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*Published in:*  
Environmental science & technology

*DOI:*  
[10.1021/acs.est.0c00536](https://doi.org/10.1021/acs.est.0c00536)

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*Document Version*  
Publisher's PDF, also known as Version of record

*Publication date:*  
2020

[Link to publication in University of Groningen/UMCG research database](#)

*Citation for published version (APA):*

Peng, X., Tao, X., Feng, K., & Hubacek, K. (2020). Drivers toward a Low-Carbon Electricity System in China's Provinces. *Environmental science & technology*, 54(9), 5774-5782.  
<https://doi.org/10.1021/acs.est.0c00536>

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# Drivers toward a Low-Carbon Electricity System in China's Provinces

Xu Peng, Xiaoma Tao, Kuishuang Feng,\* and Klaus Hubacek\*



Cite This: *Environ. Sci. Technol.* 2020, 54, 5774–5782



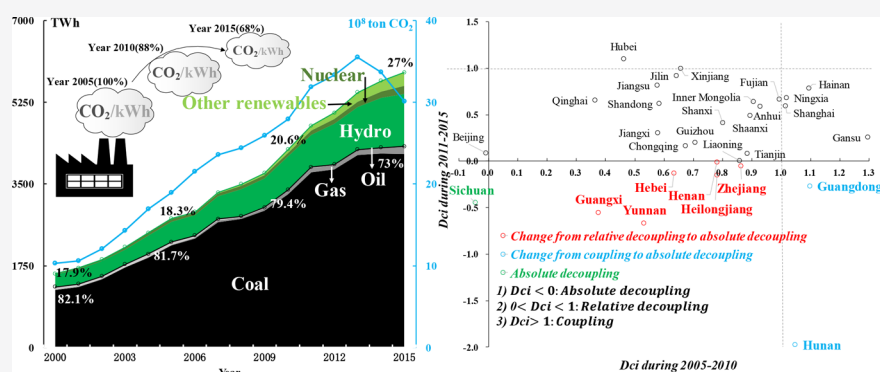
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**ABSTRACT:** Decarbonization of the power sector is one of the most important efforts to meet the climate mitigation targets under the Paris Agreement. China's power sector is of global importance, accounting for ~25% of global electricity production in 2015. The carbon intensity of China's electricity is still much higher than the global average, but the country has made important strides toward a low-carbon transition based on two main pillars: improvement of energy efficiency and decreasing the share of fossil fuels. By applying a decoupling indicator, our study shows that 21 provinces achieved a "relative decoupling" of carbon emissions and electricity production and the remaining nine provinces achieved "absolute decoupling" between 2005 and 2015. We updated China's emission factors based on the most recent data by also considering the quality of imported coal and compared our results with the widely used Intergovernmental Panel on Climate Change coefficients to show the sensitivity of results and the potential error. Our decomposition analysis shows that improvement of energy efficiency was the dominant driver for decarbonization of 16 provincial power sectors, while the access to low-carbon electricity and substitution of natural gas for coal and oil further accelerated their decarbonization.

## 1. INTRODUCTION

Targets for mitigating climate change have been agreed upon by most countries.<sup>1–3</sup> Decarbonizing the power sector and electrification of direct energy use is an important precondition to achieve the target set out by the Paris agreement to pursue efforts to limit global temperature rise to 1.5 °C above preindustrial levels by 2100.<sup>4–6</sup> Given the large and increasing share of electricity as input to industrial production, transportation, and household consumption, many more efforts are needed to rapidly decarbonize this sector. The low-carbon transition, especially in the power sector, is a key pathway to achieve the Paris Agreement. A recent Intergovernmental Panel on Climate Change (IPCC) 1.5 °C special report highlighted that the global power sector needs to be fully decarbonized no later than 2050 to achieve climate mitigation targets;<sup>4–7</sup> however, only very few countries (e.g., Norway, France, Brazil, Sweden, and New Zealand) have achieved fairly low carbon intensity in their power sector (of less than 80 gCO<sub>2</sub>/kWh).<sup>8,9</sup> The decarbonization targets proposed by the IPCC faces huge challenges especially in fast growing developing countries such as China. With rapid economic

growth, the global share of China's electricity production increased from 15.1 to 24.2% from 2005 to 2015, and this trend is predicted to continue in the next few decades.<sup>8</sup> Although the carbon intensity of China's electricity is still higher than the global average, we can observe a pronounced decline in its carbon intensity of electricity over the past decade. As the largest CO<sub>2</sub> emitter globally, China committed to peak its CO<sub>2</sub> emissions around 2030.<sup>10,12</sup> Furthermore, China pledged to increase its share of nonfossil electricity in primary energy use to 31% by 2020 and 50% by 2030.<sup>4,11,12</sup> This proposed transition toward a low-carbon economy requires a deep decarbonization of China's industrial and power sectors. To achieve these targets, a stringent and coordinated package of low-carbon policies is needed.<sup>13</sup>

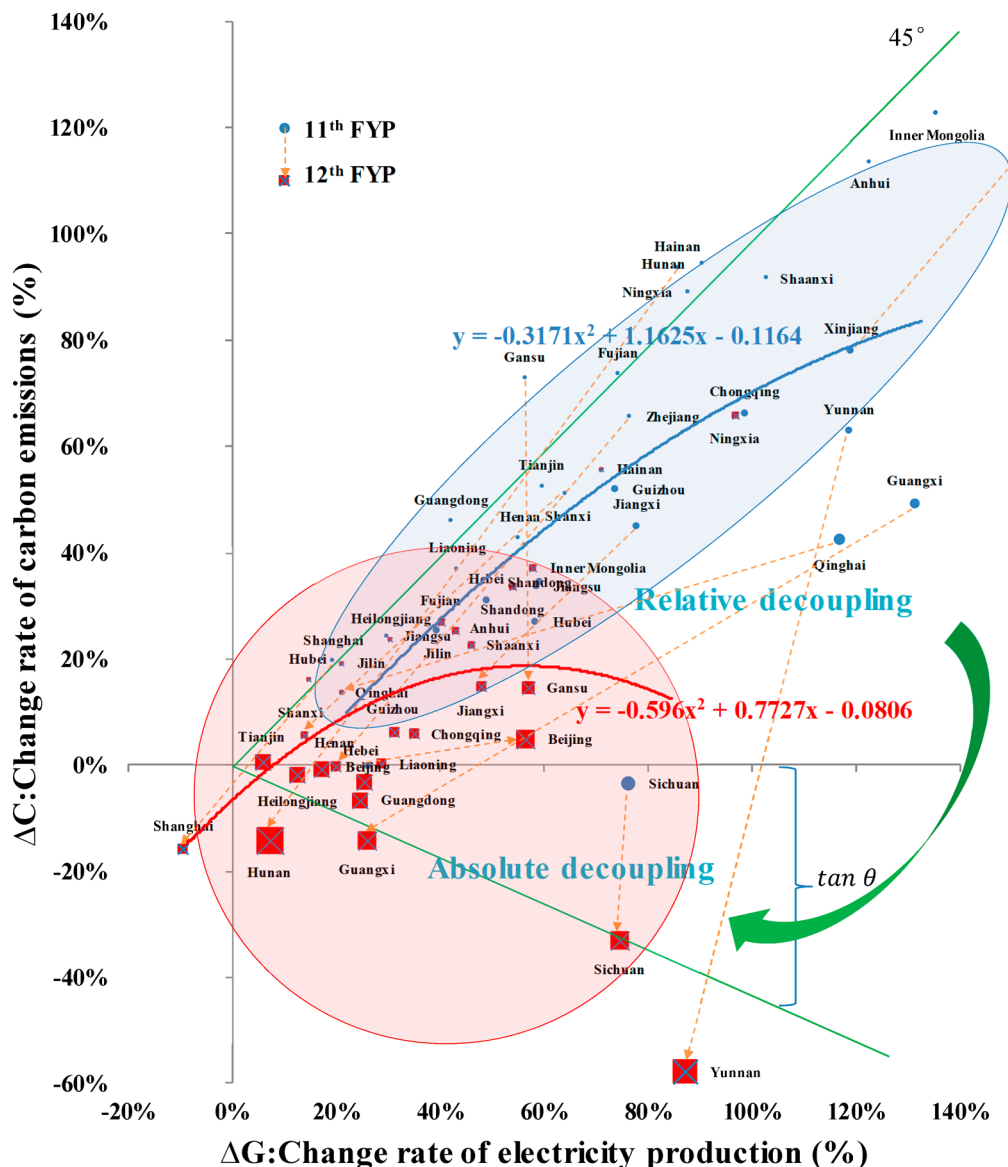
Received: January 27, 2020

Revised: April 4, 2020

Accepted: April 6, 2020

Published: April 6, 2020





**Figure 1.** Low-carbon transition from “relative” to “absolute” decoupling in provincial power sectors. Circle and box size represent the degree of decarbonization. [The bigger the size, the greater the degree of decoupling. The smaller the elasticity value  $\tan \theta$ , the greater (smaller) the degree of decoupling when  $-90^\circ < \theta < 45^\circ$  (when  $-135^\circ < \theta < -90^\circ$ ). OECD used the concept of resource decoupling for environmental policy analysis in their influential report.<sup>29</sup> Relative decoupling means that the growth rate of the environmental indicator is lower than the growth rate of GDP, and their calculated elasticity is below 1. In contrast, absolute decoupling means that the environmental indicator declines, irrespective of the growth rate of GDP. In comparison, the Tapio’s decoupling index, another a popular decoupling index, improves and further divides the degree of decoupling into eight types according to their relevant relations, namely, expansive negative decoupling, expansive coupling, weak decoupling, strong decoupling, recessive coupling, weak negative decoupling, and strong negative decoupling.<sup>31</sup> Comparing Tapio’s with OECD’s decoupling index, we can see that strong decoupling is the same as absolute decoupling, while weak decoupling ( $0 < \text{elasticity value} < 0.8$ ) largely overlaps with relative decoupling ( $0 < \text{elasticity value} < 1$ ). Given the degree of decoupling index in Figure 1 (most are concentrated in the first and fourth quadrants), OECD’s decoupling method is simpler and sufficient to support our analysis in this paper.]

The development of renewable energy and improvement in energy efficiency are deemed the two pillars of the decarbonization of the power sector.<sup>14–16</sup> Despite high costs, risks, and resource constraints, nuclear electricity is also seen by many as an important element in decarbonizing the power sector.<sup>17</sup> Given its large global share and relatively high carbon intensity, the decarbonization of China’s power sector has important implications for achieving global climate mitigation goals. Although previous studies have assessed CO<sub>2</sub> emissions (and intensity) from the power sector either at the national level and regional level,<sup>18–26</sup> they provide little information about

China’s low-carbon transition in the provincial power sector. Although previous studies have highlighted that significant technological advancement and nonfossil fuel substitution together contributed to China’s decline in the carbon intensity of electricity,<sup>27,28</sup> they did not quantify the drivers of decline in carbon intensity of electricity during the past two Five-Year Plans (FYPs). Moreover, there are considerable regional disparities within China due to geography, resource endowment, and different development pathways, which may impose constraints on the low-carbon transition of power generation. Understanding such regional differences can provide reference

points for policy makers to inform context specific climate mitigation policies. To fill these research gaps, we first analyze the degree of decoupling between CO<sub>2</sub> emissions and electricity generation across 30 Chinese provinces by using a decoupling index (the quotient of the growth rates).<sup>29</sup> This allows us to investigate the low-carbon transition progress in China’s provincial power sectors between 2005 and 2015. In addition, we use the Logarithmic Mean Divisia Index (LMDI) to identify the drivers of decarbonization in the provincial power sectors and quantify their contributions.

2. MATERIALS AND METHODS

2.1. Decoupling Index. To describe the decarbonizing trend in China’s power system, this paper used a decoupling method developed by the Organisation for Economic Co-operation and Development (OECD) to measure the change in carbon emissions relative to the change in electricity production.<sup>29</sup> The decoupling index used in this study is expressed as elasticity values under 1.0. The decoupling index can be derived from the percentage change of carbon emission divided by the percentage change of electricity production during a given time period (see eq 1).

$$Dci_j = \frac{\Delta C_j}{\Delta G_j} = \tan \theta = \left( \frac{C_j^b - C_j^a}{C_j^a} \right) / \left( \frac{G_j^b - G_j^a}{G_j^a} \right) \tag{1}$$

where Dci<sub>j</sub> is the decoupling index; θ is the angle of tangent function; C<sub>j</sub><sup>a</sup> denotes the carbon emissions in province j in year a; and G<sub>j</sub><sup>b</sup> denotes the electricity production in province j in year b.

The decoupling index can be further divided into three subcategories: (1) “Relative decoupling”, where electricity production and carbon emissions both increase [Dci = tan θ ε(0, 1), θ ε(0, 45°)] or decrease [Dci = tan θ ε(1, +∞), θ ε(-135, -90°)]. (2) “Absolute decoupling”, which occurs when electricity production grows but carbon emissions decrease: Dci = tan θ ε(-∞, 0], θ ε(-90, 0°] (see Figure 1).<sup>29–33</sup> (3) “Coupling” occurs when the growth rate of electricity production is equal or slower than associated carbon emissions: Dci = tan θ ε(1, +∞], θ ε(45, 90°].

2.2. Intertemporal Decomposition with LMDI. In addition to the decoupling analysis, it is important to know which factors lead to changes in provincial carbon intensity of electricity and how much these drivers have contributed to provincial decoupling. Such information may also provide references for accelerating the low-carbon transition in other carbon-intensive regions.<sup>34</sup> Low-carbon transition (or decoupling) in the power system has been commonly measured by the “carbon intensity of electricity” (i.e., carbon emission per unit of electricity output in kgCO<sub>2</sub>/kWh).<sup>1,22</sup> LMDI has various desirable attributes satisfying the factor-reversal test and time-reversal test.<sup>18,19,35–41</sup> In this paper, LMDI is adopted to analyze the absolute change of carbon intensity of electricity during the 11th and 12th FYPs<sup>27,42–44</sup> and the contributions from four drivers: (a) improved coal quality (emission factor effect), (b) the fossil fuel substitution effect β<sub>ij</sub> (including coal, gas, oil and others), (c) the energy efficiency effect φ<sub>ij</sub> (standard coal consumption per unit of electricity output, g/kWh), and (d) the nonfossil energy substitution effect θ<sub>ij</sub> (including nuclear, hydroelectricity and other renewable electricity).

Equation 2 shows that the carbon intensity of electricity CI is determined by the emission factor γ<sub>i</sub>, the type of fossil fuel f<sub>i</sub>, aggregated energy consumption F<sub>j</sub>, the fossil electricity output Q<sub>j</sub>, and total electricity output G<sub>j</sub>. The ratio of the two variables indicates the drivers. Subscript i represents the type of fossil fuel, and j represents the region.

The primary decomposition form is denoted as

$$CI = C/G = \sum_{ij} [(\gamma_i f_i)/F_j](F_j/Q_j)(Q_j/G_j) \tag{2}$$

$$\sum_i f_{ij} = F_j \tag{3}$$

$$\text{share}_{ij} = f_{ij}/F_j \tag{4}$$

$$CI = \sum_j (\gamma_{\text{coal}} \text{share}_{\text{coal}} + \gamma_{\text{oil}} \text{share}_{\text{oil}} + \gamma_{\text{gas}} \text{share}_{\text{gas}} + \gamma_{\text{others}} \text{share}_{\text{others}}) (F_j/Q_j)[(G_j - Q_{\text{non-}j})/G_j] = \left( \sum_j \sum_{i=1}^4 \alpha_{ij}^{\text{tot}} + \sum_j \sum_{i=1}^4 \beta_{ij}^{\text{tot}} \right) + \sum_j \varphi_j^{\text{tot}} + \sum_j \sum_{i=5}^7 \theta_{ij}^{\text{tot}} \tag{5}$$

Defining parameter ε as

$$\phi^{(a,b)} = L(C^a/G^a, C^b/G^b) \tag{6}$$

$$x = \gamma_i f_i / F_j \tag{7}$$

$$y = F_j / Q_j \tag{8}$$

$$z = Q_j / G_j \tag{9}$$

$$\Delta CI = \sum_{ij} \Delta(x \cdot y \cdot z) \tag{10}$$

where L is the logarithmic mean algorithm. The nine decomposed factors are denoted as

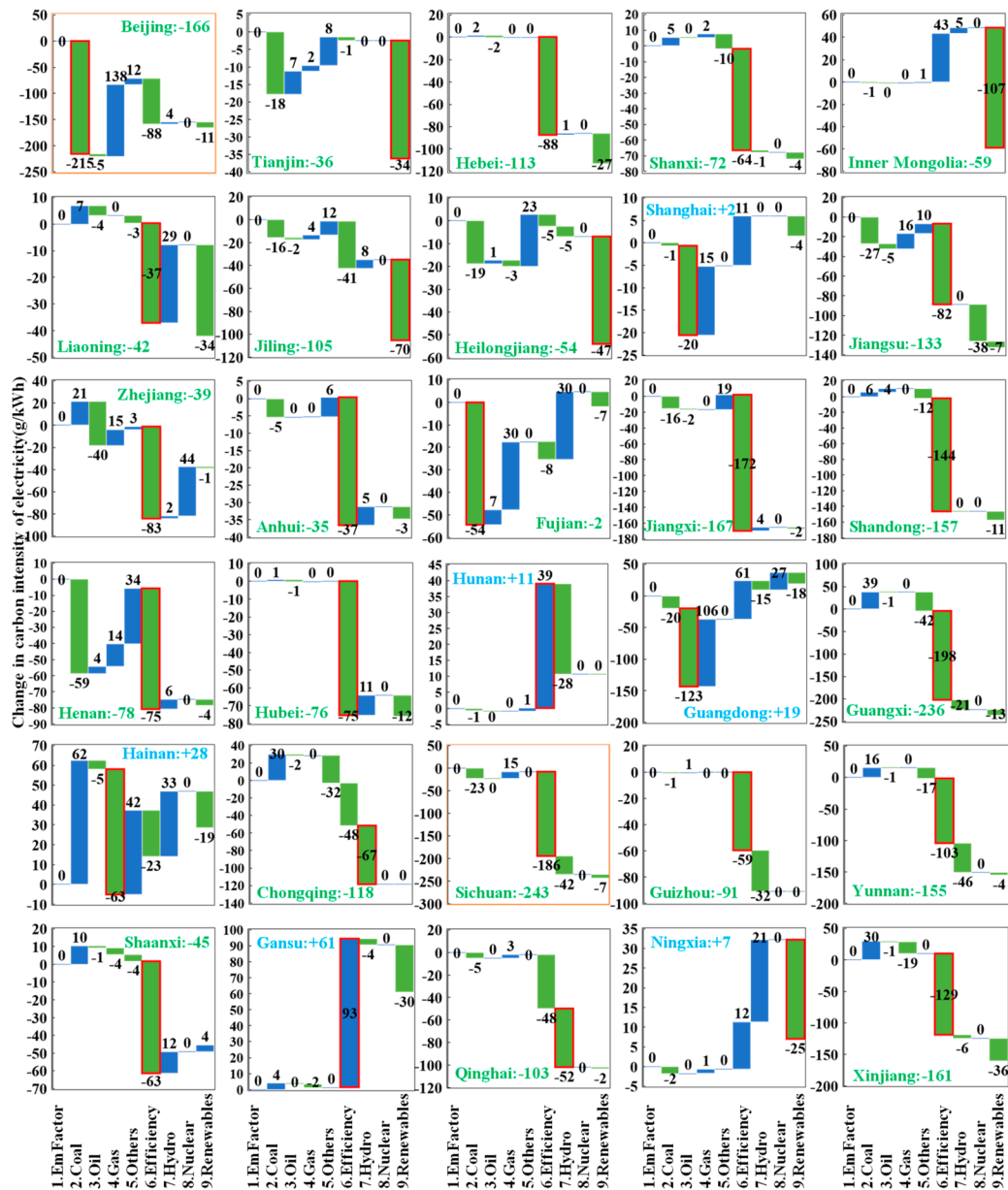
$$\Delta CI = \sum_{ij} \Delta(x \cdot y \cdot z) = \sum_{ij} \phi^{(a,b)} [\ln(x^t/x^0) + \ln(y^t/y^0) + \ln(z^t/z^0)] = a + b + c \tag{11}$$

where a and c can be further decomposed by a two-stage decomposition method.

$$a = \sum_{ij} \phi^{(a,b)} \ln(x^t/x^0)/(x^t - x^0) \left\{ \sum_{i=1}^4 \sum_j L(x^0, x^t) [\ln(\gamma_{ij}^t/\gamma_{ij}^0) + \ln(\text{share}_{ij}^t/\text{share}_{ij}^0)] \right\} \tag{12}$$

$$b = \sum_{ij} \phi^{(a,b)} \ln(y^t/y^0) \tag{13}$$

$$c = \sum_{ij} \phi^{(a,b)} \ln(z^t/z^0)/(z^t - z^0) \left( \sum_{i=5}^7 \sum_j \text{share}_{ij}^{*\text{tot}} \right) \tag{14}$$



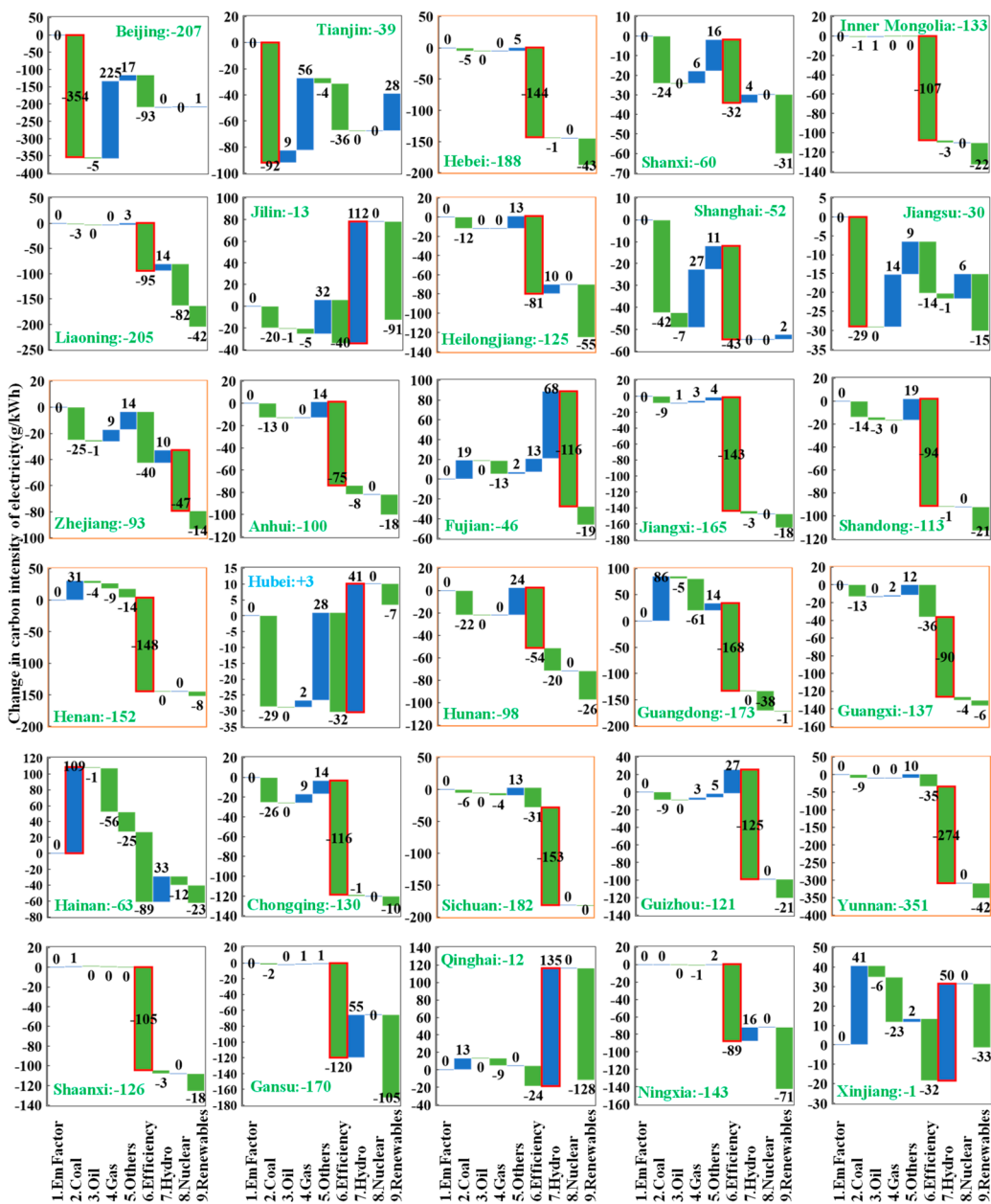
**Figure 2.** Emission factor (bar 1), fossil fuel substitution (bars 2–5), energy efficiency (bar 6) and nonfossil energy substitution effects (bars 7–9) (in g/kWh) in provincial power sector during the 11th FYPs. [(a) The raw data of fossil fuel consumption for power generation is collected from the “Thermal Power Generation” part in Provincial Energy Balance Table from 2005 to 2015, excluding fossil fuel consumption for heating supply. Notably, China also supplies heat in winter; many units of power plants in Northern China are cogeneration of heat and power (CHP). Thus, our carbon intensity of electricity only includes the carbon emissions for electricity but not for heat production. (b) The carbon emission factors are extracted from recent studies by Liu et al.<sup>46</sup> and Shan et al.<sup>47</sup> The decomposition results of control groups in the SI are calculated using IPCC’s method. (c) Provincial power generation data is collected from the National Bureau of Statistics of China from 2005 to 2015. (d) A green bar indicates a driver to reduce the carbon intensity of electricity, while a blue bar contributed to an increase. In this work, the dominant driver indicates the biggest decomposition effect among all four factors in this period. Furthermore, we represent the dominant driver with a red frame in each province. (e) The category of “others” represents biomass, industrial, and nonrenewable municipal waste for power generation. Efficiency represents aggregated thermal power production productivity, including coal, gas and oil. The category of “renewables” mainly refers to wind and solar PV in China. (f) We show absolute decoupling provinces with orange frames but relative decoupling provinces with black frames.]

### 3. FROM RELATIVE TO ABSOLUTE DECOUPLING

Achieving absolute decoupling of carbon emissions from electricity production in China is difficult given the existing scale of renewables, low-carbon technologies, and climate policies, but we have found a promising decarbonizing trend since 2000.<sup>45</sup> Different degrees of decarbonization in the electricity system can be observed in most Chinese provinces. Our results show that the power sector of eight provinces

experienced a low-carbon transition (changing from relative decoupling or coupling during the 11th FYP to absolute decoupling during the 12th FYP), which means their carbon emissions have declined despite increasing electricity production.

Figure 1 shows that there are two different decoupling trends during the past two FYPs. First, the leftward shift of the provincial decoupling index indicates that the growth rate of



**Figure 3.** Emission factor (bar 1), fossil fuel substitution (bars 2–5), energy efficiency (bar 6), and nonfossil energy substitution effects (bars 7–9) (g/kWh) in provincial power sectors during the 12th FYPs.

electricity production during the 12th FYP is getting slower than that during the 11th FYP. The slowing down of electricity production is highly associated with the slowdown of China’s GDP growth during the 12th FYP. Second, the decline of the decoupling index indicates that a stronger decoupling trend in the power system took place from the 11th to 12th FYP. Most provinces have changed from a weak relative decoupling (close to the 45° line) to a stronger relative decoupling (close to the 0° line) since 2005. Even more provinces achieved absolute decoupling of the power sector during the 12th FYP.

The 45° line in Figure 1 represents equal growth rates of electricity production and carbon emissions. Thus, if a region falls into the region below the 45° line, it indicates a growth rate of carbon emissions which is slower than the rate of electricity production. During the 11th FYP, most provinces had a slower growth rate of carbon emissions than electricity production. Their decoupling indexes were near to the 45° line

and were concentrated in the blue area, which indicates a relatively weak relative decoupling of carbon emission from power generation at provincial level (See Figure 1). Only Beijing and Sichuan provinces show absolute decoupling. The decarbonizing trend in the provincial power sector was not very pronounced for most regions during this period.

Compared with the 11th FYP, in the 12th FYP more provinces’ decoupling indexes were close to the 0° line and were concentrated in the red area. A stronger relative decoupling in the power sector can be observed in most provinces during the 12th FYP (see Figure 1). Many decoupling indexes of the provincial power sector show a downward shift, and seven more provinces have moved from relative decoupling to absolute decoupling in the power sector during this period. For example, Hebei, Heilongjiang, Zhejiang, Henan, Hunan, Guangdong, Guangxi, Sichuan, and Yunnan provinces experienced a strong decarbonization trend and

achieved absolute decoupling during the 12th FYP. Shanghai shows a relative decoupling (recessive decoupling in Tapio's decoupling index) during this period, which can be partly explained by the "West–East Electricity Transmission Project". Shanghai has consumed 43.6% of electricity from neighboring provinces through the "West–East Electricity Transmission Project", which reduced the local requirement for electricity production. Thus, its electricity production declined during this period. Overall, the decarbonizing trend from relative decoupling to absolute decoupling reflects China's efforts toward a low-carbon power system in the past decade.

#### 4. DRIVER OF CHANGE IN CARBON INTENSITY OF ELECTRICITY

The Log-Mean Divisia Index (LMDI) method is adopted here to quantify the drivers of decarbonization process in provincial power sectors during the past two FYs. All fossil fuel data is converted into tons of standard coal equivalent (tce). According to the formulas in Supporting Information (SI) Note 3, the results of the decomposition analysis show the changes in power related CO<sub>2</sub> emissions from four contributing factors: emission factor, fossil fuel substitution, energy efficiency and nonfossil energy substitution effects. Specifically, we used up-to-date carbon emission factors provided by Liu et al.<sup>46</sup> and Shan et al.<sup>47</sup> and updated their emission factors by considering the role of imported coal. To capture the impacts from using different carbon emission factors, we compared our results with the widely used IPCC coefficients to show the sensitivity of the results to the coefficients and the potential error by using outdated coefficients in SI Note 4.

Figure 2 displays the contributions of the four drivers in each province during the 11th FYP. Overall, 24 out of 30 provinces have reduced their carbon intensity of electricity, except Shanghai (+0.2%), Hunan (+2%), Guangdong (+3%), Hainan (+4%), Gansu (+11%), and Ningxia (+1%). Only Beijing (mainly due to gas-for-coal substitution) and Sichuan (mainly due to improved energy efficiency) have achieved absolute decoupling in this period. The increasing share of renewables is the dominant driver for the decline in the CIs of Tianjin (−4%), Inner Mongolia (−10%), Jilin (−7%), Heilongjiang (−5%), and Ningxia (−3%) (5 out of 30 provinces). Energy efficiency is another important dominant driver for the decline of carbon emission intensity in Hebei (−9%), Shanxi (−7%), Liaoning (−4%), Jiangsu (−10%), Zhejiang (−13%), Anhui (4%), Jiangxi (−19%), Shandong (−14%), Henan (−8%), Hubei (−20%), Guangxi (−30%), Sichuan (−35%), Guizhou (−8%), Yunnan (−17%), Shaanxi (−8%), and Xinjiang (−15%) (16 out of 30 provinces). Hydroelectricity dominated the low-carbon transition only in Chongqing (−9%) and Qinghai (−17%), while its shrinking share has markedly increased carbon intensity of electricity in Liaoning (+3%), Fujian (+6%), Hainan (+5%), and Ningxia's (+2%) during this period. Only three provinces show a visible change to their carbon intensity of electricity driven by nuclear energy. Jiangsu reduced emission intensity by −4% due to an increase in nuclear power, while Zhejiang and Guangdong increased emission intensity by +7 and +4%, respectively, due to their shrinking shares of nuclear power. Shanghai and Guangdong reduced their carbon intensity of electricity by −3 and −18% g/kWh, respectively, due to using less oil for electricity production. Hainan reduced its carbon intensity by −9% due

to decreasing gas inputs to electricity production. Finally, the emission factor effect is negligible in all provinces.

During the 12th FYP (Figure 3), only Hubei slightly increased its carbon intensity of electricity (+1% g/kWh), while the remaining 29 provinces' CIs have declined since 2010. Nine provinces have achieved absolute decoupling in the 12th FYP, namely, Hebei, Heilongjiang, Zhejiang, Henan, Hunan, Guangdong, Guangxi, Sichuan, and Yunnan. The gas-for-coal substitution is the major contributing factor for the decline of CIs in Beijing (−10%) and Fujian (−5%) (2 out of 30 provinces) during the 11th FYP, while it reduced Beijing (−20%), Tianjin (−5%), and Jiangsu (−2%) provinces (3 out of 30 provinces) during the 12th FYP. Beijing has adopted a Clean Air Action Plan and abandoned 99.8% of the coal-fired electricity supply since 2013. The shortage is compensated by natural gas power plants or imports from neighboring provinces. However, renewable electricity is the dominant driver for Tianjin, Jilin, Heilongjiang, and Inner Mongolia in the 11th FYP, while it is no longer the dominant driver for any province in the 12th FYP. It still helps to reduce CI in many provinces (for example, −10% in Jilin, −6% in Heilongjiang, −17% in Gansu, −65% in Qinghai, and −8% in Ningxia) in this period. Energy efficiency is still the dominant driver for Hebei (−17%), Shanxi (−4%), Inner Mongolia (−11%), Liaoning (−10%), Heilongjiang (−8%), Shanghai (−6%), Anhui (−9%), Jiangxi (−19%), Shandong (−11%), Henan (−16%), Hunan (−11%), Guangdong (−24%), Chongqing (−19%), Shaanxi (−13%), Gansu (−19%), and Ningxia (−10%) (16 out of 30 provinces; see SI Note 2). Hydroelectricity is China's largest share of nonfossil fuel electricity, while its share has shrunk and been replaced by other renewables and nuclear since 2005 (see Figure S1). A decline in the share of hydroelectricity is the dominant driver for increasing CIs in Jilin (+12%), Qinghai (+68%), Hubei (+13%), and Xinjiang (+7%), while an increase in hydro contributed to a reduction in carbon intensity in Sichuan (−52%), Guizhou (−20%), Yunnan (−61%), and Guangxi (−21%). Nuclear is the dominant driver for reducing carbon intensity in Zhejiang (−8%) and Fujian (−24%). Oil-fired and other electricity effects are negligible for most provinces. Overall, the emission factor effect is negligible in all provinces due to the small share of imported coal (~5%) and small difference in coal quality (0.499 for local coal compared with 0.508 tC per ton of coal for imported coal).<sup>46</sup> Indeed, previous studies have shown that using higher carbon coefficients based on assumed lower quality of coal would lead to an over reporting of China's total carbon emissions.<sup>46</sup> However, compared with other factors, the small share of imported coal (~5%) and only small differences in carbon content ( $\pm 0.017$  tC per ton of coal) have not significantly affected the carbon intensity of electricity. Comparing our coefficients with the ones suggested by the IPCC, we found that IPCC's values led to overestimating the decline in carbon intensity of electricity at the province level in both periods.

#### 5. DISCUSSION

Decoupling of carbon emissions from electricity production is a huge challenge for the existing fossil-fuel-dependent power sector in most countries. To achieve the Paris agreement goals and the 1.5 °C target, the global power sector should be fully decarbonized by no later than 2050<sup>7</sup> preferably even earlier. According to a recent report published by the International Renewable Energy Agency (IRENA), electricity consumption

in end-use sectors was projected to be doubled by 2050 (relative to 2015 levels), while the carbon intensity of the power sector would need to decline by 85%.<sup>14</sup> Moreover, the share of renewable electricity would need to increase to 85% from an estimated 24% in 2017.<sup>14</sup> No newly built coal-fired power plants (without carbon capture and storage) should be permitted by government, and 95% of existing coal-fired power plants in operation would need to be phased out by 2050 under the REmap Case.<sup>14,48</sup> Decarbonization of the power system has already begun, especially driven by recent rapid developments in renewable electricity and improved energy production efficiency. Given China's large increase in its global share of electricity output and relatively high CO<sub>2</sub> intensity, it is vital to understand the contributing factors for the change in emission intensity of the power sector. Despite limited access to renewable energy resources, China's provinces have made significant progress in increasing their share of nonfossil electricity and energy production efficiency toward a low-carbon power system. Specifically, China's power sector has initiated a transition toward a hydro- and renewables-based low-carbon energy system. China's nonfossil electricity shows steady growth increasing from 17.9% in 2000 to 27% in 2015 (see Figure S1), which accounts for a large share of global low-carbon sources. However, coal is still playing a dominant role in energy production in China, accounting for 68% of total electricity production in 2015, while the Chinese government has pledged to further increase the share of nonfossil electricity to 31% by 2020 and 50% by 2030.<sup>12</sup>

Reduction in carbon intensity through an increase in the share of renewables and improvement of energy efficiency together contributed toward the overall low-carbon transition in provincial power sectors from the 11th to 12th FYP (see Figure 1). We adopted a widely used decoupling index to quantify China's efforts toward a low-carbon power system at the province level. During the 11th FYP, most provinces showed weak relative decoupling, indicating that the growth rate of carbon emissions is lower than the growth rate of electricity production, but both are still growing. Only Beijing and Sichuan achieved absolute decoupling of the power sector in this period. In contrast, during the 12th FYP, more provinces had a strong relative decoupling, and nine provinces achieved absolute decoupling, namely, Hebei, Heilongjiang, Zhejiang, Henan, Hunan, Guangdong, Guangxi, Sichuan, and Yunnan (see Figure 1). However, achieving absolute decoupling in China's power system is not easy given the lack of widespread low-carbon technologies, but there are some promising decarbonizing examples at the provincial level. Beijing entered into absolute decoupling mainly due to replacing coal-fired power plants with gas-fired power plants. In addition, outsourcing of power-related pollution to other provinces could also contribute to the reduction of local emissions,<sup>49</sup> but we did not investigate this issue of outsourcing in greater detail in our paper.<sup>50</sup> Sichuan achieved absolute decoupling mainly due to improved energy efficiency. During the 12th FYP, Hebei, Heilongjiang, Henan, Hunan, and Guangdong achieved absolute decoupling mainly due to the improved energy efficiency, while the main contributing factor was the increasing use of nuclear in Zhejiang and increasing use of renewable electricity (mainly hydroelectricity) in Guangxi, Yunnan, and Sichuan. Overall, energy efficiency is the dominant driver for the low-carbon transition in 16 out of 30 provinces. Therefore, policies to further promoting the

improvement of energy efficiency across all provinces are crucial for archiving the emission mitigation goals.

Wind and solar photovoltaics are the most promising low-carbon sources worldwide.<sup>51</sup> China's natural resource endowment enables the further development of large-scale wind and solar electricity especially in the southwestern and northwestern regions,<sup>52,53</sup> in addition to the huge potential for offshore wind power in coastal regions<sup>54</sup> to move further along the low-carbon transition in the future. Further exploring these renewable energy sources would accelerate the emissions and energy production decoupling trend in China, in particular the decoupling in the renewable resource rich provinces such as Jilin, Qinghai, and Gansu.

The Chinese government largely developed nuclear power plants in coastal regions based on the 13th FYP.<sup>55</sup> At present, nuclear power is available in Jiangsu, Liaoning, Zhejiang, Fujian, Guangxi, and Hainan. From the government's 13th FYP, nuclear power is likely to further contribute to the decoupling in China's coastal provinces. However, attention should be given to the potential risks of nuclear power development as extreme events are likely inevitable under the fast-changing climate.<sup>56</sup>

The power industry is a highly capital-intensive sector, and most power plants are built by state-owned enterprises in China. Thus, China's government is the main actor to improve generation efficiency, optimize the power structure, and incentivize competition where possible. The China National Development and Reform Commission has issued and implemented a series of policies since 2005, such as "shutting down small fossil power units" and "upgrading and reconstructing conventional power plants".<sup>57,58</sup> During the time period under investigation, China and other countries have made progress toward a low-carbon power system. However, given China's large dependency on coal, China's low-carbon transition pathway might be different from that of other countries with a larger initial focus on improvement of generation efficiency. Further decarbonization still faces many challenges ahead (e.g., energy security, relatively high cost of renewable energy production). How to accelerate the low-carbon transition is still a big challenge for policy makers. Strategies may vary from country to country, but the common dominator is that much greater effort is required in the future.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.est.0c00536>.

Detailed information about increasing nonfossil electricity consumption, coal efficiency improvement, intertemporal decomposition and control group results (PDF)

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## Notes

The authors declare no competing financial interest.

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