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Multi-Scale GHG Emission Relations in Resource-Based Heavy Industrial Cities: A Case Study of Tangshan City, Hebei Province

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The greenhouse gas (GHG) emission pressure faced by resource-based heavy industrial cities was mainly induced by multi-scale interactions, which require systematical assessments from local, regional, national and global scales. Taking Tangshan city, a heavy industry base in Hebei Province of China, as the research area, this study carried out a multi-scale analysis on the GHG emissions in terms of final demand, final consumption and trade balance. The main results are as follows: (1) The average embodied intensity of GHG emissions in Tangshan was 27.6 tons/10,000 CNY, of which 66.2% was caused by local inputs; (2) The secondary industry was the main source for the relatively high GHG emissions in Tangshan; (3) The GHG emissions embodied in final demand were 201.6 million tons, within which the proportion of fixed capital formation reached 59.4%; (4) As for the trade balance, Tangshan was a net exporter of embodied GHG emissions, with the total net outflows of 411.6 million tons. Depicting the GHG emission flows and sorting out the multiple GHG emission inventory would be helpful to identify the transformation pressure of resource-based heavy industry cities, which would be significant for the adjustments in industrial structures and policy optimization of energy saving and emissions reduction.

Keywords: Resource-based heavy industry city; embodied greenhouse gas emissions; multi-scale input–output analysis.

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1. Introduction

Cities are the main energy consumers and greenhouse gas (GHG) emitters, being responsible for more than 80% of the total GHG emissions caused by human activities (IPCC, 2006). Resource-based heavy industrial cities, mainly driven by the growth of heavy industries, have played an essential role in regional and national economic development for a long time (Wang and Guo, 2012). Compared with other cities, resource-based heavy industrial cities are characterized by high emissions and high energy consumption (Siriji and Mao, 2019). Due to the reliance on non-renewable resources and the excessive exploration of natural resources, the advantages brought by natural resources to these cities are gradually declining, making these cities facing a dilemma in economic development (Pan, 2017). Among the resource-based heavy industrial cities, Tangshan city, Hebei province is one of the most typical one in China and one of the central cities in the Beijing–Tianjin–Tangshan industrial base, China's second largest comprehensive industrial base, occupying a pivotal position in the industrial and economic development of the Beijing–Tianjin–Hebei region as well as the whole country. The abundant iron ore and coal resources and the related industries have promoted the rapid development of Tangshan's heavy industries, but also kept the GHG emissions in Tangshan at a high level, making it urgent to transform and upgrade its industrial structures (Gong *et al.*, 2010).

Up to now, there have been a large number of studies worldwide related to urban GHG emissions, most of which were conducted from the direct GHG emission perspective (Bai *et al.*, 2013; Cai, 2012; Jiang *et al.*, 2013). Among them, Liu *et al.* (2011) sorted out the inventory of carbon dioxide (CO_2) emissions in Shanghai and proposed that the industry and energy productions were the main contributors to CO_2 emissions. Kennedy *et al.* (2012) analyzed the GHG emission inventories in six global cities and found that the per capita GHG emissions in most of the cities were reducing, primarily through stationary combustion changes. Schulz (2010) quantified the overall inventory of GHG emissions in Singapore and proposed that the direct emissions accounted for only 20% of the overall upstream emissions to maintain the economic production processes.

With the increasing relations among economies, the input–output analysis has been applied to the economic connectivity and resources/environment research between countries/regions (Leontief, 1970). Among them, some studies explored the relations between economic systems and GHG emissions, and analyzed economic activities and GHG emissions in economies by scale (Guan *et al.*, 2008; Liu *et al.*, 2010). In terms of the global carbon emissions, Davis and Caldeira (2010) conducted a multi-regional analysis on CO_2 emissions related to production, consumption, and trade activities driven by the fossil fuel burning in 57 sectors in 113 countries. Peters *et al.* (2011) quantified the growth in emission flows via international trade and constructed the global database of trade-related CO_2 emissions covering 113 countries and 57 sectors. Wang and Xiang (2011) quantified major countries' carbon emissions embodied in international bilateral trade, and argued that developing countries exhausted a great amount of CO_2 emissions for consumers in developed countries through international trade. Zhou (2010) calculated the carbon emissions embodied in the international trade in 10 countries/regions including China, and proposed that the United States was the largest net importer of embodied carbon emissions based on the multi-regional input–output analysis. Yao *et al.* (2018) conducted the embodied carbon flows in regions along the Belt and Road, and revealed that the production-based carbon intensities were significantly higher than those of the consumption-based emissions based on the MRIO analysis, with the significant carbon leakage in the Belt and Road regions.

Regarding the GHG emissions in different countries, the input–output analysis was also applied to carbon emission accounting in the economic activities (Du and Zhang, 2012; Yan and Zhao, 2012). Among them, Li and Fu (2010) assessed the carbon emissions embodied in China's exports, and argued that the main reasons for the increased carbon emissions embodied in exports were the growing total export volume and changes in intermediate production technologies. Yu and Peng (2017) assessed the carbon emissions transfers in China's foreign trade, and indicated that developing countries emitted a huge amount of CO_2 emissions for developed countries as consumers through international trade. Based on the IPCC inventory and MRIO analysis, Sun *et al.* (2010) analyzed the direct and indirect carbon emissions of the products/services that were produced to meet the final consumption of China's national economy, and found that the carbon emissions in China mostly came from final use, making China a net importer of carbon emissions.

In terms of urban scale, Zhong *et al.* (2015) explored the carbon emissions embodied in the trade of Shanghai, and analyzed the impacts of trade on the carbon emissions in urban industries and final demand and the responsibilities for emission reduction. Meng *et al.* (2018) traced the carbon flows in Beijing from production and consumption perspectives based on the multi-scale input–output model. Hu *et al.* (2016) tracked the carbon flows of eight Chinese cities and measured the carbon footprints from four perspectives. Besides, to distinguish the differences of resources and environment at different scales, some studies established vertical linkages between different scales (Chen *et al.*, 2013; Guo and Chen, 2013), and analyzed the embodied environmental flows at different scales (Han *et al.*, 2018; Li *et al.*, 2018; Shao *et al.*, 2016).

With a deep understanding of sustainable development and the continuous revolution of resource-based heavy industrial cities, it has become increasingly significant to analyze the impact of embodied GHG emissions on multi-scale relations in resource-based heavy industrial cities. The above-mentioned research has conducted a systematic accounting on GHG emissions for typical economies, achieving a huge progress in theory, concepts and methods. Although scholars have carried out a series of input–output studies related to GHG emissions in provinces and municipalities (Guo *et al.*, 2012), while the impacts of embodied carbon emissions of resource-based heavy industrial cities at local, regional, national, and global scales have not been fully explored. The problems of GHG emissions faced by resource-based heavy industrial cities resulted from the combination of multiple scale effects, which requires full understanding of the GHG emissions at urban, regional, national and global scales. Compared with the existing research, the main innovations of this study include: (i) The innovation in research objects: this study assessed carbon emission linkages in a typical economy characterized as resource-based heavy industrial cities, for which the method and framework could provide references for other cities' transition and upgrading with the same characteristics; (ii) The innovation in research methods: this study assessed the carbon emissions at the urban scale, carried out research on carbon emission linkages based on the MSIO analysis, and traces the carbon emission flows at the global, national, provincial and urban scales.

Based on the multi-scale GHG emission accounting framework and taking Tangshan city, Hebei province as the case, this study constructs the multi-scale inventory of GHG emissions in typical resource-based heavy industrial city by combining the urban, regional, national and global scales, tracks the major flows of GHG emissions, and depicts the multi-scale system of GHG emissions in Tangshan city, Hebei province. By considering the trade exchanges between economies at different scales, this study explores the correlations of GHG emissions in Tangshan and different scales from the aspects of embodied intensity, final demand, and trade balance, and puts forward feasible policy implications through comparing the GHG emission intensities and equilibrium relations at different scales, which would be of significance for promoting the economic transition and low-carbon development of resource-based heavy industrial cities and achieving the low-carbon development during China's industrialization.

2. Methods and Data Sources

2.1. *Direct GHG emission accounting*

The GHG emissions at the global and national scales were accounted based on the Emissions Database for Global Atmospheric Research (EDGAR) jointly established by the EU Joint Research Centre and the Netherlands Environmental Assessment Agency. To evaluate the impacts of various GHG emission on climate change, existing studies usually use Global Warming Potential (GWP) to uniformly measure the effective degree of each type of GHG emissions per unit mass. This study quotes the 100-year GWP ratio of carbon dioxide, methane and nitrous oxide (1:25:310) given by the IPCC, converting the units of all GHG emissions into CO_2 equivalent. As for the inventories of direct GHG emissions at the regional and local scales, this study mainly referred to the accounting methods in the *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)* compiled by the National Development and Reform Commission of China (NDRC). The accounting methods and data sources of GHG emission sources are shown in Table 1.

2.2. *MSIO analysis*

Based on the economic input–output table and considering the different ecological elements embodied in similar products inside and outside of the system, the basic structure of

Table 1. GHG emission inventory.

Unit	Emission sources	Calculation methods	Data sources at the regional scale	Data sources at the urban scale	Attribution of emission sources
Energy production and consumption activities	The burning of fossil fuel	$E_{GHG} = \sum\sum(EF_{i,k} \times Activity_{i,k} \times GWP_k)$ where E_{GHG} is the GHG emissions of the sector, EF is the emission factor of fuel combustion, *Activity* is the measure of fuel consumption, GWP is the global warming potential, i is the fuel type, and k is the type of GHG emissions.	*EF*: IPCC (2006); *Activity*: Shan *et al.* (2018)	*EF*: IPCC (2006); *Activity*: *Tangshan Statistical Yearbook 2013*.	Involving the GHG emissions attributed to 42 sectors
	The burning of biomass	$E_{GHG} = \sum\sum(EF_{i,k} \times Activity_{i,k} \times GWP_k)$.	*EF*: Tian *et al.* (2011); *Activity*: Yang and Zhang (2012)	The data are not available, but the deviation could be accepted.	Attributed to Sector 1
	Fugitive methane emissions from coal mining and post-mining activities	$E_{GHG} = \sum(EF_i \times Yield_i \times 25)$ where EF is the fugitive emission factor of methane, Yield is the raw coal output, i is the type of coal mine, and 25 is the warming potential of methane (the same below).	*EF*: *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial); Yield*: *China Coal Industry Yearbook 2012*	*EF*: *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)*; *Yield*: *Tangshan Statistical Yearbook 2013*.	Attributed to Sector 2
Industrial production process	Cement production process	$E_{GHG} = EF \times Yield$ where EF is the CO_2 emission factor of cement production, and Yield is the output of cement.	Shan *et al.* (2018)	*EF*: *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)*; *Yield*: *Tangshan Statistical Yearbook 2013*.	Attributed to Sector 13

(*Continued*)

Table 1. (*Continued*)

Unit	Emission sources	Calculation methods	Data sources at the regional scale	Data sources at the urban scale	Attribution of emission sources
Agriculture	Methane emissions from rice field	$E_{GHG} = \sum(EF_i \times Area_i \times 25)$ where EF is the emission factor of methane from rice field, Area is the rice planting area, and i is the rice type.	*EF*: Shang *et al.* (2015); *Area*: *China Agriculture Yearbook 2012*	*EF*: Shang *et al.* (2015); *Area*: *Tangshan Statistical Yearbook 2013*.	Attributed to Sector 1
	Methane emissions from animal enteric fermentation	$E_{GHG} = \sum(EF_i \times Amount_i \times 25)$ where EF is the emission factor of methane from enteric fermentation, Amount is the animal breeding stock at the end of the year, and i is the animal species (the same below).	*EF*: Shang *et al.* (2015); *Amount*: *China Animal Husbandry Yearbook 2012*	*EF*: Shang *et al.* (2015); *Amount*: *Tangshan Statistical Yearbook 2013*.	
	Methane and nitrous oxide emissions from animal manure treatment	$E_{GHG} = \sum\sum(EF_{i,k} \times Amount_{i,k} \times GWP_k)$ where EF is the emission factor of methane from manure treatment.			
Waste disposal	Landfill treatment of municipal solid waste	$E_{GHG} = [(MSW \times L_0) - R] \times (1 - OX) \times 25$ where MSW is the total domestic waste at landfill, L_0 is the methane generation potential, R is the methane recovery amount, and OX is the oxidation factor.	*MSW*: *China Urban Construction Statistical Yearbook 2013*; L_0, *R*, *OX*: *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)*.		Attributed to Sector 23
	Methane emissions from domestic and industrial wastewater treatment	$E_{GHG} = TOW \times B_0 \times MCF \times 25$ where TOW is the content of degradable organic matter in the wastewater, B_0 is the maximum methane-producing capacity, and MCF is the methane correction factor.	*TOW*: *China Statistical Yearbook on Environment 2013*; B_0, *MCF*: *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)*.	*TOW*: *Tangshan Statistical Yearbook 2013*; B_0, *MCF*: *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)*.	

Table 1. (*Continued*)

Unit	Emission sources	Calculation methods	Data sources at the regional scale	Data sources at the urban scale	Attribution of emission sources
	Carbon dioxide emissions from solid waste incineration	$E_{GHG} = IW \times CCW \times FCF \times EF \times 44/12$ where IW is the total amount of domestic waste incineration, CCW is the proportion of carbon of the domestic waste incineration, FCF is the fraction of fossil carbon in the total carbon of the domestic waste incineration, EF is the combustion efficiency of the incinerator, and 44/12 is the conversion coefficient of carbon-to-carbon dioxide.	*IW*: *China Urban Construction Statistical Yearbook 2013*; *CCW*, *FCF*, *EF*: *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)*.		

the multi-scale input–output table with embodied GHG emissions is established, as shown in Table 2. In Table 2, $z^L_{i,j}$ represents the intermediate flows from Sector i to Sector j within the system; $z^P_{i,j}$ represents the intermediate flows from Sector i at the provincial scale to Sector j within the system; $z^d_{i,j}$ represents the intermediate inputs from Sector i at the national scale to Sector j within the system; $z^F_{i,j}$ represents the economic flow of intermediate inputs from Sector i of the global economy to Sector j within the system; d^L_i, d^P_i, d^d_i and d^F_i, respectively, represent the economic flows provided by Sector i at the provincial, national, and global scales to the final demand; ex^{LP}_i, ex^{LD}_i and ex^{LF}_i, respectively, represent the economic flows from Sector i to the provincial, national and global scales; y_i represents the total economic output by Sector i within the system; $d_{k,i}$ represents the k type of direct GHG emissions by Sector i within the system.

Figure 1 further presents the input–output balance of GHG emission flows of Sector i at the urban scale. Among them, $\varepsilon^L_{k,j}$, $\varepsilon^P_{k,j}$, $\varepsilon^d_{k,j}$ and $\varepsilon^F_{k,j}$, respectively, represent the k type of GHG emission intensities of Sector j at the urban, provincial, national and global scales; im^{PL}_j, im^{DL}_j and im^{FL}_j, respectively, represent the economic flows from Sector j to Sector i at the provincial, national, and global scales. Introduce $\varepsilon^L_{k,j}$, $\varepsilon^P_{k,j}$, $\varepsilon^d_{k,j}$ and $\varepsilon^F_{k,j}$ into Fig. 1, respectively, representing the k type of GHG emission intensities of Sector j at the urban, provincial, national and global scales; im^{PL}_j, im^{DL}_j and im^{FL}_j, respectively, represent the economic flows from Sector j at the provincial, national and global scales to Sector i within the system.

Considering the economic flows involving inputs, inflows and imports, the intermediate use and final use will not be differentiated. In the context, the equilibrium equation regarding embodied GHG emissions of Sector i could be obtained

$$d_{k,i} + \sum_{j=1}^{n} \varepsilon^L_{k,j} z^L_{j,i} + \sum_{j=1}^{n} \varepsilon^P_{k,j} im^{PL}_j + \sum_{j=1}^{n} \varepsilon^d_{k,j} im^{DL}_j + \sum_{j=1}^{n} \varepsilon^F_{k,j} im^{FL}_j = \varepsilon^L_{k,i} \left(\sum_{j=i}^{n} z^L_{j,i} + e_i + d^L_i \right), \tag{2.1}$$

where

$$e_i = ex^{LP}_i + ex^{LD}_i + ex^{LF}_i. \tag{2.2}$$

The total economic output y_i follows the economic equilibrium as follows:

$$y_i = \sum_{j=1}^{n} z^L_{i,j} + e_i + d^L_i. \tag{2.3}$$

Equation (2.1) can be simplified into an equilibrium equation containing n sectors and m types of GHG emissions

$$D + \varepsilon^L Z^L + \varepsilon^P im^{PL} + \varepsilon^d im^{DL} + \varepsilon^F im^{FL} = \varepsilon^L Y. \tag{2.4}$$

By reorganizing Eq. (2.3), Eq. (2.4) can be obtained as follows:

$$\varepsilon^L = (D + \varepsilon^P im^{PL} + \varepsilon^d im^{DL} + \varepsilon^F im^{FL})(Y - Z^{\boldsymbol{L}})^{-1}, \tag{2.5}$$

Table 2. Multi-scale input–output structure of GHG emissions.

		Intermediate use	Final demand	Urban outflows within the province	Provincial outflows within the country	Exports	
		Sector 1, ..., Sector *n*	Sector 1, ..., Sector *n*	Sector 1, ..., Sector *n*	Sector 1, ..., Sector *n*	Sector 1, ..., Sector *n*	Total output
Local input	Sector 1, ..., Sector *n*	$z_{i,j}^L$	d_i^L	ex_i^{LP}	ex_i^{LD}	ex_i^{LF}	y_i
Urban inflows within the province	Sector 1, ..., Sector *n*	$z_{i,j}^P$	d_i^P				
Provincial inflows within the country	Sector 1, ..., Sector *n*	$z_{i,j}^d$	d_i^d				
Imports	Sector 1, ..., Sector *n*	$z_{i,j}^F$	d_i^F				
Environmental emissions	CO_2	$d_{1,i}$					
	CH_4	$d_{2,i}$					
	N_2O	$d_{3,i}$					

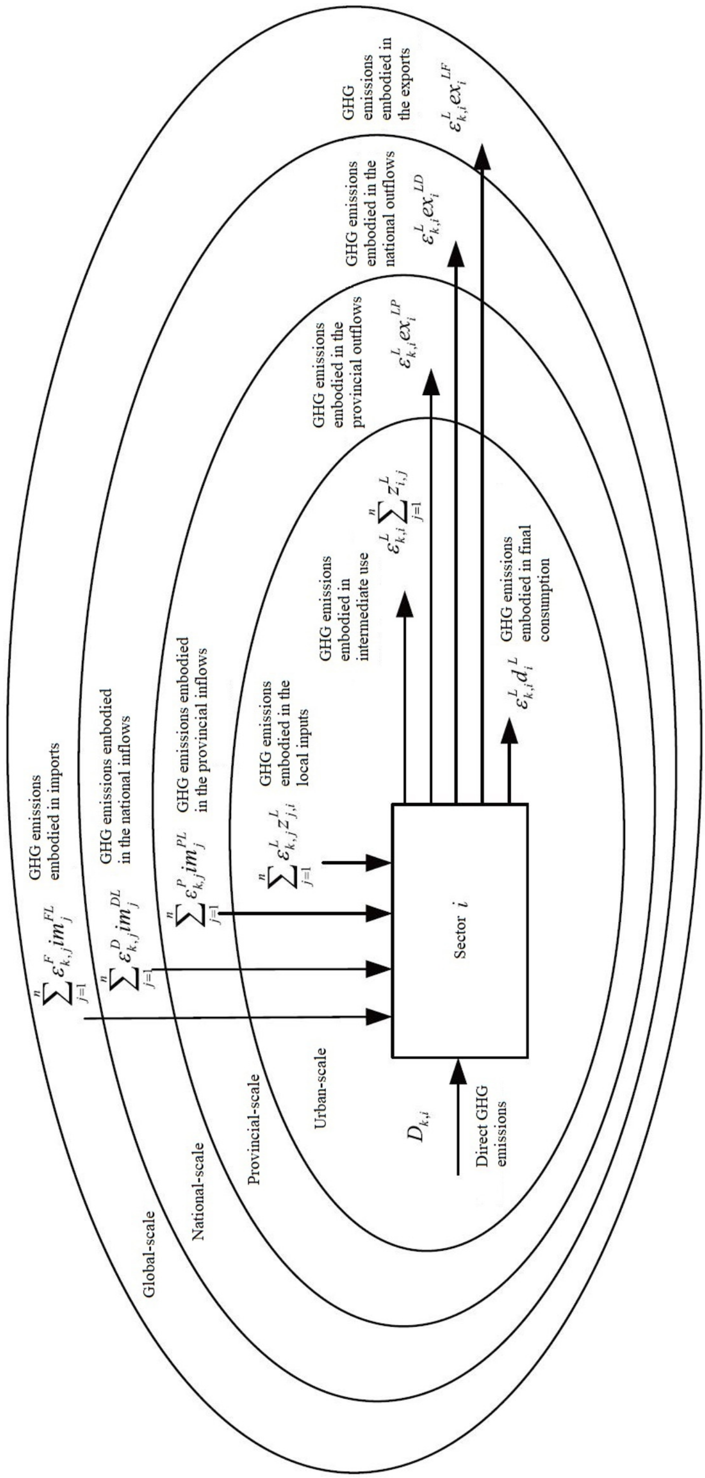


Fig. 1. The input–output relationship of GHG emissions embodied in Sector *i*.

where $D = (d_{k,i})_{m\times n}$, $\varepsilon^L = (\varepsilon^L_{k,i})_{m\times n}$, $\varepsilon^P = (\varepsilon^P_{k,i})_{m\times n}$, $\varepsilon^d = (\varepsilon^d_{k,i})_{m\times n}$, $\varepsilon^F = (\varepsilon^F_{k,i})_{m\times n}$, $Z^L = (z^L_{i,j})_{n\times n}$, $im^{PL} = (im^{PL}_{i,j})_{n\times n}$, $im^{DL} = (im^{DL}_{i,j})_{n\times n}$, $im^{FL} = (im^{FL}_{i,j})_{n\times n}$, $Y = [\mathrm{diag}(y_i)]_{n\times n}$, and $im^{PL}_{i,j} = im^{PL}_j$, $im^{DL}_{i,j} = im^{DL}_j$, $im^{FL}_{i,j} = im^{FL}_j$ $(i = j)$; $im^{PL}_{i,j} = 0$, $im^{DL}_{i,j} = 0$, $im^{FL}_{i,j} = 0$ $(i \neq j)$.

From Eq. (4), the emission GHG emission intensities by sector could be obtained, representing the total (direct and indirect) GHG emissions per unit economic output in the process of production and consumption. In the multi-scale accounting processes, it is mainly to depict the internal relations between the monetary value and GHG emissions of each sector.

Based on the multi-scale input–output relations, the embodied GHG emission intensities are related to the local direct emissions, the emissions embodied in the urban inflows within the province, in the provincial inflows within the country, and in imports. To separately account the different sources on the local GHG emissions by referring to Han *et al.* (2020), ε^{LL}, ε^{PL}, ε^{DL} and ε^{FL}, respectively, represent the intensities at local, provincial, national and global scales, and E^{LL}, E^{PL}, E^{DL} and E^{FL}, respectively, represent the emissions from local sources, embodied in urban inflows within the province, in provincial inflows within the country, and in imports. The equations are presented in Table 3.

2.3. *Case introduction and data sources*

Being adjacent to Beijing and Tianjin and located in the center of the Bohai Sea Rim, Tangshan city is one of the core cities in the Capital Economic Circle and the Bohai Rim Economic Circle, with advantages in resources, location and transportation. In 2018, the cargo throughput of Tangshan Port reached 640 million tons, ranking third in the world in terms of throughput. According to the *National Plan for Sustainable Development of Resource-Based Cities of China (2013–2020)*, Tangshan is an essential resource-based city

Table 3. Multi-scale input–output accounting framework.

Scales	Description	Equations
Urban	Local direct emissions	D
	Local intermediate use	$\varepsilon^L Z^L$
	Embodied emissions from local sources for local final demand	$D(Y - Z^L)^{-1} d^L$
Provincial	Embodied emissions in urban inflows within the province	$\varepsilon^P im^{PL}$
	Embodied emissions in urban outflows within the province	$\varepsilon^L ex^{LP}$
	Embodied emissions in urban inflows within the province for local final demand	$\varepsilon^P im^{PL}(Y - Z^L)^{-1} d^P$
National	Embodied emissions in provincial inflows within the country	$\varepsilon^d im^{DL}$
	Embodied emissions in provincial outflows within the country	$\varepsilon^L ex^{LD}$
	Embodied emissions in provincial inflows within the country for local final demand	$\varepsilon^d im^{DL}(Y - Z^L)^{-1} d^d$
Global	Embodied emissions in imports	$\varepsilon^F im^{FL}$
	Embodied emissions in exports	$\varepsilon^L ex^{LF}$
	Embodied emissions in imports for local final demand	$\varepsilon^F im^{FL}(Y - Z^L)^{-1} d^F$

with abundant iron ore resources, of which the holding capacity reached 6.2 billion tons, and among one of the three largest iron ore concentration areas in China. In addition, Tangshan city is rich in energy resources, with more than 100 years of large-scale coal mining, with the holding capacity reaching 6.25 billion tons, making it an important coking coal production area in China. According to the *Tangshan Statistical Yearbook 2018*, the regional GDP of Tangshan in 2017 was 653.01 billion Yuan, of which the secondary industry contributed 364.06 billion Yuan, accounting for 55.75% of the total. Meanwhile, the industrial production of Tangshan consumed 61.20 million tons of raw coal and 39.38 million tons of coke, accounting for 22.3% and 49.0% of the province's total, respectively. Due to the dependence of industrial production on fossil fuels, Tangshan's economic development was accompanied by huge GHG emission pressure, making it inevitable to accelerate the transformation of the economic growth model and achieve regional sustainable development.

The multi-scale GHG emissions in this study covered four scales including the world, China, Hebei and Tangshan. Considering the scale correlations and data availability, the year 2012 was chosen as the base year. At the global scale, this study applied the GHG emissions by country from the EDGAR database and the global MRIO table from the Eora database. Among them, the EDGAR database covers greenhouse emission data including carbon dioxide, methane, nitrous oxide in different countries, and the Eora database contains input–output data of 26 sectors in 189 countries/economies around the world. To ensure the consistency of accounting scope and sectoral classification at the global scale, this study corresponded the GHG emissions in the EDGAR database to the economic sectors in the Eora input–output database by country according to the sector classification and IPCC (2006). By referring to Chen and Chen (2011) and based on the GHG emissions from the EDGAR database and the global input–output tables from the Eora database, this study established an inventory of the embodied GHG emission intensities in 189 countries, and obtains the average embodied GHG emission intensities of 26 sectors by the weighted average of the total output. To ensure the consistency with China's sectoral classification, this study matched the average embodied GHG emission intensities of 26 sectors with the weighted average, and obtained the average embodied GHG emission intensities of 42 sectors. The sector classifications and their corresponding relations are shown in Table 4. At the national scale, according to the GHG emissions database and the *Input–output Tables of China 2012* compiled by the National Bureau of Statistics of China (NBS), it is possible to calculate the embodied GHG emission intensities of 42 sectors in China. At the regional scale, this study mainly referred to the accounting methods in the *Guidance for Compiling Provincial Greenhouse Gas Emission Inventory (Trial)* compiled by the NDRC. By combining with the input–output table of Hebei Province and introducing the direct GHG emissions from Table 1, this study established the multi-scale input–output analysis framework of GHG emissions and obtained the embodied GHG emission intensities of 42 sectors in Hebei province. For Tangshan city, through combining with the input–output table of Tangshan and introducing the direct GHG emissions of 42 sectors from Table 1, this study established the multi-scale input–output analysis framework (Liu *et al.*, 2019) and obtained the embodied GHG emission intensities of 42 sectors in Tangshan.

Table 4. Sector classifications for GHG emissions and corresponding relations.

Code	26-sector classification	Code	42-sector classification
1	Agriculture	1	Agriculture, forestry, animal husbandry and fishery
2	Fishing		
3	Mining and quarrying	2	Coal mining products
		3	Petroleum and natural gas extraction
		4	Metal ores mining and processing
		5	Mining and processing of non-metal ores and other ores
4	Food & beverages	6	Foods and tobacco
5	Textiles and wearing apparel	7	Textile products
		8	Textile, clothes, leather, feather and related products
6	Wood and paper	9	Timber manufacturing and furniture
		10	Paper, printing, culture, education and sport products manufacturing
7	Petroleum, chemical and non-metallic mineral products	11	Petroleum, coking products and nuclear fuel processing
		12	Chemical products
		13	Non-metallic mineral products
8	Metal products	14	Metal smelting and pressing
		15	Metal products
9	Electrical and machinery	16	General machinery manufacturing
		17	Special machinery manufacturing
		19	Electrical machinery and apparatus
		20	Communication equipment, computers and other electronic equipment
		21	Instruments and machinery
10	Transport equipment	18	Transport equipment
11	Other manufacturing	22	Other manufactured products
12	Recycling	23	Waste and scrap
13	Electricity, gas and water	25	Electricity and heat production and supply
		26	Gas production and supply
		27	Water production and supply
14	Construction	28	Construction
15	Maintenance and repair	24	Metal products and equipment repairing service

(*Continued*)

Table 4. (*Continued*)

Code	26-sector classification	Code	42-sector classification
16	Wholesale trade	29	Wholesale and retail
17	Retail trade		
18	Hotels and restaurants	31	Accommodation and catering
19	Transport	30	Transportation, storage and post
20	Post and telecommunications	32	Information transmission, software and information technology service
21	Financial intermediation and business activities	33	Financial intermediation
		34	Real estate
		35	Leasing and business service
22	Public administration	37	Water conservancy, environment and public facilities management
		42	Public management, social insurance and social organization
23	Education, health and other services	39	Education
		40	Health and social service
24	Private households	38	Household service, repair and other services
25	Others	36	Scientific research and technical service
		41	Culture, sport and entertainment
26	Re-export & re-import		

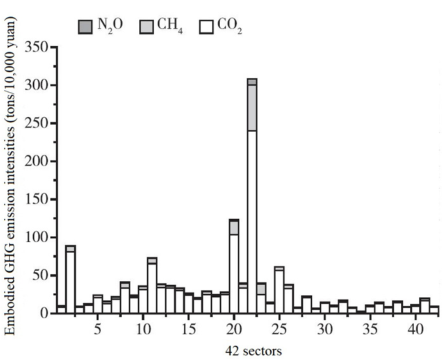
Note: According to the national standard *Industrial Classification for National Economic Activities* (GB/T 4754-2017), Sector 1 belongs to the primary industry, Sectors 2–28 belong to the secondary industry, and Sectors 29–42 belong to the tertiary industry.

3. Results

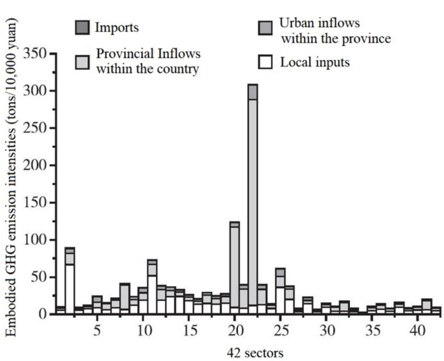
3.1. *Embodied GHG emission intensities*

The embodied GHG emission intensity represents the total (direct and indirect) GHG emissions per unit economic output in the production and consumption processes, reflecting the relations between the monetary value and GHG emissions of different sectors. Figure 2 presents the structures of Tangshan's embodied GHG emission intensities by GHG emission type and source. Overall, the average intensity of embodied GHG emissions in Tangshan was 27.6 tons/10,000 Yuan. Among them, the embodied GHG emission intensity of Sector 22 (Other manufactured products) was 308.3 tons/10,000 Yuan, with an intensity much higher than that of other sectors due to the coverage of the production of coal products like briquettes. In addition, the intensities of embodied GHG emissions of Sector 20 (Communication equipment, computers and other electronic equipment), Sector 2 (Coal mining products), Sector 11 (Petroleum, coking products and nuclear fuel processing), and Sector 25 (Electricity and heat production and supply) were also prominent, with 123.6, 89.0, 72.9 and 61.4 tons/10,000 Yuan, respectively. From the GHG emission proportions, the embodied emission intensities of most sectors accounted for more than 80.0% of the total, except for Sector 22 (other manufacturing products) and Sector 23 (Waste and scrap).

From the GHG emission sources, the intensity of GHG emissions caused by local inputs was 18.2 tons/10,000 Yuan, contributing to 66.2% of the total. The following sectors contributed the most were Sector 2 (Coal mining products), Sector 11 (Petroleum, coking products and nuclear fuel processing) and Sector 25 (Electricity and heat production and supply), accounting for 74.9%, 71.2% and 59.0% of the total, respectively. In terms of urban inflows within the province, the GHG emission intensity was 6.0 tons/10,000Yuan, with a contribution rate of 21.6%. The contributions of Sector 22 (Other manufacturing industry) and Sector 20 (Communication equipment, computers and other electronic equipment) far exceeded those of other sectors, respectively, accounting for 89.6% and 87.2% of the total, far greater than the proportions of local inputs, provincial inflows within



(a) By GHG emission type



(b) By GHG emission source

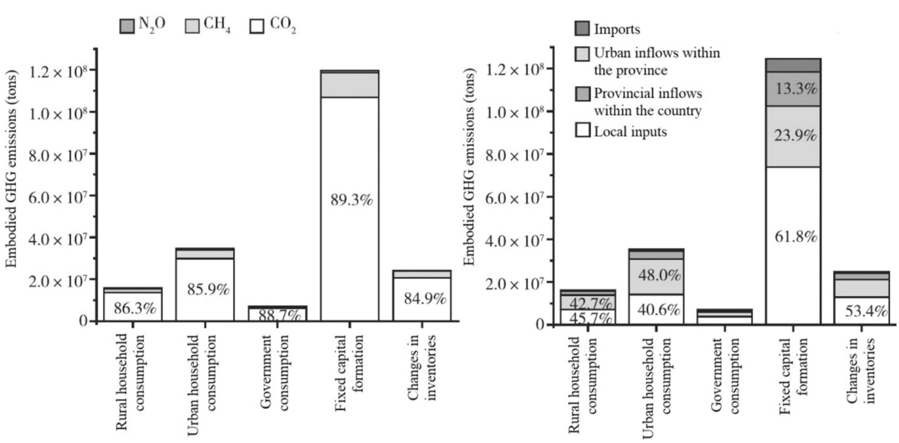
Fig. 2. Embodied GHG emission intensities.

the country, and imports, indicating that Tangshan's embodied GHG emission intensities were greatly affected by local inputs and urban inflows within the province.

3.2. *Embodied GHG emissions*

Based on Tangshan's embodied GHG emission intensities and economic input–output tables, it is possible to obtain the GHG emissions embodied in Tangshan's final demand. The GHG emissions embodied in Tangshan's final demand consists of final consumption and gross capital formation, in which final consumption includes rural household consumption, urban household consumption, and government consumption, and gross capital formation includes fixed capital formation and changes in inventories. The GHG emissions embodied in final demand are shown in Fig. 3. Overall, the total GHG emissions embodied in final demand were 201.6 million tons. From the sources, the emissions embodied in final demand from local inputs ranked the top, accounting for 61.7%, while those from urban inflows within the province, provincial inflows within the country, and imports accounted for 25.8%, 11.4% and 1.1%, respectively. From the final demand types, the most embodied GHG emissions were embodied in the fixed capital formation, reaching 119.7 million tons and accounting for 59.4% of the total. The GHG emissions embodied in urban household consumption accounted for 17.3%, 22.2 times that of rural household consumption. The differences in proportions are mainly due to the fact that most heavy industrial enterprises in Tangshan were of capital-intensive featuring a large number of heavy equipment and large investment, making it difficult to shut down outdated heavy industrial enterprises or upgrade the technical equipment, thus slowing down the processes of industrial transformation within the city.

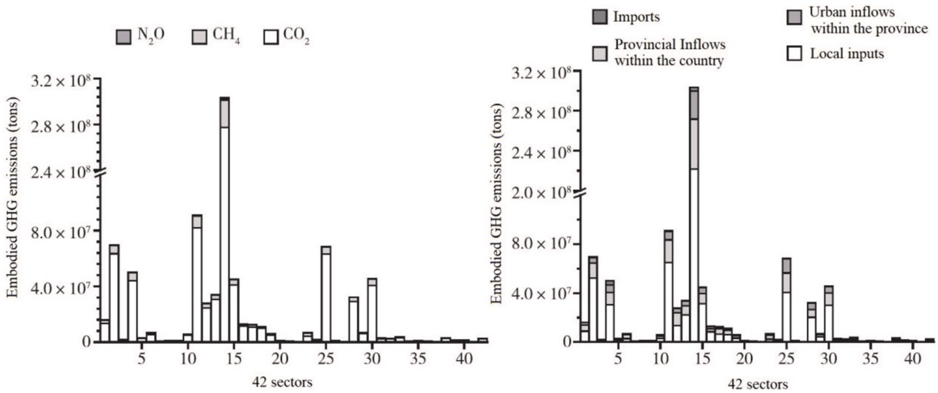
Figure 4 presents the embodied GHG emissions in various activities including production, trade and utilization. As a resource-based heavy industrial city, a large amount of high-carbon fossil fuels mainly composed of coal was consumed during the industrial



(a) By GHG emission type

(b) By GHG emission source

Fig. 3. GHG emissions embodied in final demand.



(a) By GHG emission type

(b) By GHG emission source

Fig. 4. GHG emissions embodied in total outputs.

production in Tangshan. Among them, Sector 14 (Metal smelting and pressing) was the largest emission source, accounting for 34.3% of the total, while the proportions of other sectors were less than 10%. The distribution of Tangshan's embodied GHG emissions at different scales is shown in Fig. 4(b). As for the GHG emissions at different scales, the GHG emissions from local inputs accounted for approximately 66.2%, and those from urban inflows within the province, provincial inflows within the country, and imports accounted for 21.6%, 10.9% and 1.3%, respectively. Overall, the GHG emissions embodied in the total output of Tangshan were mostly emitted by local sources, but the embodied GHG emissions were also affected by the urban inflows within the province and provincial inflows within the country.

3.3. *GHG emissions embodied in trade*

Figure 5 shows the GHG emissions embodied in Tangshan's trade, which can be divided into the trade inside and outside of the city, the province, and the country. Overall, Tangshan was a net exporter of embodied GHG emissions, with the net outflow of 411.6 million tons. From the import and export, provincial inflows and outflows within the country, and urban inflows and outflows within the province, the total GHG emissions embodied in Tangshan's inflows were 271.6 million tons, far less than that of the outflows trade with 682.2 million tons. In the foreign trade of Tangshan, the total GHG emission embodied in imports was 11.7 million tons; Sector 2 (Coal mining products) and Sector 4 (Metal ores mining and processing) highly related to the metallurgical industry were with import-related emissions, in which that of Sector 4 (Metal ores mining and processing) was 9.5 million tons, accounting for 81.1% of the total. The GHG emissions embodied in exports were 38.9 million tons, most of which were contributed by the secondary industry, accounting for 99.8% of the total emissions embodied in exports, especially that of Sector 14 (Metal smelting and pressing) reached 23.1 million tons, accounting for 60.0% of the total.

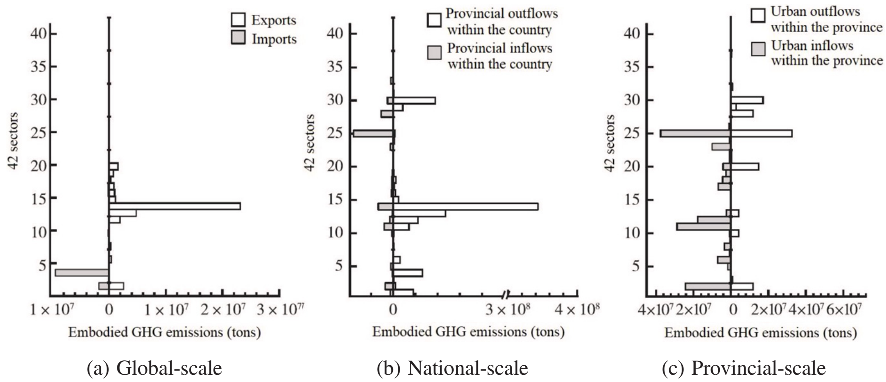


Fig. 5. Multi-scale correlations of GHG emissions embodied in trade.

In the trade between Tangshan and other provinces/cities, the GHG emissions embodied in inflows were 102.3 million tons, in which the secondary industry dominated, accounting for 89.6%, to which Sector 25 (Electric and heat production and supply) contributed 36.1 million tons, accounting for 35.2%, with certain proportions taking up by the other two industries; the GHG emissions embodied in outflows were 541.7 million tons, in which the secondary industry still accounted for the largest proportion, reaching 87.9%, to which Sector 14 (Metal smelting and pressing) contributed 343.1 million tons, accounting for 63.3%, while Sectors 29 and 30 in the tertiary industry also took a certain share.

In the trade between Tangshan and other cities within the province, the GHG emissions embodied in inflows were 156.7 million tons, which were mainly concentrated in the secondary industry, accounting for 99.8%, to which Sector 25 (Electricity and Heat production and supply), Sector 11 (Petroleum, coking products and nuclear fuel processing) and Sector 2 (Coal mining products) contributed the most, accounting for 24.0%, 18.4% and 15.5%, respectively, while the tertiary industry accounted for only 0.2%. The GHG emissions embodied in outflows were 101.7 million tons, of which the tertiary industry accounted for a certain proportion that was mainly concentrated in Sector 30 (Transportation, storage and post), while the secondary industry still accounted for a large proportion, reaching 79.3%, in which Sector 14 (Metal smelting and pressing) accounted for the highest proportion, reaching 32.2%, and the proportion of Sector 20 (Communication equipment, computers and other electronic equipment) reached 14.5%.

3.4. *Multi-scale GHG emission comparisons*

In the context of the coordinated development of the Beijing–Tianjin–Hebei region, Tangshan, as a resource-based heavy industrial city, still faced huge pressure of GHG emissions. To systematically assess Tangshan's GHG emissions, this study introduced Beijing's embodied GHG emissions in the same year (Shao *et al.*, 2016), and compared the intensities of embodied GHG emissions in Tangshan, Beijing, Hebei, China and the world in Table 5. Through comparisons, the average intensity of GHG emissions in Tangshan reached 27.6 tons/10,000 Yuan, far exceeding those of the world, China, and Hebei.

Table 5. Average embodied GHG emission intensities in different economies (unit: tons/10,000Yuan).

Economies	Primary industry	Secondary industry	Tertiary industry	Overall
World	3.2	2.0	0.7	1.4
China	3.2	5.1	1.9	4.1
Hebei	4.5	9.6	4.0	8.1
Beijing	1.5	2.6	0.9	1.7
Tangshan	9.7	32.8	4.7	27.6

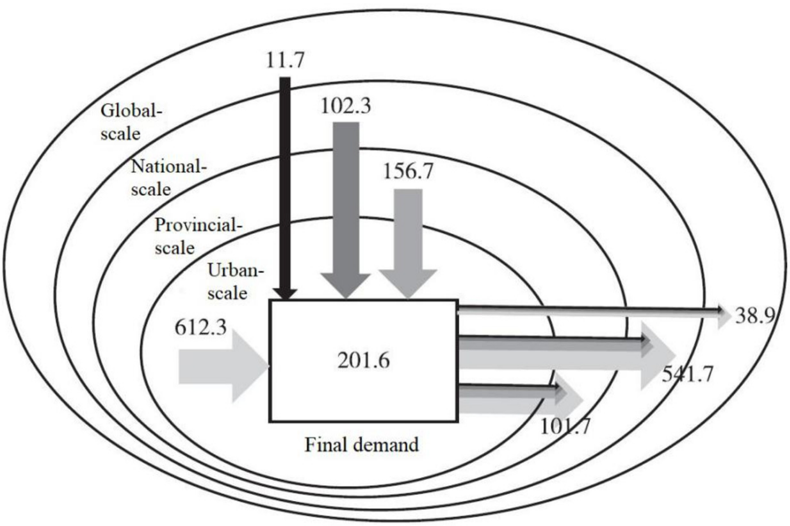
The average emission intensity of the secondary industry was 32.8 tons/10,000 Yuan, becoming the main reason for the high intensity of GHG emissions in Tangshan. Considering the embodied intensity and trade balance, it is found that Tangshan still supplied a large scale of heavy industrial products to other regions despite its high intensity of embodied GHG emissions, putting itself under even greater pressure of GHG emissions.

Based on the existing research, this study further compared the intensities of embodied GHG emissions in Tangshan and other cities (Chen *et al.*, 2020; Shao *et al.*, 2016). Overall, resource-based heavy industrial cities such as Tangshan were net GHG exporters, mainly relying on urban inflows within the province and local inputs oriented to manufactured heavy industrial products. In contrast, consumption-based cities such as Beijing had much lower intensity of GHG emissions compared with Tangshan, whose emission intensities were more balanced compared to those of Tangshan, with less imbalanced industrial structure. In addition, the embodied GHG emissions of consumption-based urban economies mostly came from inflows, mainly relying on the imports of external resources and products, especially the inflows from the electricity and heat production and supply. Furthermore, most cities' secondary industry contributed a relatively small share to the embodied GHG emission intensities than that of Tangshan, while the emission intensity of their tertiary industry was higher than that of Tangshan. In this case, reducing the emission intensity of the secondary industry through upgrading and iterating technologies and vigorously developing the tertiary industry with technology-intensive characteristics were practical strategies.

4. Discussion and Policy Implications

Tangshan city is an essential component of facilitating the integration of the Capital Economic Circle and building the Bohai Rim Economic Circle, which plays an important role in advancing the national development strategies and a significant node in the implementation of GHG emission reduction targets. In recent years, Tangshan, as a resource-based heavy industrial city, has witnessed a continuous growth in its secondary industry, of which the added value increased from 220.21 billion Yuan in 2009 to 331.98 billion Yuan in 2018. Moreover, the average intensity of embodied GHG emissions in Tangshan was 27.6 tons/10,000 Yuan, far exceeding that of other economies such as Beijing and Hebei; the GHG emission intensity of the Tangshan's secondary industry was relatively high, reaching 32.8 tons/10,000 Yuan in average; the GHG emissions embodied in final demand reached 201.6 million tons, with the GHG emissions embodied in fixed capital accounting for 59.4% of local final demand; the net GHG emissions embodied in trade reached 411.6 million tons. However, along with the increasing industrial output value, the pressure from GHG emissions became more severe, and the contradiction between industrial production and high GHG emissions was increasingly intensified.

Based on the input–output relations, this study depicted Tangshan's GHG emissions at the global, national, provincial and local scales (see Fig. 6). During the economic development of Tangshan city, the local direct GHG emissions were 612.3 million tons, and the GHG embodied in products/services from global, national and provincial scales were 11.7, 102.3 and 156.7 million tons, respectively. According to the input–output relations, the manufactured heavy industrial products were used for the final demand including fixed capital formation and household consumption, as well as outflows and exports. At the global scale, the net exports of Tangshan's embodied GHG emissions to other countries were 27.2 million tons. At the national scale, the net outflows of Tangshan's embodied GHG emissions to other provinces/cities were 439.4 million tons, bearing the GHG emission pressure from the economies at other scales. At the provincial scale, the net inflows of embodied GHG emissions to Tangshan from other cities within Hebei Province were 55 million tons, indicating that most of the cities in Hebei province, a major heavy industry province, faced serious pressure of GHG emissions. By comparisons, Tangshan was exposed to a huge pressure of local embodied GHG emissions, while providing heavy industrial products to the domestic market, which in turn reflects the necessity and urgency to upgrade Tangshan's industrial structures, and to adjust the energy structures, industrial structures, and emission reduction policies systematically.



Note: The unit is one million tons.

Fig. 6. Multi-scale GHG emissions in Tangshan city.

By examining the GHG emissions at multiple scales, and in consideration of the emission structures, industrial structures, and emissions sources, the following policy implications are provided for reference:

(i) From the embodied GHG emission intensities, the vast majority of GHG emissions in Tangshan were caused by fuel combustion in the production activities of the secondary industry, with the relatively lower emission intensity of the tertiary industry. Since the tertiary industry is mainly composed of technology-intensive low-carbon industries such as transportation, storage and post, wholesale and retail, accommodation and catering, and finance intermediation, the government should actively adjust the industrial structures, combine the transformation of traditional industries with emerging industries, and coordinate the development of the secondary and the tertiary industries. Within the secondary industry, measures such as replacing traditional steelmaking with electric furnace steelmaking can also reduce GHG emissions caused by fuel combustion in production activities. Furthermore, Tangshan's heavy industry is mainly energized by fossil fuels such as coke, which could be further optimized. Being adjacent to Bohai Sea, Tangshan city can also build tidal power stations and offshore wind power stations to increase the proportion of renewable energy power generation through wind and tidal energy and facilitate the diversification of its energy sources.

(ii) To analyze the GHG emissions embodied in the final demand of Tangshan, the GHG emissions embodied in the fixed capital formation accounted for the largest proportion, most of which came from capital-intensive heavy industries. Such industries are characterized by a large number of heavy equipment and large investment, which are prone to slow capital turnover, slow investment return, and long payback years. As a typical resource-based heavy industrial city, it is difficult for Tangshan to shut down outdated heavy industry enterprises or upgrade the technical equipment, thus slowing down the industrial transformation processes, consuming development funds and potentials, and lowering the short-term economic benefits and return rates, further reducing its potential for development and transformation, and hard to achieve industrial diversification and sustainable development. In this respect, the government still needs to encourage heavy industrial enterprises to eliminate obsolete energy-intensive equipment and provide policy support in eliminating outdated production facilities.

(iii) As an essential heavy industry base in China and the largest port in Hebei province, Tangshan still has serious deficiencies on the trade-related embodied GHG emissions. Overall, Tangshan was a net exporter of GHG emissions, mainly oriented towards the manufactured heavy industrial products. In this regard, the GHG emissions embodied in imports were concentrated in the primary energy sector dominated by Sectors 2 and 4, while the GHG emissions embodied in exports are mainly concentrated in the secondary industry with higher intensity and amount of embodied GHG emissions. The net trade volume of embodied GHG between the trade between Tangshan and other provinces was about 439.4 million tons, of which Sector 14 (Metal smelting and pressing) accounted for the largest proportion, further aggravating the GHG emission pressure in the city. By adjusting the policies in the resource-based heavy industrial city, the government could gradually reduce the proportion of heavy industrial products exported, shift its orientation to the tertiary industry, and achieve industrial transformation. With these efforts, it would be possible to address excessive embodied GHG emissions in several dominated sectors and reduce the GHG emission pressure at multiple scales.

(iv) Considering the proportion of heavy industries in the industrial structure of Tangshan, it is possible to clarify and monitor the GHG emissions embodied in heavy industrial products, and step up the construction of the intelligent energy consumption system and carbon emission management system, introduce technologies to save energy, reduce emissions, and recycle resources in the industries such as metal smelting and pressing as well as coal mining through multiple coordination, intensify efforts to promote the diversification of energy and industrial structures, introduce policies to encourage and attract domestic and foreign enterprises to invest and set up factories, establish the diversified industrial system led by high-tech industries and service industries, to promote the city's low-carbon transition and alleviate the high GHG emissions in the resource-based heavy industrial city.

5. Conclusions

This study systematically assessed the GHG emissions in Tangshan city, Hebei province based on the MSIO analysis, and conducted quantitative analysis from the embodied intensity, final demand, and trade balance. By establishing the multi-scale relations between Tangshan's industrial development and GHG emissions, this study discussed the environmental emissions in Tangshan city and the correlation with other scales. Main conclusions were drawn as follows: (i) Most of Tangshan's GHG emissions were caused by fuel combustion in the production activities of the second industry, of which the metal smelting and pressing accounts for the largest proportion; (ii) In Tangshan's final demand, the GHG emissions embodied in fixed capital formation and in local inputs accounted for the largest shares; (iii) From the trade balance perspective, Tangshan was a net exporter of embodied GHG emissions, with 411.6 million tons of GHG emissions embodied in the net exports; (iv) The outflow of Tangshan's embodied GHG emissions was mainly concentrated in the secondary industry with higher embodied intensity, bearing the GHG emission pressure from other economies, reflecting the necessity and urgency in industrial transition and upgrade.

Overall, resource-based heavy industrial cities imposed huge GHG emission pressure on the local environment while promoting national economic development. However, the GHG emission problems these cities faced resulted from the combined effects of multiple scales, requiring the full understanding of the GHG emission relations at local, provincial, national and global scales. This study takes Tangshan city, a typical resource-based heavy industrial city in Hebei province as a case, to establish a multi-scale GHG accounting framework including local, provincial, national and global scales. However, the data and methods could be further improved in the following aspects: some activity-level indicators were not included in the statistical scope during compiling urban GHG inventories; due to the difficulty in directly measuring local emission factors, this study mainly referred to the recommended provincial emission factors, IPCC emission factors, and previous studies; some differences may exist in the statistical departments and methods when constructing multi-scale GHG emission inventories; and it is difficult to obtain and compare the original data at different scales. Although there are still uncertainties in data and methods, by examining the GHG emission inventories at multiple scales, this study strives to develop a multi-scale GHG emission inventory for typical resource-based heavy industrial cities, depict the directions and flows of GHG emissions, and clarify the obstacles in the low-carbon transition of resource-based heavy industrial cities, which is of significance for industrial restructuring, policy optimization, and sustainable development for the cities with similar characters.

Acknowledgments

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