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How China's electricity generation sector can achieve its carbon intensity reduction targets?

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ABSTRACT

As the largest sector with decarbonization potential, electricity generation is critical for achieving carbon intensity reduction targets of China by 2020 and 2030. This study combines temporal decomposition and scenario analysis to identify the key drivers and provinces with increasing carbon intensity of electricity generation (CIE) and designs four scenarios by integrating efficiency improvement and structural adjustment in 30 provinces of China, and estimates the possible reduction of CIE by 2020 and 2030. Results show that 1) CIE in China decreases by 7.25% during 2001-2015. The estimated CIE during 12th FYP in this study is 25% lower than the estimation using IPCC emission factors, which is closer to China's reality. 2) Driving forces of CIE changes in 30 provinces vary greatly across provinces. The increasing CIE in four worse-performance regions (i.e. Northeast, South Coast, Southwest, Northwest) is mainly caused by energy mix effect and geographic distribution effect. The CIE growth in South Coast is also

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related to thermal power share effect. 3) Both 2020/2030 targets can be achieved by regulating the drivers for CIE growth in 30 provinces (i.e., RAK scenario). CIE decline is concentrated in three types of provinces, namely provinces with large economic size, strong policy support and clean energy implementation. The findings and recommendations provide insights into achieving 2020/2030 targets for CIE reduction.

Keywords: Driving forces, Scenario analysis, Carbon intensity, Electricity generation, 2020/2030 targets

1. Introduction

Exploring the low-carbon pattern of electricity generation and the possible reduction in the future is an important and urgent issue for China and the world. Electricity generation has been identified by IPCC (2014) as the sector where major changes are expected to take place and decarbonization is to happen more rapidly than other energy supply and end-use sectors, especially for China (Wang and Feng, 2017). China's CO_2 emissions from electricity generation have increased by 264% from 2002 to 2016, with thermal power accounting for 75% of this growth (CEC, 2017). CO_2 emissions of China's electricity sector accounts for 48.19% of national CO_2 emissions and 13.57% of global CO_2 emissions from energy combustion in 2016 (IEA, 2018). Despite the significant growth, CIE in China decreases by 27.89% from 2002 to 2016 and electricity generation growth slows down due to the restraint for energy-intensive sectors since the implementation of "new normal" economic development strategy during 2011-2013 (Xu et al., 2016). In line with global efforts to mitigating emissions, China has promised to reduce its carbon intensity by 40-45% by 2020 (UNFCCC, 2015) and by 60-65% in 2030 below 2005 level (NDRC, 2015). Recognizing the significant role of electricity generation sector in emission reduction, China's national carbon emission trading scheme (ETS) covers only electricity generation sector at the initial period (Ju and Fujikawa, 2019). To achieve the targets of CIE reduction, China also announces many policies and regulations from the perspective of technological and structural improvements in electricity generation sector (see Appendix Table B.1).

Whether and how China will achieve these carbon intensity reduction targets are important questions for China and the global community. Given the significant growth rate and global share, any significant variation in China's CIE will directly impact global efforts to limit global temperature rise to 2 degree and have a serious effect on global carbon and fossil fuel markets and renewable energy industry. However, due to a lack of specific intensity reduction target for China's electricity generation sector, few researches have paid attention to the quantitative projections of China's CIE for 2020 and 2030. Although some of the existing studies conclude that China would meet its carbon intensity target (Zhao et al., 2017a), it is uncertain how to combine technological and structural drivers under regional heterogeneity, as well as how much the carbon intensity will be reduced.

This study employs multiplicative LMDI-II to explore the driving forces of CIE changes during 2001-2015, and then simulates four scenarios to achieve the 2020/2030 targets for carbon intensity reduction. The study makes the following contributions: (1) This study calculated the carbon intensity from electricity generation sector in China's 30 provinces with the new emission factors from 17 fossil fuels proposed by Shan et al. (2017). Previous studies that adopt the new emission factors often focus on the absolute indicator (i.e., carbon emissions), while no one has calculated the relative indicator (i.e., carbon intensity). The estimation of carbon intensity using new emission factors could reflect the actual situation of power generation sector in China. (2) This study combines temporal decomposition with scenario analysis to explore whether and how will China achieve the 2020/2030 targets for carbon intensity reduction in power generation sector. Most of existing studies emphasized the historical trend of carbon intensity, while the projection of carbon intensity of power generation sector is limited. Based on a multilevel decomposition results in 30 provinces, this paper attempts to consider the regional heterogeneity and then explore the optimal portfolio to achieve 2020/2030 targets in various possible scenarios. The multilevel decomposition allows for quantitatively investigating the impact of technological and structural policies in 30 provinces that are crucial for projections.

The reminder of this paper is organized as follows: Section 2 reviews the existing literature. Section 3 introduces the methodology and data, including multiplicative LMDI-II and forecasting model. Section 4 presents the CIE changes and its drivers in 2001-2015. Section 5 simulates four scenarios to achieve the 2020/2030 targets. Section 6 concludes this study.

2. Literature review

Many of existing studies attempted to understand carbon intensity reduction in electricity generation from different perspectives (including the drivers of CIE changes, reduction potential forecasting, etc.), and using various methods.

An accurate accounting of China's CO_2 emissions is the first step in achieving 2020/2030 targets for CIE reduction. Due to a lack of officially published emission report in China, CO_2 emission accounting by academic institutes and scholars shows great discrepancies. Most of current emission accounting uses the IPCC default emission factors, such as Carbon Dioxide

Information Analysis Centre (CDIAC), U.S. Energy Information Administration (EIA), International Energy Agency (IEA), etc. The findings of Liu et al. (2015) showed that IPCC default emission factors are approximately 40% higher than China's actual survey value. China's CIE from IEA (2017) is 25% higher than the estimated CIE during 12th FYP (i.e., 2011-2015) in this study. Besides, Guan et al (2012) found that all the existing datasets constructing emission inventories for China's 30 provinces are limited.

The existing drivers of CIE changes are mainly decomposed into technological and structural drivers, both of which are found to have positive impact on national CIE reduction. Technological drivers include thermal generation efficiency effect and emission coefficient effect. Structural drivers consist of thermal power share effect and energy mix effect. For example, Steenhof (2007) indicated that generation efficiency is the most important driver to decrease national CIE, which is higher than the impact of structural drivers. Ang and Su (2016) revealed the positive impact of efficiency drivers on decreasing CIE in most countries, while structural drivers show varying degrees of inhibiting effects on CIE. Goh et al. (2018b) conducted a literature survey on the drivers of CIE in China and confirmed the dominant role of efficiency on CIE reduction. Peng and Tao (2018) proposed a three-dimensional decomposition model to measure the CIE decline due to technological innovation and structural adjustment.

Most of existing studies focused on CIE at national level, but less attention was paid to CIE at regional level. So far, only two studies focused on the drivers of CIE changes in 30 provinces of China. Liu et al. analyzed the driving forces of 30 provinces in China in 2000-2014 and found thermal efficiency improvement was a major driver for CIE decline, followed by clean power penetration. There was also significant difference of emission performance of electricity generation in different provinces (Liu et al., 2017). Wang et al. (2018b) found that geographic distribution effect, utilization efficiency effect, and thermal power proportion effect were responsible for CIE decrease in most provinces. Given the large diversities among provinces, various drivers and performance for CIE changes in provinces varied greatly.

Scholars used different tools to identify the driving forces of emission indicator changes, such as econometric techniques (Wang and Chao, 2017), systems dynamics (Zhao et al., 2018a), computable general equilibrium models (Zhao et al., 2018b), etc. Compared with these tools, decomposition analysis shows some unique advantages, such as conducting perfect decomposition without residual term, respecting reality without assuming conditional-mean function, etc. (Cao et al., 2019). Due to data availability, Index Decomposition Analysis (IDA) is extensively applied to analyze driving forces of carbon intensity changes (Goh et al., 2018a). Currently, LMDI-II is the most preferred method for IDA because LMDI-II framework further shows some desirable properties, e.g. theoretically sound, free selection for base year, ease in use and interpretation, etc. (Wang et al., 2017). IDA method is widely used in combination with other methods, such as production-theoretical decomposition analysis (PDA) to illustrate the impact of technological productivity (Du et al., 2017), etc. There are two terms of IDA, namely additive and multiplicative decomposition. Compared with the additive method, multiplicative method gives the same structure and intensity effect regardless of the indicator chosen (Ang, 2015). Studies applying multiplicative LMDI-II to explore carbon intensity changes are growing, such as Liu et al. (2015), Wang et al. (2016), Zhao et al. (2017b), etc.

In addition to the common decomposition framework, in recent years, some studies conduct prospective analysis to explore possible future changes in the main drivers of emissions indicators by combining decomposition with scenario analysis, such as Belakhdar et al. (2014), Hasanbeigi et al. (2013), Lin and Ouyang (2014), O'Mahnoy (2013). Projection and decomposition of future trends will provide a theoretical basis for policymakers to evaluate quantitatively how emission indicators will change in the future, and how to effectively control the main drivers and provinces for deteriorating emission indicators. Previous studies combining decomposition and scenarios analysis focuses on the absolute indicator (i.e., carbon emissions), less of them investigate the driving mechanism of relative indicator (i.e., carbon intensity) changes and then provide corresponding scenarios for future emission mitigation.

3. Methods and data

This study uses multiplicative LMDI-II method to decompose the driving forces of CIE changes among 30 provinces of China and thus project future CIE based on those key drivers.

3.1. Multiplicative LMDI-II analysis

Aggregate carbon intensity of electricity generation sector (CIE) is defined as the ratio of total CO_2 emissions from fossil fuels in electricity generation to the total electricity generated (Ang and Su, 2016)[1].

Supposing that there are N provinces and M types of fossil fuels, national CIE is expressed as:

$$\mathrm{CIE}=\frac{C}{G}=\sum_{j,i}\frac{G_j}{G}\cdot\frac{T_j}{G_j}\cdot\frac{F_j}{T_j}\cdot\frac{F_{ij}}{F_j}\cdot\frac{C_{ij}}{F_{ij}}=\sum_{j,i}s_j\cdot p_j\cdot u_j\cdot m_{ij}\cdot e_{ij} \tag{1}$$

where *C* and *G* denote CO_2 emissions and total electricity production in China, respectively, in the

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[1] This definition is guided by the *Interim Measures for the Promotion and Management of Energy Saving and Low Carbon Technologies* issued by the National Development and Reform Commission (NDRC, 2016a). The unit of CIE is g /kWh, which is consistent with the unit in 13th FYP of China.

same year; G_j is total electricity generation in province j; T_j is thermal power generation in province j; F_j is total consumption of fossil fuel in thermal power generation in province j; F_{ij} is consumption of fossil fuel i in thermal power generation in province j; C_{ij} is CO_2 emissions from fossil fuel i in thermal power generation in province j. The definition of five variables is shown in Table 1.

Table 1

Definitions of five variables in Eq.(1)

Variable	Definition
s_j	The share of the electricity production in province *j* from the total
p_j	The ratio of electricity produced from fossil fuels in province *j* to the total
u_j	The ratio of energy input to electricity output in thermal electricity generation
m_{ij}	The ratio of each type of fossil fuel in thermal electricity generation of province *j*
e_{ij}	CO_2 emissions factor of certain fuels

Based on the multiplicative LMDI-II method, temporal change of CIE between year T and year 0 is expressed as Eq. (2).

$$D_{CIE}=\frac{CIE^{T}}{CIE^{0}}=D_{s}^{T\text{-}0}\times D_{p}^{T\text{-}0}\times D_{u}^{T\text{-}0}\times D_{m}^{T\text{-}0}\times D_{e}^{T\text{-}0} \qquad (2)$$

The definition of five drivers is explained in Table 2. Five temporal drivers are categorized into two types, namely technological efficiency (i.e., thermal generation efficiency effect and emission coefficient effect) and structural improvement (i.e., geographic distribution effect, thermal power share effect and energy mix effect). Each driver of Eq.(2) can be computed by Table 3.

Table 2

Definitions of five drivers in Eq.(2)

Variable	Definition
$D_{s}^{T\text{-}0}$	**Geographic distribution effect**, represents the shift in regional structure of electricity generation
$D_{p}^{T\text{-}0}$	**Thermal power share effect**, measures the impact of a shift in the proportion of total electricity generation from fossil to non-fossil fuels
$D_{u}^{T\text{-}0}$	**Thermal generation efficiency effect**, gives the impact of changes in the thermal

	efficiency of fossil fuel generation
$D_m^{T\text{-}0}$	**Energy mix effect**, measures the impact of changes in fossil fuel mix in electricity generation
$D_e^{T\text{-}0}$	**Emission coefficient effect**, captures the impact of changes in fuel emission factors

Notes: Emission factors are assumed to be constant over time (Kang et al., 2014). Namely, $\Delta CF^{T\text{-}0} = 0$ and $\Delta CF^{r\text{-}u} = 0$. Emission factors are 3.99 for coal, 3.08 for oil and 2.33 for natural gas in tonnes of CO_2 per tonnes of oil equivalent (IPCC, 2006).

Table 3

Formulas of multiplicative LMDI-II for quantifying drivers of CIE changes

Temporal-IDA effects	Single-period decomposition	Multi-period decomposition
Geographic distribution effect (D_s)	$D_s{}^{0,1} = exp\left(\sum_{ij} w_{ij} ln \frac{s_i^1}{sI_i^0}\right)$	$D_s^{0,T} = \prod_{t=1}^{T} D_s^{t\text{-}1,t}$
Thermal power share effect (D_p)	$D_p{}^{0,1} = exp\left(\sum_{ij} w_{ij} ln \frac{p_i^1}{p_i^0}\right)$	$D_p^{0,T} = \prod_{t=1}^{T} D_p^{t\text{-}1,t}$
Thermal generation efficiency effect (D_u)	$D_u{}^{0,1} = exp\left(\sum_{ij} w_{ij} ln \frac{u_{ij}^1}{u_{ij}^0}\right)$	$D_u^{0,T} = \prod_{t=1}^{T} D_u^{t\text{-}1,t}$
Energy mix effect (D_m)	$D_m{}^{0,1} = exp\left(\sum_{ij} w_{ij} ln \frac{m_i^1}{m_i^0}\right)$	$D_m^{0,T} = \prod_{t=1}^{T} D_m^{t\text{-}1,t}$

Notes: $w_{ij} = \frac{L(CIE_{ij}^0/ECI^0, CIE_{ij}^t/CIE^t)}{\sum_{ij} L(CIE_{ij}^0/ECI^0, ECI_{ij}^t/CIE^t)}$ is the Sato-Vartia index weight. $L(A,B) = \frac{B\text{-}A}{ln(B)\text{-}ln(A)}$.

3.2. Forecasting model

Based on the decomposition results, scenario simulation analysis is further used to forecast the CIE in 2020 and 2030[2] (Ju and Fujikawa, 2019), and to identify the critical pathways for achieving 2020/2030 targets for CIE reduction. Due to a lack of specific intensity reduction target for China's electricity generation sector, this study adopts China's national carbon intensity

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[2] China made the ambitious targets for carbon intensity reduction in 2020 and 2030. Since there is no special target for China's electricity generation sector, this study takes two national CIE targets as the target. Since 2020 is the next year, this study attempts to use CIE in 2020 to validate the accuracy.

reduction by 40-45% and 60-65% respectively in 2020 and 2030 as the baseline. Based on the combination of multiplicative LMDI-II model and forecasting model, CIE in the target year can be estimated (Lin and Ahmad, 2017).

Assume $\alpha, \beta, \gamma, \delta$ and ε are the predicted change rate in geographic distribution effect, thermal power share effect, thermal generation efficiency effect, energy mix effect and emission coefficient effect, respectively. CIE can be predicted as,

$$\begin{aligned} CIE^T &= s^T \times p^T \times u^T \times m^T \times e^T \\ &= \{s^0 \cdot (1+\alpha)\} \times \{p^0 \cdot (1+\beta)\} \times \{u^0 \cdot (1+\gamma)\} \times \{m^0 \cdot (1+\delta)\} \times \{e^0 \cdot (1+\varepsilon)\} \\ &= CIE^0 \cdot (1+\alpha) \times (1+\beta) \times (1+\gamma) \times (1+\delta) \times (1+\varepsilon) \end{aligned} \tag{3}$$

3.3. Data sources

The sample observation ranges from 2001 to 2015, which is consistent with China's Five-Year Plan (FYP), i.e., from 10th FYP to 12th FYP. The spatial scale includes China's eight regions, which consists of 30 provinces and municipalities in mainland China[3].

This study uses three datasets: electricity generation, fuel consumption and energy-related CO_2 emissions. Electricity generation from thermal power plants and other sources such as solar power, wind power, nuclear power, etc. are obtained from Provincial Electric Power Yearbook. Regional fossil fuels for thermal power in 2001-2016 are collected from Provincial Energy Balance Tables reported by China Energy Statistics Yearbook. Raw data on energy consumption are estimated using the item of "thermal power" of "input & output of thermal power in transformation". Three types of fossil fuel are considered: coal (including raw coal, cleaned coal, other washed coal, briquettes, gangue, coke, coke oven gas, other gas and other coking products), oil (including crude oil, gasoline, kerosene, diesel oil, fuel oil, refinery gas, liquid petroleum gas, and other petroleum

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[3] Tibet is excluded in this study. In addition, Hong Kong, Macao, and Taiwan are not included in the decomposition analysis because they have independent statistical data according to their own system and legal provisions (Xu et al., 2016).

products), and natural gas. Electricity generation, fuel consumption and energy-related CO_2 emissions in 2016 are employed to calibrate the forecasting model in Section 5.

This study follows sectoral emissions accounting provided in Intergovernmental Panel on Climate Change (IPCC) reference (IPCC, 2006) and uses the new emission factors by Shan et al (2017). Detailed estimation of CO_2 emission can be seen in Appendix A. Schema of decomposition and scenario simulation in this study is shown in Fig.1.

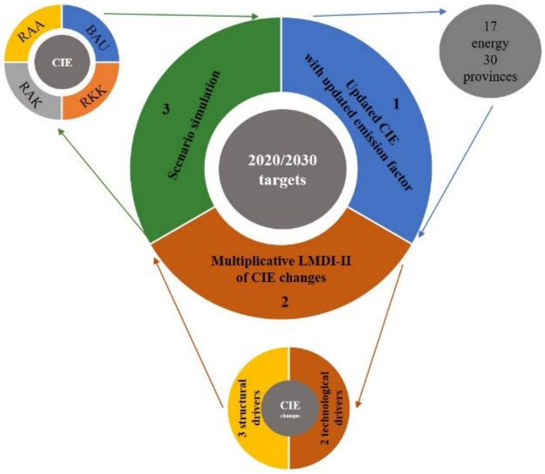

Fig.1. Schema of decomposition and scenario simulation in this study.

Note: BAU, RKK, RAK and RAA represent four scenarios based on different combination of technological and structural drivers.

4. Carbon intensity change and its drivers in electricity generation sector

4.1 Overview of carbon intensity changes

From 2001-2015, China’s electricity generation increases by 287.65%, from 1480.11 to 5736.12 tWh (Fig.2), and CO_2 emissions rise by 268.97%, from 837.07 Mt to 3088.50 Mt. The difference between their growth rates causes the CIE decline by 7.25%, from 565.55 g/kWh to 538.43 g/kWh during 2001-2015 (Fig.2). The decreasing trend of CIE using new emission factors is consistent with the estimation using IPCC emission factors (Fig.2). Estimated CIE during 12th FYP in this study is 25% lower than the IEA estimation (IEA, 2017), which is closer to China's reality.

CIE varies from provinces to provinces. CIE in the most provinces of the Northeast, North Coast, Central Coast and Central[4] is higher than national CIE in 2015, while the other provinces show lower CIE than national level (Fig.3). Moreover, the worse-performance provinces (i.e., with increasing CIE) are mainly located at coastal region and Central from 2001 to 2015 (Fig.3). The overall decoupling trend between electricity generation and CO_2 emissions verifies the effectiveness of China's efforts on emission reduction, especially in generation efficiency of thermal power, energy structure, electricity structure and power electricity transmission by provinces.

(1) Thermal power is dominant in China during 2001-2015 (Fig.2). The sharp decline of thermal power generation (-7.23%), is attributed to the policies about encouraging non-fossil energy.[5] From Appendix Table B.2, gas capacity is mainly located in Northwest due to lower gas price and larger demand to offset the gap caused by the elimination of coal unit (NDRC, 2016a). Hydroelectricity is mainly from Southwest due to abundant hydraulic power resources. New inland wind capacity is converged in Northeast.

(2) The share of coal declines and coal-fired generation efficiency increases. Energy intensity of thermal electricity in China drops by 8.9% in 2001-2015 (Appendix Table B.1). To improve thermal efficiency, China promises to eliminate inefficient coal-fired plants above 20 GW during

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[4] China is generally divided into eight regions, namely Beijing-Tianjin, Northeast (Heilongjiang, Jilin and Liaoning), North Coast (Hebei ang Shandong), Central Coast (Jiangsu, Shanghai and Zhejiang), South Coast (Fujian, Guangdong and Hainan), Central (Shanxi, Henan, Anhui, Hubei, Hunan and Jiangxi), Northwest (Xinjiang, Gansu, Qinghai, Inner Mongolia and Shaanxi) and Southwest (Sichuan, Chongqing, Yunnan, Guangxi and Guizhou).

2016-2020 (IEA, 2016), control net coal consumption rate of current coal-fired unit below 310 g/kWh in 2020 (NDRC, 2016a). 13th FYP also plans to control power supply of major generators at 550 g/kWh (Appendix Table B.2).

(3) Regional share of electricity generation is related to non-fossil power development and West-East Electricity Transmission Projects. With the increasing substitution effect, clean power in Northwest and Southwest surges, with the growth in Xinjiang by 223.70%, Yunnan by 83.23%, etc. (Appendix Table B.2). West-East Electricity Transmission Project promotes cross-regional power transmission and satisfies electrification demand in Northern, Central, and Central Coast (NDRC, 2013). China plans to increase the transmission capacity to 2.7×10^8 kWh by 2020 (NDRC, 2016b).

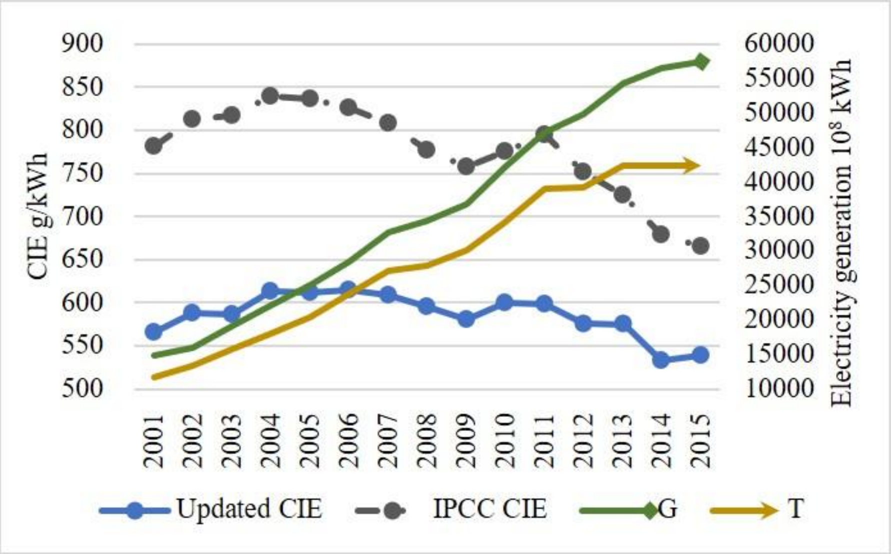

Fig.2. Variation results of electricity generation and CIE in China (2001-2015).

Source: Authors' calculation.

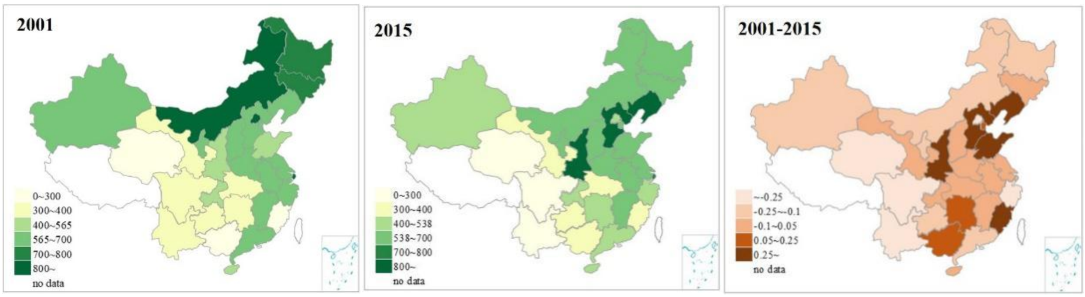

Fig.3. CIE and the variation results of 30 provinces of China in 2001-2015.

Note: The former two figures show regional CIE in 2001 and 2015. The third figure illustrates the changes of regional CIE in 2001-2015.

Source: Authors' calculation.

4.2 Key drivers of carbon intensity changes

Since Chinese government has issued many policies and measures to promote CIE reduction (see Appendix Table B.1), better-performance provinces show substantial CIE reduction continuously. Yet, there are provinces that have poor performances with CIE growth continuously.

From Table 4, CIE of China in 2001-2015 decreases by 27.11 g/kWh (-7.25%). This decline is mainly driven by thermal generation efficiency effect (-11.57%), thermal power share effect (-4.11%) and geographic distribution effect (-3.46%). The only inhibiting driver is energy mix effect, which increases CIE by 13.30%. From 2001 to 2015, 13 provinces in Northeast, South Coast, Southwest and Northwest show an increasing CIE. The drivers of CIE growth in worse-performance provinces vary greatly (Fig.4).

Energy mix effect and geographic distribution effect are the common drivers for CIE growth in 13 provinces. China is heavily dependent on coal for power generation over decades (Du and Lin, 2015). Since 11th FYP, China issues many policies to promote the implementation of renewable energy, such as the Renewable Energy Law (NDRC, 2008), Renewable Portfolio Standard (He et al., 2012), switch from coal to gas (Wang et al, 2018a), etc. Energy mix effect drives CIE decline especially for provinces adopting "switch from coal to gas", for example Zhejiang. Geographic distribution effect drives CIE growth in most developing provinces in Northwest and Southwest. It is related to their rising electricity demand. Besides, CIE growth in South Coast is driven by thermal power share effect.

Thermal power share effect and thermal generation efficiency effect drive CIE decline in most provinces, while there exist some exceptions. Since 11th FYP, clean power increases rapidly and China's power supply tends towards low-carbon sources (NDRC, 2008). For coal-rich provinces such as Shaanxi and Xinjiang, the proportion of coal-fired power is still increasing. Thermal generation efficiency effect is related to generator unit size, energy conversion efficiency and running time of generators, etc. (Wu et al., 2014). The degradation of thermal generation efficiency in Liaoning is possibly caused by low utilization rate of power plants. While the growth of CIE in Shaanxi and Hebei is due to traditional production technology and outdated capacity (Xu et al., 2017).

CIE changes vary greatly and can be divided into four periods: high-speed growth period (2001-2004), high-speed decline period (2004-2009), low-speed growth period (2009-2011) and transition period (2011-2015). Among 30 provinces, 18 provinces perform a continuously increasing CIE during four periods. These worse-performance provinces show centralization in Southern China (2001-2004), then decentralization in Western border (2004-2009), then centralization in Western China (2009-2011), and then decentralization across China (2011-2015). Since China has issued many policies and measures to promote the reduction of CIE, other 12 provinces show large CIE reduction continuously. Although 13 provinces show increasing CIE during the whole period (i.e., from 2001 to 2015), it is necessary to consider temporal fluctuations and discuss 18 provinces to design emission-mitigating strategies. To design the scenarios for achieving 2020/2030 targets, more regulation should be payed to key provinces and drivers for CIE growth.

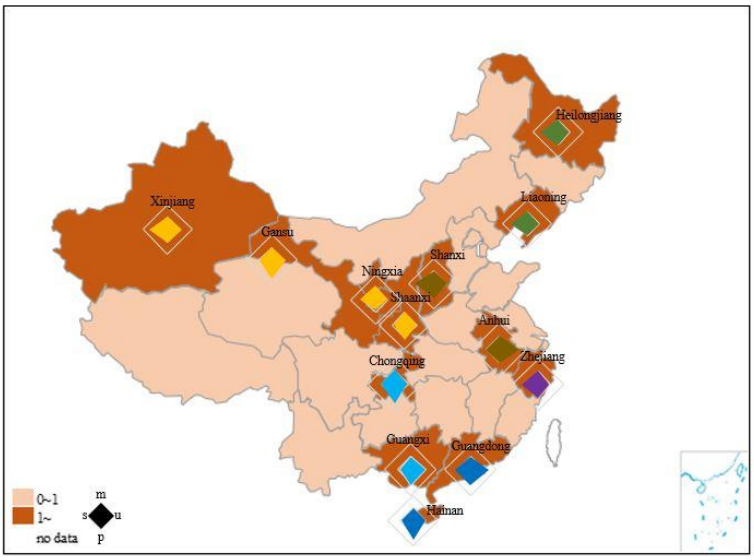

Fig.4. Decomposition results of CIE changes in worse-performance provinces (2001-2015).

Notes: 13 provinces show an increasing CIE, including 6 provinces in Central (marked in brown), 5 in Southwest (light blue), 3 in Northwest (yellow), 2 in Northeast (green), 2 in South Coast and others (Zhejiang, Tianjin and Hebei).

Source: Authors' calculation.

Table 4

CIE changes of electricity generation during 2001-2015.

Regions	**Provinces**	**m**	**u**	**p**	**s**	**Tot-Province**	**Tot-Region**
Beijing-Tianjin	Beijing	0.9959	0.9766	0.9998	0.9911	**0.9638**	**0.9558**
	Tianjin	1.0015	1.0024	0.9996	0.9882	**0.9917**	
Northeast	Liaoning	1.0251	1.0080	0.9954	0.9797	**1.0077**	**1.0296**
	Jilin	1.0043	0.9973	0.9987	0.9951	**0.9954**	
	Heilongjiang	1.0006	0.9947	0.9945	1.0369	**1.0264**	
North	Hebei	1.0104	1.0062	0.9923	0.9799	**0.9886**	**0.9611**

Coast	Shandong	1.0016	0.9962	1.0009	0.9735	**0.9722**	
Central Coast	Shanghai	1.0006	0.9931	0.9968	0.9730	**0.9637**	**0.9217**
	Jiangsu	1.0004	0.9973	0.9996	0.9568	**0.9542**	
	Zhejiang	1.0062	0.9925	0.9978	1.0058	**1.0022**	
South Coast	Fujian	1.0000	0.9923	0.9966	1.0016	**0.9905**	**1.0066**
	Guangdong	1.0056	0.9960	1.0001	1.0096	**1.0113**	
	Hainan	1.0020	0.9987	1.0047	0.9994	**1.0049**	
Central	Shanxi	1.0083	0.9873	1.0030	1.0055	**0.9889**	**0.9889**
	Anhui	1.0062	1.0032	0.9998	1.0029	**1.0121**	
	Jiangxi	1.0059	0.9945	1.0000	0.9926	**0.9930**	
	Henan	1.0047	0.9980	0.9957	1.0002	**0.9986**	
	Hubei	1.0077	0.9940	1.0035	0.9940	**0.9990**	
	Hunan	0.9961	0.9971	1.0000	0.9891	**0.9825**	
Southwest	Guangxi	1.0100	0.9946	0.9992	1.0032	**1.0069**	**1.0079**
	Chongqing	0.9995	0.9913	1.0104	1.0128	**1.0140**	
	Sichuan	1.0065	0.9964	0.9949	1.0013	**0.9990**	
	Guizhou	1.0062	0.9953	0.9885	1.0029	**0.9928**	
	Yunnan	1.0001	0.9949	1.0005	0.9998	**0.9953**	
Northwest	Inner Mongolia	1.0073	0.9975	0.9798	1.0133	**0.9975**	**1.0605**
	Shaanxi	1.0110	1.0017	1.0108	0.9926	**1.0161**	
	Gansu	1.0006	0.9996	0.9989	1.0013	**1.0003**	
	Qinghai	1.0000	0.9964	0.9960	0.9997	**0.9922**	
	Ningxia	1.0015	0.9963	0.9972	1.0268	**1.0217**	
	Xinjiang	1.0001	0.9885	1.0035	1.0402	**1.0319**	
Tot-China		**1.1330**	**0.8843**	**0.9589**	**0.9654**	**0.9275**	

5. Scenario simulations

5.1 Scenarios setting

Four scenarios are designed to simulate future situations under different efficiency improvement and structural adjustment of 30 provinces. Four scenarios include Business as Usual (BAU) scenario, and three alternative scenarios: Regulation on All Provinces with All Drivers (RAA) scenario, Regulation on All Provinces with Key Drivers (RAK) scenario and Regulation on Key Provinces with Key Drivers (RKK) scenario. RKK, RAK and RAA scenarios represent the estimated data of low, medium and high expectations respectively.

Because there is no special target for China’s electricity generation sector, this study takes the two national CIE targets as BAU target, namely national CIE reduction by 40-45% by 2020 and 60-65% by 2030. Under the constraint of mandatory policies, national CIE is expected to reach within 336-367 g/kWh by 2020 and 214-244 g/kWh by 2030. The projections in this study are mainly from literature, historical data and policy documents. BAU scenario represents current portfolio of efficiency improvement and structural adjustment without policy interventions.

RAA scenario: As the highly expected scenario, RAA scenario attempts to conduct a whole life cycle management, namely controlling four types of drivers in 30 provinces. This study uses four drivers (i.e., total installed capacity, installed capacity of thermal power, coal consumption of power supply and the share of non-fossil fuels in energy consumption) to estimate the possible annual change rate of four drivers, which are proposed in regional *13th FYP for Power Sector* and *13th FYP for Energy Development* (see Appendix Table B.3). Annual change rates of these drivers represent policy orientation to some extent (see Table 5).

RAK scenario: China is enforcing more stringent environmental regulation during 14th and 15th FYP than 13th FYP. For example, annual CIE decline rate of “60-65%” target is 1.44-3.9% higher than that of “40-45%” target. The Chinese government has also intended to increase the share of non-fossil fuels in primary energy consumption to about 20% by 2030. To fulfill the target by 2030, China adopts more stringent regulation during 2020-2030. Although RAA scenario attempts to control the whole life cycle of 30 provinces, this ideal scenario is hard to be implemented due to the contradiction between economic benefits and environmental costs (Liu et al., 2017), regional heterogeneity, etc. In this regard, RAK scenario focuses on controlling the drivers for regional CIE growth of 30 provinces (see Table 6), which shows much possibility of implementation.

RKK scenario: Based on decomposition results, 18 provinces show an increasing CIE during the four periods, which are regarded as the worse-performance provinces. To explore the emission-mitigating effect, RKK scenario is designed to focus on the drivers for regional CIE growth in the 18 provinces (see Table 7). Under the constraint of environmental regulation and increasing emission-mitigating pressure, the achievement of 2020/2030 targets for CIE reduction depends on both national and regional efforts (Zhao et al., 2017b). While RKK scenario mainly focusing on the key drivers in key provinces, turns out to be an ideal situation with uncertain effect.

Table 5

Annual change rate of driving forces in RAA scenario.

	s	**p**	**u**	**m**		**s**	**p**	**u**	**m**
Beijing	-19.03	-1.39	-0.32	-0.92	Henan	-18.17	-1.59	-0.06	-0.24
Tianjin	-16.56	-3.03	-0.64	-0.92	Hubei	-17.78	0.78	-0.13	0.78
Hebei	-13.51	-5.62	-1.02	-0.83	Hunan	-18.04	-0.92	-0.82	-0.81
Shanxi	-11.75	-2.23	-0.60	-0.21	Guangdong	-17.11	-8.02	-0.06	-1.55
Inner Mongolia	-14.56	-2.80	-0.72	-1.47	Guangxi	-17.16	-1.39	-0.57	1.04
Liaoning	-22.10	-0.08	-0.50	-0.92	Hainan	-13.38	-6.32	-0.90	-4.25
Jilin	-16.71	-3.86	0.12	-0.65	Chongqing	5.50	-1.39	-0.32	-0.92
Heilongjiang	-13.91	-4.57	-1.18	-0.65	Sichuan	-18.31	-2.66	-0.76	-1.87
Shanghai	-20.47	-1.14	-0.27	-0.23	Guizhou	-17.68	-1.39	-0.43	-0.35
Jiangsu	-16.86	-3.59	-0.34	-0.66	Yunnan	-19.72	-6.44	-0.32	-1.20
Zhejiang	-20.62	-2.67	-0.20	-3.11	Shaanxi	5.50	-1.39	-1.92	-0.92
Anhui	-15.46	-2.85	-0.07	-1.24	Gansu	-18.06	0.35	-0.25	-0.25
Fujian	-16.93	1.97	-0.94	-0.43	Qinghai	-6.26	-9.10	0.06	-1.30
Jiangxi	-12.77	-1.39	-0.13	-0.66	Ningxia	-13.26	-0.46	-1.00	-1.39
Shandong	-16.56	-2.49	0.26	-2.49	Xinjiang	5.50	-1.39	-0.32	-0.92

Notes: Four indicators are used to calculate the value of four drivers. Detailed values are shown in Appendix Table B.3. Missing value is represented by national change rate. The values are derived from regional 13th FYP for energy development from Regional Development and Reform Commission, Bureau of Energy and Government site. The unit is %.

Source: Authors' calculation.

Table 6

Annual change rate of driving forces in RAK scenario.

	s	p	u	m		s	p	u	m
Beijing	/	-1.39	/	-0.92	Henan	-18.17	/	/	-0.24
Tianjin	-16.56	/	-0.64	-0.92	Hubei	/	0.78	/	0.78
Hebei	/	/	/	-0.83	Hunan	/	/	/	-0.81
Shanxi	/	/	-0.60	-0.21	Guangdong	-17.11	/	-0.06	-1.55
Inner Mongolia	-14.56	/	-0.72	-1.47	Guangxi	-17.16	/	/	1.04
Liaoning	/	/	-0.50	-0.92	Hainan	/	/	-0.90	-4.25
Jilin				-0.65	Chongqing	5.50	-1.39	/	/
Heilongjiang	-13.91	/	/	/	Sichuan	-18.31	/	/	/
Shanghai	/	/	/	-0.23	Guizhou	-17.68	/	-0.43	-0.35
Jiangsu	/	/	-0.34	-0.66	Yunnan	-19.72	/	-0.32	-1.20
Zhejiang	-20.62	/	/	/	Shaanxi	5.50	/	-1.92	-0.92
Anhui	-15.46	/	/	-1.24	Gansu	/	/	/	-0.25
Fujian	/	1.97	/	-0.43	Qinghai	-6.26	/	0.06	-1.30
Jiangxi	/	-1.39	-0.13	-0.66	Ningxia	/	/	/	-1.39
Shandong	/	-2.49	0.26	-2.49	Xinjiang	5.50	-1.39	/	/

Notes: Drivers with / leads to regional CIE decline. / is denoted as annual change rate of drivers in BAU scenario.

Table 7

Annual change rate of driving forces in RKK scenario.

	s	p	u	m		s	p	u	m
Hebei	/	/	/	-0.83	Guangxi	-17.16	/	/	1.04
Shanxi	/	/	-0.60	-0.21	Hainan	/	/	-0.90	-4.25
Liaoning	/	/	-0.50	-0.92	Chongqing	5.50	-1.39	/	/
Jilin				-0.65	Sichuan	-18.31	/	/	/
Heilongjiang	-13.91	/	/	/	Yunnan	-19.72	/	-0.32	-1.20
Zhejiang	-20.62	/	/	/	Shaanxi	5.50	/	-1.92	-0.92
Anhui	-15.46	/	/	-1.24	Gansu	/	/	/	-0.25
Hubei	/	0.78	/	0.78	Ningxia	/	/	/	-1.39
Guangdong	-17.11	/	-0.06	-1.55	Xinjiang	5.50	-1.39	/	/

Notes: Drivers with / leads to the regional CIE decline. / is denoted as the annual change rate of drivers in BAU scenario. Annual change rate of drivers in other 12 provinces is the same as that in BAU scenario.

5.2 Results and discussions

In BAU scenario, national CIE decreases by 25.91% and 43.95% respectively in 2020 (453 g/kWh) and 2030 (343 g/kWh) compared with 2005 level (612 g/kWh) (Table 8). Without policy interventions, both “40-45%” and “60-65%” targets cannot be achieved. Nearly half of 30 provinces show a lower CIE than national level, which are mainly concentrated in Southwest and South Coast (Fig.5a-b). Nonetheless, regional CIE varies greatly and CIE in most provinces show smaller decline than national targets. From Fig.5c, only 4 provinces reach the “40-45%” level, namely Beijing (-58%), Yunnan (-82%), Sichuan (-76%) and Qinghai (-56%). By 2030, 7 provinces achieve “60-65%” (i.e., Beijing, Shanghai, Hubei, Sichuan, Yunnan, Gansu, Qinghai) and 3 new-added provinces include Shanghai (-67%), Hubei (-67%) and Gansu (-71%) (Fig.5d). For Hubei and Gansu, substantial decline of CIE during 2020-2030 is attributed to long-term benefits of national strategies. Strategies like Yangtze River Economic Zone, the Rise of Central China etc. have reinforced the hub status of Hubei in national power grid. Gansu, benefited from the long-term funds for infrastructure construction by “One Belt and One Road”, shows a large improvement on clean technologies. Shanghai develops the Integrated Gasification Combined Cycles Power Generating, which pushes its thermal technology to be the world’s advanced level.

In RAA scenario, national CIE decreases by 64.83% and 86.28% respectively in 2020 (215 g/kWh) and 2030 (84 g/kWh) (Table 8). Both 2020/2030 targets for CIE reduction can be achieved based on stringent whole life cycle management on drivers for CIE changes in 30 provinces. Despite that, this ideal scenario is hard to be implemented. Most provinces perform the opposite situation, namely a higher CIE and a lower decline rate of CIE than national level. For example, only 3 provinces (i.e., Sichuan, Yunnan and Qinghai) show a lower CIE than national level (Fig.5i-j). 8 provinces in Southwest and the coast demonstrate a higher decline rate than national target (Fig.5k-l). Among that, Beijing and Guizhou successfully achieve the 2020 target, while fail to realize the regional CIE decline by 60-65% in 2030. Installed capacity of clean energy contributes 46.1% of Guizhou's total installed capacity by 2015, which is 14% higher than national level. In contrast to the positive impact of power structure, the ratio of power generation pushes CIE growth, which is mainly caused by huge electricity demand in regional cooperation, such as West-to-East Power Transmission Project, One Belt and One Road, Yangtze River Economic Belt, etc. 13th FYP for energy development estimates that the maximum of electricity delivering reaches 2080 GW in 2020. For Beijing, both insufficient local-power supply and Coal-to-Power Switch project in 0.62 million rural households reduce the negative impact on CIE growth, while poor peak-regulating capacity increases CIE. The contradiction among drivers demonstrates the difficulty on resource allocation, which verifies the unfeasibility of RAA scenario.

In RAK scenario, national CIE decreases by 49.71% and 64.83% respectively in 2020 (308 g/kWh) and 2030 (166 g/kWh) (Table 8). Both 2020/2030 targets for CIE reduction can be achieved through the regulation on the drivers for CIE growth in 30 provinces. In 2030, 4 provinces perform a lower CIE and 8 provinces show a higher decline rate of CIE than national level (Fig.5e-h). National CIE decline is mainly concentrated in three types of provinces, such as the developed provinces (i.e., Beijing, Shanghai), clean energy-rich provinces (i.e., Sichuan, Yunnan and Qinghai) and strong policy-support provinces (i.e., Gansu, Hubei, etc.). Sichuan obtains much financial support in hydroelectric development. Hydroelectric installed capacity is estimated to be 8301 GW in 2020, which ranks the top. Rapid development of international cooperation in Yunnan, such as the construction of China-Myanmar oil and gas pipeline, power cooperation with countries of greater Mekong subregion (GMS), etc., enriches energy structure and expands power trade. Accumulative electricity trade during 12th FYP reaches 244 tWh and ranks the forefront. As the key participant in Silk Road Economic Belt, Qinghai shows a huge CIE decline, which is related to the encouragement policies for increasing revenue in new-energy enterprises to support national ETS development.

In RKK scenario, national CIE decreases by 33.55% and 55.07% respectively in 2020 (406 g/kWh) and 2030 (275 g/kWh) (Table 8). Both 2020/2030 targets for CIE reduction cannot be achieved through the regulation on drivers for CIE growth in 18 worse-performance provinces. Compared with BAU scenario, regulation on drivers for CIE growth in 18 worse-performance provinces drives the decline of national CIE by 7.64% and 11.12% respectively in 2020 and 2030, which contributes 18% of national targets. From regional level, only 4 and 7 provinces in 2020 and 2030 satisfy the decline rate of CIE in “40-45%” and “60-65%” targets. This indicates that 1) the drivers in 18 worse-performance provinces proposed by 13th FYP for Energy Development and 13th FYP for Power Planning should be intensified 2) the range of emission mitigation should cover all the provinces.

Table 8

Scenario simulation results of national CIE

	National CIE (g/kWh)		Change Rate of CIE	
Scenario	2020	2030	2020	2030
BAU	453.46	343.04	-25.91%	-43.95%
RAA	215.26	83.96	-64.83%	-86.28%
RAK	307.77	166.08	-49.71%	-72.87%
RKK	406.73	274.98	-33.55%	-55.07%

Source: Authors' calculation.

There exist two differences between the simulation results of this study and the existing studies: 1) The estimated CIE in 2020 (453.46 g/kWh) and 2030 (343.04 g/kWh) is lower than the results of previous studies, such as in Zhang et al. (2019), Qu et al. (2017), Li et al. (2018). While the CIE during 12th FYP is 25% lower than the estimation of IPCC. This difference is mainly caused by CO_2 emission accounting using different emission factors. This study adopts the default value of emission factor proposed by Shan et al (2017), and most of existing studies uses the IPCC emission factors. Emission factor used in this study is closer to the survey value of China than IPCC emission factors. 2) Existing studies provide policy suggestions from various perspectives to achieve 2020/2030 targets for carbon intensity reduction at national level, such as Liu et al.(2015) suggested the adjustments of primary energy structure and thermal power development, Zhao et al. (2018b) analyzed the influence of ETS, Zhang et al. (2017) identified the impact of investment intensity for CIE growth, etc. National studies design scenarios based on "one size fits all" regulations of CIE growth in 30 provinces. The reasons behind this difference are mainly related to scenario setting. It is hard to design differentiated regulation in 30 provinces due to data availability. In this regard, this study designs the annual change rate of drivers for CIE growth of 30 provinces based on the data collected in 13th FYP for Power Planning.

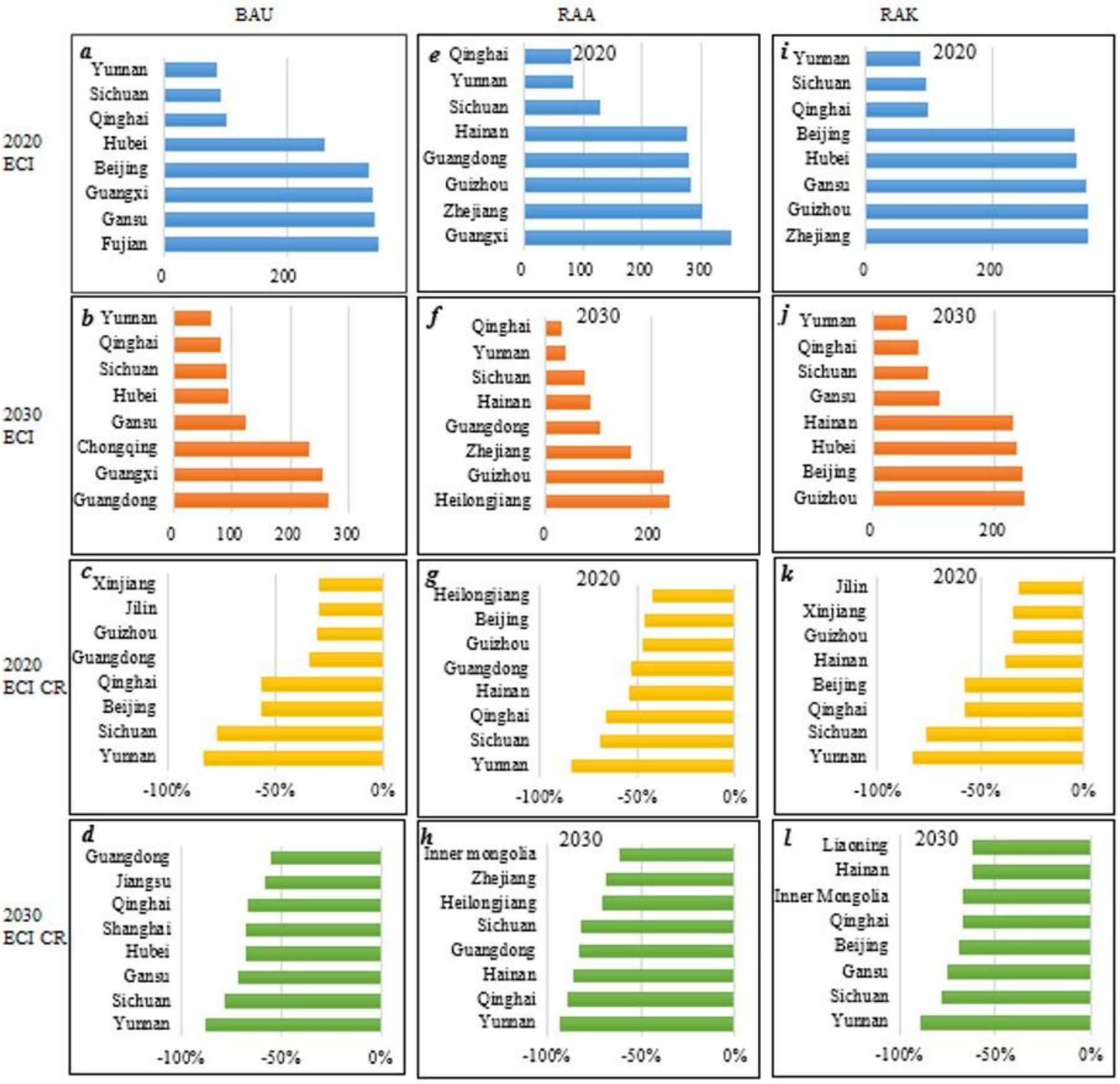

Fig.5. Variation results of CIE of 30 provinces in 2020 and 2030 over 2005.

Notes: CR is denoted as change rate. RKK scenario is designed to explore the impact of 18 worse-performance provinces on national CIE changes. Here, the CIE changes and its drivers of 30 provinces in RKK scenario are not further explored.

5.3 Uncertainty

Uncertainty in CIE estimation of China has three main sources. 1) The first is that from energy statistics. Researches on China's emissions accounting mainly use energy consumption data from China's national statistics bureau. In previous study, there is a 20% gap between aggregated energy consumption from 30 provinces and reported national total consumption (Shan et al., 2016). This gap may have been caused by the adoption of different statistical standards, misuse of units for different provinces and the total (Shan et al., 2015). 2) The second source of uncertainty is the differences from emission factors. Most studies use IPCC emission factors or National Development and Reform Commission (NDRC), whereas few works have used emission factors based on experiment and field measurements. Emission factors from different sources can vary by as much as 40% (Chen et al., 2005). This study adopts the default value of emission factor proposed by Shan et al (2017) to calculate CIE, which is closer to actual survey value of China. 3) The third is that from scenario setting. RAA and RAK scenarios are based on the regulation on drivers for CIE growth in 30 provinces. Considering data availability, this study uses the national data to replace the missing data. This data processing is consistent with national target.

6. Conclusions

Electricity generation is critical for achieving carbon intensity reduction targets of China by 2020 and 2030. This study uses new emission factors to calculate carbon intensity of China's electricity generation sector (CIE) during 2001-2015, and then employs multiplicative LMDI-II method to identify the drivers for CIE changes in 30 provinces. Based on the annual change rate of drivers in 30 provinces proposed by 13th FYP for Energy Development and 13th FYP for Power Planning, this study designs four scenarios to estimate the possible reduction of CIE by 2020 and 2030 through integrating technological and structural improvements in 30 provinces.

The findings are as we expose below:

(1) CIE in China decreased by 7.25% from 2001 to 2015. The decreasing trend of CIE using

new emission factors is consistent with the estimation using IPCC emission factors. The estimated CIE during 12th FYP in this study is 25% lower than IEA estimation (IEA, 2017). Compared with existing studies, the estimated CIE in 2000-2014 is 7.89% lower than the findings in Liu et al. (2017) and Wang et al. (2018b). Considering that the emission factors proposed by (Shan et al., 2016) are closer to China's actual survey value, the updated CIE could reflect the actual situation of China. The case of China's electricity generation (2001-2015) reflects the driving mechanism of CIE of provinces with great spatio-temporal differences in economy development, resource endowment and electricity generation.

(2) Due to different policy interventions in 13th FYP for Energy Development and 13th FYP for Power Planning, provincial CIE in 2001-2015 varies greatly and CIE reduction in most provinces is small. 18 provinces with increasing CIE mainly lie in the Northwest, Southwest, Central, Northeast, Coast region. For these worse-performance regions, the regulation focus should be payed to the adjustment of energy structure, electricity distribution structure, as well as improvement of electricity structure.

(3) During scenario simulations, most provinces perform opposite situation, namely a higher CIE and a lower decline rate of CIE than national level. CIE decline is mainly concentrated in three types of provinces, including the developed, clean energy-rich and strong policy-support provinces. Except these provinces, most provinces fail to achieve national "40-45%" and "60-65%" targets. Through regulating the drivers for CIE growth in 30 provinces (i.e., RAK scenario), national CIE decreases by 49.71% and 64.83% respectively in 2020 (308 g/kWh) and 2030 (166 g/kWh).

To achieve carbon intensity reduction targets in 2020 and 2030, the following actions should be initiated:

First, more regulation attention should be payed to regional heterogeneity. Significant heterogeneity among provinces suggests that the policy should be regional-specific. Besides, a national policy framework is needed to prevent inefficient localized polices. For example, relocating electricity generation from rich to poor provinces may not lead to large emission reduction and thus should be discouraged by national policy.

Second, national regulation should be implemented to force the provinces lagged with technical frontier provinces. Our findings of significant regional disparity in emission performance suggests there are significant technical gaps among provinces which have been quantified by many recent studies, such as Li et al. (2018) and Wang et al. (2017) among provinces for power sector. These gaps suggest that CIE could be improved through narrowing the gaps by facilitating transfer of advanced technologies in thermal power from Eastern China to Western China, etc.

Third, clean power generation technologies should be further promoted in provinces with abundant clean energy resources. For example, coastal affluent areas (i.e., Beijing, Shanghai and Zhejiang) with limit renewable resource should promote substitution of coal fire power plants with gas power plants; Hainan should develop nuclear power, while Southwest and Hubei -where hydraulic power resources are rich- should expand hydroelectric generation capacity; Northwest should advance wind power through mining its curtailment of wind power etc. While the cost of clean power generation technologies would be too high for underdeveloped regions (Du and Li, 2019). Thus, financial support from the central government should be enforced.

Lastly, resource endowment, technological level, economic development, policy orientation, etc. vary greatly in 30 provinces. The huge disparity in provinces will lead to discrepant reduction for carbon intensity. Based on above-mentioned findings, national carbon intensity decline in electricity sector is mainly concentrated in three types of provinces, such as the developed provinces (i.e., Beijing, Shanghai), clean energy-rich provinces (i.e., Sichuan, Yunnan and Qinghai) and strong policy-support provinces (i.e., Gansu, Hubei, etc.). There is a necessity to strengthen the interregional cooperation, especially the innovation diffusion, clean energy transmission, power transmission, etc. Besides, the different electricity development strategy in regions will cause unbalanced development of the electricity generation capacity, while the non-storage nature of electricity will promote the cooperation between exporting and exporting provinces.

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Appendix

Appendix A

This study uses energy-related sectoral emissions accounting method in Intergovernmental Panel on Climate Change (IPCC) reference (IPCC, 2006). Energy-related emissions refer to the CO_2 emitted during fossil fuel combustion. According to the IPCC guidelines, CO_2 emissions are expressed as,

$$CE_{ij}=AD_{ij}\times NCV_i\times CC_i\times O_{ij}=AD_{ij}\times EF_{ij}$$

where CE_{ij} refers to CO_2 emissions from fossil fuel i burned in sector j; AD_{ij} represents fossil fuel consumption by corresponding fossil fuel types and sectors; EF_{ij} is emission factor; NCV_i refers to net caloric value, which is heat value produced per physical unit of fossil fuel combustion; CC_i (carbon content) is CO_2 emissions per net caloric value produced by fossil fuel i; and O_{ij} is oxygenation efficiency, which refers to oxidation ratio during fossil fuel combustion.

According to previous survey on China's fossil fuel quality and cement process (Shan et al., 2016), IPCC default emission factors are approximately 40% higher than China's survey value. This study used the updated emission factors released by Shan et al. (2017) as follows:

	NCV (PJ/10_4 tonnes, 10^8m^3)	CC (tonne C/TJ)	O (tonne CO_2/ton)	Emission factor (Mt $CO_2/10^4$ ton)
Raw Coal	0.21	26.32	0.92	0.0183
Cleaned Coal	0.26	26.32	0.92	0.0231
Other Washed Coal	0.15	26.32	0.92	0.0133
Briquettes	0.18	26.32	0.92	0.0160
Coke	0.28	31.38	0.92	0.0296
Coke Oven Gas	1.61	21.49	0.92	0.1167
Other Gas	0.83	21.49	0.92	0.0602
Other Coking Products	0.28	27.45	0.92	0.0259
Crude Oil	0.43	20.08	0.98	0.0310
Gasoline	0.44	18.9	0.98	0.0299
Kerosene	0.44	19.6	0.98	0.0310
Diesel Oil	0.43	20.2	0.98	0.0312
Fuel Oil	0.43	21.1	0.98	0.0326
LPG	0.51	17.2	0.98	0.0315
Refinery Gas	0.47	20	0.98	0.0338
Other Petroleum Products	0.43	20.2	0.98	0.0312
Natural Gas	3.89	15.32	0.99	0.0216

Note: EF=NCV*(CC*44/12)*O

Appendix B

Table B.1

Overview of regulations on electricity generation within two decades

Object	Regulations
Geographic distribution effect	(1) China planned to increase the transmission capacity by 1.3×10^8 kWh, about 2.7×10^8 kWh by 2020 (NDRC, 2016a). (2) As part of the implementation of the Energy Development Strategy Action Plan (2014-2020), China actively advanced the West-East power transmission project and the North-South power transmission project.
Thermal power share effect	(1) Total coal capacity is controlled within 1100 GW and gas capacity is within 110 GW. (2) Total installed capacity is planned to reach 2000 GW, with expanding its power generation capacity with 110 GW of gas power, 340 GW of hydroelectric, 210 GW of wind power, 110 GW of solar power and 58 GW of nuclear power by 2020.
Energy mix effect	(1) Coal-To-Gas Switch project is issued in 2016. (2) The scale of coal-fired generation should be controlled, and construction of natural gas distributed energy projects should be promoted. Installed capacity of natural gas electricity generation reach 110 million kW by 2020 (NDRC, 2016b). (3) Since 2006, Chinese government introduced the Renewable Energy Law of the People’s Republic of China, the Medium-and Long-Term Renewable Energy Development Plan, and the Medium- and Long-Term Development Plan of Nuclear Power.
Thermal generation efficiency effect	(1) China promised to eliminate the inefficient coal power plants above 20 GW during 2016-2020, control the net coal consumption rate of new coal-fired unit below 300 g/kWh, improve the net coal consumption rate of operational coal-fired unit below 310 g/kWh in 2020 (NDRC, 2016a). Carbon intensity of coal-fired unit is projected to below 865 g/kWh. (2) 13th FYP stated a target of power supply from major power generators to reach 550 g/kWh (Ju and Fujikawa, 2019). (3) Planning for Energy Development proposed the use of ultra-low emission supercritical pressure circulating fluidized bed boilers (NDRC, 2016b).
Other	(1) In December 2017, China launched national ETS. At the initial period, emission quotas are limited only to power generation sector. Over 1700 power generating companies are included, each of which have emissions over 0.026 Mt CO_2 emissions.

Table B.2

Overview of China’s electricity generation in 2001 and 2015.

Provinces	Regional share of electricity	Share of thermal power in total	Energy intensity of thermal power	Coal share in total fossil fuel used in

	generation (%)			electricity generation (%)			generation (g/kWh)			thermal power (%)		
	2001	2015	AGR%	2001	2015	AGR%	2001	2015	AGR%	2001	2015	AGR%
Beijing	0.90	0.73	-18.49	97.80	97.86	0.06	419.74	225.61	-46.25	95.44	12.28	-87.13
Tianjin	1.47	1.05	-28.68	100.00	98.84	-1.16	293.71	328.67	11.90	98.09	86.58	-11.73
Hebei	6.09	4.01	-34.15	99.58	91.53	-8.09	356.23	409.28	14.89	99.67	99.90	0.23
Shanxi	4.80	4.28	-10.75	97.30	94.38	-3.00	364.08	342.42	-5.95	100.00	97.79	-2.21
Inner Mongolia	3.14	6.84	117.46	98.16	87.23	-11.14	463.25	412.72	-10.91	99.82	99.89	0.07
Liaoning	4.47	2.82	-36.91	96.46	82.09	-14.90	356.74	414.11	16.08	97.98	99.80	1.86
Jilin	2.23	1.23	-44.88	82.18	83.81	1.98	472.75	435.92	-7.79	99.44	99.56	0.11
Heilongjiang	2.96	1.56	-47.32	97.04	89.83	-7.43	436.71	369.90	-15.30	97.33	98.76	1.48
Shanghai	3.88	1.43	-63.15	99.65	98.66	-0.99	331.74	314.50	-5.20	96.44	90.66	-6.00
Jiangsu	6.67	7.72	15.65	99.90	93.81	-6.10	372.88	303.86	-18.51	99.66	93.88	-5.80
Zhejiang	4.97	5.18	4.35	83.58	74.76	-10.55	364.55	277.45	-23.89	91.82	92.84	1.11
Anhui	2.69	3.59	33.48	95.63	96.46	0.86	346.81	310.33	-10.52	99.88	99.95	0.07
Fujian	3.39	3.28	-3.07	42.24	58.90	39.45	346.50	316.76	-8.58	96.50	92.74	-3.90
Jiangxi	1.47	1.71	16.80	74.77	81.16	8.54	442.30	311.13	-29.66	98.64	99.03	0.39
Shandong	7.46	8.05	7.92	96.79	97.08	0.29	284.74	320.35	12.50	97.68	99.83	2.20
Henan	5.36	4.46	-16.72	95.08	95.15	0.08	391.09	338.44	-13.46	99.89	99.22	-0.68
Hubei	4.04	4.11	1.66	53.99	43.72	-19.03	341.85	302.54	-11.50	99.63	98.81	-0.83
Hunan	2.71	2.18	-19.54	47.05	56.66	20.43	403.54	317.66	-21.28	99.15	99.80	0.65
Guangdong	9.58	6.61	-31.03	75.84	75.32	-0.68	336.18	303.96	-9.58	71.94	88.10	22.47
Guangxi	1.97	2.30	16.43	39.76	41.24	3.74	405.36	316.72	-21.87	99.81	99.22	-0.59
Hainan	0.30	0.45	50.50	65.19	91.41	40.22	385.53	290.13	-24.75	84.03	89.81	6.88
Chongqing	1.20	1.19	-1.04	76.86	65.89	-14.28	340.61	316.63	-7.04	99.87	97.61	-2.27
Sichuan	4.28	5.59	30.73	32.96	13.37	-59.44	541.44	414.49	-23.45	96.29	96.50	0.23
Guizhou	3.31	3.37	1.58	54.75	55.46	1.30	381.56	307.94	-19.29	100.00	99.02	-0.98
Yunnan	2.43	4.45	83.23	39.77	10.81	-72.82	512.52	434.57	-15.21	99.68	99.95	0.27
Shaanxi	2.87	2.30	-19.65	64.83	91.98	41.86	366.61	367.17	0.15	99.76	99.75	-0.01
Gansu	2.04	2.14	4.73	60.86	57.49	-5.53	334.94	328.53	-1.91	98.17	99.72	1.58
Qinghai	0.96	1.00	4.36	31.75	20.94	-34.04	453.51	350.67	-22.68	100.00	98.08	-1.92
Ningxia	1.02	2.03	100.18	94.95	87.99	-7.33	379.92	343.73	-9.53	100.00	99.99	-0.01
Xinjiang	1.34	4.32	223.70	76.56	83.38	8.90	460.50	333.13	-27.66	94.08	99.12	5.36
China				**79.50**	**73.75**	**-7.23**	**369.68**	**336.78**	**-8.90**	**96.16**	**96.82**	**0.69**

Note: AGR is denoted as average change rate from 2001 to 2015.

Source: Authors’ calculation.

Table B.3

Collection of four drivers in the Regional 13th FYP

	2015				2020			
	Total installed capacity (10^4 kWh)	Installed capacity of thermal power (10^4 kWh)	Coal consumption of power supply (g/kWh)	The share of non-fossil fuels in primary energy consumption	Total installed capacity (10^4 kWh)	Installed capacity of thermal power (10^4 kWh)	Coal consumption of power supply (g/kWh)	The share of non-fossil fuels in primary energy consumption
Beijing	1071	203	/	/	1300	/	/	100%
Tianjin	1418	1074	/	/	2000	1300	305	/
Hebei	5836	4115	321	3.00%	9850	5200	305	7.00%
Shanxi	6966	5517	/	4.00%	13000	9200	325	5.00%
Inner Mongolia	10391	7260	337	8.00%	16500	10000	325	15.00%
Liaoning	5000	4959	/	/	5000	4940	/	/
Jilin	2611	1736	/	6.50%	3648	1992	/	9.50%
Heilongjiang	2647	1976	329	6.50%	4364	2579	310	3.40%
Shanghai	1406	1339	300	13.00%	1560	1404	296	14.00%
Jiangsu	9529	7207	300	/	13198	8315	295	11.00%
Zhejiang	7240	4061	298	25.40%	7954	3897	295	36.30%
Anhui	5153	4605	301	6.10%	7760	6000	300	11.80%
Fujian	4930	2478	325	19.90%	6800	3768	310	21.60%
Jiangxi	2482	/	310	/	4370	/	308	11.00%
Shandong	9715	8600	310	12.00%	13700	10690	314	22.00%
Henan	6800	6188	311	6.00%	8700	7308	310	7.00%
Hubei	6410	5211	312	18.70%	8400	7098	310	15.50%
Hunan	3944	1993	323	13.00%	5087	2455	310	16.00%
Guangdong	9817	7126	310	20.00%	13390	6400	/	26.00%
Guangxi	3455	1654	319	25.00%	4700	/	310	21.00%
Hainan	670	375	316	33.00%	1139	460	302	46.00%
Chongqing	/	/	/	/	2687	/	310	/
Sichuan	8672	1624	322	31.65%	11000	1800	310	37.81%
Guizhou	5236	2813	327	14.00%	6900	/	320	15.00%
Yunnan	8000	1440		40.20%	9300	1200	310	43.70%
Shaanxi	/	/	/	/	/	/	/	15.00%
Gansu	4643	1930		19.00%	5980	2530	320	20.00%
Qinghai	2171	415		37.00%	5480	650	/	41.00%
Ningxia	3154	1913	326	7.45%	5400	3200	310	13.70%
Xinjiang	/	/	/	/	/	/	/	/

Note: / is denoted as the missing data.

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Tables

Table 1

Definitions of five variables in Eq.(1)

Variable	Definition
s_j	The share of the electricity production in province *j* from the total
p_j	The ratio of electricity produced from fossil fuels in province *j* to the total
u_j	The ratio of energy input to electricity output in thermal electricity generation
m_{ij}	The ratio of each type of fossil fuel in thermal electricity generation of province *j*
e_{ij}	CO_2 emissions factor of certain fuels

Table 2

Definitions of five drivers in Eq.(2)

Variable	Definition
$D_s^{T\text{-}0}$	**Geographic distribution effect**, represents the shift in regional structure of electricity generation
$D_p^{T\text{-}0}$	**Thermal power share effect**, measures the impact of a shift in the proportion of total electricity generation from fossil to non-fossil fuels
$D_u^{T\text{-}0}$	**Thermal generation efficiency effect**, gives the impact of changes in the thermal efficiency of fossil fuel generation
$D_m^{T\text{-}0}$	**Energy mix effect**, measures the impact of changes in fossil fuel mix in electricity generation
$D_e^{T\text{-}0}$	**Emission coefficient effect**, captures the impact of changes in fuel emission factors

Table 3

Formulas of multiplicative LMDI-II for quantifying drivers of CIE changes

Temporal-IDA effects	Single-period decomposition	Multi-period decomposition
Geographic distribution effect (D_s)	$D_s{}^{0,1} = exp\left(\sum_{ij} w_{ij} ln \frac{s_i^1}{sI_i^0}\right)$	$D_s^{0,T} = \prod_{t=1}^{T} D_s^{t\text{-}1,t}$
Thermal power share effect (D_p)	$D_p{}^{0,1} = exp\left(\sum_{ij} w_{ij} ln \frac{p_i^1}{p_i^0}\right)$	$D_p^{0,T} = \prod_{t=1}^{T} D_p^{t\text{-}1,t}$
Thermal generation efficiency effect (D_u)	$D_u{}^{0,1} = exp\left(\sum_{ij} w_{ij} ln \frac{u_{ij}^1}{u_{ij}^0}\right)$	$D_u^{0,T} = \prod_{t=1}^{T} D_u^{t\text{-}1,t}$

Energy mix effect (D_m)	$D_m{}^{0,1}=exp\left(\sum_{ij} w_{ij} ln\frac{m_i^1}{m_i^0}\right)$	$D_m^{0,T}=\prod_{t=1}^{T} D_m^{t-1,t}$

Notes: $w_{ij}=\frac{L(CIE_{ij}^0/ECI^0,CIE_{ij}^t/CIE^t)}{\sum_{ij} L(CIE_{ij}^0/ECI^0,ECI_{ij}^t/CIE^t)}$ is the Sato-Vartia index weight. $L(A,B)=\frac{B-A}{ln(B)-ln(A)}$.

Table 4

CIE changes of electricity generation during 2001-2015.

Regions	Provinces	m	u	p	s	Tot-Province	Tot-Region
Beijing-Tianjin	Beijing	0.9959	0.9766	0.9998	0.9911	**0.9638**	**0.9558**
	Tianjin	1.0015	1.0024	0.9996	0.9882	**0.9917**	
Northeast	Liaoning	1.0251	1.0080	0.9954	0.9797	**1.0077**	**1.0296**
	Jilin	1.0043	0.9973	0.9987	0.9951	**0.9954**	
	Heilongjiang	1.0006	0.9947	0.9945	1.0369	**1.0264**	
North Coast	Hebei	1.0104	1.0062	0.9923	0.9799	**0.9886**	**0.9611**
	Shandong	1.0016	0.9962	1.0009	0.9735	**0.9722**	
Central Coast	Shanghai	1.0006	0.9931	0.9968	0.9730	**0.9637**	**0.9217**
	Jiangsu	1.0004	0.9973	0.9996	0.9568	**0.9542**	
	Zhejiang	1.0062	0.9925	0.9978	1.0058	**1.0022**	
South Coast	Fujian	1.0000	0.9923	0.9966	1.0016	**0.9905**	**1.0066**
	Guangdong	1.0056	0.9960	1.0001	1.0096	**1.0113**	
	Hainan	1.0020	0.9987	1.0047	0.9994	**1.0049**	
Central	Shanxi	1.0083	0.9873	1.0030	1.0055	**0.9889**	**0.9889**
	Anhui	1.0062	1.0032	0.9998	1.0029	**1.0121**	
	Jiangxi	1.0059	0.9945	1.0000	0.9926	**0.9930**	
	Henan	1.0047	0.9980	0.9957	1.0002	**0.9986**	
	Hubei	1.0077	0.9940	1.0035	0.9940	**0.9990**	
	Hunan	0.9961	0.9971	1.0000	0.9891	**0.9825**	
Southwest	Guangxi	1.0100	0.9946	0.9992	1.0032	**1.0069**	**1.0079**
	Chongqing	0.9995	0.9913	1.0104	1.0128	**1.0140**	
	Sichuan	1.0065	0.9964	0.9949	1.0013	**0.9990**	
	Guizhou	1.0062	0.9953	0.9885	1.0029	**0.9928**	
	Yunnan	1.0001	0.9949	1.0005	0.9998	**0.9953**	
Northwest	Inner Mongolia	1.0073	0.9975	0.9798	1.0133	**0.9975**	**1.0605**
	Shaanxi	1.0110	1.0017	1.0108	0.9926	**1.0161**	
	Gansu	1.0006	0.9996	0.9989	1.0013	**1.0003**	
	Qinghai	1.0000	0.9964	0.9960	0.9997	**0.9922**	
	Ningxia	1.0015	0.9963	0.9972	1.0268	**1.0217**	
	Xinjiang	1.0001	0.9885	1.0035	1.0402	**1.0319**	
Tot-China		**1.1330**	**0.8843**	**0.9589**	**0.9654**	**0.9275**	

Table 5

Annual change rate of driving forces in RAA scenario.

	s	p	u	m		s	p	u	m
Beijing	-19.03	-1.39	-0.32	-0.92	Henan	-18.17	-1.59	-0.06	-0.24
Tianjin	-16.56	-3.03	-0.64	-0.92	Hubei	-17.78	0.78	-0.13	0.78
Hebei	-13.51	-5.62	-1.02	-0.83	Hunan	-18.04	-0.92	-0.82	-0.81
Shanxi	-11.75	-2.23	-0.60	-0.21	Guangdong	-17.11	-8.02	-0.06	-1.55
Inner Mongolia	-14.56	-2.80	-0.72	-1.47	Guangxi	-17.16	-1.39	-0.57	1.04
Liaoning	-22.10	-0.08	-0.50	-0.92	Hainan	-13.38	-6.32	-0.90	-4.25
Jilin	-16.71	-3.86	0.12	-0.65	Chongqing	5.50	-1.39	-0.32	-0.92
Heilongjiang	-13.91	-4.57	-1.18	-0.65	Sichuan	-18.31	-2.66	-0.76	-1.87
Shanghai	-20.47	-1.14	-0.27	-0.23	Guizhou	-17.68	-1.39	-0.43	-0.35
Jiangsu	-16.86	-3.59	-0.34	-0.66	Yunnan	-19.72	-6.44	-0.32	-1.20
Zhejiang	-20.62	-2.67	-0.20	-3.11	Shaanxi	5.50	-1.39	-1.92	-0.92
Anhui	-15.46	-2.85	-0.07	-1.24	Gansu	-18.06	0.35	-0.25	-0.25
Fujian	-16.93	1.97	-0.94	-0.43	Qinghai	-6.26	-9.10	0.06	-1.30
Jiangxi	-12.77	-1.39	-0.13	-0.66	Ningxia	-13.26	-0.46	-1.00	-1.39
Shandong	-16.56	-2.49	0.26	-2.49	Xinjiang	5.50	-1.39	-0.32	-0.92

Notes: Four indicators are used to calculate the value of four drivers. Detailed values are shown in Appendix Table B.3. Missing value is represented by national change rate. The values are derived from regional 13th FYP for energy development from Regional Development and Reform Commission, Bureau of Energy and Government site. The unit is %.

Source: Authors' calculation.

Table 6

Annual change rate of driving forces in RAK scenario.

	s	p	u	m		s	p	u	m
Beijing	/	-1.39	/	-0.92	Henan	-18.17	/	/	-0.24
Tianjin	-16.56	/	-0.64	-0.92	Hubei	/	0.78	/	0.78
Hebei	/	/	/	-0.83	Hunan	/	/	/	-0.81
Shanxi	/	/	-0.60	-0.21	Guangdong	-17.11	/	-0.06	-1.55
Inner Mongolia	-14.56	/	-0.72	-1.47	Guangxi	-17.16	/	/	1.04
Liaoning	/	/	-0.50	-0.92	Hainan	/	/	-0.90	-4.25
Jilin				-0.65	Chongqing	5.50	-1.39	/	/
Heilongjiang	-13.91	/	/	/	Sichuan	-18.31	/	/	/
Shanghai	/	/	/	-0.23	Guizhou	-17.68	/	-0.43	-0.35
Jiangsu	/	/	-0.34	-0.66	Yunnan	-19.72	/	-0.32	-1.20
Zhejiang	-20.62	/	/	/	Shaanxi	5.50	/	-1.92	-0.92

Anhui	-15.46	/	/	-1.24	Gansu	/	/	/	-0.25
Fujian	/	1.97	/	-0.43	Qinghai	-6.26	/	0.06	-1.30
Jiangxi	/	-1.39	-0.13	-0.66	Ningxia	/	/	/	-1.39
Shandong	/	-2.49	0.26	-2.49	Xinjiang	5.50	-1.39	/	/

Notes: Drivers with / leads to regional CIE decline. / is denoted as annual change rate of drivers in BAU scenario.

Table 7

Annual change rate of driving forces in RKK scenario.

	s	**p**	**u**	**m**		**s**	**p**	**u**	**m**
Hebei	/	/	/	-0.83	Guangxi	-17.16	/	/	1.04
Shanxi	/	/	-0.60	-0.21	Hainan	/	/	-0.90	-4.25
Liaoning	/	/	-0.50	-0.92	Chongqing	5.50	-1.39	/	/
Jilin				-0.65	Sichuan	-18.31	/	/	/
Heilongjiang	-13.91	/	/	/	Yunnan	-19.72	/	-0.32	-1.20
Zhejiang	-20.62	/	/	/	Shaanxi	5.50	/	-1.92	-0.92
Anhui	-15.46	/	/	-1.24	Gansu	/	/	/	-0.25
Hubei	/	0.78	/	0.78	Ningxia	/	/	/	-1.39
Guangdong	-17.11	/	-0.06	-1.55	Xinjiang	5.50	-1.39	/	/

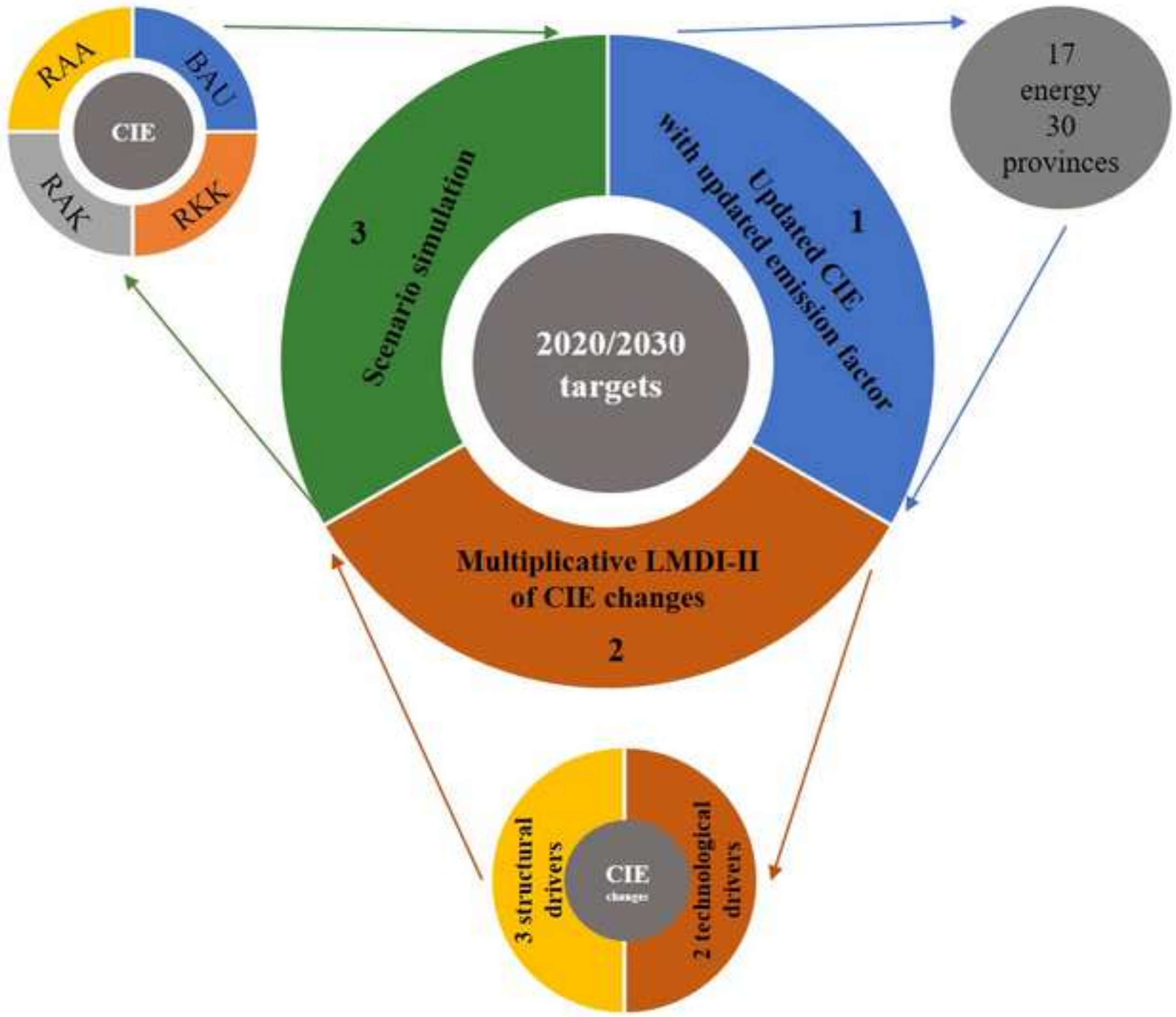
Notes: Drivers with / leads to the regional CIE decline. / is denoted as the annual change rate of drivers in BAU scenario. Annual change rate of drivers in other 12 provinces is the same as that in BAU scenario.

Table 8

Scenario simulation results of national CIE

	National CIE (g/kWh)		Change Rate of CIE	
Scenario	2020	2030	2020	2030
BAU	453.46	343.04	-25.91%	-43.95%
RAA	215.26	83.96	-64.83%	-86.28%
RAK	307.77	166.08	-49.71%	-72.87%
RKK	406.73	274.98	-33.55%	-55.07%

Source: Authors’ calculation.


RAA
BAU
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RAK
RKK
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30
provinces
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Scenario simulation
Updated CIE
with updated emission factor
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Multiplicative LMDI-II
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3 structural
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CIE
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2 technological
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fig.2.jpg

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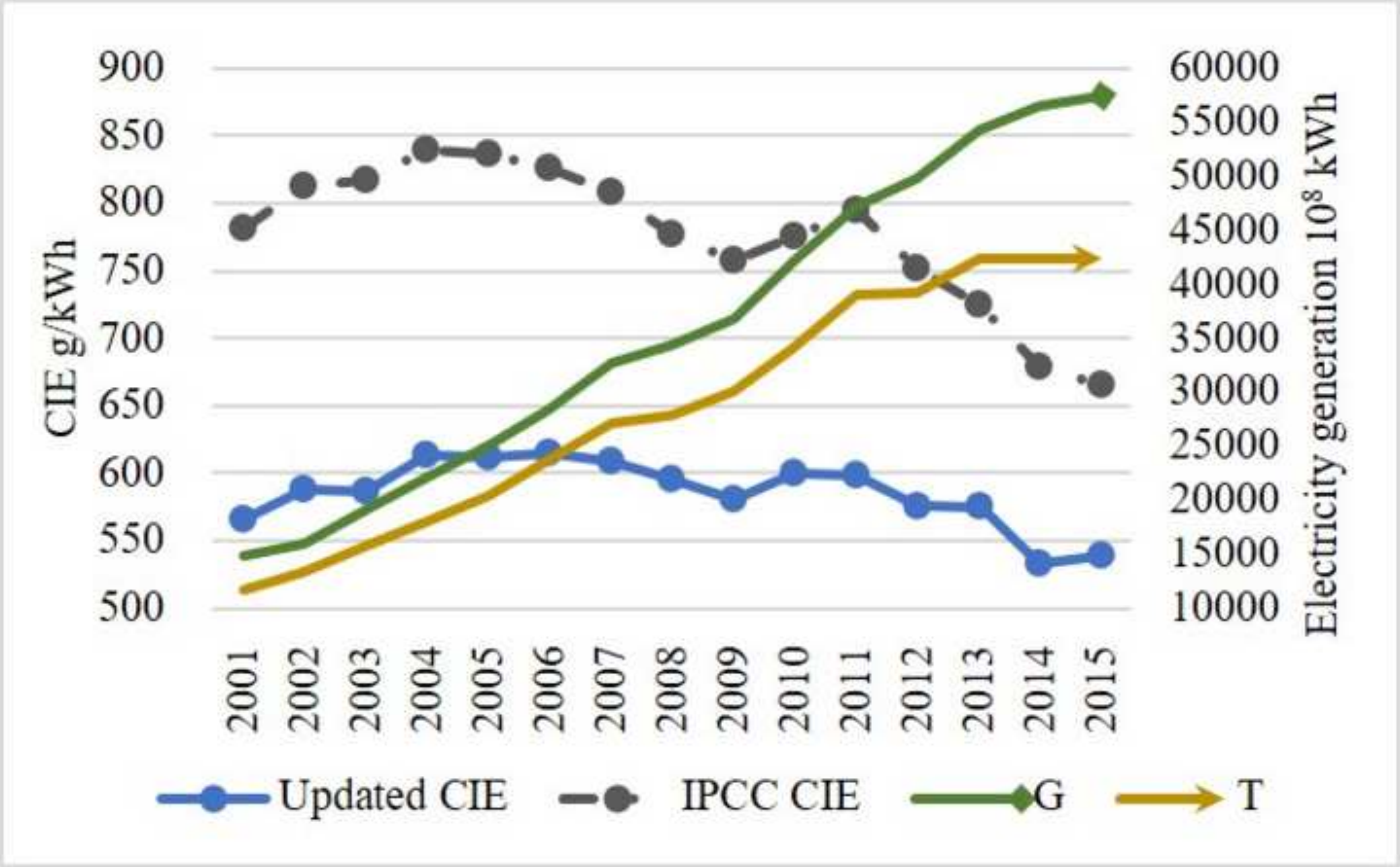

fig.3-1.jpg

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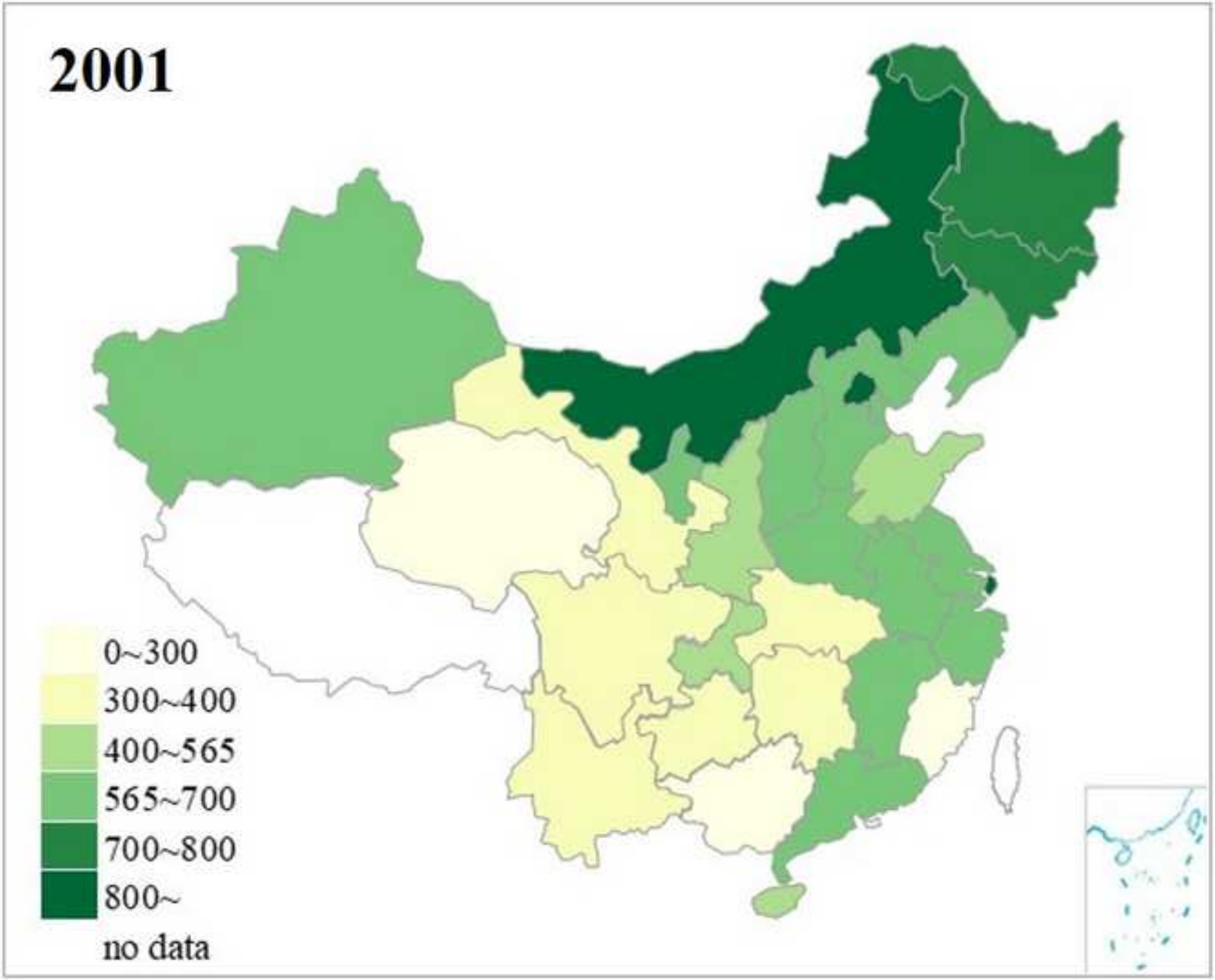

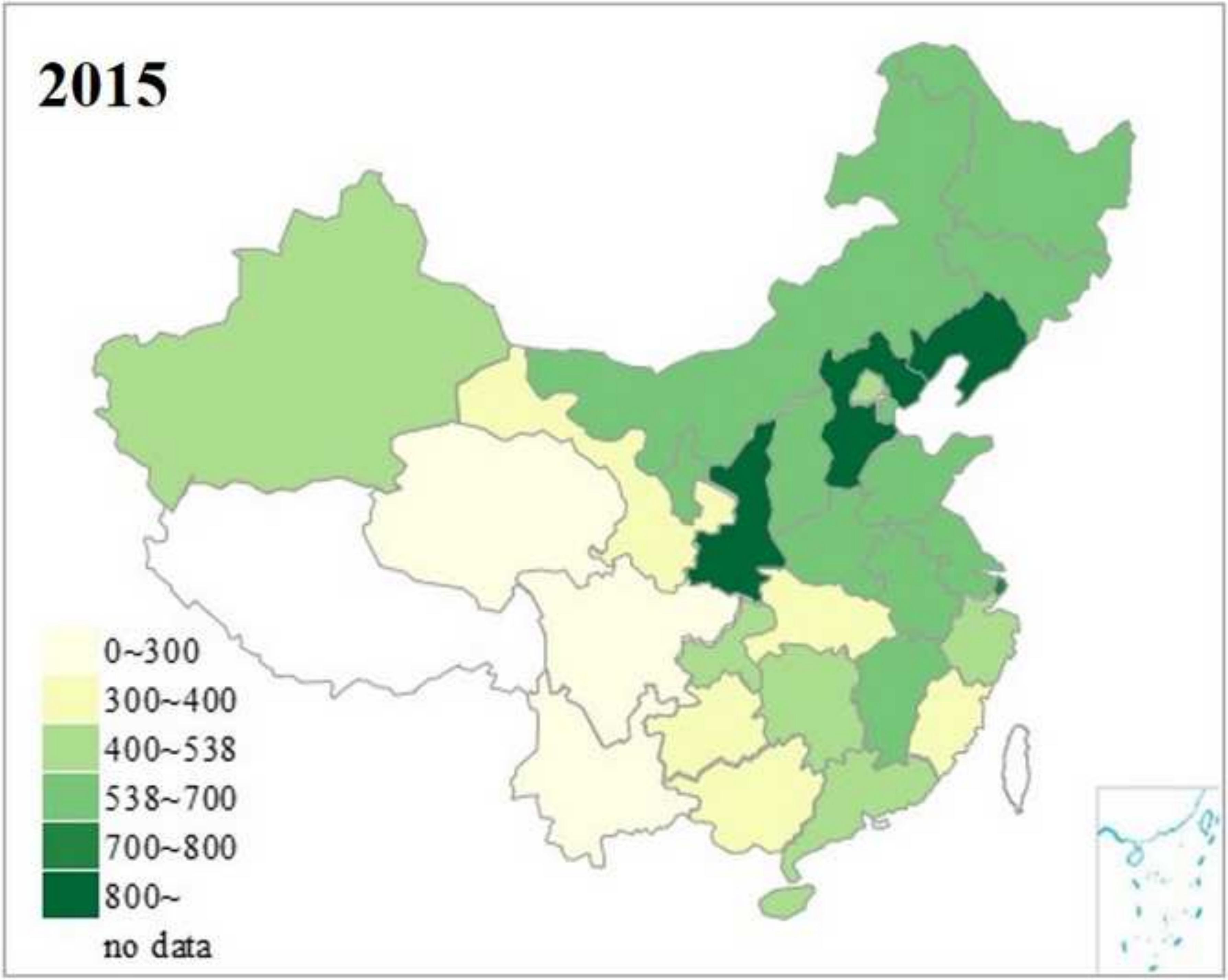
2015
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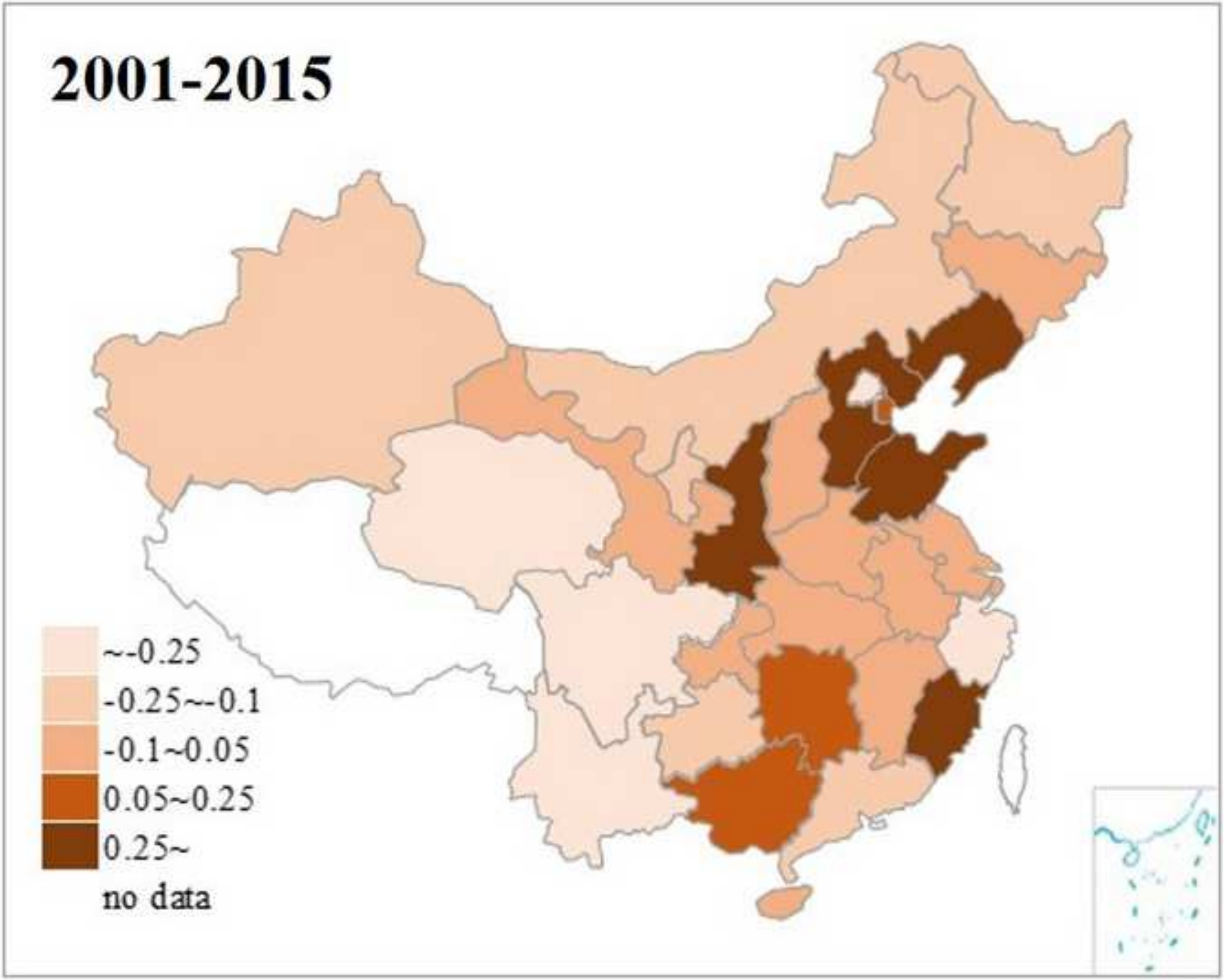

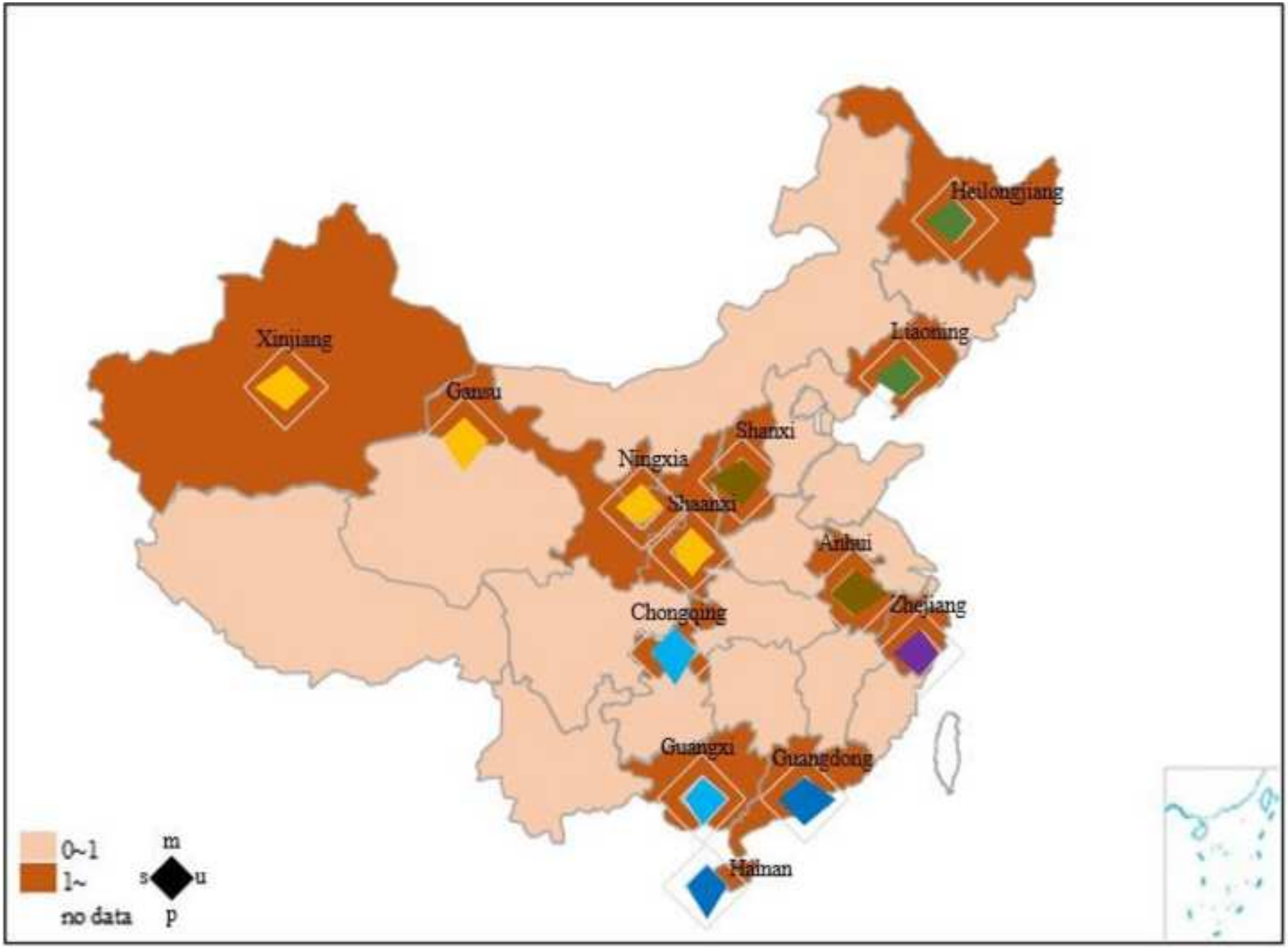
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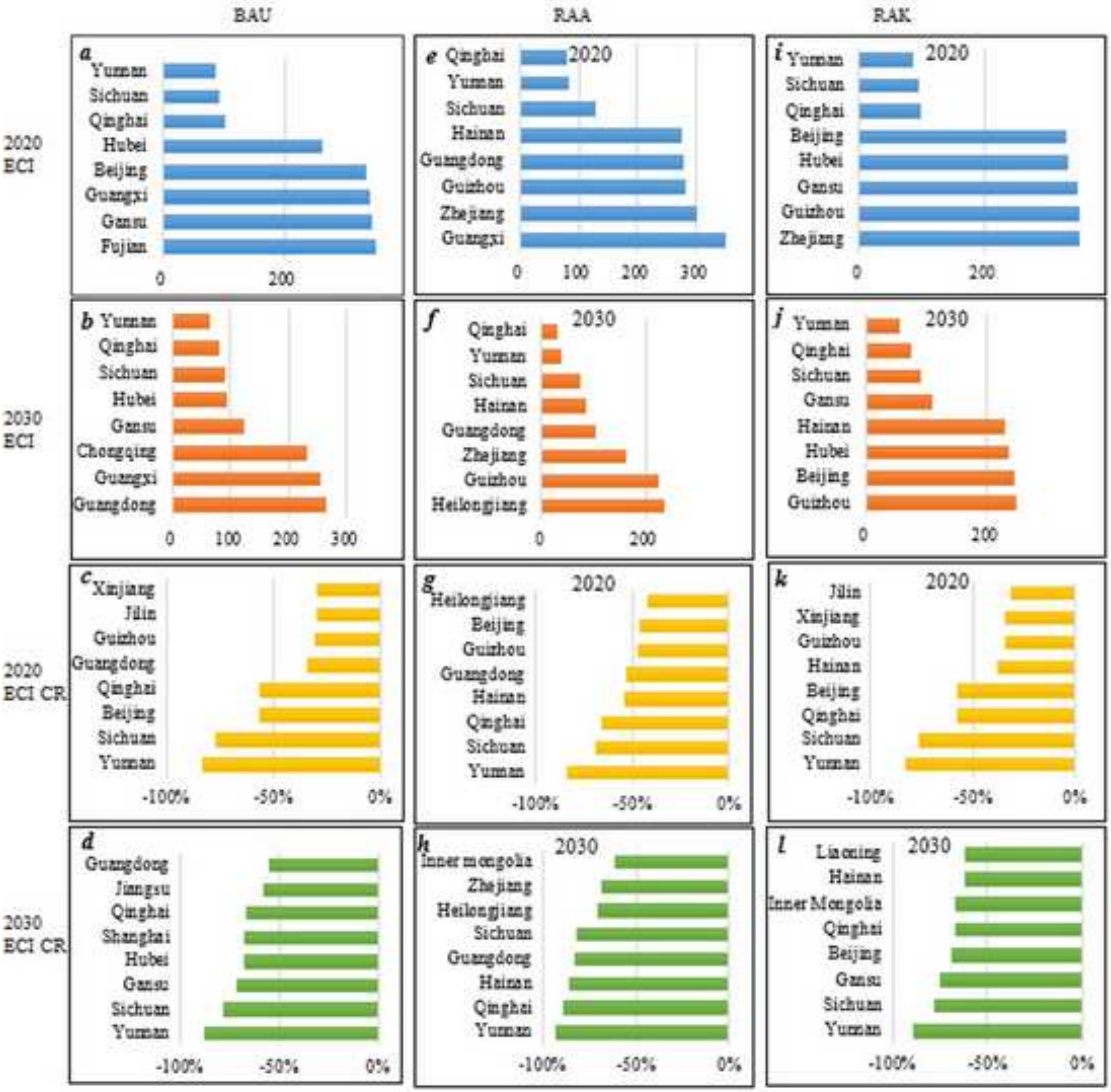
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