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RESEARCH ARTICLE

Inventory of CO_2 emissions driven by energy consumption in Hubei Province: a time-series energy input-output analysis

Jiashuo LI[1,2], Ran LUO[3], Qing YANG (✉)[1], Haiping YANG[2]

1 Department of New Energy Science and Engineering, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
2 National Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China
3 School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

Abstract Based on an input-output analysis, this paper compiles inventories of fuel-related CO_2 emissions of Hubei economy in the years of 2002, 2005, and 2007. Results show that calculated total direct CO_2 emissions rose from 114,462.69 kt (2002) to 196,650.31 kt (2005), reaching 210,419.93 kt in 2007, with an average 22.50% rate of increase. Raw coal was the dominant source of the direct emissions throughout the three years. The sector of Electric Power, Heat Production, and Supply was the main direct emissions contributor, with the largest intensities observed from 2002 (1192.97 g/CNY) to 2007 (1739.15 g/CNY). From the industrial perspective, the secondary industry, which is characterized as manufacture of finished products, was still the pillar of the Hubei economy during this period concerned, contributing more than 80% of the total direct emissions. As a net exporter of embodied CO_2 emissions in 2002 and 2007, Hubei reported net-exported emissions of 4109.00 kt and 17,871.77 kt respectively; however, Hubei was once a net importer of CO_2 emissions in 2005 (2511.93 kt). The CO_2 emissions embodied in export and fixed capital formation had the two leading fractions of emissions embodied in the final use. The corresponding countermeasures, such as promoting renewable and clean energy and properly reducing the exports of low value added and carbon-intensive products are suggestions for reducing CO_2 emissions in Hubei.

Keywords input-output analysis, fuel-related CO_2 emissions, Hubei Province

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E-mail: qyang@hust.edu.cn

1 Introduction

Out of numerous greenhouse gas (GHG) emissions sources, CO_2 from fossil fuel combustion is regarded as the major contributor (Liang and Zhang, 2011). CO_2 from energy was responsible for about 80% of global anthropogenic GHG emissions (Quadrelli and Peterson, 2007). The reduction of fuel-related CO_2 emissions therefore has become a focal point of the global community, attracting the attention of policy makers and scholars from all over the world. As the world's largest energy consumer and CO_2 emitter (Minx et al., 2011), China is now under great pressure to mitigate CO_2 emissions from fuel combustion (Xia et al., 2014; Zhang et al., 2014a). China has 32 provincial regions and 2 special administrative regions. It has been shown that the provincial regions are major contributors of CO_2 emissions for the whole nation. Consequently, to draw a holistic picture of China's fuel-related CO_2 emissions, it is vital to analyze CO_2 emissions from these regions.

A huge body of literature exists that evaluates carbon emissions at sub-national scale, especially in provincial regions (e.g., Guo et al., 2012a; Wang et al., 2013a; Ge and Lei, 2014; Zhang et al., 2014b). For instance, Guo et al. (2012b) compiled an inventory of CO_2 emissions induced by the fossil combustion of the Beijing economy in 2007 and found that total direct CO_2 emissions amounted to 9.45E + 07 t, within which 56.81% were released from coal combustion. Taiwan, Jiangsu, and Liaoning are marked as hot regions in China's provincial level of CO_2 emission studies (e.g., for Taiwan, see Lee et al., 2001; Lin et al., 2012; Liu et al., 2012; for Jiangsu, see Liang and Zhang, 2011; Zhang and Huang, 2012; for Liaoning, see Xia, 2012; Geng et al., 2013; for arid-alpine regions in Gansu, Qinghai and Ningxia, see Qu et al., 2013). In addition, the literature has been written that highlights

energy and related CO_2 emissions in Macao, one of China's two special administrative regions (Li and Chen, 2013; Li et al., 2013, 2014a, b). These studies shed light on China's fuel and CO_2 emission research.

As one of the provinces with good economic performance in central China, Hubei Province has a strong, conventional industrial base (Li, 2007), and plays an important role in China. In 2013, Hubei's per capita Gross Domestic Product (GDP) reached as high as 42,686.43 CNY with a total GDP of 2466.85 billion CNY, ranking the top and second, respectively, among six central provinces in China. However, with the rapid pace of economic development, Hubei has simultaneously faced increasingly serious environmental problems and great pressure to mitigate carbon emissions. As observed by Li (2007), coal is the primary source for energy production and energy consumption in Hubei, resulting in high levels of carbon emissions and environmental contamination. To ensure a sustainable, low carbon, and energy saving environment in the development of Hubei's economy, it is urgent that the characteristics and temporal structure of fuel-related CO_2 emissions are examined and that actions are implemented for their reduction. Since IO analysis has been globally proven an effective research instrument for identifying embodied (direct plus indirect) GHGs or CO_2 emissions (e.g., Munksgaard et al., 2005; Kok et al., 2006; Alcántara and Padilla, 2009; Chung and Tohno, 2009; Liu et al., 2009; Minx et al., 2009; Parikh et al., 2009; Acquaye and Duffy, 2010; Chen et al., 2010; Chen and Chen, 2010; Liu et al., 2010; Zhang and Chen, 2010; Liang et al., 2012; Su and Ang, 2013; Das and Paul, 2014; Meng et al., 2014; Zeng et al., 2014), this paper is utilizing input-output model analysis to clarify the embodiment of CO_2 emissions driven by fuel consumption in Hubei Province during the period of 2002−2007. The target of current work is to present inventories of fuel-related CO_2 emissions by 42 economic sectors of Hubei Province in the years of 2002, 2005, and 2007. In addition, the embodiment of CO_2 emissions in relevant economic activities will be calculated via the input-output analysis (IOA) approach.

The rest of this research is organized as follows: Section 2 articulates the methodological aspects of IOA employed in this paper and shows the data sources for this study, Section 3 describes the detailed results including the direct and indirect CO_2 emissions inventory, as well as corresponding embodiment analyses for Hubei in the years of 2002, 2005, and 2007, remarks are concluded in Section 4, and lastly, the policy implications for the mitigation of fuel-related CO_2 emissions in Hubei are discussed in Section 5.

2 Methodology and data sources

Each step of the construction of inventories of embodied CO_2 emissions driven by energy use in Hubei province in the years of 2002, 2005, and 2007 is presented in this section.

2.1 Economic sectors aggregation

The Hubei Input-Output Table (IOT, Table 1) 2002, issued by the Hubei Statistical Bureau, covers 42 sectors (including primary, secondary, and tertiary industries), and reflects the interaction between sectors within the Hubei economy as a whole. Each entry has been standardized by current producers' prices. Since 24 industrial sectors of the Hubei IOT 2002 have been subdivided into 39 departments (with more meticulous definitions found in the Hubei Statistical Yearbook (HSY, 2003)), the 39 departments have been aggregated into the corresponding 24 sectors to ensure compliance with data homogeneity in the input-output analysis. The 42 sectors in the Hubei Input-Output Table 2002 are listed in Table 2. Departments of industry in HSY (2003) and the incorporation of sectors of industry are presented in Tables 3 and 4, respectively.

2.2 Algorithm

Through the aggregation of economic flows and carbon flows, a traditional economic input-output table has been transformed into an environmental input-output table. As shown in Table 1, Q_1 represents inter-industrial flows, Q_2 stands for final use (GDP with expenditure approach), Q_3 is half the value added (GDP with income approach), and Q_0 represents the fuel-related direct CO_2 emissions (Guo et al., 2012a).

According to previous input-output studies (Chen and Chen, 2010; Chen et al., 2010; Zhou et al., 2010; Li et al., 2015), it is assumed that imported commodities from other domestic and foreign regions have the same embodied emission intensities as those from local regions. Following these studies, the basic row balance of the input-output table for Hubei Province can be demonstrated as

$$X = AX + F - X^m, \tag{1}$$

where X denotes the total economic output; X^m and F represent imports and the final demand from rural and urban household consumption, government consumption, gross capital formation, export, and others, respectively; and A signifies the technology coefficients matrix whose element $\alpha_{ij} = Z_{ij}/X_j$, with Z_{ij} and X_j indicates the input from Sector i to Sector j, and the total output of Sector j, separately. Thereafter, with the introduction of the identity matrix I, the form of Eq. (1) can be transformed as

$$F - X^m = X - AX = (I - A)X. \tag{2}$$

According to Zhou (2008), the emissions balance can be expressed as

$$E^d + \varepsilon AX = \varepsilon X, \tag{3}$$

where E^d is the total amount of direct CO_2 emissions, and ε symbolizes the embodied CO_2 emissions intensity, both in terms of a row vector. Thus, with the combination of Eq. (2) and Eq. (3), the embodied CO_2 emission intensity ε is obtained by

$$\varepsilon = \varepsilon^d (I - A)^{-1}, \tag{4}$$

where ε^d is the vector of direct CO_2 emission intensity and $(I–A)^{-1}$ the Leontief inverse matrix (Miller and Blair, 2009). CO_2 emissions embodied in trade balance (*EEB*) are also taken into consideration in this research, which can be defined as

$$EEB = EEE - EEI, \tag{5}$$

in which $EEE = \varepsilon F$, reflecting the CO_2 emissions embodied in export (*EEE*) with F^e standing for a column vector of exported productions, and $EEI = \varepsilon X^m$ in the name of CO_2 emissions embodied in imports (*EEI*) (Ahmad and Wyckoff, 2003; Yan and Yang, 2010), representing the emissions avoided by imports of Hubei Province.

More complete descriptions of the input-output models are presented in other existing input-output analysis related works (Peters et al., 2006; Miller and Blair, 2009; Chen and Zhang, 2010; Zhang and Chen, 2010; Li et al., 2016).

The CO_2 emissions embodied in electricity only occur at the power plant and not at the actual site of electrical use, likewise, heat has the same feature (Peters et al., 2006). As a result, electricity and heat are not considered when estimating direct CO_2 emissions. Hence, energy inputs for Hubei economy can be classified into 16 categories as raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, crude oil, gasoline, kerosene, diesel oil, fuel oil, Liquefied Petroleum Gas (LPG), refinery gas, natural gas, other petroleum products, and other coking products. In some statistical views, only 16 types of direct energy inputs in the agriculture construction, and tertiary industries are illustrated in the Hubei energy balance sheet 2002 by raw units, but not in every sector. To estimate the direct energy consumption of all types of all sectors, direct energy inputs are distributed in each sector in proportion to the total economic output of that sector according to Peters et al. (2006) and Zhou et al. (2010).

For the deduction of influence of variation in the price of the energy sources (Chung et al., 2009), a double deflation method is adopted via conversion of IOTs from current prices into constant prices on the foundation of a series of Hubei Statistical Yearbooks (HSY, 2003−2008) and China Statistical Yearbooks (CSY, 2006−2008) to enable the comparisons (Minx et al., 2011). The concrete data manipulations can be seen in Wang (2011).

The latest information and statistics are derived from relevant Chinese official documents and the Hubei Statistical Bureau, such as the China Energy Statistical Yearbooks (CESY, 2003, 2006, 2008). Other data, such as CO_2 emission factors by different energy sources and Net Calorific Values, come from the "Revised 2006 IPCC Guideline for National Inventories: Reference Manual" (IPCC, 2006) and the back page of the China Energy Statistical Yearbook (CESY, 2013) respectively (Peters et al., 2006). As energy consumptions by economic sectors are prescribed in terms of raw units and economic inputs are presented in terms of monetary values (Chinese CNY),

Table 1 Systematic structure of input-output table

Input		Output									
		Intermediate use				Final use					
		Sector 1	Sector 2	…	Sector *n*	Household consumption (Rural)	Household consumption (Urban)	Government consumption	Fixed capital formation	Inventory increase	Export
Intermediate inputs	Sector 1	Q_1				Q_2					
	Sector 2										
	…										
	Sector *n*										
Value added	Wages	Q_3									
	Taxes										
	Depreciation of fixed capital										
	Surplus										
Net environmental inputs	CO_2 emissions	Q_0									

Table 2 42 sectors in Hubei Province's economic input-output table 2002

Sector code	Sector content	Sector code	Sector content
1	Farming, Forestry, Animal Husbandry, Fishery (Agriculture)	22	Scrap and Waste
2	Coal Mining and Dressing	23	Electric Power, Heat Production and Supply
3	Petroleum and Natural Gas Extraction	24	Gas Production and Supply
4	Metals Mining and Dressing	25	Tap Water Production and Supply
5	Nonmetal and Other Minerals Mining and Dressing	26	Construction
6	Food Manufacturing and Tobacco Processing	27	Transport and Storage
7	Textile Industry	28	Postal Services
8	Garments and Other Fiber Products, Leather, Furs, Down and Related Products	29	Information Transfer, Computer Services and Software Industry
9	Timber Processing and Furniture Manufacturing	30	Wholesale and Retail Trade Services
10	Papermaking and Paper Products, Printing and Record Processing, Stationery, Education and Sports Goods	31	Accommodation and Catering Services
11	Petroleum Processing, Coking Products and Nuclear Fuel Processing	32	Finance
12	Chemical Products Related Industry	33	Real Estate
13	Nonmetal Mineral Products	34	Tenancy and Business Services
14	Metals Smelting and Pressing	35	Research and Development Services
15	Metal Products	36	Integrated Technology Services
16	Manufacturing of Ordinary Machinery and Equipment for Special Purpose	37	Management of Water Conservancy, Environment and Public Facilities
17	Transportation Equipment Manufacturing	38	Resident Services and Other Service Activities
18	Electric Machinery and Equipment	39	Educational Services
19	Telecommunication Equipment, Computer and Other Electronic Equipment Manufacturing	40	Sanitation, Social Security and Welfare
20	Instruments, Meters, Cultural and Office Machinery	41	Culture, Sports and Recreation Services
21	Handicraft Article and Other Manufacturing Activities	42	Public Administration and Social Organizations

Table 3 Sectors in HSY (2003)

Sector code	Sector content	Sector code	Sector content
1	Coal Mining and Dressing	17	Printing and Record Medium Reproduction
2	Petroleum and Natural Gas Extraction	18	Stationery, Education and Sports Goods
3	Ferrous Metals Mining and Dressing	19	Petroleum Processing, Coking Products and Nuclear Fuel Processing
4	Nonferrous Metals Mining and Dressing	20	Raw Chemical Material and Chemical Products
5	Nonmetal Minerals Mining and Dressing	21	Medical and pharmaceutical Products
6	Other Minerals Mining and Dressing	22	Chemical Fibers
7	Food Processing	23	Rubber Products
8	Food Production	24	Plastic Products
9	Beverage Production	25	Nonmetal Mineral Products
10	Tobacco Processing	26	Smelting and Pressing of ferrous Metals
11	Textile Industry	27	Smelting and Pressing of Nonferrous Metals
12	Textile Garments, Shoes and Hats Products	28	Metal Products
13	Leather, Furs, Down and Related Products	29	Ordinary Machinery Manufacturing
14	Timber Processing and Wood, Bamboo, Rattan, Palm and Straw Works	30	Special Purpose Equipment Manufacturing
15	Furniture Manufacturing	31	Transportation Equipment Manufacturing
16	Papermaking and Paper Products	32	Electric Machinery and Equipment

(*Continued*)

Sector code	Sector content	Sector code	Sector content
33	Telecommunication Equipment, Computer and Other Electronic Equipment Manufacturing	37	Electric Power, Heat Production and Supply
34	Instruments, Meters, Cultural and Office Machinery	38	Gas Production and Supply
35	Handicraft Article and Other Manufacturing Activities	39	Tap Water Production and Supply
36	Waste Resources and Junk Material Recycled		

Table 4 Sector aggregation

Sector code in Hubei IOT 2002	Sector code in HSY (2003)
2	1
3	2
4	3 + 4
5	5 + 6
6	7 + 8 + 9 + 10
7	11
8	12 + 13
9	14 + 15
10	16 + 17 + 18
11	19
12	20 + 21 + 22 + 23 + 24
13	25
14	26 + 27
15	28
16	29 + 30
17	31
18	32
19	33
20	34
21	35
22	36
23	37
24	38
25	39

the approach taken in the study is the representational hybrid-units type input-output framework (Chung et al., 2009).

3 Results

3.1 Direct CO_2 emissions

While both the usage of energy sources and the manufacture of industrial products can cause CO_2 emissions, CO_2 emissions driven by energy consumptions (as discussed in this work), and consequently their direct CO_2 emissions, are calculated by multiplying the fuel data by the corresponding CO_2 emission factors sourced from IPCC (2006).

As shown in Table 5, there was a conspicuous upward trend from 2002–2007 when the total amount of direct CO_2 emissions, climbed from 114,462.69 kt in 2002 to 196,650.31 kt in 2005 and then to 210,419.93 kt in 2007. As displayed in Figs. 1, 2, and 3, raw coal was the prominent direct CO_2 emission source, accounting for approximately 70% of total direct emissions in three years, with 77,218.46 kt in 2002, 138,708.17 kt in 2005, and 139,982.16 kt in 2007 (see Table 5). Apparently, the proportion of direct emissions sourced from raw coal combustion declined from 70.54% to 66.53% during 2005 to 2007, but its absolute amounts increased between 2002 and 2007 (see Table 5) due to the increase of total direct emissions in Hubei Province. In contrast to raw coal, the proportions of direct emitted CO_2 from both coke and diesel use experienced a slight reduction from 2002 to 2005, decreasing from 14.06% (16,093.40 kt) to 10.59% (20,822.51 kt) and 6.43% (7,355.88 kt) to 6.36% (12,510.35 kt), respectively. Subsequently, the proportions rose to 11.87% (24,971.78 kt in 2007) and 7.31% (15,387.47 kt in 2007), respectively (as seen in Figs. 1, 2, and 3, and Table 5).

For direct CO_2 emissions of each economic sector in Hubei, obvious distinctions are demonstrated in Fig. 4. Sector 23 (Electric Power, Heat Production and Supply) was the major source of total direct CO_2 emissions in 2002, 2005, and 2007 (30.27%, 27.70%, and 31.05% of total, respectively). In the meantime, the amount of direct emissions from this sector rocketed from 34,642.89 kt in 2002 to 54,467.43 kt in 2005, and soon afterward to 65,345.61 kt at the end of the period, with an average growth rate of 23.56% (even higher than the previous 22.50%). This may partly reflect the coal-based energy structure in Hubei. The second largest emitter was Sector 12 (Chemical Products Related Industry), where directly emitted CO_2 emissions approximately tripled between 2002 (13,396.42 kt) and 2005 (36,973.74 kt) before moderately falling to 28,516.18 kt in 2007. Sector 27 (Transport and Storage) was the third largest contributor of direct emissions in 2002 (11,497.79 kt) and 2007 (22,076.25 kt), but ranked fourth in 2005 (18,708.97 kt) when direct emissions from Sector 13 (Nonmetal Mineral Products) totaled 22,166.96 kt in 2005.

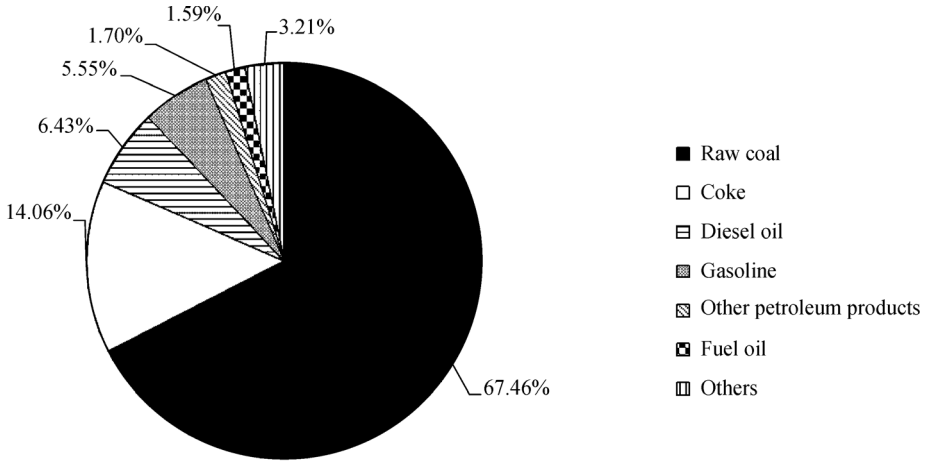

Fig. 1 The structure of direct CO_2 emissions by fuel type in 2002.

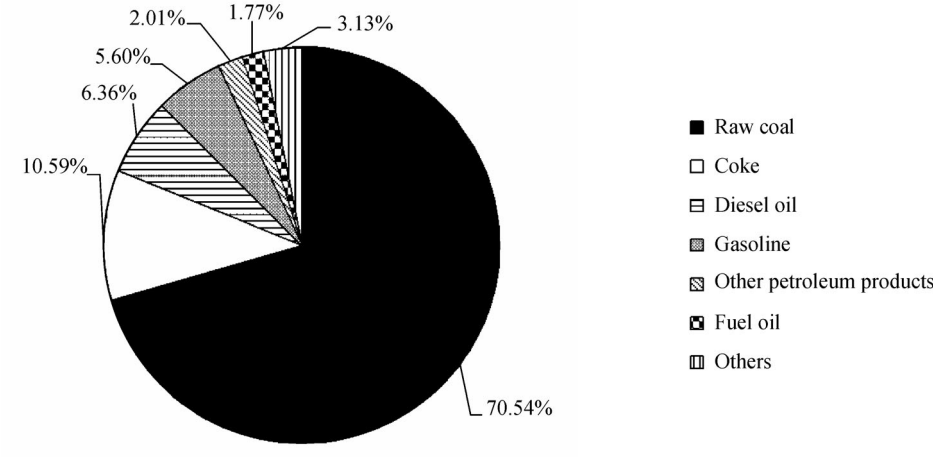

Fig. 2 The structure of direct CO_2 emissions by fuel type in 2005.

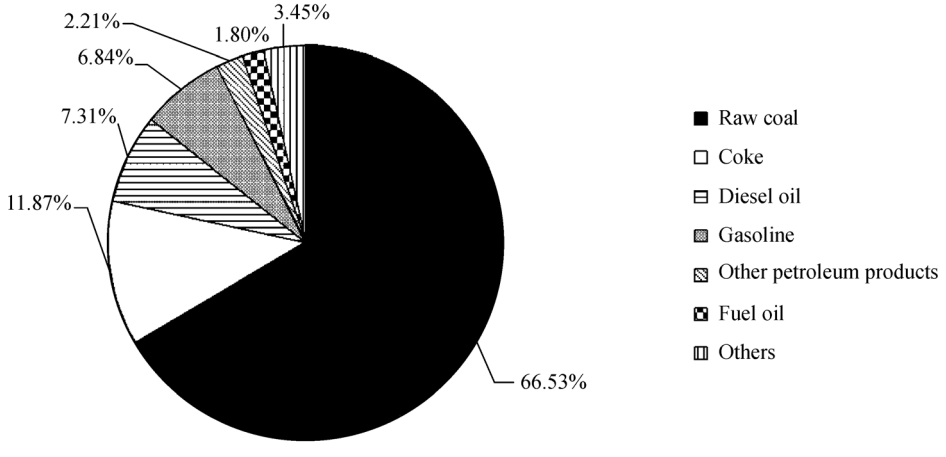

Fig. 3 The structure of direct CO_2 emissions by fuel type in 2007.

Table 5 Direct CO_2 emissions by 16 fuel types in Hubei 2002–2007 (Unit: kt)

Fuel category	2002	2005	2007
Raw coal	77,218.46	138,708.17	139,982.16
Cleaned coal	555.77	641.58	1197.35
Other washed coal	0.00	22.96	28.51
Briquettes	0.00	0.00	795.99
Coke	16,093.40	20,822.51	24,971.78
Coke oven gas	1049.33	2387.30	659.42
Crude oil	53.08	182.55	293.30
Gasoline	6357.49	11,016.41	14,399.82
Kerosene	531.16	665.26	961.21
Diesel oil	7355.88	12,510.35	15,387.47
Fuel oil	1819.81	3481.52	3785.41
Lpg	263.05	396.79	450.99
Refinery gas	526.64	762.26	667.64
Natural gas	198.95	898.53	1158.69
Other petroleum products	1942.60	3950.92	4640.55
Other coking products	497.07	203.19	1039.63
Total emissions	114,462.69	196,650.31	210,419.93

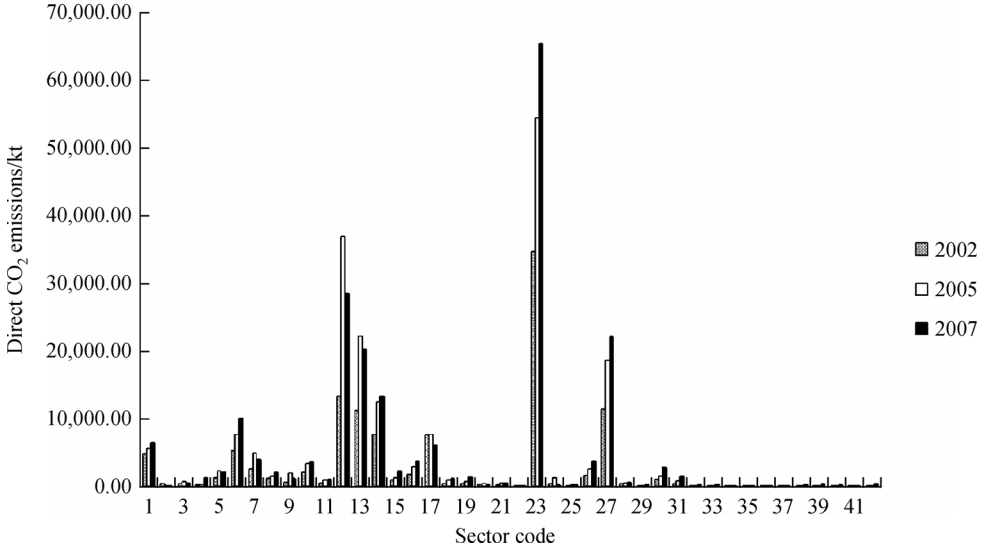

Fig. 4 The sectoral direct CO_2 emissions in Hubei 2002−2007.

As presented in Fig. 5, the trend for direct emission intensities for 42 sectors of Hubei economy from 2002 to 2007 did not entirely coincide with the sectoral emissions. The direct emission intensities of Sector 23 (1026.49 g/CNY, 1219.20 g/CNY, and 1512.59 g/CNY in 2002, 2005, and 2007, respectively) were still much larger than that of other sectors in all the three years. Though direct emission intensity of Sector 3 (Petroleum and Natural Gas Extraction) marginally declined by 45.38 g CO_2/CNY between 2002 and 2005, it surprisingly soared to 665.27 g/CNY in 2007, which is only less than that of Sector 23. It should also be noted that Sector 2 (Coal Mining and Dressing) had the second highest direct emission intensity in 2002 (388.42 g/CNY) before its direct emission intensity plummeted.

The direct emissions and intensities of three major industries in Hubei in 2002, 2005, and 2007 are depicted in Figs. 6 and 7. Clearly, during this period, both the largest direct emissions and intensities belonged to the secondary industry (Sector 2−26). The direct emissions derived from

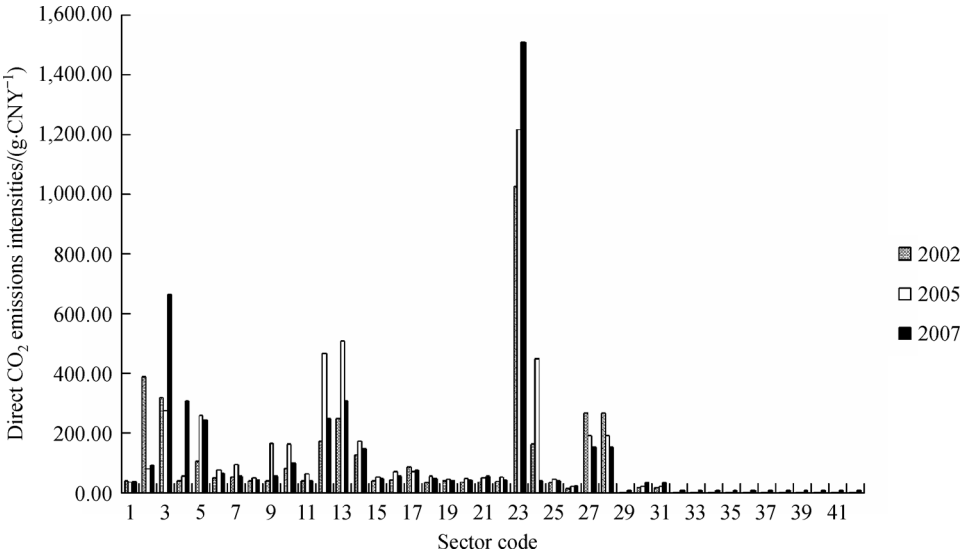

Fig. 5 Direct CO_2 emission intensities for each sector in Hubei 2002–2007.

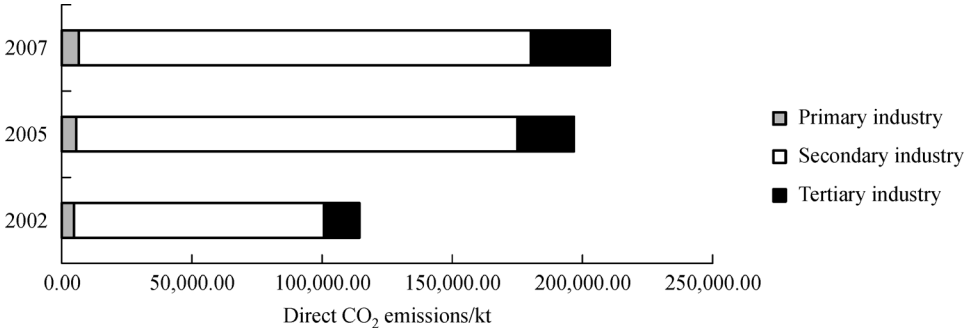

Fig. 6 The direct CO_2 emissions for three major industries in Hubei 2002–2007.

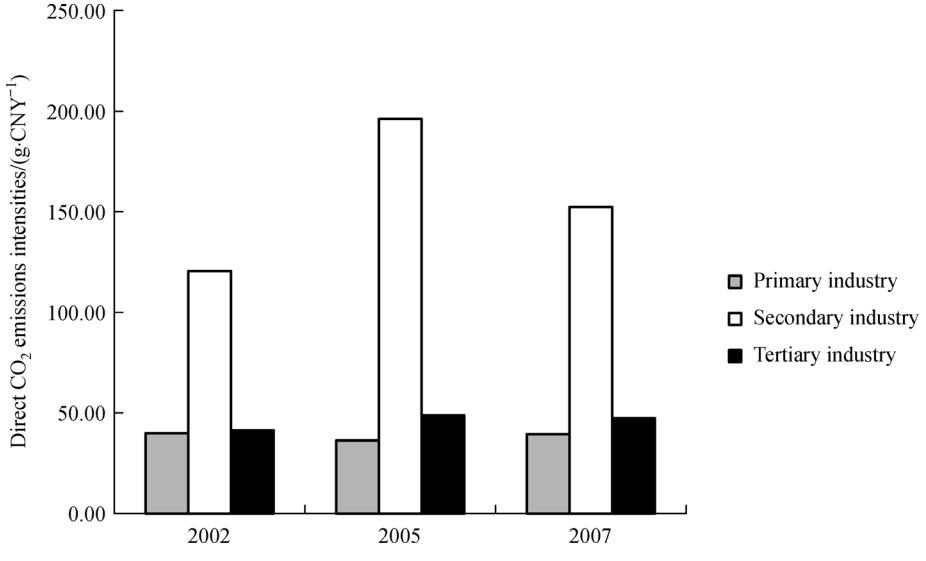

Fig. 7 The direct emission intensities for three major industries in Hubei 2002–2007.

the secondary industry boomed from 95,869.63 kt to 169,206.02 kt and later to 173,851.53 kt, constituting 83.76%, 86.04%, and 82.62% of total in 2002, 2005, and 2007, respectively. Upward tendencies were also seen in the direct emissions of primary industry (namely Sector 1) and tertiary industry (Sector 27−42) over the same period. As can be seen in Fig. 7, the direct CO_2 emission intensity for secondary industry rose from 120.08 g/CNY in 2002 to 196.02 g/CNY in 2005 and then dropped to 152.01 g/CNY in 2007, while fluctuations only occurred in the direct emission intensities of both primary and tertiary industries between 2002 and 2007.

3.2 Embodied CO_2 emissions

Figure 8 shows the embodied CO_2 emission intensities by 42 economic sectors in Hubei Province in 2002, 2005, and 2007. Needless to say, Sector 23 (Electric Power, Heat Production and Supply), had the highest embodied intensities in three respective years, with 1192.97 g/CNY ascending to 1510.72 g/CNY, then to 1739.15 g/CNY. The reason behind this could be explained by the fact that Sector 23 is the main supplier of electricity and heat power for other sectors. It is also worth mentioning that there were, overall, three different trends amongst the 42 sectors' embodied emission intensities during the period, with the exception of Sector 33 (Real Estate) which had its own variation tendency. The embodied intensities of Sector 2 and Sectors 27−30 witnessed reductions for three separate years, with Sector 2 (Coal Mining and Dressing) as the second emission-intensive sector in 2002 with an embodied intensity of 638.44 g/CNY. In contrast, embodied emission intensities of Sectors 4, 9, and 21−23 experienced successive rises during the same time, making Sector 4 (Metals Mining and Dressing) the third emission-intensive sector in 2007 with 929.54 g/CNY, only 1739.15 g/CNY less than Sector 23 and 1043.39 g/CNY less than Sector 3. The embodied intensities of the remaining sectors increased from 2002 to 2005 and then declined from 2005 to 2007.

3.3 CO_2 emissions embodied in trade

EEB of each economic sector in Hubei is calculated by Eq. (5) and shown in Fig. 9. Sectors with positive (negative) *EEB* are considered as net exporters (importers) of embodied CO_2 emissions. Hubei Province was a net exporter of CO_2 emissions in 2002 and 2007, totaling 4109.00 kt and 17,871.77 kt, respectively. Alternatively, the area's total imported net of CO_2 was 2511.93 kt.

On a sectoral basis, all economic sectors can be grouped into three types: 1) those with positive net emissions (net CO_2 exporters) in three separate years; 2) those with negative net emissions (net CO_2 importers) between 2002 and 2007; and 3) those with positive net emissions in some years, but negative in others. In the first group, Sector 23 (Electric Power, Heat Production and Supply) was the largest net exporter of emissions, nearly doubling in all three years, increasing from 8557.92 kt in 2002 to 19,629.17 kt in 2007. It is obvious that coal-related heat and electricity were not generated solely from Sector 23 of Hubei, but also from other sectors within Chinese province sectors and foreign regions. There seems to be an upward trend for Hubei to supply power to other outside regions . What's more, the net exported emissions of Sector 17 (Transportation Equipment Manufacturing) nearly remained stable from 2002 (7127.91 kt) to 2005 (7102.41 kt), enabling Sector 17 to become the second largest net exporter. Subsequently, net export emissions dramatically fell to only 94.74 kt in 2007. In view of three-

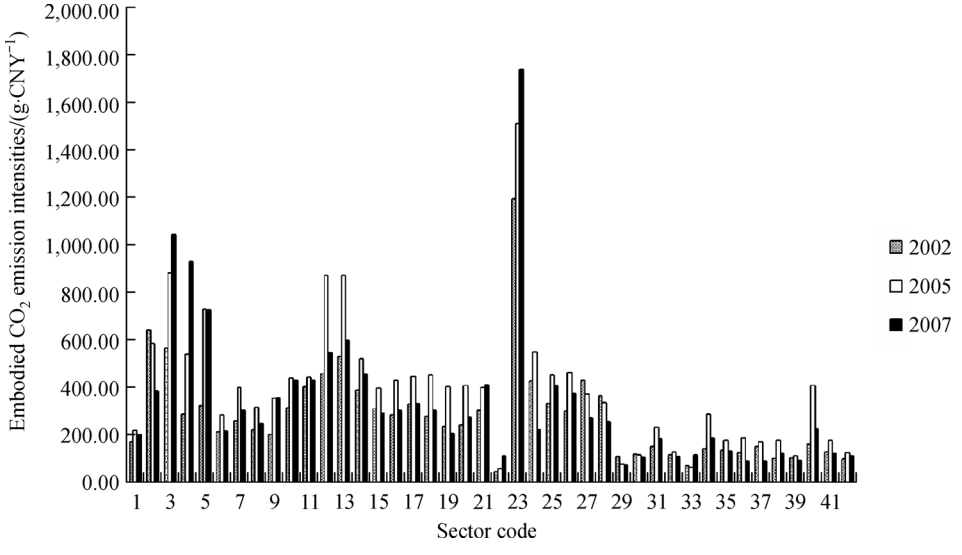

Fig. 8 The embodied CO_2 emission intensities for 42 sectors in Hubei 2002−2007.

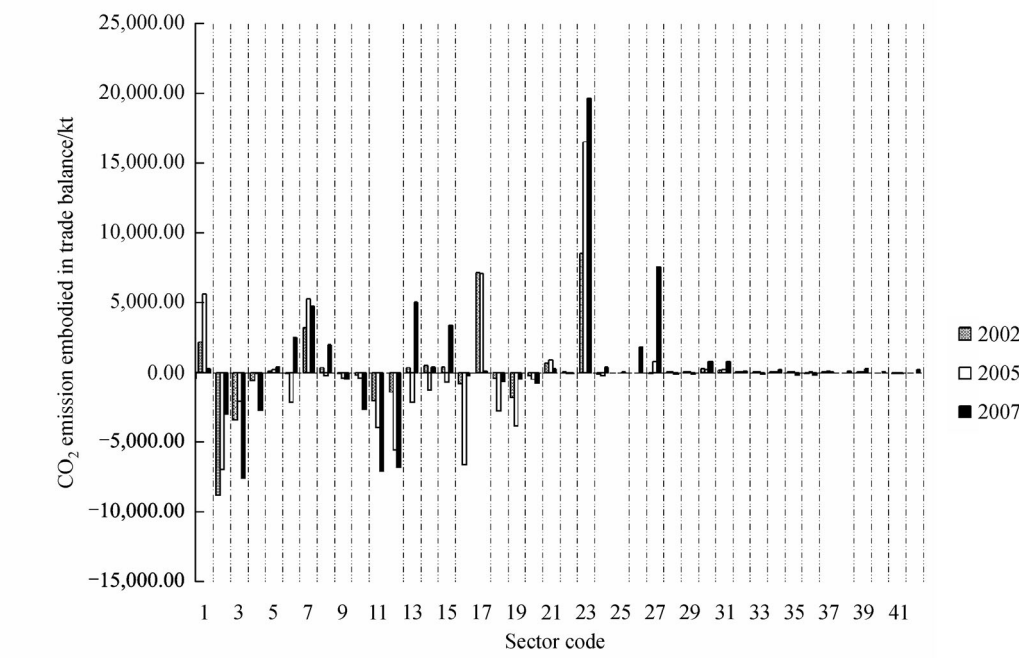

Fig. 9 The embodiment of CO_2 emission in trade balance.

year average, Sector 7 (Textile Industry) had a smaller amplitude of variation in net exported emissions with 3198.11kt, 5271.36 kt, and 4708.61 kt in three separate years.

The second group, Sector 11 (Petroleum Processing, Coking Products and Nuclear Fuel Processing) and Sector 12 (Chemical Products Related Industry), saw jumps in their net imported emissions between 2002 and 2007, ultimately ranking them the second and third largest net importers of CO_2 emissions in 2007 (7069.69 kt and 6772.37 kt, respectively). Comparatively, net imported emissions in Sector 3 (Petroleum and Natural Gas Extraction) skyrocketed from 2005 to 2007 by as much as 7558.98 kt. Dissimilarly, Sector 2, the top sectoral net importer in 2002, saw a decrease in emissions from 8816.93 kt in 2002 to 2976.58 kt in 2007.

For the third group, the most interesting finding is that Sector 27 (Transport and Storage) became the second largest sectoral net exporter in 2007 (7597.74 kt) five years after having a negative net emission rate of 35.40 kt in 2002 kt.

3.4 CO_2 emissions embodied in final use

The components of embodied CO_2 emissions by six different categories in Hubei's local final use from 2002 to 2007 are presented in Table 6. The final use here is comprised of rural household consumption, urban household consumption, government consumption, fixed capital formation, and inventory increase and export. The total CO_2 emissions embodied in Hubei's final use increased from 158.21 Mt (2002) to 274.10 Mt (2005), finally reaching 294.71 Mt in 2007, approximately three times that observed in 2002.

To be concrete, export contributed the largest percentage of the total emissions embodied in 2002 and 2007 in final use, with 30.25% and 34.67%, respectively. Another important contributor is fixed capital formation, with embodied emissions nearly doubling from 47.43 Mt in 2002 to 103.96 Mt in 2005. Following export and fixed capital formation are urban household consumption and rural household consumption. Urban household consumption was responsible for 18.23% of total emissions embodied in final use in 2002 and its share of total maintained steady at 20.76% in 2005 and 20.65% in 2007. Over the five years, emissions embodied in urban household consumption had more than doubled, growing from 28.84 Mt in 2002 to 60.86 Mt in 2007. Alternatively, CO_2 emissions embodied in rural household consumption had a fluctuant tendency. Apparently, with the growth of total emissions embodied in final use and steady embodied emissions in rural household consumption, the contribution of rural household consumption to the total embodied emissions from final use underwent a downward trend in the period concerned. The proportion decreased from 11.92% to 7.10%, indicating a widening gap between embodied emissions of rural and urban household consumption over the period. For inventory increase, its proportion had been steadily decreasing for five years, from 5.83% in 2002 to 1.24% in 2005, then minimally to 1.16% in 2007. While the embodied CO_2 emissions of government consumption increased from 6.00 Mt in 2002

Table 6 The distribution of embodied CO_2 emissions by final use in Hubei

Final use	2002		2005		2007	
	Emission/Mt	Fraction/%	Emission/Mt	Fraction/%	Emission/Mt	Fraction/%
Rural	18.86	11.92	21.96	8.01	20.93	7.10
Urban	28.84	18.23	56.91	20.76	60.86	20.65
Government	6.00	3.79	12.94	4.72	12.48	4.23
Fixed capital formation	47.43	29.98	103.96	37.93	94.86	32.19
Inventory increase	9.22	5.83	3.40	1.24	3.41	1.16
Export	47.86	30.25	74.94	27.34	102.17	34.67
Total	158.21	100.00	274.10	100.00	294.71	100.00

to 12.94 Mt in 2005, finally reaching 12.48 Mt in 2007, the percentage remained constant during the period, at about 4%, more or less.

4 Discussion

Hubei's fuel-related embodied CO_2 emissions in 2007 were estimated at about 180,000 kt. Compared to other provincial regions, Hubei's emissions were found to be higher than those of Beijing (Zhang et al., 2013), Tianjin (Ma et al., 2011), and Jiangsu (Wang et al., 2013a), comparative to those of Shanghai (Wang et al., 2013b) and Chongqing (Tan et al., 2016), but seemingly lower than those of Liaoning (Geng et al., 2013) and Guangdong (Zhou et al., 2013). Apparently, Hubei faces increasing pressure as direct CO_2 emissions from fuel consumption show an upward trend in the period concerned. Moreover, the direct emissions are projected to ascend into the following years due to an increased demand of energy, particularly from coal use with relatively high emission factors. From the point of emission structure by fuel type raw coal is likely to maintain the leading position in fuel-related direct CO_2 emissions in the future. With energy conservation and CO_2 emission reduction tasks, the Hubei local government should launch relevant policies, edicts, and regulations to encourage the utilization of renewable and clean energy. For instance, natural gas use could be increased to replace raw coal. Moreover, as a conventional heavy industry base, Hubei should make efforts to control energy consumption and high emission-intensive industries and eliminate outdated production capacity.

According to the calculated results, Sector 23 (Electric Power, Heat Production and Supply) remained the top direct CO_2 emitter and held the highest direct CO_2 emission intensity compared with other sectors. This is due to the fact that most of the electric and heat power in Hubei comes from coal combustion. This phenomenon is likely to continue for a long period of time unless the energy sectors use other energy sources with lower carbon emission factors to replace the dominant coal.

After analyzing the industrial structure of the Hubei economy, this paper shows that Hubei, like many other less developed provinces in China, is a typical province where the secondary industry (Sector 2−26) plays the dominant role for the entire economic structure. During the period concerned, the secondary industry was a holder of not only the largest direct CO_2 emissions, but also the highest direct emission intensities. Based on the results above, one of the effective countermeasures for reducing the direct CO_2 emissions from Hubei is to restructure, adjust, and optimize the industrial structure, triggering and prompting a shift from heavy energy-consuming industries to less carbon-intensive industries, such as tertiary or high-tech manufacturing industries.

Sectors 23, 3, and 4 are expected to remain the top three embodied CO_2 emissions intensive sectors into the future according to their sustained growth momentum. As a result, the Hubei government is expected to cut down a proportion of the large-scale mining industries and develop an advanced mining technology which is low in carbon intensity and will control the embodied emissions in its economy.

In the next decades, Hubei will likely continue as a net exporter of CO_2 emissions, even though it was a net importer in 2005. Sectors 23 and 27 (Transport and Storage) are predicted to export an increasing amount of CO_2, while Sectors 3 (Petroleum and Natural Gas Extraction), 4 (Metals Mining and Dressing), 10 (Paper-making and Paper Products, Printing and Record Processing, Stationery, Education and Sports Goods), 11 (Petroleum Processing, Coking Products and Nuclear Fuel Processing), and 12 (Chemical Products Related Industry) are expected to import more CO_2 in future years. Based on these statistics, Hubei Province should increase its export of low carbon products and upgrade its carbon-consuming industries. In the meantime, greater efforts should be made to adjust the industrial structure characterized by the exports of low value added products at the expense of environmental degradation (Chen and Zhang, 2010).

Export and fixed capital formation were the top two largest embodied CO_2 emission sources in final use. Their prominent positions are likely to be irreplaceable into the

future since investments and exports are two leading engines for Hubei's economic growth. Thus, another effective measure for effectively mitigating CO_2 emissions would be a modification of Hubei's traditional energy-consumption and carbon-intensive economic growth pattern by increasing the economy's reliance on local consumption.

5 Conclusions

Hubei Province, one of the first batches of low carbon pilot provinces, is now exerting itself to become a green and ecologically friendly province by saving energy and reducing CO_2 emissions. To that goal, this paper analyzes fuel-related CO_2 emissions for each sector in Hubei in the years of 2002, 2005, and 2007 on the grounds of input-output analysis.

The amount of total direct CO_2 emissions rose from 114,462.69 kt (2002) to 196,650.31 kt (2005), with final totals reaching 210,419.93 kt in the year 2007, showing a surprising average increase rate of 22.50%. From the viewpoint of different types of fuel inputs, raw coal was the largest direct emission source. On average across the three years, direct emissions from the burning of raw coal shared nearly 70% of the total, followed by lesser emissions from coke and diesel.

On the sectoral basis, Sector 23 (Electric Power, Heat Production and Supply) took the largest responsibility for total direct emissions in the Hubei economy 2002, 2005, and among all the sectors. Other predominant sectors for direct CO_2 emissions were Sector 12 (Chemical Products Related Industry), Sector 13 (Nonmetal Mineral Products) and Sector 27 (Transport and Storage). These three sectors together contributed around 1/3 of the total emissions in the years concerned. The secondary industrial structure was dominant in Hubei's economy for three years, contributing more than 80% of the total direct emissions, while the primary industry was the lowest CO_2 emitter, with a three-year average of 5654.47 kt. The tertiary industry intervened between the primary industry and the secondary industry, with an average contribution of 21,880.78 kt in the same period.

Meanwhile, this study found a wide variation in the embodied CO_2 emission intensities among 42 sectors. Sector 23 (Electric Power, Heat Production and Supply) had the largest intensities during the period. Sector 3 (Petroleum and Natural Gas Extraction) and Sector 4 (Metals Mining and Dressing) were the second and third largest embodied CO_2 intensive sectors in the final year after their intensities experienced continuous rises from 2002 to 2007.

Hubei Province was a net exporter of embodied CO_2 emissions in the years of 2002 and 2007, totaling 4109.00 kt and 17,871.77 kt, respectively. In 2005, Hubei had a net negative emission embodied in trade balance (2511.93 kt), meaning Hubei was a net importer of CO_2 emissions in that year. Although CO_2 emissions embodied in import outnumbered those in export in 2005, Hubei was still a typical net CO_2 exporter. In 2007, the leading CO_2 export sectors were Sector 23 (Electric Power, Heat Production and Supply) and Sector 27 (Transport and Storage) at 38.46% and 14.89%, respectively, while Sector 23 and Sector 17 (Transportation Equipment Manufacturing) were the top two in 2002 and 2005.

Compared with other components, export and fixed capital formation were CO_2-intensive and had the leading fractions in final use.

It is suggested that the Hubei government optimize its fuel structure by increasing its use of renewable energy, thus replacing the dominant use of coal. What's more, policies should be developed to properly control the export of low value added, but high carbon-intensive, products to ensure the development of a more sustainable economy.

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