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Determinants of Greenhouse Gas Emissions from Interconnected Grids in China

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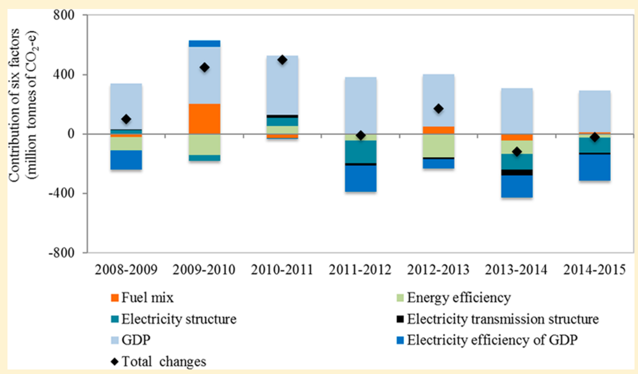
Supporting Information



ABSTRACT: While direct greenhouse gas (GHG) emissions by China's power sector from the generation side have been widely investigated, driving forces from the electricity consumption perspective and inter-regional electricity transmission have been overlooked to a large extent. This study quantified relative contributions of six factors to changes in GHG emissions from interconnected grids in China during 2008−2015. These six factors include three generation-side factors (i.e., fuel mix of thermal power generation, energy efficiency of thermal power generation, and electricity structure), two consumption-side factors (i.e., electricity efficiency of GDP and GDP), and electricity transmission structure. GDP growth and changes in fuel mix of thermal power generation are two major drivers of increased GHG emission during 2008−2015, especially for the North China Grid. In contrast, changes in electricity transmission structure (especially in East China Grid and Southern China Grid), the increase in electricity efficiency of GDP (except for Northwest China Grid), improvements in energy efficiency of thermal power generation (especially in North China Grid and Central China Grid), and changes in electricity structure (especially in Southern Power Grid) are major factors offsetting GHG emission increments. Findings of this study can provide multiple-perspective policy implications for GHG mitigation in China's power sector.

INTRODUCTION

Power sector is the largest fossil fuel consumer and greenhouse gas (GHG) emitter in China. It accounted for over 42% of China's coal consumption[1] and contributed over 52% of fossil-based CO_2 emissions in 2014.[2] Thus, decarbonizing the power sector is critical for China to peak its carbon emissions before 2030.[3]

In order to mitigate GHG emissions from the power sector, it is necessary to uncover critical factors influencing changes in GHG emissions of the electricity system. This can help policy-makers to identify potential pathways and corresponding measures for GHG mitigation. Existing studies have revealed critical factors at the electricity generation side.[4−6] It was found that changes in energy intensity and fuel mix of thermal power generation are major contributors to CO_2 emission reductions during 2004−2010.[4] Expanding nonfossil fuel electricity generation capacities (e.g., hydropower, nuclear, wind, and solar photovoltaic power generation) is another factor to reduce CO_2 emissions from electricity generation.[6] In addition, based on these identified critical factors, existing studies proposed various generation-side measures to reduce CO_2 emissions. These measures can be generally classified into three categories: (1) improving energy efficiency of electricity generation through technological innovation;[7] (2) promoting the installation of large-scale generation units and closing down small-scale ones of power plants;[8] and (3) reducing the use of fossil fuels in

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Table 1. Quasi Input−Output Table for the Interconnected Grids

		intermediate electricity outflows							
		grid 1	grid 2	grid 3	..	grid $n-1$	grid n	electricity consumption	total outflows
intermediate electricity inflows	grid 1	0	T_{12}	T_{13}	..	T_{1n-1}	T_{1n}	c_1	x_1
	grid 2	T_{21}	0	T_{23}	..	T_{2n-1}	T_{2n}	c_2	x_2
	grid 3	T_{31}	T_{32}	0	..	T_{3n-1}	T_{3n}	c_3	x_3
	:	:	:	:	:	:	:	:	:
	grid $n-1$	$T_{n-1\ 1}$	$T_{n-1\ 2}$	$T_{n-1\ 3}$	..	0	$T_{n-1\ n}$	c_{n-1}	x_{n-1}
	grid n	T_{n1}	T_{n2}	T_{n3}	..	$T_{n\ n\text{-}1}$	0	c_n	x_n
electricity generation		p_1	p_2	p_3	..	p_{n-1}	p_n		
total inflows		x_1	x_2	x_3	..	x_{n-1}	x_n		

electricity generation through promoting low-carbon electricity technologies.[9−13]

In addition to generation-side factors concerned by most of existing studies, there are also two categories of important critical factors influencing GHG emissions from electricity systems: (1) consumption-side factors (e.g., electricity efficiency of gross domestic products (GDP) and GDP) which drive electricity generation and the consequential CO_2 emissions; and (2) electricity transmission structure connecting power generation and electricity consumption. Some studies have tried to connect electricity generation and consumption through modeling electricity flows within interconnected grids.[14−18] The differences in environmental pressures interpreted from the generation- and consumption-side for a specific time point were revealed in these studies.

Changes in GHG emissions from the interconnected grids are influenced by changes in various factors including generation-side factors, consumption-side factors, and electricity transmission structure. China's power sector has undergone rapid transitions in the past decade. Contributions of various factors to GHG emissions have been evolving with different scale and structural factors. However, the physical electricity transmission structure, an important factor of the interconnected grids, is not well characterized in existing studies. This study fulfills this knowledge gap by paying special attention to the influences of the changes in physical electricity transmission structure.

In addition, previous study investigated influencing factors of CO_2 emission changes in China's electricity generation based on traditional monetary input-output models.[19] However, traditional monetary input−output models are not suitable to characterize the physical electricity flows (especially the electricity transmission structure) among interconnected grids,[16] mainly due to two reasons: the unique sectoral price assumption[20,21] and unique sectoral product assumption.[16] Traditional monetary input−output theory assumes that each sector allocates its products to other sectors in the same price and each sector only produces one type of products (i.e., products of a sector purchased by other sectors are all produced by this sector). However, for the interconnected grids, sectors usually purchase the electricity of a grid at different prices. Moreover, electricity outflows of a grid include not only the electricity generated by this grid but also the electricity directly or indirectly transmitted from other grids.[16] Thus, traditional monetary input-output models are not suitable to characterize the physical electricity flows among interconnected grids, and contributions of influencing factors to changes in GHG emissions from interconnected grids in China have not been well characterized in existing studies. Properly quantifying the changing contributions of these factors (especially the electricity transmission structure) can provide a more accurate view of the dynamic characteristics of China's electricity system.

The Quasi input−output (QIO) model is regarded as the suitable method to track physical electricity flows (especially the electricity transmission structure) within interconnected grids.[16] This study fulfills the knowledge gap using the structural decomposition analysis (SDA) based on the QIO model (QIO-SDA). In particular, using the QIO-SDA model, we can investigate the change in electricity transmission structure and its impacts on GHG emissions of the electricity system. This is quite different from existing studies which mainly use traditional monetary input−output models.

We quantify the contributions of six factors to changes in GHG emissions from the interconnected grids in China during 2008−2015. These six factors include three generation-side factors (i.e., fuel mix, energy efficiency of thermal power, and electricity structure), two consumption-side factors (i.e., electricity efficiency of gross domestic products (GDP) and GDP), and electricity transmission structure. We used a Quasi input−output (QIO) model to simulate interprovincial electricity flows and embodied GHG flows from electricity generation to electricity consumption. We combined the QIO model and structural decomposition analysis (SDA) to quantify the contributions of six factors. Findings of this study can provide generation-side, consumption-side, and transmission-side policy implications for GHG mitigation in China's power sector.

■ MATERIALS AND METHODS

Quasi Input−Output (QIO) Model. This study uses the QIO model proposed by Qu et al.[15,16] to simulate the processes of electricity generation and subsequent emissions, electricity transmission, and electricity consumption. The QIO table for the interconnected grids is shown in Table 1. A grid in Table 1 plays the roles of both an electricity generator and an electricity consumer. The electricity generation and consumption of the i^{th} grid are denoted as p_i and c_i, respectively. The electricity flow from grid i to grid j is denoted as T_{ij}. The total electricity inflow of grid i is denoted as x_i. It equals to the electricity transmitted from other grids plus the electricity generated by itself (i.e., the sum of the values in column i). In addition, the total electricity outflow of grid i equals to the sum of the values in row i. The total electricity inflow of grid i is equal to its total electricity outflow.

Based on the QIO table and input-output theory, we can derive the QIO model. The QIO model (including Quasi-Leontief model and Quasi-Ghosh model) describes the balances of electricity inflows and outflows of each grid and the whole interconnected grid network. Details about the QIO model can be found in the study of Qu et al.[16]

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The Quasi-Leontief model evaluates emissions of interconnected grids caused by electricity consumption of each grid or region. Total emissions of interconnected grids can be calculated by emission factors of total electricity flux (f) of each grid multiplied by electricity consumption of each grid (c), as shown in eq 1.

$$e^{C} = f\hat{c} = f^{G}T\hat{c} = f^{G}(WL)\hat{c} = f^{G}(W(I - A)^{-1})\hat{c} \quad (1)$$

The row vectors e^{C}, f, and f^{G} represent emissions embodied in electricity consumption, emission factors of total electricity flux, and emissions factors of electricity generation, respectively. The notation $\hat{c}$ indicates a diagonal matrix of electricity consumption c. The notation **T** stands for the electricity transmission matrix. It records the electricity flows among the interconnected grids, rather than the economic values transferred among different sectors. It is calculated by the weighting matrix **W** and the *total inflow requirement matrix* (termed as the *quasi-Leontief inverse*) $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$. **W** is a diagonal matrix, with each element describing the share of electricity generation of a grid (p_i) in its total electricity flux (x_i). The element l_{ij} of matrix **L** represents electricity flows from grid i directly and indirectly required by unitary electricity consumption of grid j. The matrix **I** is the identity matrix, and matrix **A** is the *direct inflow requirement matrix*. The element a_{ij} of matrix **A** represents the fraction of electricity flow from grid i to grid j (T_{ij}) in total electricity flux of grid j (x_j). In particular, diagonal elements of matrix **A** are zeros. The forms of matrices **W** and **A** are shown below.

$$W = \begin{bmatrix} \frac{p_1}{x_1} & 0 & \cdots & 0 \\ 0 & \frac{p_2}{x_2} & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & \cdots & 0 & \frac{p_n}{x_n} \end{bmatrix}, A = \begin{bmatrix} 0 & \frac{T_{12}}{x_2} & \cdots & \frac{T_{1n}}{x_n} \\ \frac{T_{21}}{x_1} & 0 & \ddots & \frac{T_{2n}}{x_n} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{T_{n1}}{x_1} & \cdots & \frac{T_{n(n-1)}}{x_{n-1}} & 0 \end{bmatrix}$$

Structural Decomposition Analysis (SDA). The SDA is widely used to investigate the impacts of structural changes on resource uses and CO_2 emissions. For example, scholars have used the SDA to analyze the impacts of changes in domestic industrial structure, household lifestyles, and trade structure on changes in CO_2 and pollutant emissions of a region.[22−29] The SDA is also used to investigate the impacts of changes in production structure and final demand structure on changes in water use[30] and raw material consumption.[31] Moreover, the SDA is integrated with the multiregional input-output model to reveal the economic structural factors influencing global CO_2 emissions.[32] Besides the SDA, the index decomposition analysis (IDA) methods (e.g., the Logarithmic Mean Divisia index (LMDI) decomposition) can also be used to investigate the factors that influence changes in resource uses and CO_2 emissions.[33−37] However, the IDA cannot reveal the contributions of structural factors (e.g., electricity transmission structure in this study), while the SDA can solve this issue.

This study uses the QIO-SDA to investigate the relative contributions of six factors influencing GHG emissions from interconnected grids: fuel mix (i.e., fuel input structure) of thermal power generation, energy efficiency of thermal power generation, the portion of thermal power in total electricity generation, electricity transmission structure, electricity efficiency of GDP, and GDP. We use the SDA to investigate relative contributions of these six factors to changes in emissions from interconnected grids.

We decompose direct emission factors of electricity generation f^{G} and matrix $\hat{c}$ into the forms of eqs 2 and 3, respectively.

$$f^{G} = \mathrm{EF}\cdot\mathrm{Es}\cdot\mathrm{diag}(\mathrm{eff})\cdot\mathrm{diag}(\mathrm{ps}) \quad (2)$$

$$\hat{c} = \mathrm{diag}(\mathrm{GDP})\cdot\mathrm{diag}(\mathrm{GDPeff}) \quad (3)$$

Direct emissions from electricity generation are mainly from thermal power plants. Therefore, row vector f^{G} is decomposed into the portion of thermal power (i.e., fossil-fuel-based electricity) in total electricity generation (ps), energy intensity of thermal power generation (eff), fuel mix of thermal power generation (Es), and emission factors of fuel sources (EF). Electricity consumption c is decomposed into GDP and electricity efficiency of GDP (GDPeff is calculated using the inverse of electricity efficiency of GDP).

We can derive eq 4 based on eqs 1−3. The interconnected grid network of China in this study covers 30 provincial-level grids and 22 types of fossil fuels. The units of decomposed factors are listed in Table 2.

$$e^{C} = \underset{1\times22}{\mathrm{EF}}\cdot\underset{22\times30}{\mathrm{Es}}\cdot\underset{30\times30}{\mathrm{diag}(\mathrm{eff})}\cdot\underset{30\times30}{\mathrm{diag}(\mathrm{ps})}\cdot\underset{30\times30}{\mathrm{T}}\cdot\underset{30\times30}{\mathrm{diag}(\mathrm{GDP})}\cdot\underset{30\times30}{\mathrm{diag}(\mathrm{GDPeff})} \quad (4)$$

Table 2. Descriptions and Units of Decomposed Factors

factors	descriptions	units
EF	emission factors of fuel sources	t-CO_2e/tce
Es	fuel mix of thermal power generation	%
eff	energy intensity of thermal power generation	tce/MWh
ps	percentage of thermal power in total electricity generation	%
T	the electricity transmission matrix	
GDP	gross domestic products	100 million RMB
GDPeff	the inverse of electricity efficiency of GDP	MWh/100 million RMB

The decomposition form of eq 4 is shown in eq 5.

$$\begin{aligned} \Delta e^{C} = & \ \mathrm{EF}\cdot\Delta\mathrm{Es}\cdot\mathrm{diag}(\mathrm{eff})\cdot\mathrm{diag}(\mathrm{ps})\cdot T\cdot\mathrm{diag}(\mathrm{GDP})\cdot\mathrm{diag}(\mathrm{GDPeff}) \\ & + \mathrm{EF}\cdot\mathrm{Es}\cdot\Delta\mathrm{diag}(\mathrm{eff})\cdot\mathrm{diag}(\mathrm{ps})\cdot T\cdot\mathrm{diag}(\mathrm{GDP})\cdot\mathrm{diag}(\mathrm{GDPeff}) \\ & + \mathrm{EF}\cdot\mathrm{Es}\cdot\mathrm{diag}(\mathrm{eff})\cdot\Delta\mathrm{diag}(\mathrm{ps})\cdot T\cdot\mathrm{diag}(\mathrm{GDP})\cdot\mathrm{diag}(\mathrm{GDPeff}) \\ & + \mathrm{EF}\cdot\mathrm{Es}\cdot\mathrm{diag}(\mathrm{eff})\cdot\mathrm{diag}(\mathrm{ps})\cdot\Delta T\cdot\mathrm{diag}(\mathrm{GDP})\cdot\mathrm{diag}(\mathrm{GDPeff}) \\ & + \mathrm{EF}\cdot\mathrm{Es}\cdot\mathrm{diag}(\mathrm{eff})\cdot\mathrm{diag}(\mathrm{ps})\cdot T\cdot\Delta\mathrm{diag}(\mathrm{GDP})\cdot\mathrm{diag}(\mathrm{GDPeff}) \\ & + \mathrm{EF}\cdot\mathrm{Es}\cdot\mathrm{diag}(\mathrm{eff})\cdot\mathrm{diag}(\mathrm{ps})\cdot T\cdot\mathrm{diag}(\mathrm{GDP})\cdot\Delta\mathrm{diag}(\mathrm{GDPeff}) \end{aligned} \quad (5)$$

The right-hand items of eq 5 indicate relative contributions of six factors to changes in emissions from interconnected grids Δe^{C}: changes in fuel mix of thermal power generation ΔEs, changes in energy efficiency of thermal power generation $\Delta\mathrm{diag(eff)}$, changes in the portion of thermal power (i.e., fossil-fuel-based electricity) in total generated electricity $\Delta\mathrm{diag(ps)}$, changes in electricity transmission structure ΔT, changes in GDP $\Delta\mathrm{diag(GDP)}$, and changes in electricity efficiency of GDP $\Delta\mathrm{diag(GDPeff)}$.

When there are n decomposed factors, there would be $n!$ decomposition forms. This is known as the nonuniqueness problem of SDA.[38] As usually done in our previous

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studies,[25,26,39−41] we take the average of all possible first-order decompositions to solve the nonuniqueness problem of SDA.

Data Sources. The interconnected grid network of China in this study covers 30 provincial-level grids and 22 types of fossil fuels. In particular, the grids of Tibet, Taiwan, Hongkong, and Macau are not covered in this study, mainly due to data unavailability. GHG emissions considered in this study include CO_2, CH_4, and N_2O emissions. The studied period is from 2008 to 2015, depending on the availability of electricity transmission data.

This study requires four types of data: GHG emissions from electricity generation in each grid, electricity generation in each grid, intergrid electricity transmission data, and GDP data in each province. GHG emissions from electricity generation of each grid are calculated based on fuel combustion and GHG emission factors. Data for fuel combustion of thermal power generation are from China Energy Statistical Yearbooks.[42] GHG emission factors of 22 types of energy sources are from World Resources Institute.[43] Data for electricity generation and consumption of each province are collected from China Electric Power Yearbooks.[44] Intergrid electricity transmission data are from China Electricity Council.[45] Electricity transmission losses are not considered in this study due to the unavailability of electricity loss data at the grid level. The average transmission loss rate of China's electricity system is around 6% in 2014.[44] In order to eliminate small statistical differences (less than 5% for each grid), electricity consumption data of each grid are calculated based on the energy balance between electricity inflows and outflows. That is, total electricity inflows into a grid equal to local electricity generation plus electricity import from other grids. Total electricity outflows from a grid equal to local electricity consumption plus electricity export to other grids. Data for GDP of each province are from China Statistical Yearbooks.[1] All the GDP data are converted to ones in 2008 constant price.

RESULTS

The results of generation-based and consumption-based GHG emissions (calculated using the QIO model) are provided in Tables S1−S3 in the Supporting Information (SI). We first illustrate the whole picture of determinants of GHG emission changes in interconnected grids of China, and then provide analyses and policy implications at administrative levels (i.e., the subnational grid and provincial grid levels).

General Situation of China As a Whole. Figure 1a shows relative contributions of six factors to GHG emission changes in interconnected grids of China during 2008−2015. GDP growth is the major driver of increasing GHG emissions during 2008−2015. In contrast, the increase in the electricity efficiency of GDP, the improvement in energy efficiency of thermal power generation, and the declining portion of fossil-fuel-based electricity (i.e., electricity structure) are major factors offsetting GHG emission increments during 2008−2015.

The electricity efficiency of GDP have increased by 20%, and the portion of thermal power (i.e., fossil-fuel-based electricity) in total electricity generation and the energy inputs per unit of thermal power generation have decreased by 9%, and 13%, respectively, during 2008−2015. Subsequently, these changes helped offset GHG increments of interconnected grids in China during 2008−2015.

Moreover, we also observed that changes in electricity transmission structure slightly offset GHG emissions during

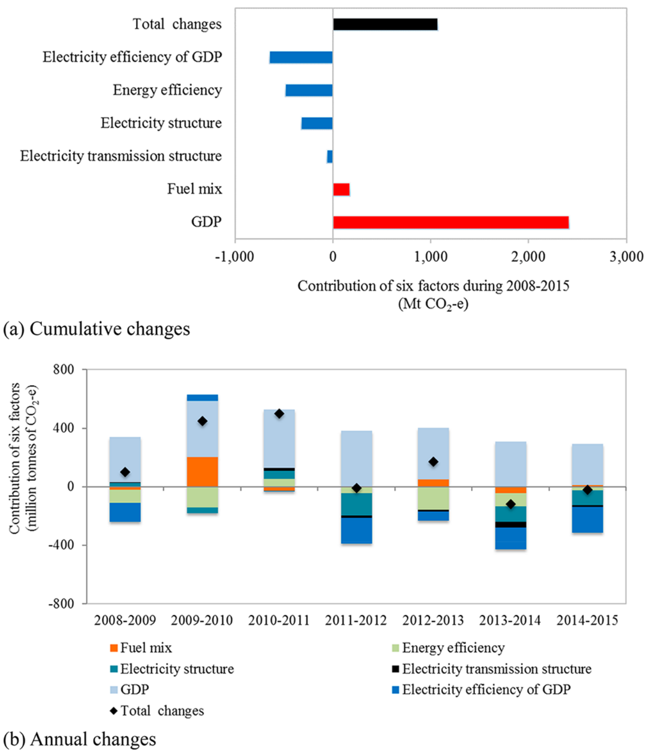

Figure 1. Relative contributions of six factors to changes in GHG emissions from interconnected grids of China during 2008−2015. Full results are listed in SI Table S4.

2008−2015, but its contribution was considerably small compared with other factors.

It is worth noting that changes in fuel mix of thermal power generation have slightly driven GHG emission increments of interconnected grids in China during 2008−2015. Although some grids have been substituting raw coal with alternative fuels that have lower carbon intensities (e.g., natural gas and residual heat), the input of fuels with higher carbon intensity (e.g., blast furnace gas) also increased during 2008−2015. The portion of natural gas in total energy inputs only increased by 1% (from 2% in 2008 to 3% in 2015). However, the portion of blast furnace gas in total energy inputs increased by 2% (from 0% in 2008 to 2% in 2015). The GHG emission factor of blast furnace gas is over four times that of natural gas. Such fuel mix changes slightly induced GHG emission increments of the interconnected grids.

We further investigated relative contributions of the six factors to changes in GHG emissions from interconnected grids of China during different time periods (Figure 1b). GHG emissions from interconnected grids of China increased during 2008−2011 and 2012−2013, while decreased during 2011−2012 and 2013−2015.GDP growth is the major driver of GHG emission increments for all periods. For the other five factors, we observed different contributions during different time periods (Figure 1b).

The increase in electricity efficiency of GDP is a major factor offsetting GHG emission increments during most periods, except for the period of 2009−2010. The national electricity efficiency of GDP has slightly decreased during 2009−2010. In particular, the electricity efficiency of GDP for Qinghai, Xinjiang, Shanxi, and Inner Mongolia have decreased by 16%, 9%, 6%, and 4%, respectively. One possible reason for such decreases might be the substantial investment to heavy manufacturing industries (e.g., metals smelting and cement

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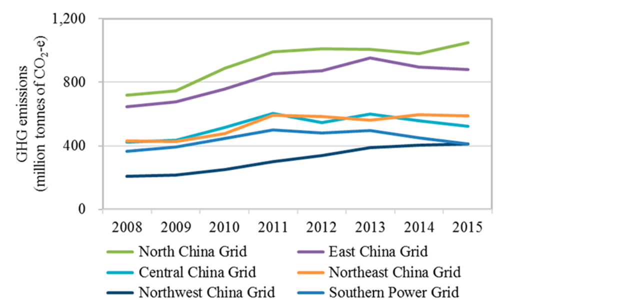
production), which have a relatively high electricity consumption for unitary GDP, during the *Four-Thousand-Billion Stimulus Plan*.

The energy efficiency of thermal power generation has slightly decreased during 2010−2011. Subsequently, although changes in energy efficiency of thermal power generation helped reduce GHG emissions in most periods, it contributed to GHG emission increments during 2010−2011.

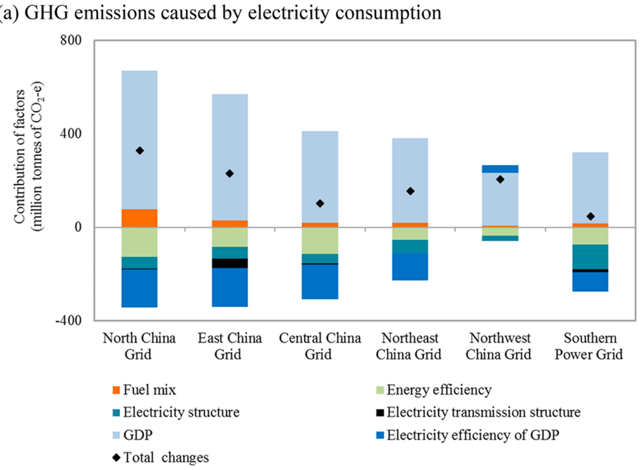
The portion of thermal power in total generated electricity slightly increased during 2008−2009 and during 2010−2011. Therefore, changes in electricity structure helped reduce GHG emissions in most periods but contributed to GHG emission increments during 2008−2009 and 2010−2011.

Similarly, we observed different contributions of fuel mix and electricity transmission structure during different periods. For instance, the portion of raw coal in fuel inputs of electricity generation has increased by about 2.4% during 2009−2010. Subsequently, changes in fuel mix contributed to GHG emission increments during 2009−2010, but helped reduce GHG emissions during 2010−2011 and 2013−2014.

The Situation of Six Subnational Grids. China's 31 provincial grids are administrated by six subnational grids, including North China Grid, East China Grid, Central China Grid, Northeast China Grid, Northwest China Grid, and Southern Power Grid (SI Table S5). Figure 2(a) shows GHG emissions caused by electricity consumption (i.e., consumption-based emissions) of six subnational grids. We observe a generally increasing trend during 2008−2015. The consumption-based emissions of North China Grid and East China Grid ranked the first and second during 2008−2015, respectively, totally contributing about 50% of GHG emissions from China's interconnected grids. Moreover, the consumption-based emissions of these two subnational grids have increased by 46% and 36% during 2008−2015, respectively.



(a) GHG emissions caused by electricity consumption



(b) Relative contributions of six factors to changes in GHG emissions

Figure 2. Consumption-based GHG emissions and relative contributions of six factors to changes in GHG emissions of subnational grids in China during 2008−2015. Full results are listed in SI Tables S6 and S7.

The Northwest China Grid ranked the last in the quantity of consumption-based emissions, while the first in the growth rate. Its consumption-based emissions have doubled during 2008−2015. In comparison, the Southern Power Grid had the least growth rate in consumption-based emissions during this period, and its consumption-based emissions have increased by around 13%.

Figure 2(b) shows the relative contributions of six factors to changes in consumption-based GHG emissions of subnational grids. The situation of subnational grids is generally similar to that of China as a whole, except for the Northwest China Grid. For the other five subnational grids, GDP growth is the major driver of GHG emission increments during 2008−2015, while the improvement in electricity efficiency of GDP, the increase in energy efficiency of thermal power generation, and the optimization of electricity structure (i.e., the increase in the proportion of nonfossil-fuel-based electricity) are major factors offsetting GHG emission increments during 2008−2015. However, for the Northwest China Grid, the change in electricity efficiency of GDP pushes its GHG emissions. This is mainly caused by the change of electricity efficiency of GDP in Xinjiang. The electricity efficiency of GDP in Xinjiang has decreased by 57% during 2008−2015. This change is expressed in two aspects: the increase in the proportion of electricity in total energy consumption; and the growth of total energy consumption per unitary GDP (i.e., the energy intensity of GDP, which has increased by 11% during 2008−2015.

Moreover, the optimization of electricity structure is an important factor offsetting GHG emissions of the Southern Power Grid, especially in Yunnan and Guizhou grids. The proportions of fossil-fuel-based electricity in total electricity of the Yunnan and Guizhou grids have decreased by 29% (from 40% to 11%) and 13% (from 69% to 56%), respectively. The portion of hydropower electricity in total electricity generated in Yunnan and Guizhou grids accounted for 85% and 43%, respectively, in 2015.

The changes in fuel mix of thermal power generation have driven GHG emission increments of six subnational grids during 2008−2015, especially the North China Grid. Hebei, Shanxi, and Shandong grids mainly contributed to GHG emission increments of the North China Grid. The inputs of fuels with higher carbon intensity (e.g., raw coal, blast furnace gas, and converter gas) in these three provincial grids have increased during 2008−2015. For instance, the portions of raw coal, blast furnace, and converter gas in total energy inputs of Hebei grid have increased by 6%, 10%, and 1%, respectively, during 2008−2015.

The changes in electricity transmission structure have helped offset GHG emissions during 2008−2015, especially in the East China Grid (mainly Shanghai, Jiangsu, and Zhejiang). In 2008, these three provincial grids mainly imported electricity from Shanxi in North China Grid and Hubei in Central China Grid. However, Shanghai, Jiangsu, and Zhejiang have begun to import electricity from Sichuan in Central China Grid since the years of 2010, 2012, and 2014, respectively. In 2015, the electricity imported from Sichuan accounted for nearly 70% of the total electricity transmitted from other subnational grids to these three provincial grids. In addition, the GHG emission factor of the electricity from Sichuan is only 14% and 33% of the

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electricity from Shanxi and Hubei, respectively. Consequently, the change in the electricity transmission structure of the East China Grid contributed to GHG emission reductions.

The Special Cases of Provincial Grids. We select a special provincial grid from each subnational grid to investigate the situation of provincial grids. The provincial grids selected include Beijing from North China Grid, Shanghai from East China Grid, Hubei from Central China Grid, Inner Mongolia from Northeast China Grid, Xinjiang from Northwest China Grid, and Guangdong from Southern Power Grid (Figure 3).

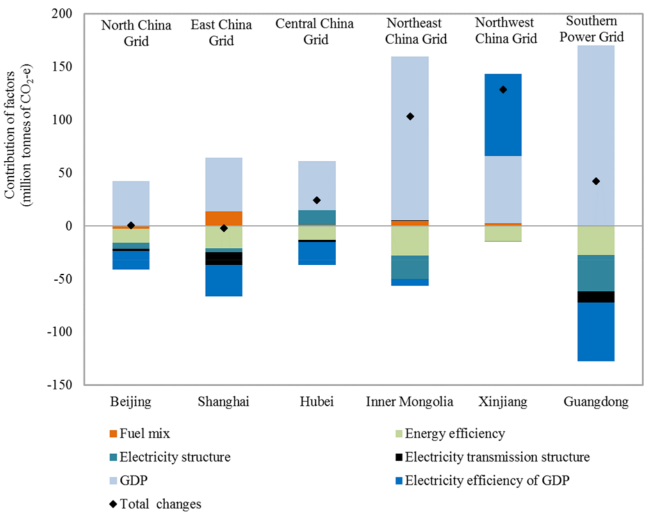

Figure 3. Relative contributions of six factors to changes in GHG emissions caused by electricity consumption of special provincial grids during 2008−2015. Full results are listed in SI Tables S8.

Among these six provincial grids, Beijing, Shanghai, and Guangdong are economically developed province/municipalities. Inner Mongolia is the largest electricity generator and exporter in Northeast China Grid. Hubei and Xinjiang are two provincial grids, whose relative contributions of factors to changes in GHG emissions are quite different from other provincial grids.

Beijing highly depends on electricity imports. The consumption-based GHG emissions of Beijing are much higher than its generation-based emissions (SI Figure S2a). Changes in GHG emissions embodied in electricity consumption of Beijing were relatively small during 2008−2015. The GDP of Beijing increased by 75% during 2008−2015. It is the only driver increasing the consumption-based GHG emissions of Beijing. Beijing's electricity efficiency of GDP increased by 26% during 2008−2015. It is a major factor contributing to reducing the consumption-based GHG emissions.

Improvements in energy efficiency of thermal power generation in Beijing's electricity suppliers and changes in their electricity structure and fuel mix are also major factors contributing to GHG emission reductions. For example, energy inputs for unitary thermal power generation in Beijing and Inner Mongolia have decreased by 27% and 12%, respectively, during 2008−2015. The portions of thermal power in total generated electricity in Inner Mongolia and Liaoning have decreased by 11% and 14%, respectively, during this time period.

The average GHG emission factor of electricity generation in Beijing (393 kg/MWh in 2015) was much lower than its external electricity providers such as Shanxi (877 kg/MWh in 2015) and Inner Mongolia (1,001 kg/MWh in 2015). Moreover, local electricity supply in Beijing has increased by 7% during 2008−2015, and the portion of external electricity supply has decreased during this time period. Therefore, such changes in electricity transmission structure contributed to the mitigation of GHG emissions caused by electricity consumption of Beijing during 2008−2015.

Results for Shanghai grid is similar to those of Beijing grid, except for the relatively large contributions of changes in fuel mix of thermal power generation and electricity transmission structure. The changes in fuel mix have driven GHG emission increments, because the inputs of raw coal and blast furnace gas (i.e., fuels with higher carbon intensity) increased by 11% and 5%, respectively, during 2008−2015.

The changes in electricity transmission structure have significantly offset GHG emission increments of Shanghai grid during 2008−2015. In 2008, Shanghai mainly imported electricity from Hubei in Central China Grid, Jiangsu and Zhejiang in East China Grid. Shanghai began to import electricity from Sichuan in Central China Grid from 2010. In 2015, the electricity imported from Sichuan accounted for 45% of Shanghai's total electricity transmitted from other provincial grids. The lower GHG emission factor of the electricity from Sichuan (33%, 17%, and 23% of the GHG emission factors of Hubei, Jiangsu, and Zhejiang, respectively) help offset GHG emissions caused by electricity consumption in Shanghai.

Guangdong grid also benefited from the changes in electricity transmission structure. The proportion of the electricity imported from Yunnan grid (in Southern Power Grid) in the total imported electricity of Guangdong increased from 18% in 2008 to 43% in 2015. The GHG emission factor of the electricity from Yunnan grid is only 35%, 27%, 36%, and 29% of those from Hubei, Hunan, Guangxi, and Guizhou, respectively. Therefore, the changes in electricity transmission structure significantly restrained GHG emissions caused by electricity consumption of Guangdong. The relative contributions of other factors for Guangdong grid are similar to those of Beijing.

Inner Mongolia grid is a net electricity exporter and its electricity is mainly transmitted to North China Grid. It benefited relatively less from the changes in electricity transmission structure. However, Inner Mongolia grid should pay attention to the changes in its fuel mix which have led to GHG emission increments during 2008−2015. Its portions of raw coal and gangue (i.e., fuels with higher carbon intensity) in total fuel inputs of thermal power generation have increased by 1% and 2%, respectively, during this period. In addition, the contribution of changes in electricity efficiency of GDP is relatively small, compared to other provincial grids, indicating that Inner Mongolia could further improve its electricity efficiency of GDP to offset GHG emissions caused by its electricity consumption.

Hubei grid is quite different from other provincial grids in terms of the relative contributions of electricity structure changes. The portions of thermal power in total generated electricity in Hubei have increased from 32% in 2008 to 44% in 2015. This change has led to GHG emission increments during 2008−2015. Hubei grid could further increase the utilization of its hydropower capacity to control GHG emissions caused by its electricity consumption.

Xinjiang grid is a special case, because the changes in its electricity efficiency of GDP pulled up, rather than offset, its GHG emissions. As mentioned above, the electricity efficiency of GDP in Xinjiang has decreased by 57% during 2008−2015, mainly due to the growth of total energy intensity of GDP

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(increased by 11% during 2008–2015). Xinjiang grid should further improve its energy efficiency of GDP to reduce GHG emissions caused by its electricity consumption.

■ DISCUSSION

This study investigated GHG emissions from interconnected grids in China from generation-based and consumption-based perspectives. We quantified relative contributions of six factors to changes in GHG emissions from interconnected grids in China. Findings of this study can provide generation-side, consumption-side, and transmission-side policy implications for GHG mitigation in China's power sector.

It is excepted that China will continue to pursue economic growth, which will further drive the increase in GHG emissions from its interconnected grids. To mitigate those GHG emissions, China could focus on the following five factors: one consumption-side factor (electricity efficiency of GDP), three generation-side factors (energy efficiency and fuel mix of thermal power generation, and electricity structure), and electricity transmission structure. Although the former four factors are also mentioned in previous studies, the last but even more important factor (i.e., the electricity transmission structure) is usually overlooked in existing studies. The results of closely related studies are summarized and compared with our results. The relative contributions of the former four factors in existing studies are similar to our results (SI Table S9), validating the rationality of our method. This study investigated relative contributions of these factors to changes in GHG emissions from interconnected grids at not only the national grid level but also subnational and provincial grid levels. Moreover, special attention is paid to the influences of electricity transmission structure changes in this study, which is not well characterized in previous studies.

First, increasing the electricity efficiency of GDP is critical to mitigating GHG emissions from interconnected grids in China. Electrification levels in China are expected to increase in the future, given the living standard improvements and the promotion of electric vehicles. The increasing electrification levels would probably increase the electricity demand and associated GHG emissions in China. Thus, special attention should be paid to increasing the electricity efficiency of GDP. During the past years, China has implemented various policies to improve the end-use efficiency. For instance, China set the targets to reduce energy intensity of GDP by 20% and 16% during the 11th Five-Year Plan (FYP) (2006–2010) and the 12th FYP (2011–2015), respectively.[46–48] Energy conservation policies were also implemented at the firm level, such as the *Top-1,000 Energy-Consuming Enterprises Program* of the 11th FYP and *Top-10,000 Energy-Consuming Enterprises Program* of the 12th FYP.[49,50] These measures have effectively facilitated GHG emission reductions. They should be implemented continuously in the future and should specially focus on regions with large embodied GHG emissions in electricity consumption such as Shandong, Jiangsu, Hebei, Guangdong, and Henan. In particular, Xinjiang in Northwest China should decrease its total energy consumption per unitary GDP to eventually improve the electricity efficiency of GDP (Figure 3). It is worth noting that this study did not specially investigate the impacts of the GDP structure. Analyzing the GDP structure in future studies can help policy decisions on GDP structure adjustments to reduce GHG emissions.

Second, increasing energy efficiency and optimizing fuel mix of thermal power generation would have significant contributions to GHG emission reductions in the interconnected grids. China has taken specific measures to improve energy efficiency and fuel mix of thermal power generation in the past decade. The power sector was covered by the *Ten Key Energy Conservation Projects* implemented during the 11th FYP.[51] For instance, electrical systems for thermal power generation have been upgraded to be more energy-efficient, and small and backward thermal power plants have been shut down during 2006–2015. By the end of 2015, more than 28 million kilowatts of small thermal power generation units have been shut down.[52] In the *Oil Conservation Project*, it is proposed to substitute oil-fired electricity generators with low-carbon coal-fired or natural-gas-fired units.[53] These projects can help reduce GHG emissions from the interconnected grids and should specially focus on grids with large generation-based GHG emissions such as Shandong, Inner Mongolia, Jiangsu, Hebei, and Guangdong. In particular, Hebei, Shanxi, and Shandong in North China Grid should optimize their fuel mix of thermal power generation by decreasing the portions of fuels with higher carbon intensity (Figure 2b).

Third, optimizing the electricity structure (i.e., reducing the portion of thermal power and increasing the portion of renewable power such as hydropower, wind power, and solar photovoltaic) can facilitate GHG emission reductions in the power sector. China highly encouraged the development of renewable energy sources during the 12th FYP.[48] This action can help optimize the electricity structure. The share of thermal power in total electricity generation in China decreased from 81% in 2008 to 74% in 2015. However, thermal power currently still dominates the generation capacity in China. Thus, the development of renewable electricity (e.g., hydropower electricity) should be further encouraged in Southern Power Grid and Central China Grid which have large potentials to develop hydropower electricity (Figure 2b).

Finally, there are large potentials to reduce GHG emissions from interconnected grids through optimizing the electricity transmission structure in China. China should improve the infrastructures and mechanisms of electricity distribution to promote the integration of low-carbon electricity (e.g., electricity generated from solar photovoltaic and wind power) into the national electricity transmission network. This action can help promote the generation, transmission, and consumption of low-carbon electricity. It will subsequently reduce GHG emissions of the power sector. Moreover, China is promoting the *West–to–East Electricity Transmission Project*. Improving energy efficiency and fuel mix of electricity generation in western grids can promote the transmission and consumption of low-carbon electricity. This can help reduce GHG emissions from interconnected grids in China. In addition, East China Grid and Southern Power Grid can increase their imports of the electricity from grids of lower GHG emission factors (e.g., Sichuan in Central China Grid and Yunnan in Southern Power Grid), to benefit more from the changes in electricity transmission structure (Figure 2b).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b06516.

Results of the QIO model and supplemental Tables supporting the main text (PDF)

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