Instruments, Meters, Cultural, and Office Machinery	S32	High-tech industry
Other Manufacturing Industry	S33	High-tech industry
Scrap and waste	S34	High-tech industry
Production and Supply of Electric Power, Steam, and Hot Water	S35	Energy production
Production and Supply of Gas	S36	Energy production
Production and Supply of Tap Water	S37	Heavy manufacturing

The sectors with lower carbon emissions and intensities are mainly those engaged in light manufacturing and high-tech industries, i.e., S11 (Leather, Furs, Down, and Related Products), S12 (Timber Processing, Bamboo, Cane, Palm Fiber, and Straw Products), S32 (Instruments, Meters, Cultural and Office Machinery), and S33 (Other Manufacturing Industry). S11 is predicted to generate carbon emissions of 0.001, 0.01, and 0.15 million tons in Beijing, Tianjin, and Hebei in 2030, with the intensities of 0.04, 0.02, and 0.02 tons/10^4 RMB, respectively. Carbon emissions from light manufacturing sectors are mainly from the widespread use of obsolete production equipment [38] and the lack of core technology [39]. In the 12th Five-Year Plan (completed well by the end of 2015), these industrial enterprises were required to establish the goal of green production. With clear government directives and effective control technology, these light manufacturing sectors have seen low direct carbon emissions currently and will witness declining trends of emissions in the future.

The high-tech industry sectors refer to five sectors aiming at producing with high and new techniques, including S30, S31, S32, S33, and S34. Since high-tech industry sectors give consideration to both production efficiency and environmental protection, these sectors emit relatively low carbon emissions, which contributes to the realization of the 2030 carbon reduction targets [16]. Carbon emission intensities of high-tech industry sectors remained at a consistently low level in these three provinces. Especially in Beijing, S30 and S34 have the least carbon intensities among the 37 industrial sectors, namely 0.004 and 0.006 10^4 tons/RMB. The Chinese government and the local government in the Jing-Ji-Ji urban agglomeration have made efforts to support the development of high-tech industry sectors in order to mitigate carbon emissions and to improve the core competitiveness of cities. Taking S34 for instance, the Chinese government implements a plan of industrial resources comprehensive utilization industry coordinated development in Jing-Jin-Ji and its surrounding areas (2015–2017) aiming at achieving the effective reuse of industrial scrap and wastes and exploring a new mode of synergistic development in S34. The plan projects to realize a reduction of carbon emissions by 4 million tons per year [40]. Relevant policies have provided effective guidance for the expansion of the production scale and carbon reduction in the high-tech industry sectors in the Jing-Jin-Ji urban agglomeration. Local governments also need to consider accelerating technological exchanges and cooperation to promote more efficient and cleaner production in these industries.

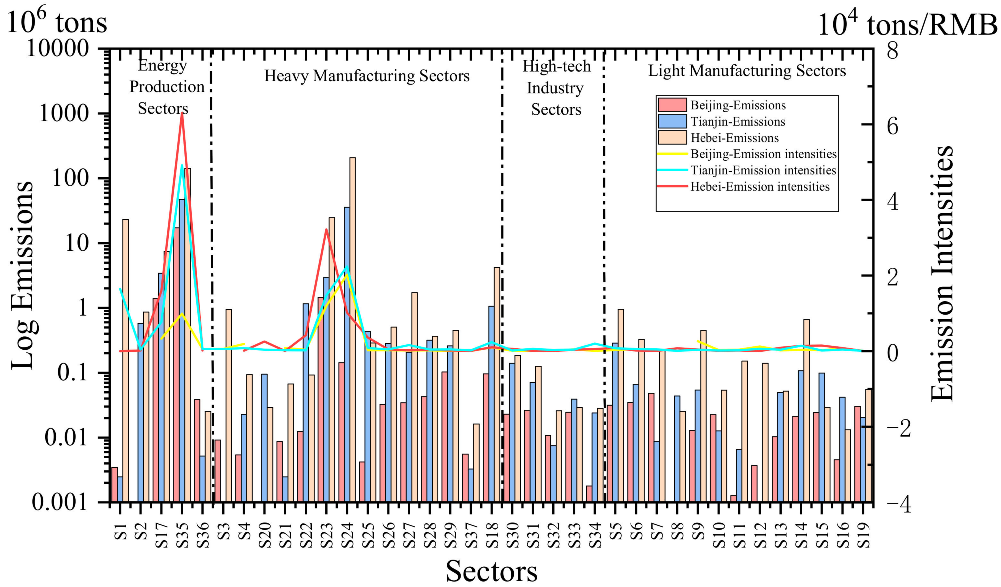

Figure 3. Predicted carbon emissions from industrial sectors in 2030.

4.3. Carbon Mitigation for Industrial Sectors

The optimized carbon quotas for 37 sectors of secondary production in the Jing-Jin-Ji urban agglomeration were further calculated. Key sectors sharing significant responsibility for reducing emissions were presented in Figure 4, occupying nearly 99% of the total reduction quotas. The rest sectors with carbon reduction quotas less than 250 hundred tons are listed in the Table S1. As the most prominent energy production sector, S35 has the largest responsibility to reduce carbon emissions in all three provinces; the predicted goal is to mitigate 4.34, 74.27, and 161.09 million tons of emissions for Beijing, Tianjin, and Hebei, respectively, to achieve the 65% target. At the national scale, S35 also has the largest carbon reduction quota to achieve 60% and 65% target levels in 2030 [16]. Another traditional energy production sector, S17 (Petroleum Processing and Coking), will have reduction quotas of 0.12, 0.33, and 1.32 million tons to achieve the 65% target in Beijing, Tianjin, and Hebei, respectively. The results indicated that S17 bears smaller carbon reduction quotas than S35 under the 2030 reduction targets. S23 and S24 are pillars of the high manufacturing sector and carry significant responsibilities for emission reductions. Note that the development of these four sectors may hinder the reduction of carbon emissions; however, the entire secondary industry would be hit hard without these sectors [18]. In fact, developing these sectors may greatly enhance the overall economic growth of the Jing-Jin-Ji urban agglomeration; as such, the trade-offs between industrial development and emission reduction deserve reconsideration.

The selected key emission reduction sectors varied largely among Beijing, Tianjin, and Hebei due to the differences of urban functions and industrial development levels. Hebei assumes significant responsibility for energy production in the Jing-Jin-Ji urban agglomeration. As a result, the energy production sector S1 holds the biggest reduction burden in Hebei: 4.06 and 8.80 million tons at 60% and 65% reduction targets, respectively. At the national level, Yan et al. [36] found that S1 bears responsibility for 62.49% of the total reduction target. S18 and S27, two typical heavy manufacturing sectors, bear 0.23 and 0.06 million tons, respectively, to achieve 65% reduction targets in Hebei. However, Beijing and Tianjin have very low responsibilities with respect to these sectors. This is because Hebei has a large number of heavy manufacturing industrial enterprises. In addition, S22

(Plastic Products) faces significant pressure to reduce emissions in Tianjin, with reduction quotas of 0.01 million tons to achieve the 60% target and 0.03 million tons to achieve the 65% target. In contrast, Beijing and Hebei have relatively small mitigation responsibilities.

The allocation of reduction quotas is closely associated with carbon emissions and intensities. Higher carbon intensities indicate a greater potential for emission reductions. Energy production and heavy manufacturing sectors tend to have high carbon emissions intensities. As such, these sectors are allocated the largest emission carbon reduction quotas. When the carbon intensities of two sectors are the same, the difficulty associated with sector-level carbon reductions is correlated with carbon emissions. For example, S14 (Papermaking and Paper Products) and S22 are predicted to have the same carbon intensities of 0.037 tons/10^4 RMB in Beijing in 2030. The carbon emissions of S14 (0.021 million tons) are predicted to be higher than those of S22 (0.012 million tons), leading to a larger mitigation responsibility being assigned to S14 compared to S22. These results were consistent with a study on the provincial allocation of carbon reduction responsibilities conducted by Wang et al. [24]. Although the results may have some uncertainties under the constraint of long time-series data, the methodology and results in our study are valid for carbon mitigation in industrial sectors at the provincial level in China.

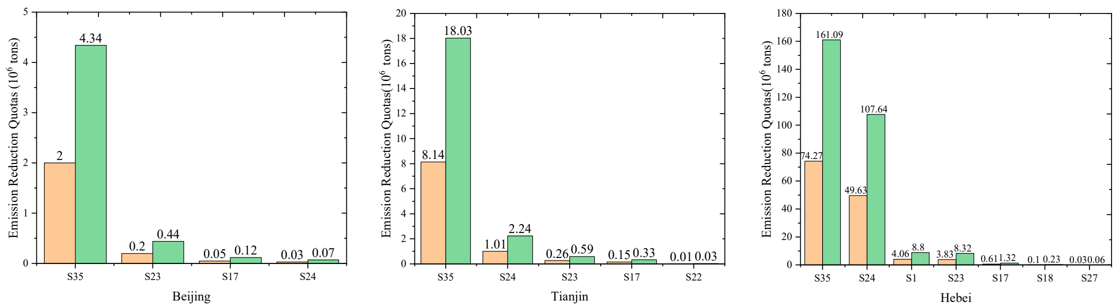

Figure 4. Carbon emission reduction quotas for key sectors. The orange and green pillar represents the allocation responsibility of carbon emission reduction under the 60% and 65% targets, respectively.

4.4. Policy Implications

The allocation of emission reduction responsibilities at the sectoral level should be clearly defined by policymakers. Unclear responsibilities are associated with low efficiency in reducing carbon emission. Heavily energy-dependent manufacturing sectors, such as S35, S23, and S24, should be responsible for major emission reductions in the Jing-Jin-Ji urban agglomeration. These sectors should stringently control pollution emissions by transforming the extensive economic development mode, accelerating the application of advanced technologies, and eliminating underdeveloped production capacity. Light manufacturing and high-tech industry sectors should consider accelerating their transformation, moving from labor-intensive to technology-intensive approaches, and thus to improve the efficiency of energy use and further to reduce carbon emissions.

Different provinces are encouraged to introduce different and coordinated control schemes to reduce carbon emissions. Regions should exchange relevant experience to maximize the synergistic effect of low-carbon economic development. Hebei should implement clean production and energy consumption structural adjustments to promote low-carbon development and to narrow the gap with Beijing–Tianjin. Many carbon-intensive enterprises have been transferred to Hebei; as such, Beijing should appropriately subsidize Hebei.

Clean production technology and equipment should be advanced in the Jing-Jin-Ji urban agglomeration and surrounding areas to combine technological upgrades and industrial restructuring. Adjusting ineffective emission structures should play a dominant role in saving energy and reducing emissions in industrial sectors.

5. Conclusions

Consistent with the Paris Climate Agreement, China has pledged to decrease its carbon intensity by 60%–65% compared to 2005 levels by 2030. The Jing-Jin-Ji urban agglomeration, a key carbon emission center in China, was an ideal case study to allocate carbon reduction quotas in industrial sectors. This study established a nonlinear quota allocation model to achieve target carbon reduction among 37 industrial sectors in the Jing-Jin-Ji urban agglomeration at targets of 60% and 65%, respectively. The results provide insights into the carbon emission reduction, industrial structure adjustment, and the future direction of industrial sectors. The major findings and their implications for future researches over carbon mitigation are as follows.

Major energy production and heavy manufacturing sectors including S17, S18, S23, S24, and S35, discharge the main share of the total carbon emissions in the Jing-Jin-Ji urban agglomeration. In contrast, light manufacturing and high-tech industry sectors discharge small amounts of carbon emissions. Sectors with large amounts of emissions and high carbon intensities offer significant potential and face relatively little difficulty in carbon reduction, so they are assigned considerable carbon mitigation responsibilities. Due to the different urban functions and industrial development levels, the same industrial sector may assume different responsibilities for emission reduction in Beijing, Tianjin, and Hebei. Overall, this study provides a theoretical basis for carbon reduction in the Jing-Jin-Ji urban agglomeration, since it could formulate a more explicit policy to optimize the carbon emission reduction allocation mechanism. Using policy guidance and clear allocation of responsibilities, the carbon emission reductions in the Jing-Jin-Ji urban agglomeration could be further enhanced, contributing to the mutual development of the economy and environment.

There are two main limitations in our research. On one hand, predictions of future carbon emissions and intensities may not accurately reflect the real situation, which is a common flaw in all predicting methods in reality. The transformation of the industrial structure and the improvement of energy-use efficiency are not taken into account when using the average growth rate to anticipate future change. On the other hand, when distributing the mitigation quotas, the criteria of accumulated emissions responsibility, current economic capacity, and emissions efficiency are not considered in our methods. Owing to the characteristics of some industrial sectors, they are bound to emit vast proportions of carbon dioxide. Once unduly stringent industry emission mitigation targets are set to these sectors, the developments of these sectors are likely to be restrained, which leads to a negative impact on the developments of other sectors and the economic development in the whole region. We suggest constructing a more rational multicriteria model to allocate mitigation burdens among numerous economic sectors in further studies.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/22/6383/s1, Table S1: Carbon emission reduction quotas (less than 250 hundred tons) for other sectors.

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