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Tracing Energy Conservation and Emission Reduction in China's Transportation Sector

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ABSTRACT. China is a large economy being troubled by excessive energy consumption, serious environmental pollution and carbon emission problems. To reduce energy consumption, pollutant and carbon emission, understanding their trend and their relationships with the socioeconomic development is essential. Among various sectors, transportation sector is energy-intensive and emits a large amount of air toxics and CO_2, and therefore deserves primary attention. This study took carbon emission as a proxy of environmental degradation and employed an analytical framework composed of input-output analysis, ecological network analysis and structural decomposition analysis to scrutinize production- and consumption-based energy consumption and carbon emission (ECCE), to analyze effects of final demand elasticity on them, mutualism relationships between transportation sector and other sectors, and pulling/ driving force of transportation sector on the ECCE of the whole economy, and to explore the drivers affecting ECCE of transportation sector. Results comprise the increase trend of ECCE of transportation sector, the noticeable relevance of transportation sector to ECCE, the domination of control relationship and the increase of competition relationship between transportation sector and other sectors, the significant effects of final demand structure, per capita final demand, production structure and sectoral carbon emission density on ECCE. According to these results, as for transportation sector, adjusting the energy structure, improving the transportation efficiency and coordinating the relations between the transportation and its relevant sectors are suggested. The analytical framework facilitates ECCE policy devising in transportation sector for China's target of energy conservation and emission reduction and are instructive for other countries' ECCE actions.

Keywords: energy, carbon emission, input-output analysis, structural decomposition analysis, transportation sector

1. Introduction

Climate change and air pollution impact each other (Zhai et al., 2020) and have been worldwide issues being concerned about for more than two decades (Antonakakis, et al., 2017). Emissions from human activities are generally considered as the major factor of them. Conversely, they may deteriorate living environment of human beings and affect economic development. According to the report from IPCC, economic activity and energy usage are key contributors to the increase of greenhouse gas emission (IPCC, 2014). Empirical study also shows that there are long-term associations between energy, economic growth and carbon emission (Armeanu et al., 2021). High productivity results in high GDP, but deteriorate environment (Xiong and Xu, 2021). Carbon emission causes 26% of the overall greenhouse effect and can be seen as a proxy of environmental degradation (Jun et al., 2021). Therefore, understanding the detail of energy consumption and carbon emission (ECCE) and the relationships of them with socioeconomic development is vital for human beings to adapt to climate change, improve environmental quality and maintain sustainability of economic development.

In the past few years many efforts have been put on energy consumption and/or carbon emission. For example, Zheng et al. (2020a) have explored the drivers of energy-related CO_2 emission. Mahapatra and Irfan (2021) have examined the asymmetric impacts of energy efficiency on carbon emission for both developed and developing economies. Nam and Jin (2021) have compared effects of energy transition, energy efficiency, and electrification on carbon emission through an empirical model. Cao et al. (2021) developed a chance-constrained urban agglomeration energy model to address carbon emission and energy-water management issues under interregional cooperation mechanism. Bartela et al. (2021) have conducted a thermodynamic analysis of compressed CO_2 energy storage system. Nathaniel et al. (2021) have explored roles of nuclear energy, renewable energy, and economic growth in carbon emission reduction in G7 countries. Apeaning (2021) have explored the role and magnitude of drivers for decoupling of energy-related carbon emission from economic growth. However, most of them focus on the global, national or regional levels, on international/interregional flows or on specific technology, which cannot sufficiently support the sectoral-scale climate change and pollution

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mitigation actions within a country. Sector-level research is often ignored while energy conservation and emission reduction work are often delegated to specific sectors within a country. How to formulate policies and measures to ensure energy conservation and emission reduction at sectoral scale and coordinate the relationships between upstream and downstream sectors is still unclear.

According to the latest Global Energy Statistical Yearbook, China is the largest energy consumer and carbon emitter. Total energy consumption and carbon emission in China are both huge. What's more, due to the rapid economic growth, population explosion and urbanization, the ECCE is still showing an increasing trend in China. China has announced the 2030 carbon emission peak and 2060 carbon neutrality goals. Though China has been encouraging energy efficiency improvement and supporting the energy transition from fossil fuel to clean ones through adjusting industrial structure, establishing and improving the legal system and implementing price, tax, financial and other economic policies that are conducive to energy conservation and emission reduction, it is still facing great pressure to save energy and reduce carbon emission. Issues such as scarcity of oil and gas resources, incompleteness and incoordination of the relevant policies and measures, uncertainty of the energy technology evolution and difficulties in energy consumption accounting constitute the resistance to energy conservation and emission reduction.

Since 2000, more than 70% of China's ECCE were caused by the industrial sectors (He et al., 2021). In terms of energy consumption, transportation sector (Due to the data availability, the transportation sector refers to the sector of Transportation, Storage, Post and Telecommunication Services) ranks third among various sectors, and in terms of carbon emission, fourth among them (Figure 1). Urbanization, economic development and improvement of people's living standards enable China's transportation to expand rapidly. Environmental deterioration and health damage effects caused by the transportation sector is serious. Therefore, considering the heterogeneity between transportation and other industry sectors ECCE issues in transportation sector have aroused attention. Relevant studies contain ECCE of high-speed railway (Wang et al., 2021), relationship between energy consumption, economic growth, and CO_2 emissions (Peng and Wu, 2020), impacts of electric vehicles on ECCE (Qian et al., 2018), ECCE under different policy scenarios (Liu et al., 2018). However, many aspects remain unclear: (1) how will economic measure affect ECCE of transportation sector; (2) what is the relationship between the transportation sector and other sectors in terms of ECCE and how does the transportation sector affect the ECCE of the national economic system; (3) which factors drive ECCE of transporttation sector; (4) are there aspects need to be improved, how can transporttation sector be improved.

There are interplays between energy use and carbon emission (Zhai et al., 2020). Empirical study shows that strong coupling of them exists in cities with different scale and population densities (Chen and Chen, 2017). Simultaneously tracking the energy consumption and carbon emission facilitates the search of feasible alternatives for low-carbon pathways and the possibilities for decoupling economic growth and carbon emission (Chen and Chen, 2017), and for decoupling energy consumption and intensive carbon emission. Now, ECCE reduction plan is an active response of Chinese government for previous effort. This study retrospectively scrutinizes the ECCE of

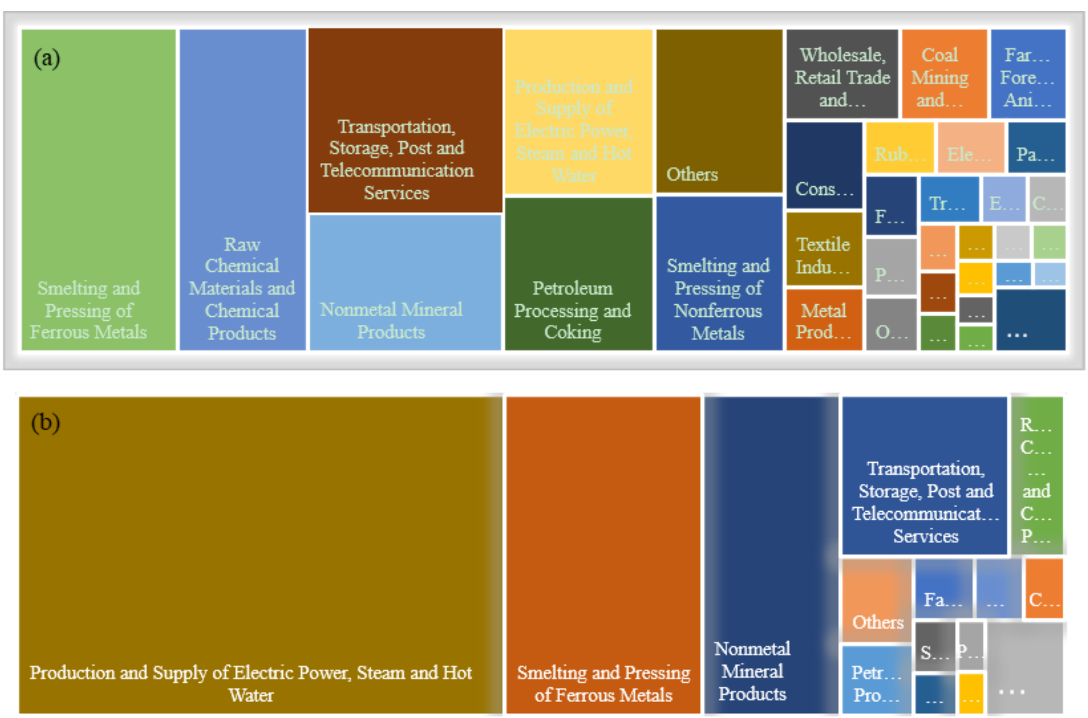

Figure 1. Energy consumption (a) (in 2018) and carbon emission (b) (in 2017) in each sector.

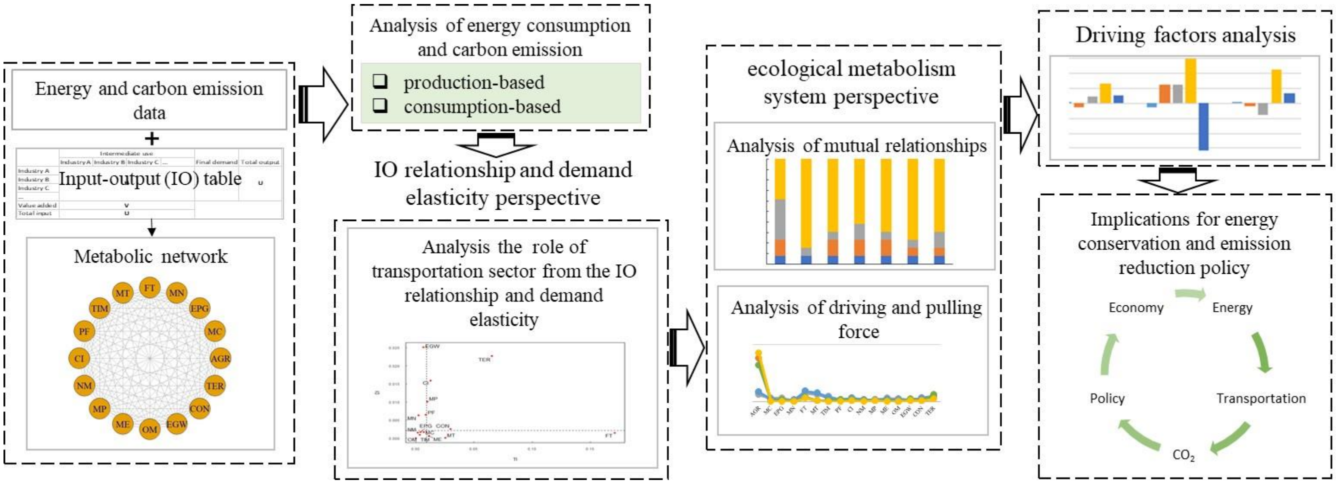

Figure 2. Analytical framework.

transportation sector in China under a framework integrated with input-output analysis (IOA), ecological network analysis (ENA) and structural decomposition analysis (SDA). Specifically, trend of ECCE of transportation sector will be revealed, intrinsic relationships between transportation and other sectors and the whole economic system will be quantified, negative relationships will be disclosed, effects of final demand elasticity on ECCE of transportation sector will be examined and the drivers of ECCE of transportation sector will be analyzed. The results are conducive to conquering ECCE issues of transporttation sector and to seeking a sustainable development pathways not only for China but also for other countries with similar situation.

2. Method

Figure 2 illustrates the analytical framework. It is an integration of IOA, ENA and SDA. Specifically, in the framework, the ECCE metabolic network representing connection and interaction of transportation sector with other sectors is constructed through ENA (Zhang et al., 2014); the production- and consumption-based ECCE are accounted based on input-output framework (Leontief, 1986); the role of transportation sector in ECCE are revealed from the input-output relationship and demand elasticity (Alcántara and Padilla, 2003; Guo et al., 2018); the mutual relationships between transportation sector and other sectors are uncovered through the ecological utility analysis; impacts of the transportation sector on ECCE of the whole economic system are demonstrated through network control analysis (Gattie et al., 2006; Fang and Chen, 2015). Analysis results from this framework could facilitate the formation of energy conservation and emission reduction policy and measures for transportation sector, which are not only beneficial to the transport sector, but to the whole economy.

2.1. Construction of Metabolic Network

Connection between transportation and the other sectors can be represented through ENA based on inter-sector trade relationships depicted as monetary transactions in the IO table. The various sectors are defined as nodes and directional flows among them are paths. Indexes of pairwise nodes are symbolized as i and j. In the constructed metabolic network the total inflows equal to the total outflows:

$$T_j = \sum_{i=1}^{n} f_{ij} + p_j = \sum_{i=1}^{n} f_{ji} + z_j \tag{1}$$

$$F = \left[f_{ij} \right] = diag(\varepsilon) \cdot X \tag{2}$$

$$\varepsilon = e \cdot \left[diag(t) - X \right]^{-1} \tag{3}$$

where, f_{ij} denotes embodied flows of energy consumption/carbon emission from node (sector) j to node (sector) i, i.e., from production side to the consumption side; p_j is boundary input; z_j is boundary output; $X = [x_{ij}]$ is the monetary transaction matrix; $t = [t_{ij}]$ is total output vector; e is sectoral production-based energy consumption/carbon emission vector; ε is sectoral production-based energy consumption/carbon emission density vector; *diag* denotes diagonalization.

2.2. Account of ECCE

Joint adoption of production- and consumption-based accountings can provide complementary insight on both supply and demand side for hotspots identification (Rocco et al., 2018). The production-based ECCE can be derived from the official statistics and relevant database. The consumption-based ECCE ec can be calculated as follows:

$$ec = diag(\varepsilon) \cdot (I - A)^{-1} y \tag{4}$$

$$A = [a_{ij}] = [x_{ij} / t_{ii}] \tag{5}$$

where, I is an identity matrix; A is a technical coefficient matrix; $(I - A)^{-1}$ is the Leontief inverse matrix; $y = [y_i]$ is final demand vector.

2.3. Effect of Final Demand Elasticity on ECCE

To explore the role of transportation sector in the metabolic network, measures quantifying increase/decrease of ECCE caused by 1% increase of final demand should be calculated as follows:

$$s=\left[diat(t)\right]^{-1}\cdot y \tag{6}$$

$$E^{y}=diag(\beta)\cdot[diag(t)]^{-1}\cdot(I-A)^{-1}\cdot diag(t)\cdot diag(s) \tag{7}$$

where *s* is a column vector with each element representing the ratio of final demand of each sector to total output of it. β is a vector with each element representing the share of energy consumption/carbon emission of corresponding sector in the total one brought about by the final demand of the specific sector.

The column sum of E_y denotes TI_j representing change rates of energy consumption/carbon emission due to expanding products and services to meet the 1% increase of final demand of sector *j*, which can be calculated by Equation (8):

$$TI_j=\sum_{i=1}^{n}E_{ij}^{y} \tag{8}$$

The row sum of E_y denotes DI_i representing sectoral effect caused by increase in product input to meet 1% increase of overall sector output:

$$DI_j=\sum_{j=1}^{n}E_{ij}^{y} \tag{9}$$

TI_j and DI_j reflect the impacts of demand structure and output on ECCE.

Then median values of TI_j and DI_i can be used as thresholds to classify all sectors into four categories. Energy consumption/carbon emission in category I (with smaller *TI* but larger *DI*) depends on the demand of products or services from its downstream sectors. Therefore, if sectors in the first category implement ECCE reduction measures, demand from the downstream sectors will be affected and thus economic development will be affected. Sectors be classified in category II (with both *TI* and *DI* higher than the thresholds) are key sectors. These sectors not only drive the relevant sectors to consume energy and release CO_2, but also consume energy and release CO_2 under the demand stimulation of other sectors. Sectors in category III (with small *TI* and *DI*) are less relevant to ECCE of the whole system. Sectors in category IV (with larger *TI* but smaller *DI*) are energy- and carbon-intensive sectors from perspectives of both production and consumption sides. ECCE of these sectors largely depends on the system's final demand for products and services which are produced and provided from themselves.

2.4. Effect of Inter-Sector Relationship and Driving and Pulling Forces on ECCE

Inter-sector relationship analysis is vital for revealing the effective pathways for eco-environmental improvement. Network utility analysis is adopted to make in-depth analysis of the mutual relationships of the pairwise sectors. The dimensionless direct utility matrix *D* representing direct relationship for evaluating the mutual benefit can be obtained by equation (10), and integral utility matrix *U* representing integral mutualism consists of both direct and indirect effects, by equation (11):

$$D=[d_{ij}]=[\frac{f_{ij}-f_{ji}}{T_j}] \tag{10}$$

$$U=(I-D)^{-1} \tag{11}$$

The positive and negative signs of *U* can be used as criteria to identify relationships among different sectors. Based on the sign matrix of *U* four kinds of inter-sector relationships can be interpreted, (+, +), (+, −), (−, +) and (−, −), symbolizing mutualistic, exploitative, exploited and competitive relationship respectively.

Network control analysis is used to quantify the driving and pulling forces i.e., control and dependence degrees of the transportation sector. Weights of driving and pulling forces are defined as follows:

$$N=(I-G)^{-1} \tag{12}$$

$$W=diag(t)\cdot N \tag{13}$$

$$wd_i=\frac{\sum_{j=1}^{n}w_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}} \tag{14}$$

$$wp_i=\frac{\sum_{j=1}^{n}w_{ji}}{\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ji}} \tag{15}$$

where $G=[g_{ij}]=[f_{ij}/T_j]$; *W* represent the weight matrix; wd_i and wp_i are driving and pulling force weight respectively. Diving and pulling force weights of transportation sector are the ones with the corresponding index.

2.5. Detection of Driving Factors of ECCE

SDA (Lenzen, 2007; Zheng et al., 2020b) is employed to detect the driving factors of embodied ECCE changes in transportation sector. *y* can be decomposed into five factors consisting of the sectoral emission intensity ε, production structure represented as $L=(I-A)^{-1}$, final demand structure *m*, per capita final demand level *d*, population *p*:

$$y=\varepsilon\cdot L_m\cdot d\cdot p \tag{16}$$

$$m=[y_i/y_{total}] \tag{17}$$

$$\begin{aligned}\Delta e &= \Delta e_{\varepsilon} + \Delta e_{L} + \Delta e_{m} + \Delta e_{d} + \Delta e_{p} \\ &= \Delta\varepsilon \cdot L \cdot m \cdot d \cdot p + \varepsilon \cdot \Delta L \cdot m \cdot d \cdot p + \varepsilon \cdot L \cdot \Delta m \cdot d \cdot p \\ &+ \varepsilon \cdot L \cdot m \cdot \Delta d \cdot p + \varepsilon \cdot L \cdot m \cdot d \cdot \Delta p\end{aligned} \tag{18}$$

where y_{total} is total final demand; Δe represents the ECCE change. Δe_{ε}, Δe_{L}, Δe_{m}, Δe_{d}, and Δe_{p} reflect ECCE changes resulted from changes of discharge intensity, production structure, final demand structure, per capita final demand level and population respectively. Driving factors of transportation sector are the ones with the corresponding index.

3. Data Collection

China's input-output table of 2002, 2005, 2007, 2012, 2015 and 2017 were acquired from National Bureau of Statistics of China and Chinese Input-Output Association. Sectoral energy and carbon emission data were derived from Statistical Yearbook of China and data sharing platform of Carbon Emission Accounts & Datasets (CEADs, http://www.ceads.net) (Shan et al., 2018, 2020), which was compiled based on China's Energy Statistical Yearbooks and available local emission coefficients. CEADs has been used for analyzing carbon emission of China's construction sector (Wang et al., 2020). The sources of energy in this study include fossil fuels, electricity and other energies. Due to data availability, the data spanning from 2002 to 2017 was examined according to the analytical framework. All IO tables have been deflated to 2002 constant prices.

To ensure the ECCE data are consistent with the input-output tables, the original sectors have been aggregated into thirteen sectors (Table 1). Original codes of various sectors, energy and carbon emission inventories can be found in the original input-output tables and CEADs data respectively.

4. Results and Discussions

4.1. Dynamic of ECCE in China's Transportation Sector

Analysis of trend of time series of ECCE could facilitate projection of future energy demand and carbon emission levels and policy-relevant revelation under different economic traits. Figure 3 shows that within the studied period both energy consumption and carbon emission exhibit an increasing trend. This may be explained by the continuous increase of passenger traffic and freight traffic volume due to the expanded demand for transportation caused by rapid social and economic development. The average annual growth rate of passenger traffic and freight traffic in 2001 ~ 2017 in China were 5.2 and 7.2% (National Bureau of Statistics, 2019), respectively. If the growth rate remains as usual, urbanization in China will make air pollution and traffic congestion too serious to be ignored (Wang et al., 2014). Furthermore, because of the high reliance on petroleum,

Table 1. Sector Aggregation

Codes	Sectors	Original sector Codes of energy inventory	2002	2005	2007	2010	2012	2015	2017
1	Agriculture	1, 8	1	1	1	1	1	1	1 ~ 5
8	Mining	2 ~ 7	2 ~ 5	2 ~ 5	2 ~ 5	2 ~ 5	2 ~ 5	2 ~ 5	6 ~ 11
2	Food and Tobacco	9 ~ 12	6	6	6	6	6	6	12 ~ 26
3	Textiles	13 ~ 15	7, 8	7, 8	7, 8	7, 8	7, 8	7, 8	27 ~ 34
4	Timbers and Furniture	16 ~ 20	9, 10	9, 10	9, 10	9, 10	9, 10	9, 10	35 ~ 40
5	Petroleum, Coking, Chemicals	21 ~ 26	11, 12	11, 12	11, 12	11, 12	11, 12	11, 12	41 ~ 53
6	Non-metallic Mineral Products	27	13	13	13	13	13	13	54 ~ 60
7	Metal Products	28 ~ 30	14, 15	14, 15	14, 15	14, 15	14, 15	14, 15	61 ~ 66
9	Machinery, Equipment and Other Manufacturing Industry	31 ~ 38	16 ~ 22	16 ~ 22	16 ~ 22	16 ~ 22	16 ~ 23	16 ~ 23	67 ~ 96
10	Electricity, Gas, Water	39 ~ 41	23 ~ 25	23 ~ 25	23 ~ 25	23, 24	25 ~ 27	25 ~ 27	98 ~ 100
11	Construction	42	26	26	26	25	28	28	101 ~ 104
12	transportation	43	27, 28	27, 28	27, 28	26, 27	30	30	107 ~ 118
13	Other Services	44, 45	29 ~ 42	29 ~ 42	29 ~ 42	28 ~ 41	31 ~ 42, 24, 29	31 ~ 42, 24, 29	119 ~ 149, 97, 105, 106

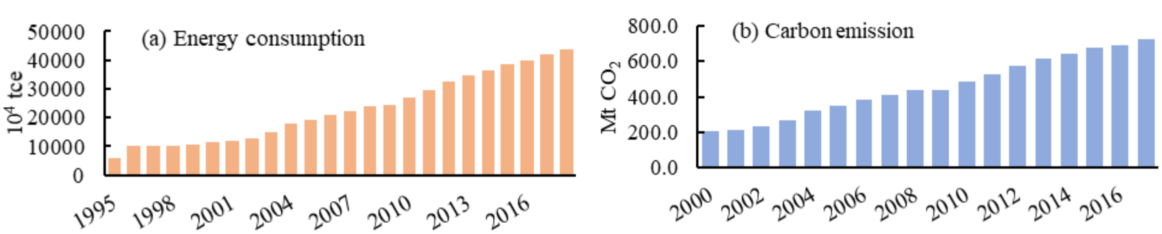

Figure 3. Dynamic of ECCE.

the energy consumption reduction and decarbonization in transportation sector cannot be realized only through a single economic policy, such as carbon price policy (Yin et al., 2015). According to the ASIF framework (Schipper et al., 2000), emission factor of fuels, energy intensity of transport modes, traffic demand are main factors for carbon emission of transportation sector. To achieve energy conservation and emission reduction in transportation sector in the future, adjusting the energy structure and travel demand and improving energy efficiency are still China's inevitable choices. In recent years, the increase of private cars, the rise of online car-hailing and bike/car-sharing travel modes, and the development of the e-commerce platform transformation pose new challenges to energy conservation and emission reduction in the transportation sector and should be incorporated into corresponding policy. Integrated transportation system interlaced with intercity rapid rail transits are constructing in China with the rise of urban agglomerations. In addition, China is investing in constructing international transport channels to facilitate global logistics. These actions will constitute new sources of ECCE and pose additional challenges to ECCE reduction in China's transportation sector.

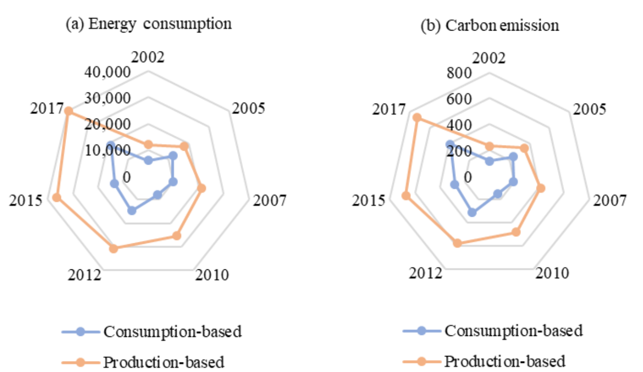

Figure 4. Production- and consumption-based energy consumption (10^4 tce) and carbon emission (Mt CO_2).

Production-based accounting is incomplete because it ignores the trade perspective. Consumption-based accounting is a complementary to production-based one for supporting policy and measure formulation, which could break down barriers between different sectors. It can allocate ECCE occurred in the production and marketing to final consumers, therefore, make it feasible to take into account the consumer's responsibilities for ECCE. Obviously, the production-based ECCE are greater than the consumption-based ones (Figure 4), i.e., the production-based energy consumption is 1.47-3.15 times of consumption-based one and production-based carbon emission is 1.47-3.23 times of consumption-based one. The dynamic of energy consumption is very similar to carbon emission from both production- and consumption-based perspectives. Different from the production-based ECCE, the consumption-based ones did not show a continuously increasing trend. This difference indicates ECCE of transportation sector were mainly caused by production process. Transportation is fundamental for a region's development because of its essential role in resources transportation and human resource mobility. However, transport energy consumption worsens CO_2 emissions (Adams et al., 2020). Currently, transportation sector is facing low transportation efficiency of transport modes, insufficient institutional capacity-building, traffic congestion and pollution (Ma et al., 2021). Therefore, improving transportation efficiency through optimizing transportation structure, coordinating development of various transport modes and adopting the clean energy through shifting the mix of energy in the transport process are necessary for ECCE growth curb and total ECCE cap targets. To realize systematic ECCE reduction consumers as beneficiaries should share the ECCE reduction responsibility with the producers through economy measures such as tax and differential pricing policy.

Figure 5 shows fluctuates of energy and carbon emission intensity in transportation sector in 2002 ~ 2017. The decrease in 2012 ~ 2017 can be attributed to actions of China on "double control" of total consumption and intensity from both production and consumption sides. For example, to build a low-carbon transport system, China has been actively optimizing the energy consumption structure, increasing the length of public transport routes, and promoting transportation equipment with high energy efficiency and low emission, new energy vehicles, shared transport and smart transport. Obviously, positive effects of replacing of the share of fossil fuels by electricity on reduction of ECCE intensity (Dong et al., 2017) and the above other measures to improve energy efficiency have surpassed retardation effects of the heavy reliance on petroleum products of transportation sector (Yin et al., 2015) and the ever-increasing demand of freight traffic and passenger traffic. The higher intensity of production-based ECCE compared with consumption-based ones indicates energy-intensive transport modes should be reduced and fuel economy standards should be further strengthened in the future.

4.2. Impacts of Demand Elasticity on ECCE

It was verified that there are positive relationships between economic growth and carbon emission (Erdogan et al., 2020). Therefore, it is essential to explore the details, i.e., the impacts of demand elasticity on ECCE, and sectoral economic performance with regard to them. Figure 6 illustrates that the TI of ECCE changed irregularly, i.e., a 1% increase in the final demand of transportation sector led to 2.6% ~ 5.6% increase of total final energy consumption, and 2.0% ~ 4.6% carbon emission. The DI curves of ECCE represent increasing trend. In the surveyed period, 1% increase of the final demand of all sectors led to more than 0.08% increase of total final energy and 0.06% increase of total final carbon emission in the whole economy were corresponding to transportation sector respectively. These results indicate that the impact of final demand elasticity on ECCE may continue to increase in the future. According to the classification criterion based on median values of TI and DI, there are two special years, 2005 and 2017, in which transportation sectors were identified as a key sector. In 2005, the transportation sector not only pull energy consumption of other sectors, but also consume a large quantity of energy under the demand stimulation of other sectors. Similar situation regarding carbon emission occurred in 2017. In other years, output

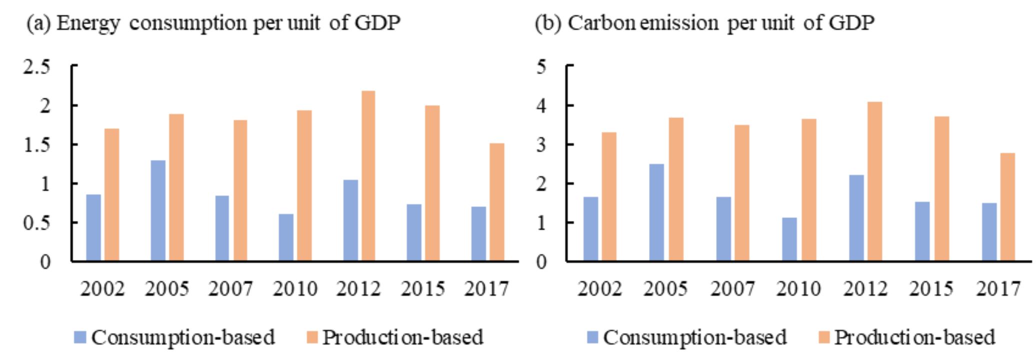

Figure 5. Energy intensity (tce/10000 Yuan RMB) and carbon intensity (t/10000 Yuan RMB) in transportation sector.

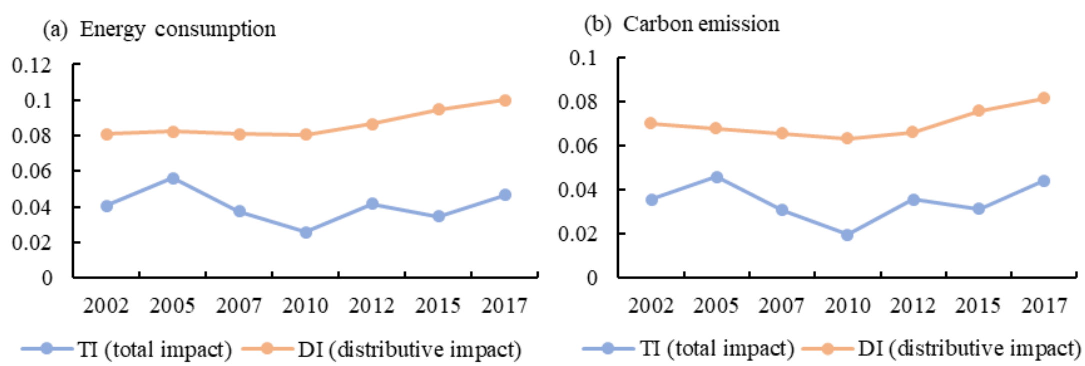

Figure 6. Impacts of demand demand elasticity on carbon emission.

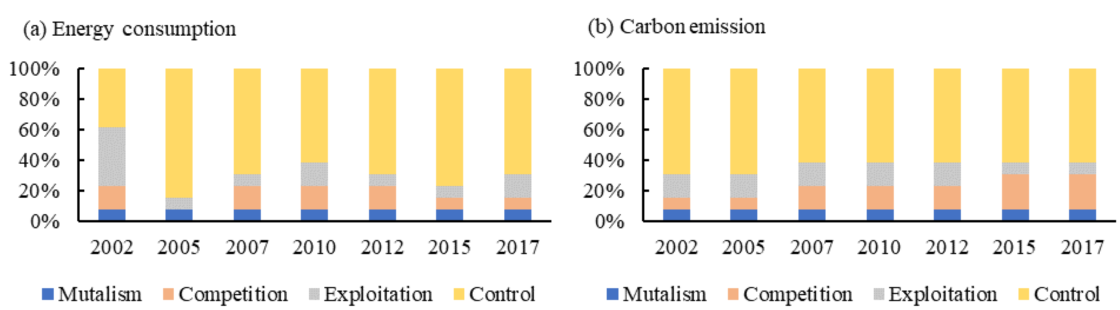

Figure 7. Relationships of transportation sector with other sectors in terms of ecological relationships.

changes in the economic system have indirect effect on ECCE of transportation sector. If the transportation sector applies ECCE reduction policies, the output of economic system may be affected, thus affecting the demand of other sectors for the products of the transportation sector and inhibiting its development eventually. Therefore, to device environmentally friendly policies, tradeoffs should made between economic development, final demand and ECCE reduction.

4.3. Inter-Sectoral Relationships and Effects of Transportation Sector on the Whole Economic System

Figure 7. shows that proportion of mutualism relationship was constant across the studied period. This relationship is self-correlation of transportation sector. After 2002, control relationship had the largest proportion among the four ecological relationships in terms of both energy consumption and carbon emission; and the percentage of this dominant relationship is stable from 2002 to 2017. Therefore, technological progress and production process adjustment is needed to reduce the proportion of control relationship and increase the proportion of mutualism one. For carbon emission, competition relationships were inversely correlated with exploitation relationships. The competition relationship between sector of transportation and Non-metallic Mineral Products was constant. Increase of competition relationship was aroused by sector of Petroleum, Coking, Chemicals, and Metal Products. This trend should arouse attention. Because it indicates that transportation sector is putting more and more pressure on other sectors and improve the production technologies of transportation sector is recommended to reduce the ECCE stress.

Regarding energy, Wang (2020) showed that transportation sector holds a central position in the supply network terms of out-degree, betweenness, and closeness centrality degree. Hence, it is necessary to reveal its role in ECCE of the whole economic system from the perspectives of driving force and pulling force. Figure 8. shows higher shares of driving force weight than pulling one. Transportation infrastructure plays a driving role in reginal economic development. The higher shares of driving force weight indicate higher control degree of transportation sector to its downstream sectors, i.e., the higher capacity of transportation sector to pass ECCE to its downstream sectors than to receive that from its downstream sectors or the system though supply linkages. The distances between the driving and pulling force present a tendency to increase first and then decrease, implying the stronger and then weaker control ability of the transportation sector on the ECCE of the whole economy and the nonlinear relationship between traffic and economic development. In addition, trends of the driving and pulling force are consistent regarding energy consumption and carbon emission respectively. The slight decrease trends suggest the effects of transportation sector in the economy regarding ECCE were weakening at a very slow rate. This may be explained by the lower and lower proportion of GDP created by transportation sector (Transportation's share of GDP has dropped from 6.16% to 4.46% from 2002 to 2017).

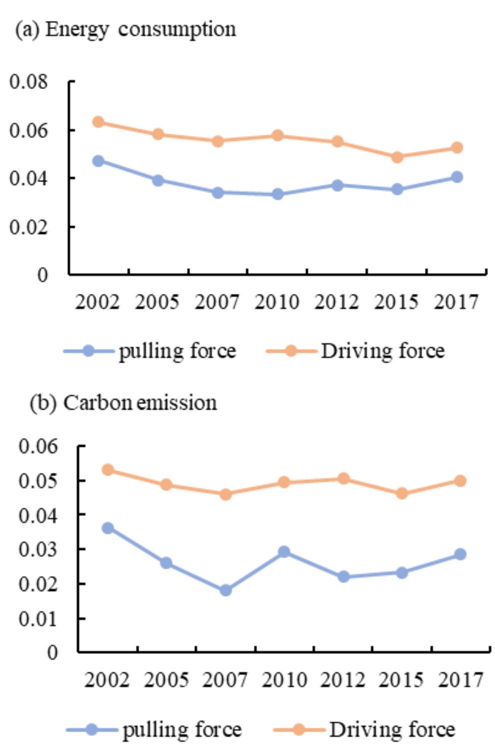

Figure 8. Driving and pulling force weights of transportation sector.

4.4. Drivers of Embodied ECCE Changes

SDA were conducted to analyze dynamic of driving factors for change of ECCE in adjacent years. The results in Figure 9 show that performance (change rate of ECCE) of most driving factors for energy consumption and carbon emission are consistent. Namely, the contribution of final demand relevant factors, population and production structure showed the same direction in corresponding year across all of the investigated years, indicating strong connection of energy consumption and carbon emission. Effects of sectoral carbon emission density and production structure in 2007-2010 were much significant on carbon emission, compared with the corresponding factors on energy consumption. This may be explained by China's actions on adjusting the economic structure and energy mix, replacing small generation units with large ones in the electricity sector, and improving energy efficiency in the 11th Five-Year Plan period. The lowest value of the sectoral carbon emission density indicates its strongest impact on the carbon emission reduction in 2007 to 2012. On the contrary the highest production structure suggests its highest capacity on its increase. Previous study shows that the final demand is a main contributor of carbon emission growth in transportation sector (Yu et al., 2021a). This study illustrates that the final demand structure is a determinant of increase of carbon emission, while per capital final demand has little effect on carbon emission. For the entire economy, it was reported that the energy intensity is the key factor to reduce energy consumption in period 2007-2012 (Yu et al., 2021b), while for transportation sector per capita final demand is the key one in 2007-2010. The difference indicates exploration of driving factors at the scale of sector is more precise for proposing pertinent countermeasure and suggestions. China's industrial structure and production mode are transferring from the one relying on heavy and chemical industry and "extensive way" to the one characterizing with emerging industries and "intensive way". This transformation may constitute an important factor of ECCE reduction in future.

5. Conclusions and Policy Implications

In this study, a concrete picture of China's transportation sector was provided. ECCE trend, effects of demand elasticity and inter-sector relationships on them, and drivers of them have been explored through an analytical framework integrated with IOA, ENA and SDA. The main findings are as follows: (1) ECCE of transportation sector escalated gradually over the studied period; (2) production-based ECCE was more than consumption-based one; (3) the impact of the transportation sector on ECCE of the the country's economic system cannot be ignored. (4) from the perspective of ecological metabolism system, particular attention should be put on the control and competition relationships and further reduce energy consumption per unit of GDP is still necessary. Face the plight of energy conservation and emission reduction, green transportation policy and the 14th Five-Year Plan provide a new opportunity for further reduction of ECCE since transportation sector can drive that of other sectors and adjusting final demand structure can be used as an alternative measure. From perspective of supply side, to cap energy consumption and reduce carbon emission, policy support to promote low-energy and low-carbon technologies for transportation sector is recommended. In addition, demand-side measures such as low carbon investment and green

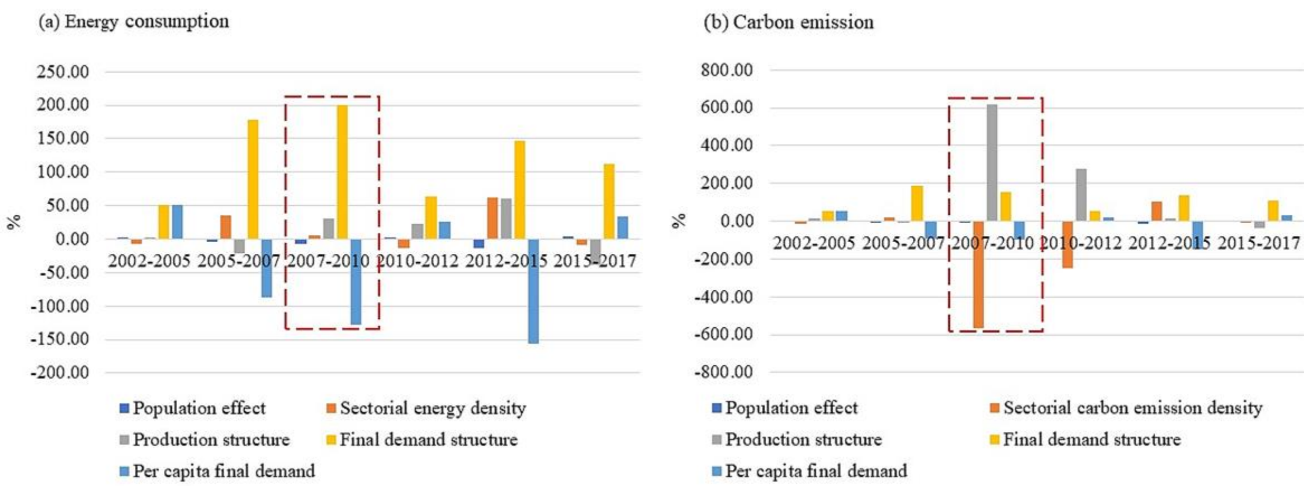

Figure 9. Effects of driving factors on ECCE of transportation sector.

consumption should be promoted, which can be realized through carbon tax, subsidy incentives. Construction of intelligent transportation system and public transport system with complementary rail transit and road traffic can be conducted to complement supply-side measures.

To obtain more instructive results on ECCE, some improvements are expected in the future. Air quality is closely related to ECCE. Complex relationships of it with energy and carbon emission deserve attention. Comprehensive research on effects of climate-resilient economic growth on reduction of energy consumption, CO_2 and pollutants emissions of transportation sector is required. Green transportation policy and carbon-neutral target may potentially promote energy consumption and emission reduction, and should be included in future studies. These efforts will further impel sustainable development promotion.

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References

Adams, S., Boateng, E. and Acheampong, A.O. (2020). Transport energy consumption and environmental quality: Does urbanization matter? *Science of the Total Environment*, 744, 140617. https://doi.org/10.1016/j.scitotenv.2020.140617

Alcántara, V. and Padilla, E. (2003). “Key” sectors in final energy consumption: an input–output application to the Spanish case. *Energy Policy*, 31, 1673–1678. https://doi.org/10.1016/S0301-4215(02)00233-1

Antonakakis, N., Chatziantoniou, I. and Filis, G. (2017). Energy consumption, CO_2 emissions, and economic growth: An ethical dilemma. *Renewable and Sustainable Energy Reviews*, 68, 808-824. https://doi.org/10.1016/j.rser.2016.09.105

Apeaning, R.W. (2021). Technological constraints to energy-related carbon emissions and economic growth decoupling: A retrospective and prospective analysis. *Journal of Cleaner Production*, 291. https://doi.org/10.1016/j.jclepro.2020.125706

Armeanu, D.S., Joldes, C.C., Gherghina, S.C. and Andrei, J.V. (2021). Understanding the multidimensional linkages among renewable energy, pollution, economic growth and urbanization in contemporary economies: Quantitative assessments across different income countries’ groups. *Renewable and Sustainable Energy Reviews*, 142, 110818. https://doi.org/10.1016/j.rser.2021.110818

Bartela, Ł., Skorek-Osikowska, A., Dykas, S. and Stanek, B. (2021). Thermodynamic and economic assessment of compressed carbon dioxide energy storage systems using a post-mining underground infrastructure. *Energy Conversion and Management*, 241, 114297. https://doi.org/10.1016/j.enconman.2021.114297

Cao, R., Huang, G.H., Chen, J.P., Li, Y.P. and He, C.Y. (2021). A chance-constrained urban agglomeration energy model for cooperative carbon emission management. *Energy*, 223, 119885. https://doi.org/10.1016/j.energy.2021.119885

Chen, S. and Chen, B. (2017). Coupling of carbon and energy flows in cities: A meta-analysis and nexus modelling. *Apply Energy*, 194, 774-783. https://doi.org/10.1016/j.apenergy.2016.10.069

Dong, K.Y., Sun, R.J., Li, H. and Jiang, H.D. (2017). A review of China’s energy consumption structure and outlook based on a long-range energy alternatives modeling tool. *Petroleum Science*, 14, 214-227. https://doi.org/10.1007/s12182-016-0136-z

Erdogan, S., Fatai Adedoyin, F., Victor Bekun, F. and Asumadu Sarkodie, S. (2020). Testing the transport-induced environmental Kuznets curve hypothesis: The role of air and railway transport. *Journal of Air Transport Management*, 89, 101935. https://doi.org/10.1016/j.jairtraman.2020.101935

Fang, D. and Chen, B. (2015). Ecological Network Analysis for a Virtual Water Network. *Environmental Science and Technology*, 49, 6722-6730. https://doi.org/10.1021/es505388n

Gattie, D.K., Schramski, J.R., Borrett, S.R., Patten, B.C., Bata, S.A. and Whipple, S.J. (2006). Indirect effects and distributed control in ecosystems: Network environ analysis of a seven-compartment model of nitrogen flow in the Neuse River Estuary, USA—Steady-state analysis. *Ecological Modelling*, 194, 162-177. https://doi.org/10.1016/j.ecolmodel.2005.10.017

Guo, J., Zhang, Y.J. and Zhang, K.B. (2018). The key sectors for energy conservation and carbon emissions reduction in China: Evidence from the input-output method. *Journal of Cleaner Production*, 179, 180-190. https://doi.org/10.1016/j.jclepro.2018.0 1.080

He, Y., Fu, F. and Liao, N. (2021). Exploring the path of carbon emissions reduction in China’s industrial sector through energy efficiency enhancement induced by R&D investment. *Energy*, 225, 120208. https://doi.org/10.1016/j.energy.2021.120208

IPCC. (2014). *Climate Change 2014*, Synthesis Report, Summary for Policymakers.

Jun, W., Mughal, N., Zhao, J., Shabbir, M.S., Niedbała, G., Jain, V. and Anwar, A. (2021). Does globalization matter for environmental degradation? Nexus among energy consumption, economic growth, and carbon dioxide emission. *Energy Policy*, 153, 112230. https://doi.org/10.1016/j.enpol.2021.112230

Lenzen, M. (2007). Structural path analysis of ecosystem networks. *Ecological Modelling*, 200, 334-342. https://doi.org/10.1016/j.ecolmodel.2006.07.041

Leontief, W. (1986). *Input-Output Economics*. Oxford University Press. ISBN: 0-19-503527-5

Liu, L., Wang, K., Wang, S., Zhang, R. and Tang, X. (2018). Assessing energy consumption, CO_2 and pollutant emissions and health benefits from China's transport sector through 2050. *Energy Policy*, 116, 382-396. https://doi.org/10.1016/j.enpol.2018.02.019

Liu, W. and Lin, B. (2021). Electrification of rails in China: Its impact on energy conservation and emission reduction. *Energy*, 226, 120363. https://doi.org/10.1016/j.energy.2021.120363

Mahapatra, B. and Irfan, M. (2021). Asymmetric impacts of energy efficiency on carbon emissions: A comparative analysis between developed and developing economies. *Energy*, 227, 120485. https://doi.org/10.1016/j.energy.2021.120485

Ma, Q., Jia, P. and Kuang H. (2021). Green efficiency changes of comprehensive transportation in China: Technological change or technical efficiency change? *Journal of Cleaner Production*, 304, 127115. https://doi.org/10.1016/j.jclepro.2021.127115

Nam, E. and Jin, T. (2021). Mitigating carbon emissions by energy transition, energy efficiency, and electrification: Difference between regulation indicators and empirical data. *Journal of Cleaner Production*, 300, 126962. https://doi.org/10.1016/j.jclepro.2021.12 6962

Nathaniel, S.P., Alam, M.S., Murshed, M., Mahmood, H. and Ahmad, P. (2021). The roles of nuclear energy, renewable energy, and economic growth in the abatement of carbon dioxide emissions in the G7 countries. *Environmental Science and Pollution Research*, https://doi.org/10.1007/s11356-021-13728-6

National Bureau of Statistics. (2019). *China Statistical Yearbook*. China Statistics Press.

Peng, Z. and Wu, Q. (2020). Evaluation of the relationship between energy consumption, economic growth, and CO_2 emissions in China' transport sector: the FMOLS and VECM approaches. *Environment, Development and Sustainability*, 22, 6537-6561. https://doi.org/10.1007/s10668-019-00498-y

Qian, Z., XunMin, O. and XiLiang, Z. (2018). Future penetration and impacts of electric vehicles on transport energy consumption and CO_2 emissions in different Chinese tiered cities. *Science China (Technological Sciences)*, 61, 1483-1491. https://doi.org/10.1007/s11431-018-9278-8

Rocco, M.V., Ferrer, R.J.F. and Colombo, E. (2018). Understanding the energy metabolism of World economies through the joint use of Production- and Consumption-based energy accountings. *Applied Energy*, 211, 590-603. https://doi.org/10.1016/j.apenergy.2017.10. 090

Schipper, L., Marie-lilliu, C. and Gorham, R. (2000). Flexing the Link between Urban Transport and CO_2 Emissions: A Path for the World Bank. *International Energy Agency*.

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z. and Zhang, Q. (2018). China CO_2 emission accounts 1997-2015. *Scientific Data*, 5, 170201. https://doi.org/10.1038/sdata.2017.201

Shan, Y., Huang, Q., Guan, D. and Hubacek, K. (2020). China CO_2 emission accounts 2016-2017. *Scientific Data*, 7, 54. https://doi.org/10.1038/s41597-020-0393-y

Wang, J., Wang, Z., Peng, S., Li, C. and Wei, L. (2020). Tracing CO_2 emissions of China's construction sector. *Journal of Cleaner Production*, 275, 124165. https://doi.org/10.1016/j.jclepro.2020.12 4165

Wang, R. (2020). Ecological network analysis of China's energy-related input from the supply side. *Journal of Cleaner Production*, 272, 122796. https://doi.org/10.1016/j.jclepro.2020.122796

Wang, Y.Z., Zhou, S. and Ou, X.M. (2021). Development and application of a life cycle energy consumption and CO_2 emissions analysis model for high-speed railway transport in China. *Advances in Climate Change Research*, 12, 270-280. https://doi.org/10.1016/j.accre.2021.02.001

Wang, Y.F., Li, K.P., Xu, X.M. and Zhang, Y.R. (2014). Transport energy consumption and saving in China. *Renewable and Sustainable Energy Reviews*, 29, 641-655. https://doi.org/10.1016/j.rser.2013.08.104

Xiong, J. and Xu, D. (2021). Relationship between energy consumption, economic growth and environmental pollution in China. *Environmental Research*, 194, 110718. https://doi.org/10.1016/j.envres.2021.110718

Yin, X., Chen, W., Eom, J., Clarke, L.E., Kim, S.H., Patel, P.L., Yu, S. and Kyle, G.P. (2015). China's transportation energy consumption and CO_2 emissions from a global perspective. *Energy Policy*, 82, 233-248. https://doi.org/10.1016/j.enpol.2015.03.021

Yu, J., Yang, T., Ding, T. and Zhou, K. (2021a). "New normal" characteristics show in China's energy footprints and carbon footprints. *Science of The Total Environment*, 785, 147210. https://doi.org/10.1016/j.scitotenv.2021.147210

Yu, Y., Li, S., Sun, H. and Taghizadeh-Hesary, F. (2021b). Energy carbon emission reduction of China's transportation sector: An input–output approach. *Economic Analysis and Policy*, 69, 378-393. https://doi.org/10.1016/j.eap.2020.12.014

Zhai, M., Huang, G., Liu, H., Liu, L., He, C. and Liu, Z. (2020). Three-perspective energy-carbon nexus analysis for developing China's policies of CO_2-emission mitigation. *Science of the Total Environment*. 705, 135857. https://doi.org/10.1016/j.scitotenv.2019.135857

Zhang, Y., Zheng, H., Fath, B.D., Liu, H., Yang, Z., Liu, G. and Su, M. (2014). Ecological network analysis of an urban metabolic system based on input–output tables: Model development and case study for Beijing. *Science of the Total Environment*, 468-469, 642-653. https://doi.org/10.1016/j.scitotenv.2013.08.047

Zheng, X., Lu, Y., Yuan, J., Baninla, Y., Zhang, S., Stenseth, N.C., Hessen, D.O., Tian, H., Obersteiner, M. and Chen, D. (2020a). Drivers of change in China's energy-related CO_2 emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 117, 29-36. https://doi.org/10.1073/pnas.190851 3117

Zheng, B., Huang, G., Liu, L., Guan, Y. and Zhai, M. (2020b). Dynamic wastewater-induced research based on input-output analysis for Guangdong Province, China. *Environmental Pollution*, 256, 113502. https://doi.org/10.1016/j.envpol.2019.113502