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Article

What can we learn from the 2008 financial crisis for global power decarbonization after COVID-19?

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ABSTRACT

Since the outbreak of the COVID-19 pandemic, power generation and the associated CO₂ emissions in major countries have experienced a decline and rebound. Knowledge on how an economic crisis affects the emission dynamics of the power sector would help alleviate the emission rebound in the post-COVID-19 era. In this study, we investigate the mechanism by which the 2008 global financial crisis sways the dynamics of power decarbonization. The method couples the logarithmic mean Divisia index (LMDI) and environmentally extended input-output analysis. Results show that, from 2009 to 2011, global power generation increased rapidly at a rate higher than that of GDP, and the related CO₂ emissions and the emission intensity of global electricity supply also rebounded; the rapid economic growth in fossil power-dominated countries (e.g., China, the United States, and India) was the main reason for the growth of electricity related CO₂ emissions; and the fixed capital formation was identified as the major driver of the rebound in global electricity consumption. Lessons from the 2008 financial crisis can provide insights for achieving a low-carbon recovery after the COVID-19 crisis, and specific measures have been proposed, for example, setting electricity consumption standards for infrastructure construction projects to reduce electricity consumption induced by the fixed capital formation, and attaching energy efficiency labels and carbon footprint labels to metal products (e.g., iron and steel, aluminum, and fabricated metal products), large quantities of which are used for fixed capital formation.

1. Introduction

The breakout of the coronavirus (COVID-19) pandemic in December 2019 has caused great damage to the global economy, leading to the deepest recession since World War II [1]. Meanwhile, lockdown measures to control the pandemic led to a sharp decline in power generation as well as the related carbon emissions in major countries [2,3]. For example, compared to 2019, India's power generation in the first half of 2020 dropped by 7.5%, and related carbon emissions have declined by 12.7%. As the lockdown measures were eased in the second half of 2020 in many countries, global power demand recovered rapidly, and power demand in many countries even exceeded that of 2019. According to the latest report from the International Energy Agency [4], the global

power demand grew by over 6% in 2021—the largest annual increase since the 2008 global financial crisis.

The pandemic can promote or hinder global power decarbonization. In terms of promotion, the declining power demand can squeeze out some high-cost thermal power, resulting in a higher proportion of renewable power, which has low variable costs and priority access to the grid [5]. Moreover, the economic crisis induced by COVID-19 may phase out companies with low energy efficiency and poor economic performance [6–9], which can mitigate the growing power demand. In terms of hindering, the lockdown measures have disrupted global supply chains [10,11], presenting challenges in the operation of the renewable energy industries in some countries. This has also delayed or suspended renewable power projects in countries such as the United States [12],

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Japan [13], and India [5]. The declining willingness to invest in renewable energy due to unclear market prospects and the decrease in company income will also hamper the development of renewable energy [14]. However, it is still unclear how the pandemic will affect global power decarbonization in the future and what measures should be taken at present [15]. Currently, some countries and regions such as the European Union and the United States have already launched large-scale economic stimulus plans [2,16], which may bring about a substantial increase in electricity consumption. Therefore, there is an urgent need to clarify the mechanisms by which an economic crisis and/or economic stimulus plan sways the decarbonization dynamics of the power system, so as to generate new insights for promoting global power decarbonization after the COVID-19 crisis.

History has shown that shocks such as economic crises [17,18], technological revolutions [19–21], and natural disasters [22,23] can greatly influence the energy system. The last global economic crisis, the great recession of 2008–2009, caused a temporary decline in global power generation, and then a rapid rebound, which had an evident impact on the decarbonization of the global power sector [24]. Although the changes in the global or regional power sector after the great recession have been widely documented in many studies [14,25–28], it remains unclear how this economic crisis and the accompanying countermeasures have affected CO₂ emission dynamics in the power sector. As a consequence, the existing literature can provide little help to the current global effort to deal with the ongoing rebound of emissions in the power sector in the post- COVID-19 era.

Lessons from history may provide insights for the future, and some recent studies argued that lessons from the 2008 financial crisis can help the effort to achieve a low-carbon economic recovery. Wang et al. [29] found an inverted-V shaped changing pattern of global carbon emission intensity during the financial crisis, with economic structure and energy intensity as the major drivers, and emphasized the importance of taking measures to avoid the rebound in carbon intensity. Based on the performance of major government stimulus plans after the financial crisis, Birol [30] put forward several strategic recommendations for renewable energy development. However, these studies paid little attention to the question about how the economic crisis and stimulus plans affect carbon emissions of the energy system.

In this study, we investigate how the 2008 global financial crisis influenced global power generation, the related CO₂ emissions, and electricity’s CO₂ emission intensity (CEI). We employ the logarithmic mean Divisia index (LMDI) method to identify nine key driving factors and quantify the contributions of each driving factor to CO₂ emissions and CEI of global and national electricity supply across 140 countries/regions from 2007 to 2017. We also quantify electricity embodied in final demand to reveal the major final demand categories that caused significant changes in global power generation. Our results highlight that during the great recession, the decline in power supply led to a reduction in carbon emissions from global power generation and thermal power generation was first squeezed out, resulting in a rise in the share of renewable energy in the power sector. The opposite dynamics were observed during the economic recovery period. Gross fixed capital formation after the financial crisis was identified as the major contributor to the emissions rebound in the global power sector. Zooming-in studies are further done for key countries that play significant roles in the global power supply and the associated emissions. Therefore, this

study is arguably the most comprehensive and detailed analysis of the mechanism by which the economic crisis of 2008 drove the emission dynamics of the power sector in comparison with the existing literature. The findings can provide insights for mitigating the carbon emission rebound after the pandemic and for accelerating the global low-carbon transition in the future.

2. Material and methods/experiment

2.1. Materials

Data of carbon emissions from electricity plants and combined heat and power (CHP) plants are derived from CO₂ Emissions from Fuel Combustion [31] published by International Energy Agency, and the fixed-heat-efficiency approach is used to eliminate the carbon emissions caused by heat production (a detailed introduction on the method can be found in the Supplementary Information). The power generation and consumption data of the countries/regions were retrieved from IEA’s World Energy Balance [32]. The multi-regional input-output tables were drawn from Exiobase [33], and the related electricity consumption satellite account can be obtained upon request. The GDP data at the constant price are collected from World Development Indicators compiled by the World Bank [34].

2.2. Methods

2.2.1. Carbon emission intensity of electricity

Using statistical data of CO₂ emissions (C_j) and power generation (G) from the IEA, electricity’s carbon emission intensity (CEI) can be calculated as follows:

$$CEI = \frac{1}{G} \sum_{j=1}^n C_j \quad (1)$$

In which C_j is CO₂ emissions induced by fuel j for power generation. Four kinds of fuels ($n = 4$) were considered in our study, including coal, oil, natural gas and other fuels. It is worth noting that the CO₂ emissions and CEIs were calculated based on the national and regional annual average CEIs of different power generation technologies in 2017 and monthly power generation information from IEA [35], which may cause underestimation for using the latest power generation technology and efficiency available by the end of the study period.

2.2.2. Decomposition analysis

The LMDI method is used in this study to quantify the contribution of the predefined driving factors. The LMDI method proposed by Ang and Liu [36] in 2001 has two desirable properties of perfect decomposition and aggregation consistency. Perfect decomposition means that the LMDI results do not have a residual term and aggregation consistency means that the decomposition at different levels has consistent results. This method has been widely used in energy and environment research to quantify driving factors, and examples can be found in studies by Peng et al. [27] and Ang and Su [26].

Decomposition analysis of the CO₂ emissions from global power generation

We use the following equation to present carbon emissions from power generation and further analyze the driving factors (Table 1) of the emissions.

Table 1
Definition of variables.

Multipliers	Abbreviations	Factor contribution	Description
A_i	a_i	ΔC_i^a	The effect of regional economic scale
$EC_{i,j}/A_i$	ee_i	ΔC_i^{ee}	The effect of energy intensity (of regional economy)
G_i/EC_i	esr_i	ΔC_i^{esr}	The effect of electricity self-sufficiency rate
$Q_{i,j}/G_i$	$es_{i,j}$	ΔC_i^{es}	Power structure effect
$ce_{i,j}$	$ce_{i,j}$	ΔC_i^{ce}	Power generation efficiency effect

$$C_g = \sum_{i=1}^m C_i = \sum_{i=1}^m \sum_{j=1}^n A_i \cdot \frac{EC_i}{A_i} \cdot \frac{G_i}{EC_i} \cdot \frac{Q_{i,j}}{G_i} \cdot cei_{i,j}$$

$$= \sum_{i=1}^m \sum_{j=1}^n a_i \cdot ee_i \cdot esr_i \cdot es_{i,j} \cdot cei_{i,j} \quad (2)$$

$$\Delta C_g = C_g^T - C_g^0 = \Delta C_g^a + \Delta C_g^{ee} + \Delta C_g^{esr} + \Delta C_g^{es} + \Delta C_g^{cei} \quad (3)$$

where C_g denotes carbon emissions induced by global power generation; C_i is carbon emissions induced by power generation in region i ; A_i is the real GDP of region i (2010 is chosen as the base year); EC_i is the electricity consumption of region i ; G_i is the power generation amount in region i ; $Q_{i,j}$ is the electricity generated using the j th fuel in region i ; and $cei_{i,j}$ is the CEI of electricity produced using the j th fuel in region i . Notably, $cei_{i,j}$ measures the carbon cost of producing a unit of electricity using the j th fuel in region i , therefore it is defined as power generation efficiency, and $cei_{i,j}$ of renewable energy is 0.

Then the effects of the driving factors in Eq. 3 can be calculated as follows:

$$\Delta C_g^a = L(C_g^T, C_g^0) \ln \left(\frac{a_g^T}{a_g^0} \right)$$

$$\Delta C_g^{ee} = L(C_g^T, C_g^0) \ln \left(\frac{ee_g^T}{ee_g^0} \right)$$

$$\Delta C_g^{esr} = L(C_g^T, C_g^0) \ln \left(\frac{esr_g^T}{esr_g^0} \right)$$

$$\Delta C_g^{es} = L(C_g^T, C_g^0) \ln \left(\frac{es_g^T}{es_g^0} \right)$$

$$\Delta C_g^{cei} = L(C_g^T, C_g^0) \ln \left(\frac{cei_g^T}{cei_g^0} \right) \quad (4)$$

where $L(x, y) = \frac{x-y}{\ln x - \ln y}$ for $x \neq y$, and $L(x, y) = x$ for $x = y$.

It should be noted that the factor of electricity self-sufficiency rate is used to connect regional electricity production and electricity consumption. CO₂ emissions from power generation are not directly related to regional power consumption, and a region can meet its power demand by importing electricity from other regions. The self-sufficiency rate is the ratio of regional electricity generation amount to electricity consumption. Using the self-sufficiency rate, we can quantify the contribution of economic scale and energy intensity, which are closely related to regional power demand instead of power generation. Although the scale of global power transmission across national borders is very small, it may have a great impact on certain countries with a large share of imported electricity in their total domestic consumption. It is worth noting that, due to the unavailability of data and its negligible contribution to global electricity-related CO₂ emissions, the factor electricity self-sufficiency rate was not considered when decomposing the 2017–2021 electricity-related CO₂ emissions. Besides, due to the unavailability of data, we assumed that the CO₂ emission intensities of different power generation technologies in each region are constant from 2017 to 2021, which means that the contribution of power generation efficiency is 0 during this period.

Decomposition analysis of the CEI

Based on previous studies [26,37], four driving factors of the CEI are considered, including regional share of global power generation, share of thermal power, fuel mix, and thermal power generation efficiency. In this study, thermal power refers to electricity produced using coal, natural gas, oil, industrial waste, and municipal waste.

$$CEI_g = \frac{1}{G_g} \cdot C_g = \frac{1}{G_g} \cdot \left(\sum_{i=1}^m \sum_{j=1}^n C_{i,j} \right)$$

$$= \frac{1}{G_g} \cdot \left(\sum_{i=1}^m \sum_{j=1}^n G_i \cdot \frac{G_i}{G_g} \cdot \frac{Q_{i,j}}{G_i} \cdot \frac{Q_{i,j}}{Q_i} \cdot \frac{C_{i,j}}{Q_{i,j}} \right)$$

$$= \sum_{i=1}^m \sum_{j=1}^n \frac{G_i}{G_g} \cdot \frac{Q_{i,j}}{G_i} \cdot \frac{Q_{i,j}}{Q_i} \cdot \frac{C_{i,j}}{Q_{i,j}}$$

$$= \sum_{i=1}^m \sum_{j=1}^n s_i \cdot p_i \cdot m_{i,j} \cdot e_{i,j} \quad (5)$$

$$\Delta CEI_g = CEI_g^T - CEI_g^0 = \Delta CEI_g^S + \Delta CEI_g^P + \Delta CEI_g^M + \Delta CEI_g^E \quad (6)$$

where CEI_g is the CEI of global electricity, C_g is carbon emissions induced by global power generation, G_g is the global power generation amount, G_i is the power generation amount in region i , Q_i is the electricity generation from fossil fuel combustion in region i , $Q_{i,j}$ is the electricity generated using the j th fuel in region i , and $C_{i,j}$ is the carbon emissions caused by $Q_{i,j}$. The meanings of s_i , p_i , $m_{i,j}$, $e_{i,j}$, ΔCEI_g^S , ΔCEI_g^P , ΔCEI_g^M , and ΔCEI_g^E are shown in Table 2.

The contribution of the above four factors can be calculated as follows:

$$\Delta CEI_g^S = \sum_{i,j} L(CEI_{i,j}^T, CEI_{i,j}^0) \ln \left(\frac{s_i^T}{s_i^0} \right)$$

$$\Delta CEI_g^P = \sum_{i,j} L(CEI_{i,j}^T, CEI_{i,j}^0) \ln \left(\frac{p_i^T}{p_i^0} \right)$$

$$\Delta CEI_g^M = \sum_{i,j} L(CEI_{i,j}^T, CEI_{i,j}^0) \ln \left(\frac{m_{i,j}^T}{m_{i,j}^0} \right)$$

$$\Delta CEI_g^E = \sum_{i,j} L(CEI_{i,j}^T, CEI_{i,j}^0) \ln \left(\frac{e_{i,j}^T}{e_{i,j}^0} \right) \quad (7)$$

where $L(x, y) = \frac{x-y}{\ln x - \ln y}$ for $x \neq y$, and $L(x, y) = x$ for $x = y$.

Spatial decomposition analysis for electricity-related CO₂ emissions and CEIs

The above two LMDI methods are the temporal LMDI, which can reveal the reasons for the changes in the development and performance of regions over time but cannot directly compare the performance between different regions. Therefore, the spatial LMDI method is used for cross-regional comparison. The first step in using spatial LMDI is to select a benchmark reference. Following previous studies [38,39], we use the average level of the region group as the reference region. The top 10 countries with the largest electricity generation in the world are selected for comparison with the average level of the region group.

Here, taking electricity-related CO₂ emissions as an example, we will introduce the spatial LMDI method. According to Eqs. 2 and 3, the difference in electricity carbon emissions between region i and the benchmark

Table 2
Definition of variables.

Multipliers	Abbreviations	Factor contribution	Description
G_i/G	s_i	ΔCEI_g^S	Regional power generation share (geographical transfer) effect
Q_i/G_i	p_i	ΔCEI_g^P	Thermal power share effect
$Q_{i,j}/Q_i$	$m_{i,j}$	ΔCEI_g^M	Thermal power's fuel mix effect
$C_{i,j}/Q_{i,j}$	$e_{i,j}$	ΔCEI_g^E	Power generation efficiency effect

region can be decomposed as follows:

$$C_i = \sum_{j=1}^n a_i \cdot ee_i \cdot esr_i \cdot es_{i,j} \cdot cei_{i,j} \quad (8)$$

$$\Delta C = C_i - C_r = \Delta C_{i-r}^a + \Delta C_{i-r}^{ee} + \Delta C_{i-r}^{esr} + \Delta C_{i-r}^{es} + \Delta C_{i-r}^{cei} \quad (9)$$

where C_i and C_r are the electricity-related CO₂ emissions of region i and the benchmark region, respectively. A more detailed introduction to the spatial LMDI method can be found in studies by Ang et al. [38,39].

2.2.3. Regional contributions to the global cei

The contributions of different countries/regions to the global electricity's CEI vary greatly, which mainly depends on the regional power generation scale and CEI of the electricity [25]. By calculating regional contributions to global electricity's CEI, we can identify the key regions which dominate the decarbonization dynamics of the global power sector. The regional contributions can be calculated as follows:

$$\begin{aligned} CEI_g &= \frac{C_g}{G_g} = \frac{C_1 + C_2 + \dots + C_m}{G_g} \\ &= \frac{C_1}{G_1} \cdot \frac{G_1}{G_g} + \frac{C_2}{G_2} \cdot \frac{G_2}{G_g} + \dots + \frac{C_m}{G_m} \cdot \frac{G_m}{G_g} \\ &= cei_1 \cdot s_1 + cei_2 \cdot s_2 + \dots + cei_m \cdot s_m \\ &= \sum_{i=1}^m cei_i \cdot s_i \end{aligned} \quad (10)$$

$$RC_i = cei_i \cdot s_i \quad (11)$$

where CEI_g is the CEI of global electricity, C_g is carbon emissions induced by global power generation, C_i is the carbon emission from power generation in region i ($m = 148$, 148 countries/regions are included), G_g is the global power generation amount, G_i is the power generation amount in region i , cei_i is the CEI of region i 's electricity, s_i is the proportion of regional power generation in the world, and RC_i is the contribution of region i to the CEI of global electricity.

2.2.4. Environmentally extended input-output analysis (EEIOA)

The EEIOA method is widely used to account for consumption-based energy use [40], pollutant emissions [41], and greenhouse gas emissions [42], and we use this method to calculate electricity embodied in final demand.

We have established a satellite account of electricity consumption for the multi-regional input-output tables in Exiobase (the detailed method can be found in the Supplementary methods, Table S1 and Fig. S1).

In the EEIOA model, the embodied electricity intensity \mathbf{e} can be calculated as follows:

$$\mathbf{e} = \mathbf{c}(\mathbf{I} - \mathbf{A})^{-1} \quad (12)$$

where \mathbf{c} is the direct electricity consumption coefficient (electricity consumption per unit sector output), \mathbf{A} is the direct input coefficient matrix of the input-output table, and \mathbf{I} is an identity matrix.

The electricity embodied in the final demand (EEF) of region i can be expressed as follows:

$$\mathbf{EEF} = \mathbf{e} \times \mathbf{Y}_i \quad (13)$$

where \mathbf{Y}_i is the column vector of the final demand of region i . In the final demand, three terms are included, i.e., final consumption expenditure, gross fixed capital formation, and changes in inventories. Notably, final consumption expenditure consists of the expenditure of the household, government, and non-profit institution on consumption goods and services, including collective consumption services; gross fixed capital formation is the long-term investments used to build up or maintain production capacity, and is defined as "the total value of a producer's acquisitions, less disposals, of fixed assets during the accounting period plus certain specified expenditure on services that adds to the value of non-produced assets"; changes in inventories is "the difference between entries into and withdrawals from inventories and recurrent losses".

2.3. Uncertainty analysis

We have quantified the uncertainties of the related CO₂ emissions and CEIs of global electricity and global embodied electricity consumption using the Monte Carlo simulation. The uncertainties of electricity-related CO₂ emissions and the CEI of global power supply mainly come from three variables, namely the carbon emission factor, fuel consumption, and the quantity of power generated. We set the distribution and the coefficient of variation (CV) of carbon emission intensity, fuel consumption and electricity generation amount based on IPCC's report [43] and previous studies [44,45]. The uncertainties of global embodied electricity consumption mainly originate from the MRIO table and the electricity consumption account. The Exiobase did not report uncertainties of the MRIO tables, and we set the distribution and the CV of MRIO elements based on previous studies [42,46]. The detailed description and statistical parameters of variables used in uncertainty analysis can be found in Table S2. The Monte Carlo simulation was set to run 1000 times, and the 95% confidence interval (CI) was reported.

3. Results

3.1. CO₂ emissions and emission intensity of global electricity fluctuated after the financial crisis

Fig. 1a shows that global power generation is closely related to GDP (Gross Domestic Product). The decline in global GDP growth rate caused by the 2008 global financial crisis led to a decrease in power generation growth rate. It's worth noting that the 2000–2001 declines in global GDP growth rate and power generation growth rate were mainly driven by the economic recession in the United States, and a detailed analysis can be found in the Supplementary Analysis. As shown in Fig. 1b, global power generation declined by 0.3% from 2008 to 2009 during the recession, and the related CO₂ emissions were reduced by 1.66% from 10.84 Gt (10.40~11.27 Gt) in 2008 to 10.66 Gt (10.24~11.13 Gt) in 2009. The level of CEI in the electricity sector kept more or less stable between 2000 and 2007 but experienced a decline of 3.1% from 546.1 g/KWh (525.5~567.3 g/KWh) in 2007 to 529.0 g/KWh (510.3~548.9 g/KWh) in 2010. The detailed 95% CI for CO₂ emissions from global power generation and the CEI of global power supply can be found in Fig. S2. An application of a fixed effect panel model (an introduction of the method can be found in the Supplementary Information) shows that the financial crisis caused a decline in the regional power generation amount, the related CO₂ emissions, and the CEI of electricity (see Table S3 for detailed results), indicating that the financial crisis promoted the progress of power decarbonization. These findings highlight the necessity of analyzing the impact of the economic crisis on the decarbonization of the power sector.

Based on the changing patterns of global power generation, the related CO₂ emissions and the CEI of the power sector, we divide the period of 2007–2019 into three stages (see Fig. 1b) to facilitate the following analysis.

During 2007–2009 (Stage 1), the growth rates of global power generation and the related CO₂ emissions declined, and the resultant CEI decreased by 14.8 g/KWh. In sharp contrast to the period of 2000–2007, when the average annual growth of global power generation was about 629 TWh, in Stage 1 the global power generation only increased by 397 TWh from 2007 to 2008, and further decreased by 66 TWh from 2008 to 2009. In this Stage, the shares of thermal power and nuclear power decreased by 1.0% and 0.3%, respectively, while the share of renewable power increased by 1.4% (see Fig. 1c). These results can be mainly explained by the following two reasons. First, the economic recession led to a reduction in electricity demand, and second, fossil fuel electricity with high marginal costs and high CEI became too expensive to be operational, resulting in a decline in both the carbon emissions from power generation and the CEI [5,47,48].

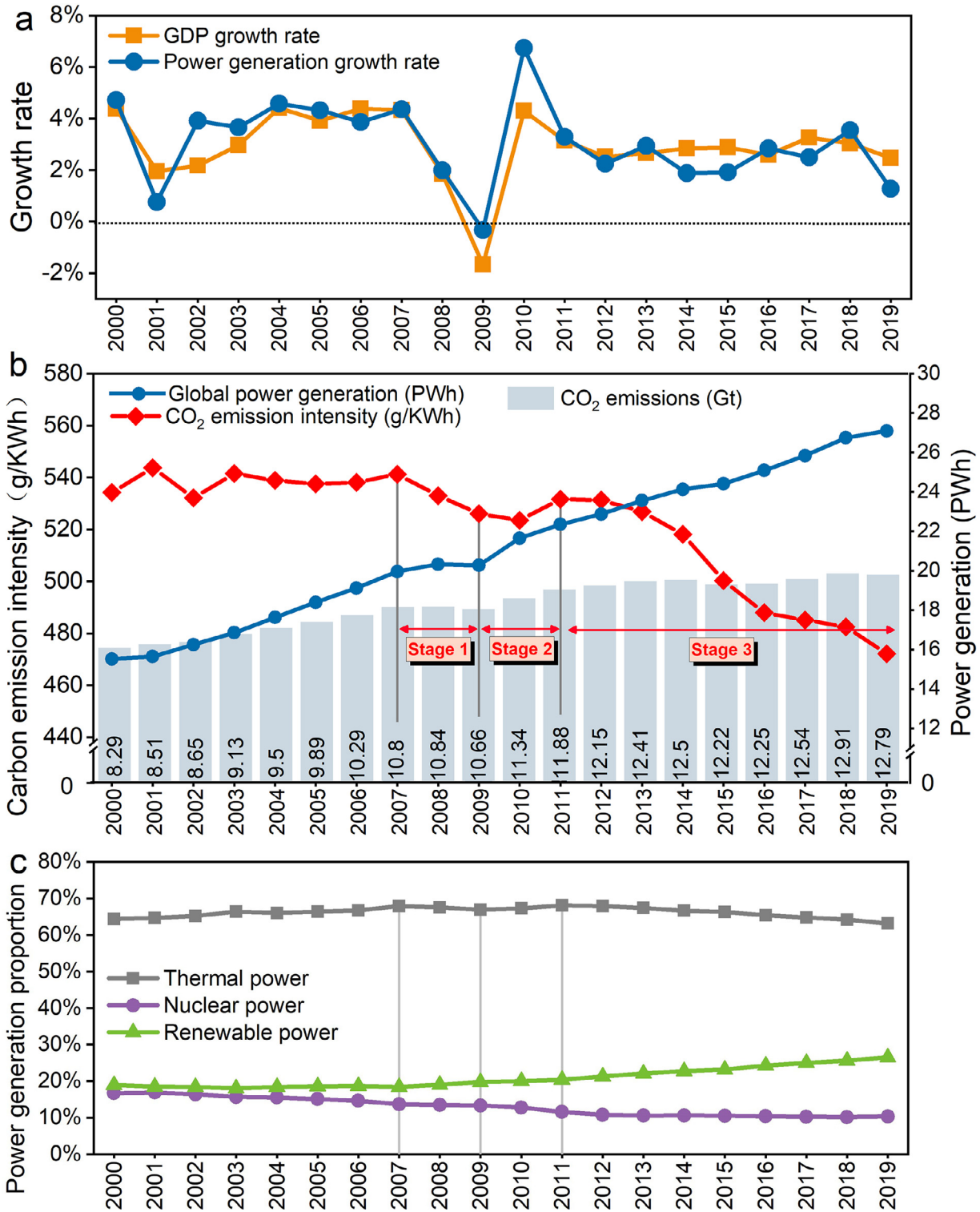


Fig. 1. Trends in global power generation and power decarbonization. (a) The growth rate of global power generation and GDP. (b) The evolution of global power generation, the related CO₂ emissions and the CEI of the power sector. (c) Global power generation structure.

During 2009–2011 (Stage 2), there was a rebound in the global power generation, the related CO₂ emissions, and the CEI. The global power generation had increased by 10.3% with an average annual growth of 1038 TWh. Specifically, thermal power increased by 12.2% (with its share in global power generation increasing from 67.9% to 69.2%), nuclear power decreased by 4.2%, and renewable power increased by 12.7%. It is worth noting that the Fukushima nuclear accident in Japan in 2011 led to a substantial reduction in the generation

of nuclear power in Japan, and thermal power was used to make up the power supply gap. The growth in thermal power share contributed to an increase in the global CEI of the power sector by approximately 5 g/KWh from 2010 to 2011 (see Table S4).

During 2011–2017 (Stage 3), there was continuous growth in the global power generation, while the global CEI of the power sector was declining. Annual global power generation increased by 3206 TWh, and renewable power accounted for more than half of the newly added

power generation. The proportion of renewable power in the total power generation increased from 20.3% in 2011 to 25.0% in 2017. The rapid development of renewable power was the major driver for the decline of global CEI of the power sector in Stage 3.

3.2. Drivers of the CO₂ emissions and cei fluctuation

Fig. 2 presents the contributions of different driving factors to the changes in CO₂ emissions (Fig. 2a) and the CEI (Fig. 2b) of the global electricity sector. The dominant countries for each driving factor were also presented.

From 2007 to 2009, the global financial crisis led to a slowdown in global GDP growth, with a small increase of 0.15% (global GDP at constant price), which resulted in an increase of CO₂ emissions from global power generation by 17.0 Mt. The proportion of thermal power generation in the global total decreased, resulting in a less carbon-intensive power structure and avoidance of CO₂ emission by 363.3 Mt. Changes in both energy mix and production efficiency contributed to a decrease in the global electricity's CEI, of which the declining share of thermal power was the largest driving force (−13.1 g/KWh). The decrease in the share of coal-fired power generation in the global total led to a decline of the global electricity's CEI by 11.0 g/KWh during this period. Concurrently, the share of coal-fired power generation in the thermal power also declined, which contributed to a reduction of the global electricity's CEI by 6.5 g/KWh. This can be mainly attributed to the fact that coal-fired power generation is one of the most carbon-intensive power generation technologies [49].

From 2009 to 2011, the global economy gradually recovered, and the global GDP rebounded by 7.6%, resulting in an increase of electricity-related CO₂ emissions by 1231.3 Mt. It is worth noting that the growing energy intensity of the global economy in 2009–2011 resulted in a 161.9 Mt increase in global electricity-related CO₂ emissions, mainly driven by China. From 2009 to 2011, China's energy intensity (electricity consumption per unit of GDP) increased by 4.8%, resulting in an increase of 159.3 Mt in electricity-related CO₂ emissions. The fast growth in thermal power generation driven by rising demand for electricity led to an increase in the related CO₂ emissions by 52.9 Mt, and the increased share of thermal power consequently led to a growth of global electricity's CEI by 4.5 g/KWh. In the opposite direction, the improvements in the fuel mix and thermal power generation efficiency contributed to a decline of CEI by 0.5 g/KWh and 6.0 g/KWh, respectively.

From 2011 to 2017, the steady economic growth resulted in a rise of electricity-related CO₂ emissions by 3178.4 Mt, which dominated the changes in global electricity-related CO₂ emissions. The improvements in global power generation efficiency, electricity consumption efficiency of the economy, and power structure contributed to the reduction of electricity-related CO₂ emissions by 501.4 Mt, 885.8 Mt, and 1194.1 Mt, respectively. The proportion of coal-fired power generation in the total had decreased by 2.5% (from 41.7% in 2011 to 39.2% in 2017) and this improvement alone resulted in a drop in the global electricity's CEI by 45.7 g/KWh. The improvement of thermal power generation efficiency also promoted a reduction of global electricity's CEI by 15.7 g/KWh.

It is worth noting that the power sector in developing and developed countries had different performances (see Fig. S3). In Stage 1 (2007–2009), while CO₂ emissions of the power sector in developed countries reduced by 593.0 Mt, the opposite was true in developing countries where the emissions increased by 465.5 Mt. This departure can be attributed to the effect of regional economic scale, which was −143.4 Mt in developed countries and 688.4 Mt in developing countries. In Stage 2 (2009–2011), developing countries experienced an energy-intensive economic recovery. Specifically, the rising energy intensity in developing countries contributed to 216.7 Mt of electricity-related CO₂ emissions growth, while the declined energy intensity in developed countries brought about a reduction of CO₂ emissions by 56.2 Mt. Meanwhile, in developed countries, especially Russia, Ukraine, and the United States, the growth of CEI in the power sector led to an increase in global

electricity-related CO₂ emissions by 22.6 Mt, and by contrast, the declined CEIs in developing countries made a negative contribution at −179.2 Mt.

At the country level, China, the United States, and India were largely the dominant contributors per each of the driving factors (Fig. 2). These three countries were the largest electricity-related CO₂ emitters, collectively accounting for 58% of CO₂ emissions from global power generation in 2017. We also measured individual country's contributions to the global CEI of the power sector and the results show that China, the United States, and India were the largest contributors (Fig. 3). In addition, electricity-related CO₂ emissions across these three countries showed different dynamics in each of the three stages. In Stage 1, China and India maintained economic growth, although with a reduced growth rate, thus exerting a positive economic scale effect at 536.8 Mt and 75.0 Mt, respectively. The absolute reduction in the size of the United States economy resulted in a negative economic scale effect at −62.4 Mt. In the economic recovery period (Stage 2), China and India quickly regained the peri-crisis growth rate, and the rapid expansion of their economic scale demanded an increasing amount of electricity input, which led to an economic scale effect at 655.9 Mt and 104.7 Mt, respectively. As thermal power (mainly coal-fired power generation) dominated the power mix in China and India, the CEI of the power sector in these two countries was much higher than the global average. The high CEIs in combination with the growing share of their power generation in the global total directly led to the growth of global CEI. A sharp contrast is that the energy intensity effect of China was 159.3 Mt, while that of the United States was −5.8 Mt. Considering that China's GDP was much smaller than that of the United States, these contrasts indicate that China's economic rebound path after the crisis was highly carbon intensive.

Furthermore, using the spatial LMDI method, we provide a cross-regional comparison of regions' performance on electricity decarbonization. The electricity-related CO₂ emissions and CEIs of each region are compared with the group average level (see the methods section), and the differences from the average level are decomposed. The detailed results are presented in Tables S4 and S5. Regions with a positive value indicate that they are above the average level for a certain indicator resulting in an increase in electricity-related CO₂ emissions or CEI. Table S5 shows that the differences in electricity-related CO₂ emissions between the 10 countries and the regional group average are mainly driven by the differences in economic scale and energy intensity, while differences in power structure and power generation efficiency have less impact. It is worth noting that economic scale is related to the size of the region and is "scale-dependent" [38], thus it can provide limited policy implications in a cross-regional comparison. In 2017, China's electricity-related CO₂ emissions were 3558.1 Gt higher than the average level, with economic scale and energy intensity contributing 43% and 38% of the difference, respectively. In addition, India and Russia have higher energy intensity than the average level, contributing 495.8 Gt and 335.1 Gt of electricity-related CO₂ emissions, respectively. This means that CO₂ emissions from electricity production can be effectively reduced by improving the overall electricity utilization efficiency of these economies. As can be seen from Table S6, from 2000 to 2017, China's contribution to the regional group's CEI continued to increase, mainly driven by China's increasing share of power generation in the regional group's total power generation, and other factors had a relatively small impact. In fact, China's thermal power share, fuel mix of thermal power, and power generation efficiency are close to the average level of the regional group.

Notably, the whole world has been attaching more importance to renewable energy. The global installed capacity of renewable power tripled during 2000–2018, and its growth rate has been accelerating since 2000 (see Fig. S4). Among renewable power sources, wind power and photovoltaic installed capacity have increased by about 32 and 400 times since 2000, respectively. This accelerating growth enables renewable power to fill the gap left by the scaling down of coal-fired power.

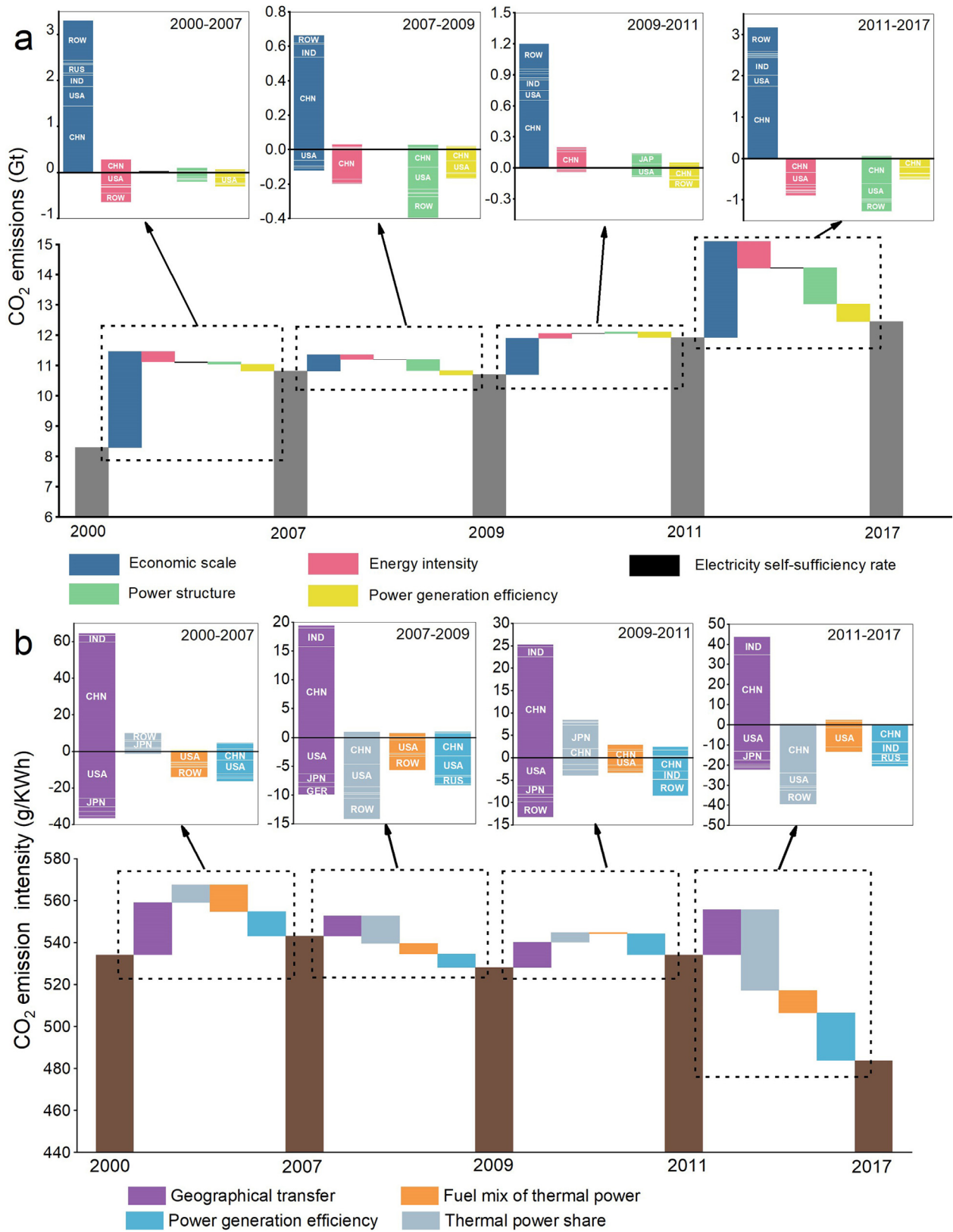


Fig. 2. The LMDI decomposition analysis of the CO₂ (a) and CEI (b) of global electricity from 2000 to 2017. For the simplicity of the presentation, the top-five countries that have large impacts on global electricity's CEI or CO₂ emissions are marked (CHN for China; USA for the United States; IND for India; JPN for Japan, and RUS for Russia. ROW represents all other countries than these five).

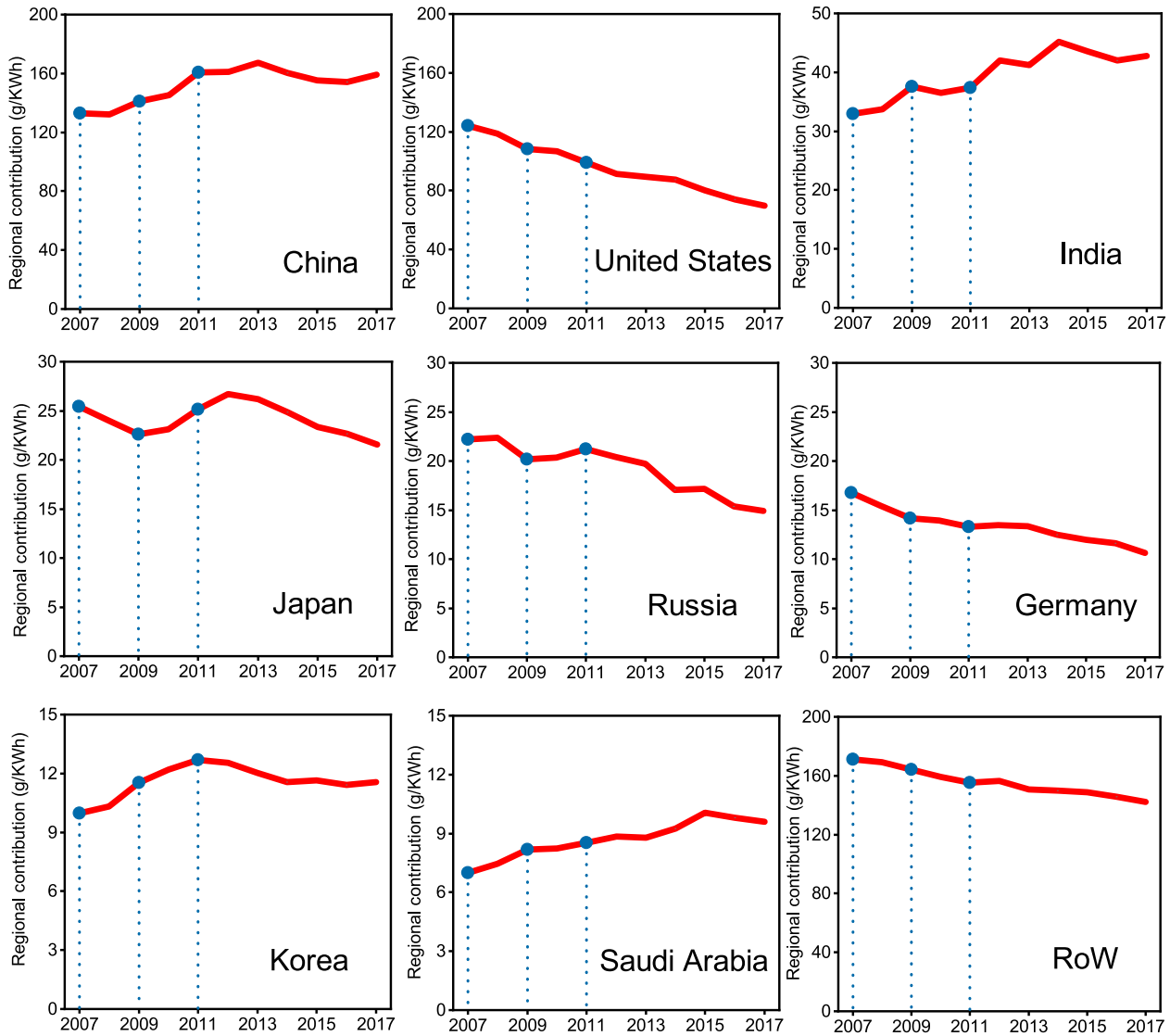


Fig. 3. Regional contributions to global electricity's CEI.

3.3. Gross fixed capital formation dominated the rebound in global electricity consumption

In this study, we matched the power consumption data reported in World Energy Balance [32] from the International Energy Agency (IEA) with the multi-regional input-output (MRIO) tables of Exiobase [33] (see the Supplementary method for more details). Consequently, the EEIOA was employed to estimate the electricity embodied in final demand (A detailed explanation is presented in the method). According to data availability, the match was done for 44 countries and regions (Table S7). In 2017, these 44 countries/regions consumed a total of 21,598 TWh of electricity, accounting for 84% of the total global power generation (Fig. 4a).

Fig. 4a shows the trend of total electricity of the 44 regions and its composition, and the 95% CI of embodied electricity consumption can be found in Fig. S5. During the whole period (2000–2017), final consumption expenditure accounted for more than half of total electricity consumption, followed by the gross fixed capital formation and residential daily electricity use. Compared with the total final consumption expenditure, residential daily electricity use, and changes in inventories, electricity induced by gross fixed capital formation exhibited a greater extent of fluctuation. The gross fixed capital formation induced elec-

tricity decreased by 4.4% from 4259.3 TWh (4170.3~4348.3 TWh) in 2007 to 4071.9 TWh (3986.7~4157.0 TWh) in 2009, and it experienced a rapid increase of 21.4% (866.3 TWh) from 2009 to 2011. The gross fixed capital formation accounted for 57.5% of global embodied electricity consumption growth from 2009 to 2011 (Fig. 4b).

We also noticed changes in sectoral electricity consumption. From 2007 to 2009, the total sectoral electricity consumption of the 44 countries increased by 0.3% (39.4 TWh). A substantial reduction in production side electricity consumption was observed in the industry sector. Industry not elsewhere specified experienced the largest extent of power consumption reduction at 129.8 TWh (14.2%), followed by Paper, pulp and printing (43.2 TWh) and Non-ferrous metals (33.3 TWh). From 2009 to 2011, the total sectoral electricity consumption increased by 11.3% (1507.5 TWh). Iron and Steel had the largest production side electricity consumption increase at 207.8 TWh (25.4%), followed by Machinery (141.6 TWh) and Non-ferrous metals (138.3 TWh). These three sectors accounted for about one-third of the growth in the sectoral gross electricity consumption. China was the largest contributor to the power consumption growth in these three sectors, accounting for 62.0% of the total growth. These three sectors are closely related to infrastructure construction, which can also verify the huge growth effect of China's Four-trillion Yuan Stimulus Plan on power consumption.

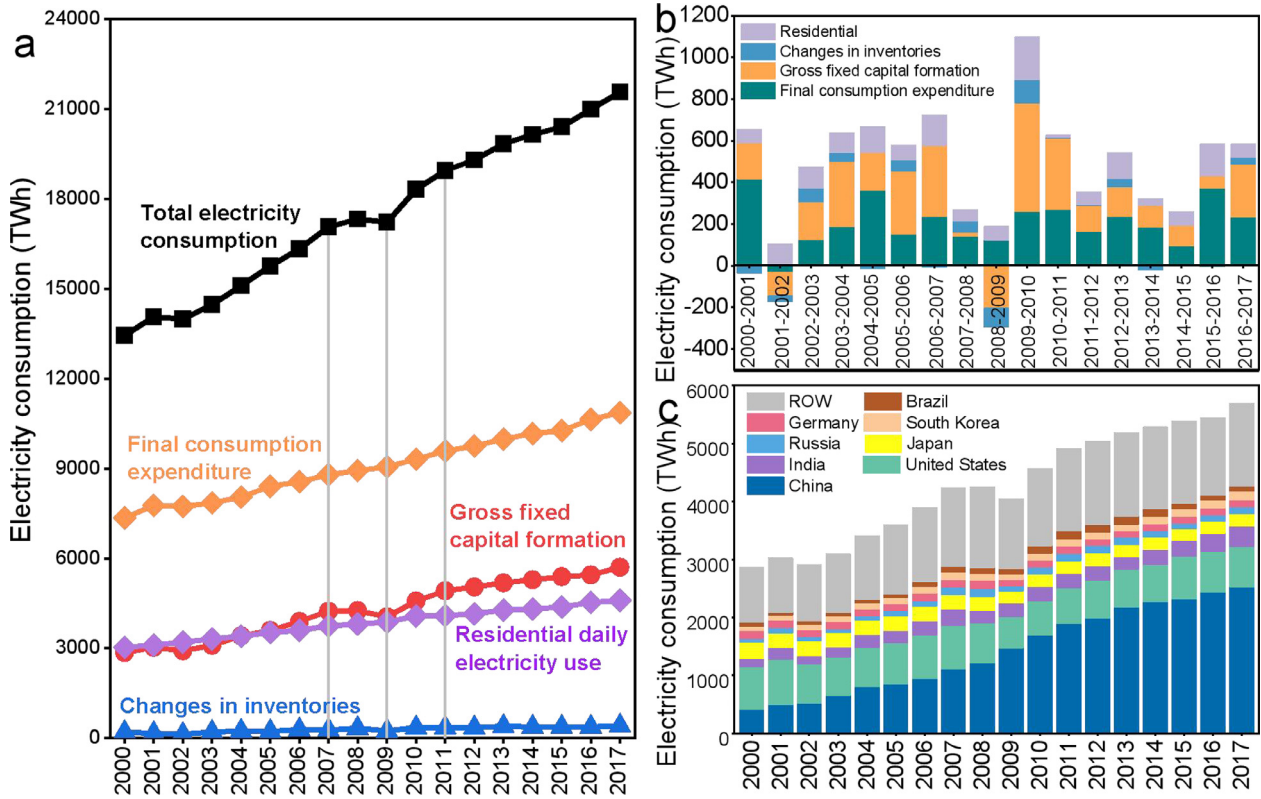


Fig. 4. Changes of global electricity consumption from 2000 to 2017. (a) Global electricity consumption induced by final demand and residential daily electricity use (residential daily electricity use refers to electricity that is used for non-productive purposes and is consumed by household daily activities, such as lighting, heating, and cooking). (b) Changes in global electricity consumption by purpose. (c) Electricity consumption induced by countries' gross fixed capital formation.

In addition, the sectoral embodied electricity consumption was evaluated. During the global financial crisis (2007–2009), the Real estate sector had the largest embodied electricity consumption growth of 42% (213.7 TWh), with developed economies as the major contributors. Specifically, Germany, the United Kingdom, the United States, Japan, and Canada were responsible for more than 90% of the growth. In comparison, from 2000 to 2007, the embodied electricity consumption of the Real estate sector only grew by 23% (95.6 TWh). The manufacturing sectors (e.g., Manufacture of fabricated metal products, except machinery and equipment, Manufacture of furniture, and Manufacture of motor vehicles, trailers, and semi-trailers) were hit by the financial crisis and had a large reduction in sectoral embodied electricity consumption. During 2009–2011, Construction had the largest growth in embodied electricity consumption of 309.0 TWh, followed by Health and social work (206.7 TWh), Manufacture of machinery and equipment (198.5 TWh), and Manufacture of motor vehicles, trailers and semi-trailers (122.7 TWh). These four sectors contributed more than half of the growth in total sectoral embodied consumption.

It is worth noting that during 2007–2009 and 2009–2011, China had the largest embodied electricity consumption growth, mainly driven by its gross fixed capital formation. For example, during 2007–2009, China's total embodied electricity consumption increased by 576.6 TWh, over 60% of which was attributable to the gross fixed capital formation (Fig. 4c). China's gross fixed capital formation consumes massive products from different sectors, among which the Construction sector and Manufacture of machinery and equipment contributed ~70% to the embodied electricity consumption growth triggered by China's gross fixed capital formation. During the global financial crisis, the embodied electricity consumption growth triggered by China's gross fixed capital formation can largely be explained by China's Four-trillion Yuan Stimulus Plan, in which the vast majority of the investment was dedicated to infrastructure development.

3.4. COVID-19 pandemic exerted a similar impact on the global power sector

Fig. 5 shows the 2016–2021 global power sector decarbonization trends (the related uncertainty analysis can be found in Fig. S2). According to data availability, 42 countries are included here, which collectively account for about three-quarters of global power generation. A list of these countries is presented in Table S8.

Fig. 5a indicates that the COVID-19 pandemic triggered a slight decrease in global power generation by 0.5% (103.9 TWh) from 2019 to 2020. From Fig. 5b we can see that compared with the same period in 2019, from January to May 2020, global power generation had experienced negative growth (Fig. 5b). The decrease in global power generation was featured by the decline in thermal power generation. Fig. 5c shows that from 2019 to 2020, the supply of global renewable power increased by 349.7 TWh, resulting in a rising share of renewable power in the total power supply. Meanwhile, global thermal power generation decreased by 349.4 TWh, leading to a reduction in the CO₂ emissions from global power generation by 3% (Fig. 5a). The changes in the power generation structure brought in a decline in the global CEI between 2019 and 2020 (Fig. 5d). In terms of monthly variation, Fig. 5d further shows that the pandemic amplified the extent of fluctuations in global power generation and carbon emissions in both 2020 and Jan-Sep 2021. From June 2020, both global power generation and the related CO₂ emissions had shown a rebound trend (Fig. 5b). Compared with 2019, global power generation and the related CO₂ emissions in 2021 increased by 6.2% and 14.2%, respectively. With the power generation rebounding, the CEI of global electricity had leveled up since Dec 2020 in comparison to that in 2019 (Fig. 5d). Currently, the structure changes in global electricity consumption after the COVID-19 pandemic are not clear as the global sectoral electricity consumption data are unavailable.

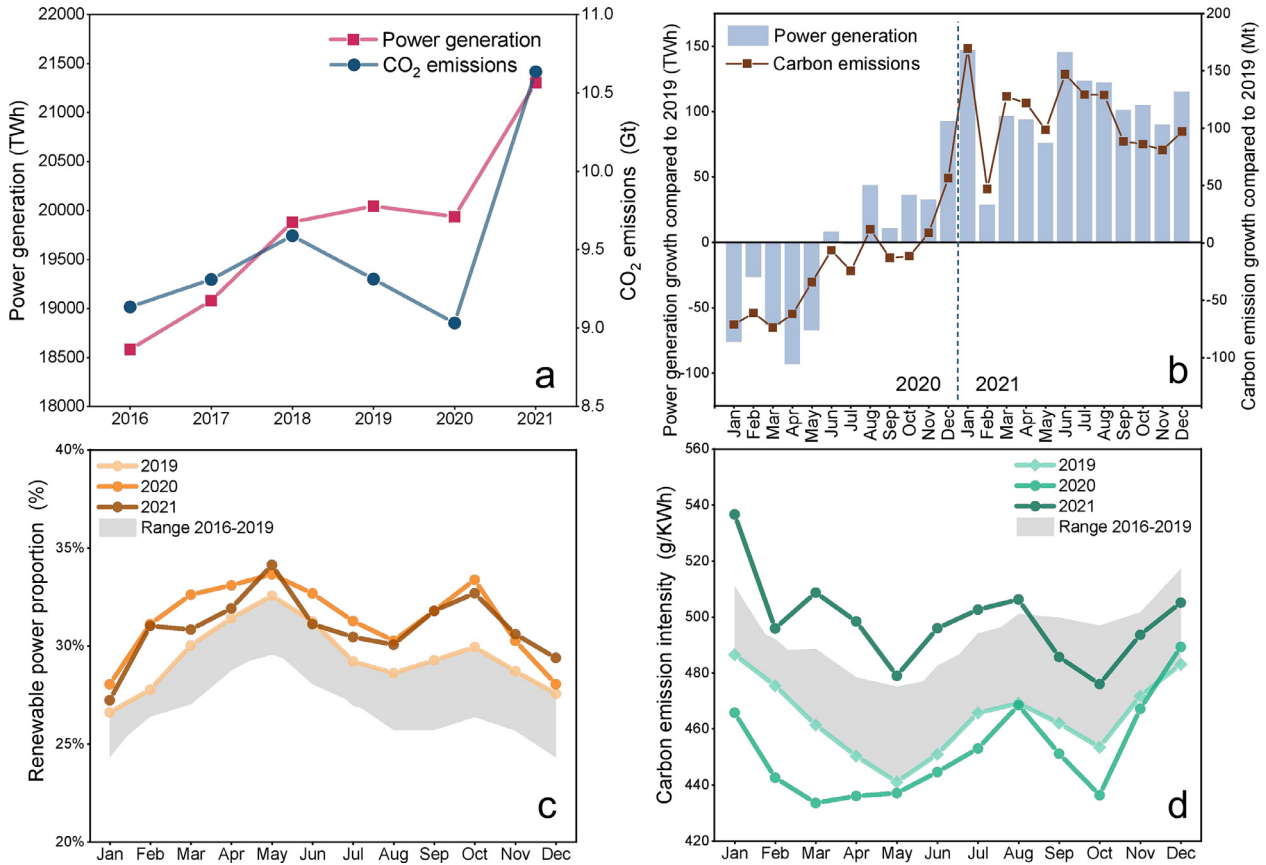


Fig. 5. Comparison of global power decarbonization from 2016 to 2021. (a) Annual global power generation and the related CO₂ emissions. (b) Global power generation and the related CO₂ emissions growth compared to 2019. (c) Share of renewable power in the total. (d) Carbon emission intensities of global electricity.

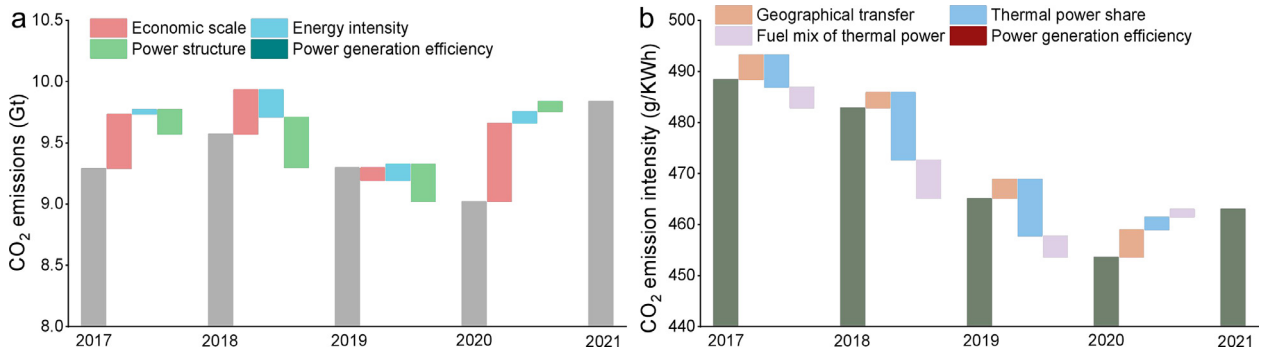


Fig. 6. The LMDI decomposition analysis of the CO₂ (a) and CEI (b) of global electricity from 2017 to 2021 (Due to the unavailability of the latest data, 42 countries and regions are included here).

The rapid rebounding in global power generation was largely driven by China. Due to the effective control of the pandemic, China gradually relaxed its anti-contagion policies in mid-2020. With the recovery of economic activities, China's electricity demand started increasing in April 2020 and had kept an increasing trend since then. Fig. S6 shows that the cumulative difference of China's power generation between the same month in 2020 and 2019 reached its bottom value of -98.5 TWh in March 2020, and then the curve rebounded upward, meaning that in April 2020, China's power generation started to exceed the corresponding value in April 2019. Taking 2020 as a whole, China's power generation increased by 190.7 TWh in comparison to 2019, which resulted in an increase in the related CO₂ emissions. By sharp contrast, in the rest of the world (ROW) except China, the accumulative difference of both power generation and related CO₂ emissions between the same month in 2020 and 2019 had been negative and showed a downward

trend (Fig. S7). The above contrast indicates that China's rapid rebound in power generation reversed the downward trend in global power generation in 2020. For the ROW, the economic recovery and the rebound in electricity demand came until May 2021, when the power generation amount surpassed its corresponding value in May 2019.

We further quantified the contributions of economic and technological factors to changes in global electricity-related CO₂ emissions and the CEIs from 2017 to 2021 (see Fig. 6). As shown in Fig. 6a, the outbreak of COVID-19 in 2019 brought about negative global economic growth, which in turn led to a reduction in global electricity-related CO₂ emissions. In 2020–2021, global electricity-related CO₂ emissions grow by 9.1% (0.82 Gt), with economic scale expansion contributing 78% of the growth. China's economic growth in 2020–2021 caused a 0.37 Gt increase in global electricity-related CO₂ emissions. From 2020 to 2021, the CEI of global electricity has increased by 9.4 g/KWh, and two

factors, namely, thermal power share and fuel mix of thermal power, have contributed to the rising emission intensity (see Fig. 6b). Notably, coal-fired power generation in the United States increased by 16% (131.5 GWh) in the same period, resulting in a 4.5 g/KWh increase in the CEI of global electricity. Overall, a similar pattern of changes in the contribution of these driving factors to the decarbonization of global power sector can be found during the 2008 global financial crisis and the recession caused by the COVID-19 pandemic (see Figs. 2 and 6).

4. Discussion

By comprehensively investigating how the 2008 financial crisis affected the global power sector, we revealed the mechanism by which the crisis drove the emission dynamics of the power sector. The analysis and findings can shed light on policies for promoting global power decarbonization in the post-COVID-19 era.

During the great recession of 2008–2009, global power generation saw a declining trend. Meanwhile, renewable power gained a higher share in total power supply. This can be partly attributed to the relatively higher variable costs of thermal power generation and the priority access obtained by renewable power to the grid. In parallel to the case of the great recession, as the power demand decreased soon after the COVID-19 outbreak, there was an opportunity to promote global or regional power decarbonization through such measures as shutting down some of the most carbon-intensive thermal power plants and strictly guaranteeing renewable electricity's priority access to the grid. Countries such as China and India still have a considerable number of small-scale coal-fired power plants in operation [50], which have low power generation efficiency and high emission intensity. By gradually phasing out small-scale coal-fired power plants, these countries can effectively reduce CO₂ emissions from power generation [51,52].

With the implementation of the economic stimulus plans and economic recovery, there was a rebound in global power generation after 2009. The rebound in turn drove up both CO₂ emissions and the CEI of the electricity sector. The economic stimulus plans boosted the fixed capital formation, which was found to be the major driver of the growth in global power generation after 2009. In the case of the COVID-19 crisis, since Spring 2020 many countries and regions, such as the United States, China, India, and countries in the European Union, have formulated and started to implement a number of economic stimulus packages that are unprecedented in size after the World-War-II. These packages are characterized, in large part, by large-scale investments in infrastructure construction [53]. Therefore, it is important for these countries to set standards on electricity consumption of investment projects, with the aim to reduce their electricity footprint and CO₂ emission footprint. Mitigation actions should pay special attention to the two sectors, Construction sector and Manufacture of machinery and equipment, which have been verified as the main contributors to the growth of embodied electricity induced by the fixed capital formation. Measures such as attaching energy efficiency labels and carbon footprint labels are recommended to improve the electricity use efficiency in the energy-intensive metal products production sectors (e.g., Manufacture of basic iron and steel, Aluminium production, and Manufacture of fabricated metal products), which provide substantial inputs to the Construction sector and Manufacture of machinery and equipment. Besides, it is also important for these stimulus packages to put an emphasis on the adoption of low-carbon technologies including demand-side management of energy, and carbon capture, utilization and storage technologies, on the development of low-carbon industries such as the new energy automobiles, and on promoting technological upgrading in energy-intensive industries. Furthermore, many countries, such as the United States and the European Union countries, are taking expansionary monetary policies (e.g., lowering the interest rates) to stimulate economic growth in the last two years. Such monetary policies can effectively reduce the financing cost of renewable energy investments [54–56].

It is worth paying more attention to the stimulus packages in the top 3 emitters of the world. The United States has passed a series of economic stimulus plans. The two under Biden's administration are the \$1.9 trillion American Rescue Plan, which was signed into law in March 2021, and the \$1.2 trillion American Job Plan, which focuses on investment in infrastructure and was signed into law in November 2021. In May 2020, China announced a plan to strengthen the construction of new infrastructure [57], including 5G network, ultra-high voltage (UHV) transmission line, rail transit, charging pile for new energy vehicles, etc. China's rapid economic recovery has led to a noticeable growth in power generation and the related CO₂ emissions. India also launched a 20 trillion rupees (equivalent to about 10% of India's GDP) economic stimulus package in May 2020. Considering the huge power generation scale and high CEIs of electricity in the above three countries, implementing these economic stimulus plans in green and low-carbon manner is very important for achieving global power decarbonization and mitigating global warming. Of course it is well acknowledged that the per capita electricity consumption and emission levels of India and China are still at relatively low levels. Nevertheless, it is in the interest of China and India to promote power decarbonization as well recognized by the governments and researcher communities in these two countries.

A major limitation of this study is that this study didn't comprehensively quantify the electricity consumption caused by major economic stimulus plans across the world. Such a quantification would generate more insights into the implications of these packages and thus lead to more effective policy recommendations for achieving a green recovery in the post-COVID-19 era. However, the work requires great efforts in data collection and consolidation, as well as an in-depth review of these packages. Besides, the influence of the decreasing costs of renewable energy technologies on power decarbonization was not considered due to data unavailability such as loans and profits of energy companies, and this may be explored in the future work.

Author contributions

P.Z.: methodology, visualization, and writing - original draft; J.L. and K.F.: conceptualization, project administration, funding acquisition, methodology, writing - original draft, and supervision; Y.S. and S.L.: data curation; P.Z., X.Z., L.S., J.Z., W.W., X.L., X.P., Y.S., S.L., L.G., J.L., and K.F.: formal analysis, and writing - review & editing.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

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Code availability

The Matlab code for establishing the satellite account of electricity consumption for the multi-regional input-output tables in Exiobase and calculating the embodied electricity consumption induced by final demand can be obtained from <https://doi.org/10.6084/m9.figshare.16432200.v1>. The version of Matlab used in this study is R2018a (9.4.0.813654).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.fmre.2023.02.017.

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