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The COVID-19 pandemic and energy transitions: Evidence from low-carbon power generation in China

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ABSTRACT

The Corona Virus Disease 2019 (COVID-19) has led to a decline in carbon emissions or an improvement in air quality. Yet little is known about how the pandemic has affected the "low-carbon" energy transition. Here, using difference-in-differences (DID) models with historical controls, this study analyzed the overall impact of COVID-19 on China's low-carbon power generation and examined the COVID-19 effect on the direction of the energy transition with a monthly province-specific, source-specific dataset. It was found that the COVID-19 pandemic increased the low-carbon power generation by 4.59% (0.0648 billion kWh), mainly driven by solar and wind power generation, especially solar power generation. Heterogeneous effects indicate that the pandemic has accelerated the transition of the power generation mix and the primary energy mix from carbon-intensive energy to modern renewables (such as solar and wind power). Finally, this study put forward several policy implications, including the need to promote the long-term development of renewables, green recovery, and so on.

1. Introduction

The Corona Virus Disease 2019 (COVID-19) and the resulting strict containment measures have resulted in huge economic contraction and social welfare losses for many countries or regions (Baker et al., 2020; Ding et al., 2020; Nicola et al., 2020). Most governments have called on people to self-isolate for the required period, forced businesses to reduce their activity, and implemented city-wide lockdowns during the pandemic (Fang et al., 2020; Liu et al., 2020). The year 2020 witnessed the sharpest economic contraction since the great depression of the 1930s (IMF, 2020).

To prevent the spread of the virus, China has taken strong prevention and control measures. These measures include but are not limited to the extension of the Spring Festival holiday (from January 24 to February 10), maintaining social distance, delaying the factory commencement dates, traffic control, and even blocking cities (Kraemer et al., 2020; Tian et al., 2020; Li et al., 2021). No doubt that the outbreak and spread of the virus are a tragedy and have exerted a tremendous impact on China's economy and society.

This study filled the gap by investigating the COVID-19 effect on energy transitions using the decarbonization of China's power generation sector as an example. China is a distinguished case study due to its status as the world's largest emitter of carbon emissions and thus faces unprecedented pressure to advance energy transitions (Zhang and Chen, 2021). China committed to achieving the carbon peak by 2030 and carbon neutrality by 2060 ("Dual Carbon") (Zhang et al., 2021). Like others, the power sector will be key to helping China meet its aggressive low-carbon generation targets as well as the broader dual carbon target (Zhao et al., 2020, 2021). The information on how the COVID-19 shock has affected the energy transition is a piece of critical information for China to make its dual carbon policy. However, the question is how to quantitatively analyze the COVID-19 effect on energy transitions from the perspective of low-carbon power generations. Moreover, any attempt to combat global warming depends critically on China's energy transition trajectory, and the direction of China's energy transition has a leading impact globally (Jiang et al., 2019). Therefore, from the perspectives of both academic research and industrial practice, it is necessary to discuss in a timely manner how COVID-19 has affected the direction of the energy transition under the current setting and how the energy industry can find a path to rapid recovery during and after this crisis.

The present research is different from the relevant literature in at

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least two aspects. To the best of our current knowledge, this is among the first empirical studies that estimate the changes in low-carbon power generation levels before and during the pandemic period relative to the previous period, which contributes to previous empirical literature concentrating on economic variables and emission reductions (Bekkers and Koopman, 2020; Dang and Trinh, 2021; Oskoui, 2020). Then, based on the stacked data of solar power, wind power, nuclear power, and hydropower, this study used a difference-in-differences (DID) model with historical controls to quantitatively identify the overall effect of the COVID-19 pandemic on the energy transition from low-carbon power generations. The method has recently been applied in a few estimations of the COVID-19 impact (He et al., 2020; Chen et al., 2020; Wang et al., 2021).

Second, this study assessed the heterogeneous impacts of the COVID-19 shock on energy production and the energy mix of different types of energy sources. In the literature, little emphasis has been placed on comparing impacts across different types of power generation or primary energy sources even though such work is essential for investigating the implications of the COVID-19 crisis on the direction of energy transitions (Liu et al., 2021). In contrast, this study analyzed how the crisis has affected the progress in expanding low-carbon or carbon-neutral energy sources.

The remainder of the study is organized as follows: In Section 2, we focused on the literature review, and we introduced the data and statistical methodology in Section 3. The overall results were presented in Section 4, which was followed by a further discussion of the heterogeneous results in Section 5. Section 6 concluded and provided some relevant policy implications.

2. Literature review

The shock of COVID-19 has stimulated intensive research activities. The majority of these studies focused on investigating the economic effects of COVID-19 from multiple perspectives, such as economic output (Morgan et al., 2021; Gharehgozli et al., 2020), household consumption (Martin et al., 2020), labor employment (Hershbein and Holzer, 2021), supply chain (Shi et al., 2021) and financial market (Ali et al., 2020; Baker et al., 2020; Ding et al., 2020). The COVID-19 effect on carbon emissions or air quality (i.e., PM2.5, PM10, and SO_2) has also been a hot topic. Recent studies have empirically discussed the reductions in global CO_2 emissions (e.g., Liu et al., 2020; Forster et al., 2020; Le Quéré et al., 2020) and the changes in China's urban air quality (e.g., Shi and Brasseur, 2020; Huang et al., 2021; Chang et al., 2020) due to COVID-19. Most studies have found that the COVID-19 crisis has lowered carbon emissions or improved air quality.

Despite the proliferation of studies, how COVID-19 has affected energy transitions is still not clear. On the one hand, COVID-19 could have slowed down energy transitions. The COVID-19 crisis and the related containment measures have significantly reduced energy consumption in many countries, which in turn has influenced the deployment of renewables (IEA, 2020; Chiaramonti and Maniatis, 2020; Zhong et al., 2020). Disruptions caused by the crisis have taken a big toll on the investment and construction of renewable energy projects. In several countries, the pandemic has made an already challenging investment environment worse, specifically with regard to renewables (Selmi et al., 2021; Ivanov and Dolgui, 2021). From an economic perspective, the crisis has exacerbated the financing challenges that also slowed the support and dampened the enthusiasm of investors for energy transitions (Karmaker et al., 2021; Mastropietro et al., 2020). Especially in countries with a strong dependence on fossil fuel industries, the governments were likely to transfer the funds originally used for the energy transition into the fields of health care and social welfare, further slowing down the switching to low-carbon or carbon-neutral energy sources (Birol, 2020; Emma, 2020).

On the other hand, COVID-19 may have accelerated energy transitions. In today's world, a dramatic fall in the costs of renewable energy has speeded up the large-scale utilization of renewable energy sources in power generation (Kåberger, 2018). During this pandemic, the power demand in various countries has generally decreased (IEA, 2020; Ghenai and Bettayeb, 2021). As a result, the power generation capacity has exceeded the demand. Grid operators may have prioritized cheap, clean, and environmentally friendly non-fossil energy. In addition, the deglobalization caused by COVID-19 isolation measures has prompted some countries to enhance the localization of supply chains or seek flexible solutions for resource development (Quitzow et al., 2021; Ba and Bai. 2020). Especially, many European countries were continuing to deploy renewable energy sources, while continuous divestment trends in the fossil fuel industries were accelerating in the wake of the crisis (European Commission, 2020; Council of the European Union, 2020).

It can be seen from the above literature that the COVID-19 effect on energy transitions is still controversial. However, the future of the energy system is going to be in a more complex, diversified, and uncertain situation. Considering that the transition from high-carbon energy to low-carbon energy sources is a fundamental way of accelerating the power sector transformation (Wei et al., 2021), we used the low-carbon power generations as the key indicator for this study. These low-carbon generation sources include renewable energy, mainly solar and wind power, and nuclear and hydropower, which are also actively promoted by the Chinese government. Through the use of modified DID models, this study analyzed the overall impact of COVID-19 on low-carbon power generations with a monthly province-specific, source-specific dataset. Then, the study compared the productions of different power generation and primary energy sources before and during the pandemic and assessed how the recent COVID-19 pandemic has affected the direction of the energy transition by fuel type.

3. Data and methodology

3.1. Data

This study used monthly power generations, energy production, and weather conditions in China's 30 provinces from July 2018 to June 2020. The province-level data for the generation of low-carbon power and the supply of other energy sources were obtained from the National Bureau of Statistics of China (NBS). In this study, low-carbon power mainly includes solar power, wind power, nuclear power, and hydropower.[1] Monthly meteorological data (average temperature, precipitation, average relative humidity, and sunshine hours) for the 30 provinces were collected from China statistical yearbooks and the National Meteorological Information Center. In addition, this study measured the energy mix by calculating the ratio of specific energy sources to the total energy supply and then examined the effects of the COVID-19 pandemic on the direction of the energy transition. In measuring the primary energy mix, the physical quantity of all primary energy sources has been converted into standard coal equivalent. [2] Table 1 presents the summary statistics of our key variables.

The data show that renewable energy development initially had a certain ability to resist external shocks. In the first half of 2020, the

[1] This is because the monthly power generation data from biomass, geothermal, or other renewables are not available. In addition, compared to wind and solar power generation, the power generated from the combined category for biomass, geothermal, and other renewables is at a negligible level. For example, in the first half of 2020 in China, the power generated from the combined category accounted for 0.0012% of the total power generation.

[2] The primary energy supply was calculated by multiplying the activity data (i.e., energy production) and the conversion factors by energy types. Here, we used the standard coal conversion factor by different energy sources from the China energy statistical yearbooks to assess the total primary energy quantity. For example, the conversion factors of various low-carbon power generations are the same, namely, 10000 kWh of low-carbon power is equal to the power produced by burning 1.229 tons of standard coal.

Table 1
Summary statistics of the main variables.

Variable	Description (unit)	Mean	Std. Dev.	Min	Max	Obs
Lcp	stacked low-carbon power generations (10^8 kWh)	14.11	37.28	0	366.8	2400
prod_hp	hydropower generation (10^8 kWh)	33.48	66.49	0	366.8	600
prod_wp	wind power generation (10^8 kWh)	9.766	21.7	0	114.2	600
prod_np	nuclear power generation (10^8 kWh)	9.94	11.65	0	72.6	600
prod_sp	solar power generation (10^8 kWh)	3.257	3.094	0	12.97	600
mix_tpg	the share of thermal power in the total power generation	0.715	0.25	0.04	0.995	600
mix_hpg	the share of hydropower in the total power generation	0.171	0.248	0	0.929	600
mix_npg	the share of nuclear power in the total power generation	0.045	0.09	0	0.391	600
mix_wpg	the share of wind power in the total power generation	0.05	0.045	0	0.225	600
mix_spg	the share of solar power in the total power generation	0.019	0.027	0	0.183	600
mix_coal	the share of raw coal in the total primary energy supply	0.479	0.341	0	0.993	600
mix_oil	the share of crude oil in the total primary energy supply	0.131	0.197	0	0.928	600
mix_gas	the share of natural gas in the total primary energy supply	0.127	0.214	0	0.976	600
mix_sps	the share of solar power in the total primary energy supply	0.013	0.019	0	0.12	600
mix_wps	the share of wind power in the total primary energy supply	0.034	0.041	0	0.426	600
mix_hps	the share of hydropower in the total primary energy supply	0.131	0.199	0	0.914	600
mix_nps	the share of nuclear power in the total primary energy supply	0.084	0.188	0	0.842	600
Temp	average temperature (°C)	17.29	9.251	−16	32.2	600
Humid	average relative humidity (%)	66.1	15.47	1.4	93	600
Sun	sunshine hours (h)	180.3	66.32	15.4	348.2	600
Preci	precipitation (mm)	87.92	95	0	574	600

Notes: This study used data that include monthly power generations, energy production, and weather conditions in China's 30 provinces (excluding Hong Kong, Macao, Taiwan, and Tibet autonomous region), from July 2018 to June 2020 (excluding January and February).

global wind and solar power generation accounted for 9.8% of the total power generation, an increase of 14% over the same period in 2019 (IEA, 2020). Also, the total installed capacity of global coal power decreased for the first time in history. In China, the most impressive progress has occurred in the power generation sector, where modern renewables (such as solar and wind power) have advanced significantly. When the total power, thermal power, and hydropower generation decreased by 0.08%, 0.59%, and 7.17%, respectively, year-on-year in the first half of 2020, the generation of domestic wind power and solar power increased by 12.65% and 23.20%, respectively (see Fig. 1).

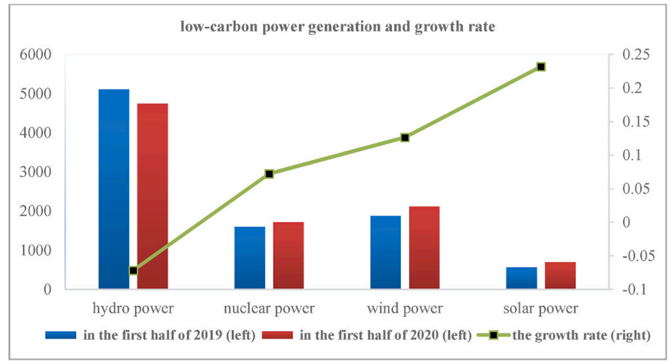

Fig. 1. The changes in low-carbon power generation during the first half-year of 2019 and 2020
Source: Author's own conception. Due to data availability, we defined four major low-carbon power sources: hydro, nuclear, wind, and solar in this study.

3.2. *The modified DID models with historical controls*

The study aimed to quantitatively identify the COVID-19 effect on energy transitions from the perspective of low-carbon power generations. As the COVID-19 shock was a major public health emergency and the resulting containment measures were highly exogenous, the impacts on the energy supply and energy transition also met the main assumptions of a quasi-natural experimental design (Kanda and Kivimaa, 2020). In this study, the DID model, using Stata software, version 15.1, was then applied to quantify power generation changes due to the pandemic.

However, the standard DID model needs to be modified for studying the COVID-19 pandemic. All Chinese provinces were in some degree of lockdown during the pandemic period, meaning that observational data at the province level provided no contemporary untreated controls, and it was difficult to estimate an average treatment effect according to the standard DID model. The literature proposed to identify a comparable group that could not receive treatment, e.g., historical controls prior to its availability (Newsome et al., 2021; He et al., 2020). With reference to Wang et al. (2021), how the COVID-19 or national-level pandemic-related measures have affected low-carbon generation relative to the trends in previous periods was examined and the first modified DID model with historical controls was as follows.

$$lcp_{sit} = \alpha_0 + \alpha_1 treat \times post + controls + \gamma_s + \mu_i + \delta_t + \varepsilon_{sit} \quad (1)$$

where s, i, and t denote low-carbon power sources (solar power, wind power, nuclear power, or hydropower), provinces, and months, respectively. This study set the low-carbon power generations from July 2019 to June 2020 as a treatment group. This group was compared to a historical control group from July 2018 to June 2019. "*Treat*" is a grouping dummy variable, the value of which is set as 1 if it is in the period July 2019 to June 2020, and set to 0 for July 2018 to June 2019. The value of "*post*" is set as 1 if it is a month during the pandemic period (March 2019 to June 2019, or March 2020 to June 2020) within our study period. [3] "*Controls*" describes the monthly weather condition variables (average temperature, precipitation, average relative humidity, and sunshine hours).

To capture the overall effect of the pandemic on the energy transition from the low-carbon power supply, this study followed the approach of Duflo et al. (2013) and Li et al. (2020) and used the stacked low-carbon

[3] Because the power generation data for January and February were missing, this paper defined the pandemic period (the treatment period) as March to June (2019, 2020), and the period before the pandemic as July to December (2018, 2019). Also, based on existing evidence, excluding the Chinese Spring Festival holidays (from January to February) could avoid any power generation changes unrelated to the pandemic (Chen et al., 2020).

power generations as the explained variable (*lcp*). [4] The parameter of interest is α_1, which reflects the COVID-19 effect on low-carbon generation. Specifically, we calculated the changes in low-carbon generation during the pandemic versus before the pandemic period, from 2019 to 2020, and compared these findings with corresponding changes in the same periods from 2018 to 2019. γ_s is the set of power source fixed effects, controlling for any time-invariant source heterogeneity. μ_i is the set of province fixed effects, controlling for time-invariant, unobserved province characteristics across provinces, such as geographic features. δ_t is the set of month fixed effects, controlling for the monthly shocks common to all provinces, such as business cycles. ε_{sit} is an error item. We estimated Eq. (1) allowing for province-level clustering of the errors.

The baseline DID model identifies the average differences in low-carbon generations between the treatment and control groups. On this basis, the monthly differences in low-carbon generation measures between the two groups were further compared. Based on Eq. (2), this study performed whether the DID model met the parallel trend requirements during the pre-pandemic period, and dynamic analysis of the COVID-19 effect. The test model is set as:

$$lcp_{sit} = \beta_0 + \sum_t \beta_t treat \times d_t + controls + \gamma_s + \mu_i + \delta_t + \varepsilon_{sit} \quad (2)$$

where d_t is a series of month dummy variables. In Eq. (2), the dummy variable indicating one month before the treatment (December) was omitted from the regression, the focus was on the month-to-month changes in the coefficients β_t within the event window. More importantly, the conditions under which the outcome variable follows a common trend are as follows: the coefficients β_t (from July to November) were nonsignificant. During the treatment period, by comparing the changes in β_t (from March to June), it is possible to analyze the dynamic effect of the COVID-19 shock on low-carbon generation.

Next, to explore whether the COVID-19 effect varies across different types of power sources or energy sources, this study tested for the existence and direction of causality between the COVID-19 pandemic and energy supply in China at disaggregated levels, like solar power, wind power, nuclear power, hydropower, and so on. Note that the heterogeneity analyses help us to understand what drives the overall effects (Nicolli and Vona, 2016) and to compare the influence on the production of various energy sources. In this study, the heterogeneity analysis is based on Eq. (3) below:

$$prod_{it} = \theta_0 + \theta_1 treat \times post + controls + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

where the explained variable *prod* is one of the energy production indexes in province *i* at month *t*, including low-carbon power sources and other primary energy sources (such as raw coal, crude oil, and natural gas). Province and month fixed effects are included in all specifications in order to control for time-unvarying province attributes and nationwide common time shocks, respectively.

Each energy source type is associated with a bundle of environmental effects. Moving further upstream in the energy supply chain, the transition toward low-carbon or carbon-neutral energy sources involves the gradual reduction of the exploitation of fossil fuel resources (Davidson, 2019; York and Bell, 2019). To better understand the impacts on the direction of the energy transition, this study measured the energy mix by calculating the ratio of specific energy sources to the total energy supply. Then, the heterogeneous effects of COVID-19 on the energy mix were examined. The specification for the energy mix of each type of energy is:

$$mix_{it} = \pi_0 + \pi_1 treat \times post + controls + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

[4] In unstacked data, each power sample is in a separate column. Alternatively, all the data can be stacked in one column, that is, the four power sources are pooled together. Of course, we also added a column of grouping indicators (numbers or text) that define each power sample.

where the dependent variable *mix* is either the share of a certain type of power source in the total electricity generation or the share of a certain type of primary energy in the total primary energy supply in province *i* at month *t*. Each regression implements model (4) and controls for the weather condition variables, province and month fixed effect.

4. Overall effects

4.1. Baseline estimation

The DID model (Eq. (1)) was used to estimate the changes in low-carbon power generation levels before and during the pandemic period, relative to the previous period, and to quantitatively assess the overall effect of COVID-19 on energy transition from the perspective of low-carbon power generations. Column (1) of Table 2 shows the effect of the COVID-19 pandemic on low-carbon power generations through the stacked data of solar and wind power. Using the stacked data of two different combinations of the three low-carbon power sources, the estimation results were reported in columns (2) and (3) of Table 2. When all four low-carbon power sources are pooled together, column (4) presents the benchmark results for the overall effect of COVID-19 on low-carbon power generations. All regressions include controls for province fixed effects, month fixed effects, source-specific fixed effects, and weather conditions. However, only the coefficients of the interaction term (*treat*×*post*) were discussed here, due to limited space.

The results show that the interaction term was significantly positive when considering weather condition variables and the fixed effects of the three dimensions. This finding means that the COVID-19 crisis had a significant promotion effect on the low-carbon energy supply, compared with the same period in 2018–2019. The benchmark estimate in column (4) of Table 2 demonstrates that, across the four measures of low-carbon energy supply, the COVID-19 pandemic on average increased the low-

Table 2
Overall effects of COVID-19 on low-carbon generations.

Column	(1)	(2)	(3)	(4)
Variable	*lcp*	*lcp*	*lcp*	*lcp*
Type	Solar and wind power	Solar, wind, and hydro power	Solar, wind, and nuclear power	Solar, wind, nuclear, and hydro power
treat×*post*	1.122***	0.547*	1.063***	0.648**
	(0.213)	(0.272)	(0.269)	(0.247)
Controls	Yes	Yes	Yes	Yes
province FE	Yes	Yes	Yes	Yes
month FE	Yes	Yes	Yes	Yes
source FE	Yes	Yes	Yes	Yes
Obs	1,200	1,800	1,800	2,400
R-squared	0.666	0.377	0.331	0.285

Notes: This table presents estimates of DID regressions of the energy transition on the COVID-19 pandemic and weather condition variables. The dependent variable is the stacked low-carbon power generations (*lcp*) for all columns (1)–(4) with different power source types. The weather condition controls are the monthly average temperature (*temp*), monthly precipitation (*preci*), monthly average relative humidity (*humid*), and monthly sunshine hours (*sun*) for each province. All the specifications control for province fixed effects, month fixed effects, and source-specific fixed effects. The estimates of weather variables, fixed effects dummies, and constant terms are suppressed for brevity. Reported in parentheses are robust standard errors clustered by province. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

carbon power generation by 0.0648 billion kWh (by 4.59%).[5] These positive impacts of COVID-19 on low carbon generation could be due to the following factors. First, the output of low-carbon power is largely unaffected by the weak demand, because low-carbon power generation has low operating costs and priority dispatch (Quitzow et al., 2021; Liu et al., 2021). Moreover, the installed capacity of wind and solar power generation continues to expand in China, further increasing the advantages of variable renewable energy sources. Therefore, low-carbon energy has ushered in an unconventional development opportunity (Hoang et al., 2021).

4.2. Robustness checks

4.2.1. Parallel trend hypothesis test and dynamic effect analysis

When applying the DID model, one validity test commonly used involves examining whether the treatment and control groups exhibit parallel pre-treatment trends. This study adopted the event study approach by estimating a series of coefficients for each month to investigate how the trends in the low-carbon generation between the two groups evolved before and during the pandemic period.

The estimated coefficients for each month within the event window, along with the 95% confidence intervals, were presented in Fig. 2. The dummy variable for December (one month before the treatment) was omitted from the regression. After introducing the interactions of month dummy variables and the term *treat*, all the estimates for the five months before the treatment were statistically insignificant at the 5% level. The results suggest that the trends in the low-carbon generation before the pandemic period were similar to those in 2018. This finding inspires confidence that the historical control group (2018.7–2019.6) provided a good counterfactual for the treatment group (2019.7–2020.6). Meanwhile, the interactive term after the treatment ($treat \times d_{Mar}$) was significantly positive, with the low-carbon generation increasing by 0.1260 billion kWh (Column (1) of Table 3). Despite an abnormal two or three months down after the spring festival, the value quickly becomes positive. These results confirm the conclusion that the COVID-19 pandemic significantly increased low-carbon generation (Supplementary Note).

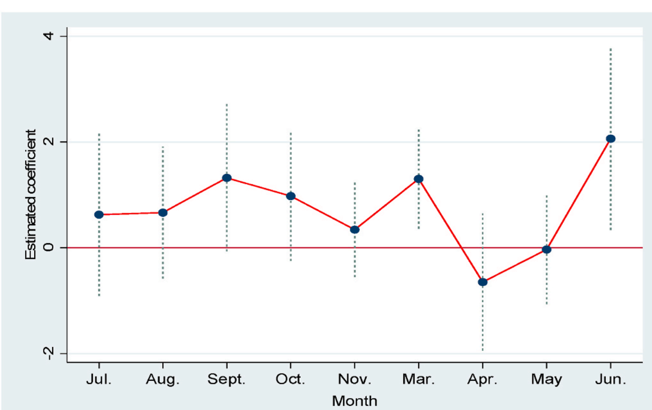

Fig. 2. Parallel trend hypothesis test and dynamic effect analysis
Source: Author's own conception based on Stata software. Low-carbon generation levels are compared between 2018.7-2019.6 and 2019.7–2020.6. The dummy variable for December (one month before the treatment) is omitted from the regression. Also, excluding the Chinese Spring Festival holidays (from January to February) could avoid any changes in power generation that were unrelated to the pandemic. Each estimate shows the difference in low-carbon generation relative to the difference one month before the treatment. The red and dashed lines represent the estimated coefficients and 95% confidence intervals, respectively.

[5] The most important thing of causal identification is to ensure the consistent estimation of causal effects (Cinelli et al., 2021). In this study, the values of R^2 in Table 2 are acceptable after considering a series of robust tests that followed.

Table 3
Robustness tests based on model specifications.

Column	(1)	(2)	(3)	(4)	(5)
Variable	*lcp*	*lcp*	*lcp*	*lcp*	*lcp*
Type	Dynamic effects	Province-time trend	Province-energy effects	Adding the square of temperature	Adding the square terms of temperature and rainfall
$treat \times post$		0.667** (0.256)	0.669*** (0.239)	0.623** (0.250)	0.508** (0.244)
$treat \times d_{Mar}$	1.260** (0.458)				
$treat \times d_{Apr}$	−0.615 (0.633)				
$treat \times d_{May}$	−0.0568 (0.513)				
$treat \times d_{Jun}$	2.006** (0.827)				
controls	Yes	Yes	Yes	Yes	Yes
province FE	Yes	Yes	Yes	Yes	Yes
month FE	Yes	Yes	Yes	Yes	Yes
source FE	Yes	Yes	Yes	Yes	Yes
Obs	2,400	2,400	2,400	2,400	2,400
R-squared	0.285	0.286	0.933	0.285	0.285

Notes: This table reports the estimation results for robustness tests based on model specifications. The dependent variable is the stacked low-carbon power generations for all columns (1)–(6) with four energy types. Other notes as Table 2.

4.2.2. Province-month trend and province-energy effects

The province-month trend terms were added to the regression model to control some of the provincial factors that may have been omitted or changed over time (Liu and Qiu, 2016). After introducing the crossovers of the province dummy variables and the monthly trend term, the COVID-19 effect in column (2) of Table 3 was still significant. thereby confirming the robustness of the baseline results. In column (3), in addition to the fixed effects considered in the baseline scenario, this study controlled for province-source fixed effects and thus rules out any bias from unobserved changes affecting specific power generations in each province. The key findings regarding the COVID-19 effect on low-carbon generations were broadly consistent.

4.2.3. Adding the square terms of weather variables

To verify whether a non-linear relationship exists between weather variables and power generations, referring to Zheng et al. (2019), column (4) added the square term of temperature to the model. The results show that the square term was not significant, and the interaction term was significantly positive. Column (5) further added the square terms of temperature and precipitation to the model. The direction and magnitude of the interaction term coefficient were consistent with those in Table 3.

4.2.4. Adding additional control variables

The commissioning of new renewable energy facilities and energy market fluctuations during the sample period could lead to estimation errors. We therefore included the renewable power commissioning indicator (measured by the "newly added renewable power capacity") and the energy price indicator (measured by the "fuel and power price index" at 2018 constant prices) in the regression to control for the potential impact of these variables. The estimation results provided in columns (1–2) of Table S1 reveal that, adding additional control variables did not alter our conclusions of the baseline regression.

4.2.5. Sample adjustment

In light of the extent and pace of the expansion of the COVID-19 outbreak in various provinces, an infection index was applied that allows taking into account the magnitude of the pandemic (Zhu et al., 2020). This index was constructed as the natural logarithm of one plus the number of accumulated confirmed cases each month. [6] The corresponding results reported in Column (1) of Table 4 indicate that the estimated coefficient for the interaction term between the treatment group and the infection index was significantly positive. This finding confirms that the severity of the pandemic has tended to impact the low-carbon energy supply positively.

Hubei province, where the new virus was first detected and strict epidemic prevention measures were imposed in China, has also been excluded from this study. It can be seen from column (2) of Table 4 that the results were not dominated by the province that was most affected by the virus. In addition, there are some "0" values in the data. Especially, this applies to marginal power generation technologies, such as nuclear power. After deleting the samples with "0" values, the regression results shown in column (3) of Table 4 suggest that the basic conclusions were not affected obviously.

We used a different starting sample month to check the sensitivity, i.e., we dropped 2 months at the head and changed the start of the sample period to September. After deleting data for July and August, the results shown in column (4) of Table 4 were consistent with the benchmark results, i.e., the level of low-carbon generations increased substantially due to the pandemic.

To mitigate potential outliers, the baseline tests were repeated with the natural logarithm of one plus the total low-carbon generation as the dependent variable. The logarithm transformation allows one to capture the percentage change in total low-carbon generation. Similar estimation results were found after the inclusion of this relative measure (column (5)), i.e., the estimated parameter for the interaction term was significantly positive.

Table 4
Robustness tests based on sample adjustment.

Column	(1)	(2)	(3)	(4)	(5)
Variable	*lcp*	*lcp*	*lcp*	*lcp*	ln (*lcp* +1)
Type	Using pandemic reporting data	Deleting the samples from Hubei	Deleting the samples with "0" values	Deleting data for July and August	Taking the logarithm value
treat×post	0.0912*	0.696**	0.831**	0.737**	0.0653***
	(0.0527)	(0.267)	(0.320)	(0.311)	(0.0133)
Controls	Yes	Yes	Yes	Yes	Yes
province FE	Yes	Yes	Yes	Yes	Yes
month FE	Yes	Yes	Yes	Yes	Yes
source FE	Yes	Yes	Yes	Yes	Yes
Obs	2,400	2,320	1,898	1,920	2,400
R-squared	0.285	0.275	0.389	0.282	0.399

Notes: This table presents the estimation results for robustness tests based on sample adjustment. The dependent variable is the stacked low-carbon power generations for all columns (1)–(5) with four power sources. Other notes as Table 2.

[6] The number of COVID-19 confirmed cases for 30 provinces is obtained from China Stock Market & Accounting Research Database (CSMAR), which tracks the real-time confirmed cases all over the country.

5. Further discussion

5.1. Heterogeneous effects on the energy production by primary energy sources

Despite the significance of the COVID-19 pandemic related to overall low-carbon generation, it hides significant heterogeneity across low-carbon power sources. To better understand the evolution of low-carbon power and other primary energy sources, this study took a step forward and compared the influence of the COVID-19 pandemic on energy production by different primary energy sources.

Fig. 3 displays the regression results of Eq. (3) for seven different primary energies (raw coal, crude oil, natural gas, solar power, wind power, hydropower, and nuclear power). The standardized regression coefficient was reported for each primary energy source by employing a pooled panel with weather variables and fixed effects dummies. The change in energy production level was estimated before and during the pandemic period, relative to the previous period.

In Fig. 3, the dependent variables are the energy production indices. Among the four electricity generation sources, the coefficients of the interaction term between the treatment group and pandemic period were significantly positive for solar power and wind power. This finding indicates that the COVID-19 pandemic improved solar and wind power generation compared with the same period in 2018–2019. Moreover, it should be pointed out that the overall results were mainly driven by solar and wind power. Especially, the pandemic had the most significant effect on solar power, with a standardized estimated coefficient of 0.103. The pandemic or the pandemic-related measures appear to have had a major driving effect on renewable project development in China.

In fact, the operation of renewable power generation was less affected by fluctuations in raw materials and manpower and has had apparent advantages during the COVID-19 pandemic (Kelvin and Brindley, 2020). The technological advancement and electricity market reform have substantially reduced the costs and affordability of renewable energy. Thus, the competitiveness of modern renewable energy sources (such as solar and wind power) has increased significantly (IRENA, 2021; Amir and Khan, 2021). However, no significant effect was observed for hydropower and nuclear power. For technologies with a long lead time for development, such as hydropower and nuclear power, electricity generation may not be significantly affected by the outbreak.

For other primary energy sources (fossil fuels), the pandemic significantly increased the supply of natural gas, at a significance of 5% and a standardized estimated coefficient of 0.02. Yet, the production of raw coal and crude oil that remain China's base energy sources have not

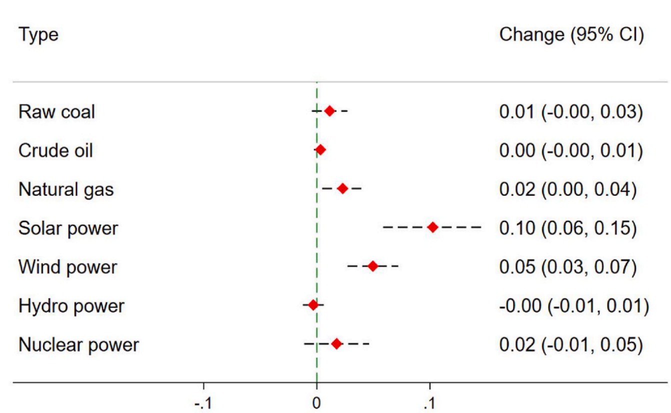

Fig. 3. Heterogeneous effects of COVID-19 on the production of various primary energy sources
Source: Author's own conception based on Stata software. Red diamonds mark the standardized estimated coefficients of the interaction term and the dashed black lines represent the 95% confidence intervals of the estimate.

changed significantly during the COVID-19 period. This finding at least shows that the pandemic has been more inclined to push the development of clean and low-carbon energy.

5.2. Heterogeneous effects on the energy mix

The COVID-19 crisis has already had significant effects on low-carbon power generations, but how has it influenced the direction of the energy transition? As the electricity sector is an important contributor to carbon dioxide emissions (Li et al., 2017), this study additionally considered a relative power generation indicator, instead of the absolute amount of energy production, i.e., the ratio of specific power sources to total power generation was used. Through variables transformation, the COVID-19 effect on the direction of the energy transition was examined.

5.2.1. On power generation mix

Given that the same set of weather control variables and fixed effects dummies are included in each regression, Table 5 presents the heterogeneous results of the COVID-19 effect on the electricity generation mix by fuel type. Specifically, the pandemic has led to a rise in the proportions of solar and wind power, while there has been a decline in the proportion of hydropower (significant at the 5% level). This finding implies that the direction of the electricity generation mix transition has shifted from hydropower to solar and wind power. From the power supply side, the decline in demand is intensifying the competition among various power generation technologies and fuels. The non-dispatching ability of modern renewable energy (including wind and solar) and renewable energy's priority in China's power system have enabled it to buck the trend and become a beneficiary in the increasingly fierce competition among various power sources. The impact of the pandemic has revealed an important message, namely that renewable energy power generation is becoming the baseload supply of electricity, due to the low marginal cost and priority grid access.

Although hydropower accounts for a large proportion of non-fossil energy generation in China, the creation of new hydropower generation has shown a downward trend in the past few years. The estimated coefficient on the interaction term of −0.011 in the hydro regression was likely due to low precipitation in hydropower regions in the first half of 2020. In addition, the estimated COVID-19 effect on the thermal and nuclear power shares of the power generation mix has been statistically insignificant. Compared with modern renewable energy power generation with a low marginal cost, fossil fuel energy power generation has experienced more frequent start-up/shutdown and has not had economic advantages during the pandemic. However, thermal power has strong flexibility, continuous production, and strong overall anti-risk ability. Nuclear energy cannot compete with renewable energy in terms of cost and construction speed and has been unaffected by the pandemic.

Table 5
Heterogeneous effects of COVID-19 on the power generation mix.

Column	(1)	(2)	(3)	(4)	(5)
Variable	mix_tpg	mix_spg	mix_wpg	mix_hpg	mix_npg
Type	Thermal power	Solar power	Wind power	Hydropower	Nuclear power
treat×post	0.00136	0.00316**	0.00510**	−0.0110**	0.00136
	(0.00434)	(0.00121)	(0.00193)	(0.00405)	(0.00171)
Controls	Yes	Yes	Yes	Yes	Yes
province FE	Yes	Yes	Yes	Yes	Yes
month FE	Yes	Yes	Yes	Yes	Yes
Obs	600	600	600	600	600
R-squared	0.913	0.919	0.907	0.919	0.900

Notes: This table presents the estimation results for the heterogeneous effects of COVID-19 on the power generation mix by fuel type. The dependent variable is the electric mix for all columns (1)–(5) with different power types. Other notes as Table 2.

The regression results provide strong evidence that COVID-19 has advanced the transition of the power generation mix. Specifically, due to the pandemic, the power generation mix is likely to move, in relative terms, from hydropower (generated using domestic resources) toward modern, capital-intensive renewables. From the current situation, the COVID-19 crisis did not necessarily crowd out decarbonization efforts in the power industry, instead, it accelerated the electricity transition (Pianta et al., 2021).

5.2.2. On primary energy mix

To further understand the impacts of the COVID-19 pandemic on the primary energy mix by fuel type, this study measured the primary energy mix by calculating the ratio of specific energy sources to the total primary energy supply (10000 tons of standard coal). From the empirical results shown in Table 6, the COVID-19 effect on the transition of the primary energy mix away from carbon-intensive energy was significant. Specifically, the estimated COVID-19 effect was negative for the shares of raw coal and crude oil in the primary energy mix during the study period and was positive for solar and wind power. The expansion of solar and wind power was closely linked to a concurrent decline in the shares of raw coal and crude oil, the most carbon-intensive forms of primary energy supply. This finding demonstrates that the primary energy mix tended to switch from raw coal and crude oil to solar and wind power. The estimates indicate that the pandemic's impacts on the shares of natural gas, hydropower, and nuclear power have been insignificant. In a word, the heterogeneous results reveal that the pandemic has accelerated the transition of the primary energy mix from high-carbon energy (i.e., raw coal and crude oil) to modern renewables, such as solar and wind power.

The results of this study are consistent findings from the literature. The previous studies did not quantitatively estimate the changes in low-carbon power generations induced by the COVID-19 pandemic, although they reached a near consensus that China's energy transition has been altered by the pandemic to a great extent (Quitzow et al., 2021; Liu et al., 2021; Hoang et al., 2021). For example, Quitzow et al. (2021) and Hoang et al. (2021) showed that the crisis caused unprecedented decarbonization of the power system. Similarly, we found that the COVID-19 shock significantly increased low-carbon power generation. Meanwhile, several studies argued that the crisis might have tremendous consequences on the direction of the energy transition (European Commission, 2020; Pianta et al., 2021; Kuzemko et al., 2020). In a similar vein, this study further revealed that COVID-19 has promoted the adoption of low-carbon power sources on the upper rungs of the electricity ladder (modern renewables such as solar and wind power). The results of this study provided direct empirical evidence on the COVID-19 effect on China's low-carbon energy transition, as well as important cross-cutting insights not only for China but also for other large and emerging economies.

6. Conclusions and policy implications

COVID-19 has profoundly changed the economy, society, and people's lives worldwide. As a crucial part of the economy, China's energy sector should have also been altered by the pandemic. Understanding the effects of COVID-19 on low-carbon energy transitions in China is necessary for China to make its plan toward "Dual Carbon" targets. However, while there are quite a few studies on the COVID-19, no one has investigated how it affected energy transitions.

On the one hand, investigating the epidemic's treatment effect on energy transitions can enrich the main contents of the impact assessment of the epidemic, without limiting the analysis to the economy and human well-being. On the other hand, when assessing a major public safety and health event such as COVID-19, it is necessary to consider the possible deductions caused by the virus in terms of welfare losses. To achieve more accurate and comprehensive evaluation results.

Table 6
Heterogeneous effects of COVID-19 on the primary energy mix.

Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Variable	mix_coal	mix_oil	mix_gas	mix_sps	mix_wps	mix_hps	mix_nps
Type	Raw coal	Crude oil	Natural gas	Solar power	Wind power	Hydro power	Nuclear power
treat×post	−0.0128*	−0.00399*	0.00600	0.00346**	0.00750**	−0.00340	0.00327
	(0.00649)	(0.00197)	(0.00410)	(0.00138)	(0.00317)	(0.00321)	(0.00315)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
province FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
month FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	600	600	600	600	600	600	600
R-squared	0.905	0.906	0.902	0.897	0.630	0.903	0.900

Notes: This table presents the estimation results for the heterogeneous effects of COVID-19 on the primary energy mix by fuel type. The dependent variable is the primary energy mix for all columns (1)–(7) with different energy types. Other notes as Table 2.

consideration is also given in this study to the impact on the low-carbon power supply and the direction of the energy transition.

It was found that, by using the stacked low-carbon power generations (we defined four major low-carbon power sources: solar, wind, nuclear, and hydro), the COVID-19 pandemic had a significant promotion effect on low-carbon power generations, compared with the same period in 2018–2019. In terms of economic magnitude, the COVID-19 pandemic on average, increased the low-carbon power generation by 4.59% (0.0648 billion kWh). This result was robust when considering the parallel trend hypothesis test, dynamic effects, province-month trend, province-energy effects, other model specifications, and changes in sample adjustment.

The heterogeneous analysis of the effect on energy production indicates that the COVID-19 pandemic improved solar and wind power generation. It is also worth noting that the overall results were mainly driven by solar and wind power generation, especially solar power generation. The heterogeneous analysis of the effect on the energy mix indicates that the pandemic has fostered the transition of the power generation mix and the primary energy mix from high-carbon energy to modern renewables (such as solar and wind power).

Our results have the following policy implications. China needs to seize the momentum to promote the low-carbon energy transition during the COVID-19 crisis. While the pandemic disrupted the world from all aspects, our results suggest that it accelerated decarbonization efforts in the power industry, and promoted the power mix toward renewable energy sources. Since renewables will play a vital role in advancing low-carbon energy transition and achieving dual carbon targets, they require a continued medium-term and long-term policy vision. Accordingly, the development strategy of the next round of the energy industry should be scientifically planned.

In addition, promoting energy transitions should be a part of the recovery plan. In order to realize the dual carbon goals, China's post-pandemic economic stimulus measures should be closely combined with long-term low-carbon development and climate policies, such as market-oriented reform and energy transitions, so as to promote green recovery. Investment in energy transitions may not only achieve economic recovery in the short term (after COVID-19) but could also contribute to long-term social development (Khan et al., 2021).

This study concluded by proposing several directions for future research. The short-term effects of COVID-19 on the energy transition were only considered in the present work, and it is still unclear whether the impacts were just a one-time shock or have permanently altered the development model of the power system. As the COVID-19 pandemic is still spreading all over the world, the long-term effects of COVID-19 on the low-carbon power generation and the transition to renewables remains to be seen, which is an important field of energy transition research (Zhong et al., 2020). Also, while monthly source-specific data do provide a knowledge base for assessing the decarbonization efforts of the power sector, information on day-to-day energy production and generation patterns induced by COVID-19 is unfortunately omitted. Therefore, a dataset on source-specific power generations with high time frequency is urgently needed to understand how the pandemic has affected the low-carbon power supply and generation patterns. Finally, the present study only focused on energy production and energy transition in the context of China, where the government sticks to the *dynamic zero-covid policy* in stopping the large-scale spread of the virus, which is quite different from most other countries. Future studies could continue to explore emerging generation patterns and cross-country differences, which can help provide additional insight to understanding the COVID-19 effects on global efforts to address energy transition.

CRediT authorship contribution statement

Kai Li: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **Shaozhou Qi:** Supervision, Resources, Validation, Funding acquisition. **Xunpeng Shi:** Conceptualization, Validation, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Ali, M., Alam, N., Rizvi, S., 2020. Coronavirus (Covid-19) – an epidemic or pandemic for financial markets. J. Behav. Exp. Finance 27, 100341. https://doi.org/10.1016/j.jbef.2020.100341.

Amir, M., Khan, S., 2021. Assessment of renewable energy: status, challenges, covid-19 impacts, opportunities, and sustainable energy solutions in Africa. Energy Built Environ. https://doi.org/10.1016/j.enbenv.2021.03.002.

Ba, S., Bai, H., 2020. Covid-19 pandemic as an accelerator of economic transition and financial innovation in China. J. Chin. Econ. Bus. Stud. 18 (4), 341–348.

Baker, S.R., Bloom, N., Davis, S.J., Kost, K.J., Sammon, M.C., Viratyosin, T., 2020. The unprecedented stock market impact of COVID-19. Rev. Asset Pricing Studies 12, 742–758. https://doi.org/10.1093/rapstu/raaa008.

Bekkers, E., Koopman, R.B., 2020. Simulating the trade effects of the Covid-19 pandemic. World Econ. 20 https://doi.org/10.1111/twec.3063.

Birol, F., 2020. Put Clean Energy at the Heart of Stimulus Plans to Counter the Coronavirus. Crisis—Analysis - IEA.
Chang, Y., Huang, R.J., Ge, X., Huang, X., Hu, J., Duan, Y., et al., 2020. Puzzling haze events in China during the coronavirus (COVID-19) shutdown. Geophys. Res. Lett., e2020GL088533
Chen, K., Wang, M., Huang, C., Kinney, P.L., Anastas, P.T., 2020. Air pollution reduction and mortality benefit during the covid-19 outbreak in China. Lancet Planet. Health 4 (6), 210–212. https://doi.org/10.1016/S2542-5196(20)30107-8.
Chiaramonti, D., Maniatis, K., 2020. Security of supply, strategic storage and Covid19: which lessons learnt for renewable and recycled carbon fuels, and their future role in decarbonizing transport? Appl. Energy 271, 115216.
Cinelli, M., Morales, G., Galeazzi, A., Quattrociocchi, W., Starnini, M., 2021. The echo chamber effect on social media. Proceedings of the National Academy of Sciences 118 (9), e2023301118.
Council of the European Union, 2020. Interinstitutional File: 2020/0036(COD). Brussels.
Dang, H.A., Trinh, T.A., 2021. Does the Covid-19 lockdown improve global air quality? new cross-national evidence on its unintended consequences. J. Environ. Econ. Manag. 105, 102401.
Davidson, D.J., 2019. Exnovating for a renewable energy transition. Nat. Energy 4, 254–256.
Ding, W., Levine, R., Lin, C., Xie, W., 2020. Corporate immunity to the COVID-19 pandemic. J. Financ. Econ. https://doi.org/10.1016/j.jfineco.2021.03.005 forthcoming.
Duflo, E., Greenstone, M., Pande, R., Ryan, N., 2013. Truth-telling by third-party Auditors: evidence from a randomized field experiment in India. Q. J. Econ. 128 (4), 1499–1545.
Emma, N., 2020. Coronavirus could weaken climate change action. Hit Clean Energy. Retrieved April 21, 2020.
European Commission, 2020. Guidance to Member States: Recovery and Resilience Plans, 2020. Commission Staff Working Document SWD, Brussels, 205 final.
Fang, H., Wang, L., Yang, Y., 2020. Human mobility restrictions and the spread of the novel coronavirus (2019-nCoV) in China. J. Publ. Econ. 191, 104273 https://doi.org/10.1016/j.jpubeco.2020.104272.
Forster, P.M., Forster, H.I., Evans, M.J., et al., 2020. Current and future global climate impacts resulting from Covid-19. Nat. Clim. Change 1–7.
Gharehgozli, O., Nayebvali, P., Gharehgozli, A., Zamanian, Z., 2020. Impact of Covid-19 on the economic output of the US outbreak's epicenter. Econ. Disasters Clim. Change 4 (3), 561–573. https://doi.org/10.1007/s41885-020-00069-w.
Ghenai, C., Bettayeb, M., 2021. Data Analysis of the Electricity Generation Mix for Clean Energy Transition during Covid-19 Lockdowns. Energy Sources Part A Recovery Utilization and Environmental Effects, pp. 1–21.
He, G., Pan, Y., Tanaka, T., 2020. The short-term impacts of COVID-19 lockdown on urban air pollution in China. Nat. Sustain. 1–7.
Hershbein, B.J., Holzer, H.J., 2021. Covid-19's impacts on the labor market in 2020. Employ. Res. 28 (2), 1–4.
Hoang, A.T., Nieti, S., Olcer, A.I., Ong, H.C., Chen, W.H., Chong, C.T., et al., 2021. Impacts of Covid-19 pandemic on the global energy system and the shift progress to renewable energy: opportunities, challenges, and policy implications. Energy Pol. 154.
Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., He, K., 2021. Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. Natl. Sci. Rev. 8 (2), nwaa137.
IEA, 2020. Global Energy Review 2020: the Impacts of the Covid-19 Crisis on Global Energy Demand and CO2 Emissions. Paris. https://www.weforum.org/agenda/2020/05/covid19-energy-use-drop-crisis/.
IMF, 2020. The great lockdown. In: World Economic Outlook (Issue May). https://www.imf.org/en/Publications/WEO/Issues/2020/04/14/weo-april-2020.
IRENA, 2021 Renewable Power Generation Costs in 2020.https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020.
Ivanov, D., Dolgui, A., 2021. OR-methods for coping with the ripple effect in supply chains during COVID-19 pandemic: managerial insights and research implications. Int. J. Prod. Econ. 232, 107921.
Jiang, J., Ye, B., Liu, J., 2019. Peak of CO_2 emissions in various sectors and provinces of China: recent progress and avenues for further research. Renew. Sustain. Energy Rev. 112 (SEP), 813–833.
Kåberger, T., 2018. Progress of renewable electricity replacing fossil fuels. Global Energy Interconnect. 1 (1), 48–52.
Kanda, W., Kivimaa, P., 2020. What opportunities could the COVID-19 outbreak offer for sustainability transitions research on electricity and mobility? Energy Res. Social Sci. 68, 101666 https://doi.org/10.1016/j.erss.2020.101666.
Karmaker, C.L., Ahmed, T., Ahmed, S., Ali, S.M., Moktadir, M.A., Kabir, G., 2021. Improving supply chain sustainability in the context of COVID-19 pandemic in an emerging economy: exploring drivers using an integrated model. Sustain. Prod. Consum. 26, 411–427.
Kelvin, T.H.C., Brindley, H., 2020. Covid-19 lockdown air quality change implications for solar energy generation over China. Environ. Res. Lett. 16 (2) https://doi.org/10.1088/1748-9326/abd42f.
Khan, S.A.R., Yu, Z., Golpîra, H., Sharif, A., Mardani, A., 2021. A state-of-the-art review and meta-analysis on sustainable supply chain management: future research directions. J. Clean. Prod. 278, 123357.
Kraemer, M., Yang, C., Gutierrez, B., et al., 2020. The effect of human mobility and control measures on the COVID-19 epidemic in China. Science 368 (6490), 493–497.
Kuzemko, C., Bradshaw, M., Bridge, G., Goldthau, A., Westphal, K., 2020. Covid-19 and the politics of sustainable energy transitions. Energy Res. Social Sci., 101685 https://doi.org/10.1016/j.erss.2020.101685.
Le Quéré, C., Jackson, R.B., Jones, M.W., et al., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Change 10, 647–653. https://doi.org/10.1038/s41558-020-0797-x.
Li, X., Hua, L., Du, Y.F., Wang, C., Liu, Y., 2017. Carbon dioxide emissions from the electricity sector in major countries: a decomposition analysis. Environ. Sci. Pollut. Res. Int. 25 (9), 1–12.
Li, P., Lu, Y., Wang, J., 2020. The effects of fuel standards on air pollution: evidence from China. J. Dev. Econ. 146 https://doi.org/10.1007/s10653-019-00396-2.
Li, Y., Li, S., Huang, L., Liu, Z., Zhu, Y., Li, L., et al., 2021. The casual effects of covid-19 lockdown on air quality and short-term health impacts in China. Environ. Pollut. 290, 117988 https://doi.org/10.1016/j.envpol.2021.117988.
Liu, Q., Qiu, L.D., 2016. Intermediate input imports and innovations: evidence from Chinese firms' patent filings. J. Int. Econ. 103, 166–183.
Liu, Z., Ciais, P., Deng, Z., Lei, R., Schellnhuber, H.J., 2020. Author correction: near-real-time monitoring of global co2 emissions reveals the effects of the covid-19 pandemic. Nat. Commun. 11 (1) https://doi.org/10.1038/s41467-020-18922-7.
Liu, Z., Zhu, B., Ciais, P., Davis, S.J., Lu, C., Zhong, H., et al., 2021. De-carbonization of Global Energy Use during the Covid-19 Pandemic. *Papers* 2102.03240, arXiv.org.
Martin, A., Markhvida, M., Hallegatte, S., Walsh, B., 2020. Socio-economic impacts of covid-19 on household consumption and poverty. Econ. Disasters Clim. Change 4.
Mastropietro, P., Rodilla, P., Batlle, C., 2020. Emergency measures to protect energy consumers during the Covid-19 pandemic: a global review and critical analysis. Energy Res. Social Sci. 68, 101678.
Morgan, A.K., Aberinpoka, B., Quartey, T., 2021. The effects of covid-19 on global economic output and sustainability: evidence from around the world and lessons for redress. Sustain. Sci. Pract. Pol. 17 (1), 77–81.
Newsome, S.J., Daniel, R.M., Carr, S.B., Diana, B., Keogh, R.H., 2021. Using negative control outcomes and difference-in-differences to estimate treatment effects in an entirely treated cohort: the effect of ivacaftor in cystic fibrosis. Am. J. Epidemiol. 263 https://doi.org/10.1093/aje/kwab263.
Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Agha, R., 2020. The socio-economic implications of the coronavirus pandemic (COVID-19): a review. Int. J. Surg. 78, 185–193.
Nicolli, F., Vona, F., 2016. Heterogeneous policies, heterogeneous technologies: the case of renewable energy. Energy Econ. 56, 190–204.
Oskoui, K.N., 2020. The growing impact of coronavirus on the global economy. March, 3–5. http://theconversation.com/the-growing-impact-of-coronavirus-on-theglobal-economy-132030.
Quitzow, R., Bersalli, G., Eicke, L., Jahn, J., Xue, B., 2021. The covid-19 crisis deepens the gulf between leaders and laggards in the global energy transition. Energy Res. Social Sci. 74 (363), 101981.
Selmi, R., Bouoiyour, J., Hammoudeh, S., Errami, Y., Wohar, M.E., 2021. The energy transition, trump energy agenda and covid-19. Int. Econ. 165.
Shi, X., Brasseur, G.P., 2020. The response in air quality to the reduction of Chinese economic activities during the COVID-19 outbreak. Geophys. Res. Lett. 47.
Shi, Xunpeng, Cheong, Tsun, Zhou, Michael, 2021. COVID-19 and global supply chain configuration: economic and emissions impacts of Australia-China trade disruptions. Front. Public Health 9, 752481.
Tian, H., Liu, Y., Li, Y., et al., 2020. An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. Science 368 (6491), 638–642.
Wang, J., Xu, B., Wang, S., He, S., He, P., 2021. Heterogeneous effects of covid-19 lockdown measures on air quality in northern China. Appl. Energy 282, 116179.
Wei, Y., Zhao, T., Wang, J., Zhang, X., 2021. Exploring the impact of transition in energy mix on the co2 emissions from China's power generation sector based on ida and sda. Environ. Sci. Pollut. Control Ser. 28 (24), 1–15.
York, R., Bell, S., 2019. Energy transitions or additions? Why a transition from fossil fuels requires more than the growth of renewable energy. Energy Res. Social Sci. 51, 40–43.
Zhang, S., Chen, W., 2021. China's Energy Transition Pathway in a Carbon-Neutral Vision Engineering. https://doi.org/10.1016/j.eng.2021.09.004.
Zhang, Y., Gao, S., Shi*, X., Qian, X., Nie, R., 2021. A market instrument to achieve carbon neutrality: is China's energy-consumption permit trading scheme effective? Appl. Energy 299, 117338.
Zhao, Y., Cao, Y., Shi, X., Li, H., Shi, Q., Zhang, Z., 2020. How China's electricity generation sector can achieve its carbon intensity reduction targets? Sci. Total Environ. 706, 135689.
Zhao, Y., Cao*, Y., Shi, X., Zhang, Z., Zhang, W., 2021. Structural and technological determinants of carbon intensity reduction of China's electricity generation. Environ. Sci. Pollut. Control Ser. 28, 13469–13486.
Zheng, S., Wang, J., Sun, C., et al., 2019. Air pollution lowers Chinese urbanites' expressed happiness on social media. Nat. Human Behav. 3, 237–243 https://doi.org/10.1038/s41562-018-0521-2.
Zhong, H., Tan, Z., He, Y., Xie, L., Kang, C., 2020. Implications of COVID-19 for the electricity industry: a comprehensive review. CSEE J. Power Energy Syst. 6 (3), 489–495.
Zhu, Y., Xie, J., Huang, F., Cao, L., 2020. Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci. Total Environ., 138704
Pianta, S., Brutschin, E., Ruijven, B., Bosetti, V., 2021. Faster or slower decarbonization? policymaker and stakeholder expectations on the effect of the covid-19 pandemic on the global energy transition. Energy Res. Social Sci. 76. https://doi.org/10.1016/j.erss.2021.102025.