Humanities & Social Sciences Communications

ARTICLE

https://doi.org/10.1057/s41599-023-02381-8 OPEN

China's climate governance for carbon neutrality: regulatory gaps and the ways forward

Shengqing Xu [1]✉

The realisation of global carbon neutrality is crucial for combating climate change. As the largest emitter, China declared to achieve carbon neutrality by 2060. However, substantial changes in the energy structure are far from being achieved. Using time series data from 2001 to 2019 and the ARDL-ECM method, this paper explored the effectiveness of climate policies in controlling China's carbon emissions. The results show that economic and technical factors such as economic growth and energy structure are the determinants of carbon emissions. A green paradox is shown since increasing climate policy density does not significantly reduce carbon emissions. The main regulatory gaps in China's climate governance include weaknesses in the rule of law, lack of accountability, and insufficient arrangements for equitable energy transitions. A binding legal system is necessary to realise absolute reduction and secure carbon neutrality, especially one including specific climate change legislation, binding reduction targets, and combining energy justice with regulatory efficiency.

[1] School of Humanities and Law, Jiangsu Ocean University, Lianyungang, Jiangsu, China. ✉email: xushengqing@jou.edu.cn

Introduction

With global carbon emissions remaining at a high level, the CO_2 concentration has reached above 420 ppm in recent years (Steinthorsdottir et al., 2022), exceeding the 400 and 350 ppm limits for controlling temperature rise under 2 and 1.5 °C, respectively. The persistence of CO_2 concentration at a high level brings climate emergency and necessitates carbon neutrality (IPCC, 2022). As the largest carbon emitter, China's actions are critical for the success of climate change mitigation. Although China has made significant progress in carbon intensity reduction, absolute reduction has become more urgent (Menzies et al., 2020).

Economic and technical factors such as economic growth, energy structure, and energy intensity are widely acknowledged as the main factors affecting carbon emission and intensity (Liu et al., 2022). Policy is also a vital variable affecting carbon emissions. Policies aiming at phasing out fossil fuels and promoting renewable energies have been widely used (Schaffrin et al., 2014). Current literature about climate change governance mainly includes renewable energy, energy efficiency, carbon emissions trading (Hübler et al., 2014; Yan et al., 2020), and collaborative governance of greenhouse gases and other pollutants (Gu et al., 2018; Mao et al., 2012). However, these measures are mainly developed for sustainable economic growth and energy security rather than combating climate change. After reviewing 30 years of climate policies in China, Heggelund (2021) noted that the 2060 carbon neutrality goal will require highly ambitious policies. To enhance the effectiveness of climate policies, China should accelerate the process of climate change legislation (Zhang et al., 2019).

As regulatory interference, climate policies are expected to reverse the increasing trend of carbon emissions. However, well-intended climate policies can have adverse consequences (Van der Ploeg and Withagen, 2015). Climate policies may coexist with increasing carbon emissions. This possibility is referred to as a green paradox (Sinn, 2008). The possible reasons for the green paradox are complex. First, carbon emissions may increase due to carbon leakage caused by an imbalanced climate policy supply among different jurisdictions (Nielsen et al., 2021). More fossil fuel would be consumed in regions with less strict climate policies. Second, with anticipation of gradually strengthening carbon regulation, enterprises may expand the production of fossil fuels in the short run, and carbon emissions may increase correspondingly (Cairns, 2014). Third, path dependency and institutional inertia could also hinder the formulation and implementation of climate policies. Existing technologies, institutions, and behavioural norms would constrain reduction rate and magnitude. The inertia due to mutually reinforcing physical, economic, and social constraints is called carbon lock-in (Seto et al., 2016). Long-lived capital stocks (LLCS), such as infrastructure and buildings, have significant and long-lasting implications for greenhouse gas emissions (Fisch-Romito et al., 2021). Fourth, the quality and stringency of climate policies could directly affect their effectiveness.

Scholars have recently stressed the importance of integrating policy density (the number of policies) and policy intensity (the quality of policies). For example, Schaffrin et al. (2015) identified six policy-intensity measures (objectives, scope, integration, budget, implementation, and monitoring) used to weigh national policy instruments. Countries possessing effective climate policy frameworks (such as Germany, Denmark, and the UK) usually have a balance between policy intensity and policy density (Lysack, 2021).

By contrast, studies also revealed the controversial features of the green paradox. Some scholars confirmed the emission reduction effect of climate policies. However, environmental policy effects have apparent heterogeneity due to different regulatory efficiency, costs, preferences, penalties, and the scope of application (Ribeiro and Kruglianskas 2015). In opposition to the assumption of the green paradox, the anticipation effects could reduce CO_2 emissions because of vital divestment in coal power plants (Bauer et al., 2018).

China has issued many climate policies, resulting in increasing policy density. However, the increasing trend of carbon emissions is continuing. This contradiction implies a green paradox is likely to exist in China. However, empirical evidence is needed to confirm this hypothesis. The current literature about the relationship between environmental regulation and carbon emission is controversial. On the one hand, some studies indicated the emission reduction effect (Khan et al., 2019; Wang, 2020). On the other hand, other studies presented a green paradox. For example, Zhang et al. (2017) indicated that fiscal decentralisation makes the environmental policy significantly promote carbon emissions, leading to a green paradox. Wang et al. (2022) pointed out that the emissions increment brought by the massive increase in demand is greater than the emission reduction brought by energy efficiency improvement.

Policy intensity could also contribute to the green paradox. As the intensity of environmental regulation changes from weak to strong, the impact changes from a green paradox to emission reduction (Guo and Chen, 2018). Therefore, effective climate policy requires integrated policy design and implementation with proper policy intensity. Policy intensity is closely related to using various policy instruments according to good governance requirements. Addressing climate change requires addressing complex interests and conflicts arising from transformative changes (Dubash, 2021). Past literature has widely discussed climate governance from polycentric and multilevel governance perspectives (Heinen et al., 2022). Schreurs (2017) noted that reversing carbon emissions growth will depend significantly on the effectiveness of policy implementation at the local and regional levels. Westman and Broto (2018) analysed China's urban climate governance by exploring 150 climate initiatives in 15 cities. They suggested climate partnerships can facilitate local climate actions by creating access to resources like information, technology, and funding. Wu et al. (2022) found a weak climate policy integration in China's local governments due to insufficient communications between policy sectors, limited professional capacity, and inefficient governance structures. Teng and Wang (2021) examined China's climate governance structure and suggested that coordination mechanisms are ad hoc and cannot guarantee that climate issues are always on the agenda.

The relationship between carbon emission and climate policies could be discovered by combining theories about climate governance and policy intensity. Have the policies significantly reduced carbon emissions? Whether climate governance is sufficient for achieving carbon neutrality? The two questions require a systematic examination of China's climate governance. Using the ARDL-ECM model, this paper explores the effectiveness of China's climate policies from the perspective of policy density. Then, regulatory gaps are identified by referring to the requirements of good governance and policy intensity. Section "Methods" describes the methods and data sources in this study. Section "Results" shows the results of the ARDL-ECM model. Section "Discussion: the regulatory gaps for carbon neutrality" identifies the key issues and gaps that impede effective climate change regulation and governance in China. In the section "Policy implications for improving China's climate governance", policy implications for the improvement of climate governance in China are provided. Finally, some concluding remarks regarding climate

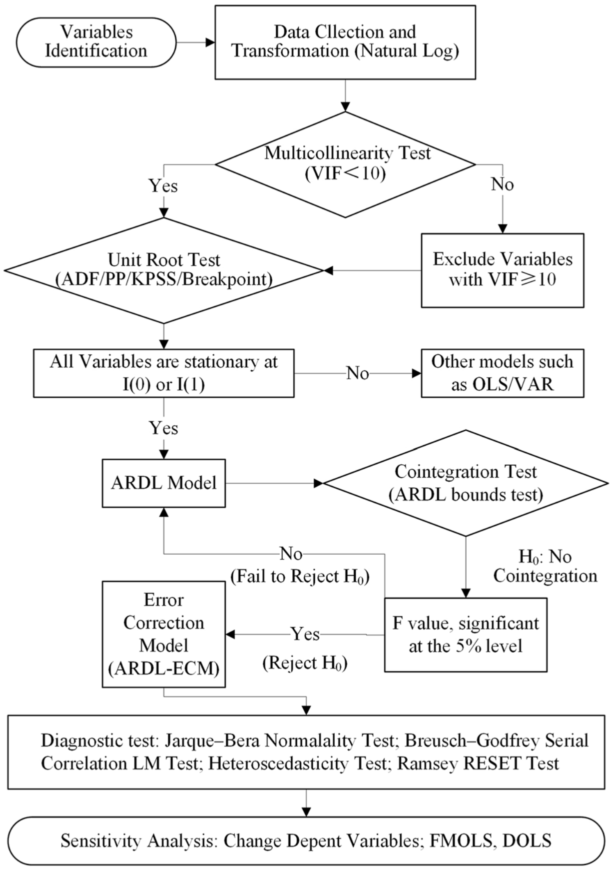

Fig. 1 The methodology framework of ARDL-ECM model. Source: Author's own elaboration (2023).

governance and the remaining research gaps are outlined in the section "Conclusion".

Methods

ARDL-ECM model. To evaluate the effects of climate-related policies, this study uses annual data to analyse the relationship among carbon emissions, energy intensity, energy structure, economic growth, and policy quantities from 2001 to 2019. The data for the former four items have been collected from the China Statistical Yearbook (National Bureau of Statistics of China, 2022) and World Bank Open Data (2023). The quantity of policies is collected from the Policy Database on the official website of China's State Council. The study uses the ARDL-ECM model to estimate the coefficients of variables (see Fig. 1).

To eliminate possible heteroscedasticity, the data are converted to their logarithmic form. The multicollinearity issue between variables is checked by variance inflation factors (VIF). A VIF factor of below 10 suggests not-so-severe multicollinearity in the variables of a specified model (O'Brien, 2007; Udayanganie and Charos, 2017; Lee, 2019). The variable representing energy intensity is dropped due to the multicollinearity issue (see Table 1).

Based on previous studies on carbon emissions, and considering the literature and data availability in China, the model is specified as follows:

$$\mathrm{lnCE}_t = \beta_0 + \beta_1 \mathrm{lnNF}_t + \beta_2 \mathrm{lnPGDP}_t + \beta_3 \mathrm{lnPGDP2}_t + \beta_4 \mathrm{lnQ}_t + \mu_t \quad (1)$$

where LNPGDP2 is the natural logarithm of the squared per capita GDP. β_0 is a constant, and μ_t is the error term, whereas β_1 to β_4 are coefficients.

Table 1 VIF tests for multicollinearity.

Variables	VIF	VIF
LNEI	67.61305	
LNNF	34.0239	4.515796
LNPGDP	17.63608	8.112655
LNQ	3.055662	3.041127
Mean	30.5822	5.2232

LNCE, LNEI, LNNF, LNPGDP, and LNQ are the natural logarithms of carbon emission, energy intensity, non-fossil energy share in total energy consumption, per capita gross domestic product (GDP) and the quantity of carbon emission policies.

Time series analysis requires performing the unit root test to check whether the collected data are stationary to avoid false regressions. This research uses the augmented Dickey–Fuller (ADF), PP and KPSS unit root tests to observe the order of integration. However, it is suggested that such tests may incorrectly indicate the existence of a unit root when the series is stationary around a one-time structural break (Zivot and Andrews, 1992). Perron (1989) noted that potential structural breaks can affect the statistical results of unit root and cointegration tests. Structural breaks may mislead unit root tests to accept the existence of unit root when in fact it is stationary (Perron and Vogelsang, 1992; Zivot and Andrews, 1992). Ignorance of structural breaks can distort the power of tests and lead to deceptive conclusions. After identifying the structural break, a dummy variable will be introduced, taking the value of 0 before the structural break and 1 after the structural break. Compared to other cointegrations, the ARDL method permits the use of variables that become stationary at I(0) or I(1) (Pesaran et al., 2001).

After confirming the long-run equilibrium among the variables, the short-run and long-run coefficients are estimated by the ARDL-ECM model. The ARDL bounds test considering structural break is applied here using the following specified model:

$$\begin{aligned}\Delta \mathrm{lnCE}_t = {} & \beta_0 + \sum_{i=1}^{p} \beta_i \Delta \mathrm{lnCE}_{t-i} + + \sum_{j=0}^{q_1} \theta_{1j} \Delta \mathrm{lnNF}_{t-j} + \sum_{j=0}^{q_2} \theta_{2j} \Delta \mathrm{lnPGDP}_{t-j} \\ & + \sum_{j=0}^{q_3} \theta_{3j} \Delta \mathrm{lnPGDP2}_{t-j} + \sum_{j=0}^{q_4} \theta_{4j} \Delta \mathrm{lnQ}_{t-j} + \varphi_1 \mathrm{lnCE}_{t-1} + \varphi_2 \mathrm{lnNF}_{t-1} \\ & + \varphi_3 \mathrm{lnPGDP}_{t-1} + \varphi_4 \mathrm{lnPGDP2}_{t-1} + \varphi_5 \mathrm{lnQ}_{t-1} + \varphi_6 \mathrm{DU} + \mu_t \end{aligned} \quad (2)$$

where Δ is the first difference operator. p, q_1–q_4 are the optimal lag lengths. β_i, θ_{1j} to θ_{4j} represent the short-run dynamics. φ_1 to φ_6 indicate a long-run relationship.

DU is the dummy variable for the structural break. If there exists a structural break in the data, DU will be 0 if data was collected before the breakpoint, and "DU" will be 1 if data was collected after the structural break.

According to Pesaran et al. (2001), cointegration is present in the model if the estimated value of F-statistics is more than the upper bound value. If a cointegration is established, then the following unrestricted ECM is estimated:

$$\begin{aligned}\Delta \mathrm{lnCE}_t = {} & \beta_0 + \sum_{i=1}^{p} \beta_i \Delta \mathrm{lnCE}_{t-i} + \sum_{j=0}^{q_1} \theta_{1j} \Delta \mathrm{lnNF}_{t-j} + \sum_{j=0}^{q_2} \theta_{2j} \Delta \mathrm{lnPGDP}_{t-j} \\ & + \sum_{j=0}^{q_3} \theta_{3j} \Delta \mathrm{lnPGDP2}_{t-j} + \sum_{j=0}^{q_4} \theta_{4j} \Delta \mathrm{lnQ}_{t-j} + \theta_5 \mathrm{DU} + \varphi ECM_{t-1} + \mu_t \end{aligned} \quad (3)$$

where ECM is the error-correction term in the model, which is the OLS disturbance term series from the long-run cointegration regression.

Table 2 Unit root test results.

Variable	ADF	PP	KPSS	Order of integration
LNCE	−5.4622*** (0.0004)	5.4622*** (0.0004)	0.1425 (0.1460)	I(0)
LNCI	−4.3313** (0.0167)	−1.9986 (0.5631)	0.1401 (0.1460)	I(0)
LNEI	−3.6156*** (0.0013)	−2.6981*** (0.0100)	0.4166 (0.4630)	I(0)
LNNF	−3.3895* (0.0861)	−0.1832 (0.1460)	0.3950 (0.4630)	I(1)
DLNNF	−6.4246*** (0.0004)	−6.4246*** (0.0004)	0.3589 (0.1460)	
LNQ	−3.3994* (0.0868)	−9.0544*** (0.0000)	0.0871 (0.1460)	I(0)
LNPGDP	−6.8882*** (0.0012)	−2.4943 (0.1330)	0.4356 (0.4630)	I(0)
LNPGDP2	−7.3495*** (0.0007)	−1.8086 (0.3646)	0.1242 (0.1460)	I(0)

***, ** and * indicate significance at the level 1%, 5% and 10%, respectively; variable stationarity is determined at the 5% significance level. The optimal lag for the ADF test is selected based on the SIC criteria. For the PP test, the spectral estimation method selected for fixing the truncation lag is the Bartlett kernel, and for the bandwidth it is the Newey–West method. For the KPSS test, the spectral estimation method chosen is the Parzen Kernel, and for bandwidth is the Newey–West method. Asymptotic critical values at the 5% significant level are in the parentheses. Because the null hypothesis for KPSS reads that the series is stationary, the null hypothesis is rejected if the test statistic is higher than the critical value at the 5% significance level.

Table 3 Breakpoint unit root test results.

Variables	T	Year of break	Result
LNCE	−4.8522**	2008	Stationary
LNCI	−6.6515***	2009	Stationary
LNNF	−1.9945	2011	Non-stationary
DLNNF	−7.4046***	2007	Stationary
LNQ	−3.1511	2010	Non-stationary
DLNQ	−7.2146***	2014	Stationary
LNPGDP	−4.5770**	2006	Stationary
LNPGDP2	−4.1850	2006	Non-stationary
DLNPGDP2	−4.7541**	2010	Stationary

*** and ** indicate significance at the level 1% and 5%, respectively.

Results

Unit root test. This study employs the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) stationarity tests to determine the order of integration. In addition, the study adopts the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test to resolve contradictions (if found) between the ADF and the PP. The results of the ADF, PP, and KPSS tests in Table 2 demonstrate that all variables are stationary at level $I(0)$ or the first difference $I(1)$.

The corresponding time of the structural break for each variable is shown in Table 3.

It can be observed that the breakpoint unit root test results of LNQ and LNPGDP2 contradict the results of KPSS tests. The inclusion of structural breaks indicates that the two variables may be non-stationary at the level. However, no variable is $I(2)$. Thus, these tests suggest using the ARDL model.

Cointegration analysis. The ARDL bounds test is applied to determine if there is a cointegration relationship between the variables in the model. The results of the ARDL bounds test are presented in Table 4.

According to Table 4. The value of the computed F-statistic is 8.0371, higher than the upper bound critical value at the 1% significance level. It can be concluded that there is a long-run cointegrating relationship between the variables.

Table 4 Results from the ARDL bounds test.

Test statistic	Value	Significance level (%)	I(0)	I(1)
F-statistic	8.0371***	10	1.9	3.01
k	4	5	2.26	3.48
		2.50	2.62	3.9
		1	3.07	4.44

*** indicates significance at the level 1%; I(0) shows the lower critical bound value, and I(1) represents the upper critical bound value.

Table 5 Selection of the ARDL model (top five models).

Model	LogL	AIC	BIC	Specification
1	47.7617	−4.7955	−4.4524	ARDL (2, 0, 0, 0, 0)
2	48.9370	−4.8161	−4.4240	ARDL (2, 0, 1, 0, 0)
3	48.8509	−4.8060	−4.4139	ARDL (2, 0, 0, 1, 0)
4	50.1607	−4.8424	−4.4013	ARDL (2, 0, 1, 1, 0)
5	48.4797	−4.7623	−4.3702	ARDL (2, 0, 0, 0, 1)

Table 5 reports the Akaike information criterion (AIC) values of different ARDL models. The ARDL model with the most negative AIC value is selected for further analysis. From Table 5, Model 1 has the most negative value of AIC; therefore, ARDL (2, 0, 0, 0, 0) is the most suitable model.

Table 6 reports the long-run and short-run coefficients of the ARDL-ECM model. The long-run coefficient of LNNF is −0.2406, which is significant at the 1% level. This means that more renewable energy has brought considerable carbon emission reduction. Renewable energy is mainly used to meet new energy demand in China (Xu, 2021). This has prevented the carbon emissions that might be emitted. The long-run coefficients of GDP per capita and GDP per capita squared are 2.6627 and −0.1032, respectively, and they are both significant at the 1% level. This implies the existence of the EKC hypothesis for CO_2 emissions in China (Sun et al., 2021). The economic growth first increased CO_2 emission but later reduced it. During the sample period, economic growth was the main reason for China's growing emissions. According to China's time series data of carbon emission, the speed of emission expansion is reducing, and this trend implies a gradual carbon peaking progress. The long-run coefficient of LNQ is 0.0038, but it is not significant even at the 10% level. Like the impact of energy structure change, the increasing carbon control policies haven't brought an absolute reduction. This also verifies the assumption that policy density alone is insufficient for carbon emission reduction.

In the short run, the increase in carbon emission is affected by the incremental emission in the last year. The coefficient of D(LNCE(−1)) is 0.3051 and significant at the 1% level. This means the inertia effect of carbon emission. The coefficient of DU is −0.0201, significant at the 1% level, and this means that after 2008, the expansion of carbon emission has decelerated significantly than before. The reason for this deceleration may be that the economic growth speed of China continued to decrease after the 2008 financial crisis during the sampling period. The ECM value shows the speed of adjustment from short-run to long-run equilibrium (Ayalew, 2013). ECM(−1) has a value of −0.6717, which is statistically significant at the 1% level. This coefficient suggests that when CO_2 emissions are above or below the equilibrium level, it will be adjusted by almost 67.17% within the first year.

Table 6 The long run and short run coefficients.

	Variable	Coefficient	Std. error	*t*-statistic	Prob.
Long run relations	LNNF	−0.2406***	0.0445	−5.4125	0.0003
	LNPGDP	2.6627***	0.0231	115.3661	0.0000
	LNPGDP2	−0.1032***	0.0029	−35.4387	0.0000
	LNQ	0.0038	0.0181	0.2071	0.8401
Short run relations	D(LNCE(−1))	0.3051***	0.0945	3.2276	0.0091
	DU	−0.0201***	0.0057	−3.5027	0.0057
	ECM(-1)	−0.6717***	0.0896	−7.5006	0.0000

*** indicates significance at the level 1%. "DU" is 0 before 2008 and 1 from 2008.

Table 7 Diagnostic test.

Test statistics	Statistics	*p*-value	Interpretation
Jarque–Bera	1.5094	0.4702	Normal distribution
Breusch–Godfrey serial correlation LM test, *F*-statistic	2.5506	0.1390	No serial correlation
Heteroscedasticity test: Breusch–Pagan–Godfrey, *F*-Statistic	1.3736	0.3214	No heteroskedasticity

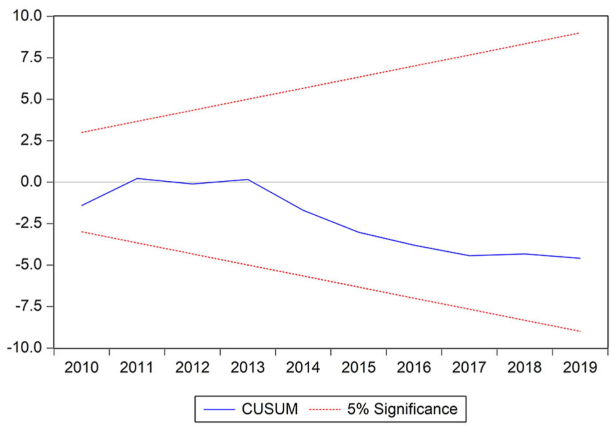

Fig. 2 Cumulative sum of recursive residuals. Source: Author construction (2023).

Diagnostic tests. Diagnostic tests for serial autocorrelation, heteroskedasticity, and normality of the residual are undertaken for the model's robustness. The study applied the Jarque–Bera test, the Breusch–Godfrey serial correlation test, the Breusch–Pagan–Godfrey heteroskedasticity test, and the Ramsey RESET test to check the reliability of the estimates and the CUSUM and CUSUM of squares plots to test the overall stability of the ARDL model. The results show that the model accepts the null hypothesis of no autocorrelation, homoscedasticity, and normal distribution (see Table 7).

Figures 2 and 3 show that the CUSUM and CUSUM of squares statistics are within the critical bounds of the 5% significance levels, indicating that the model is stable.

Sensitivity analysis. This section presents a sensitivity analysis to see whether the choice of model/methodology alters the baseline findings. For this purpose, two approaches are applied: (1) this study estimates the ARDL-ECM model using LNCI (logarithm of carbon intensity) instead of LNCE and (2) this study uses FMOLS and DOLS methods.

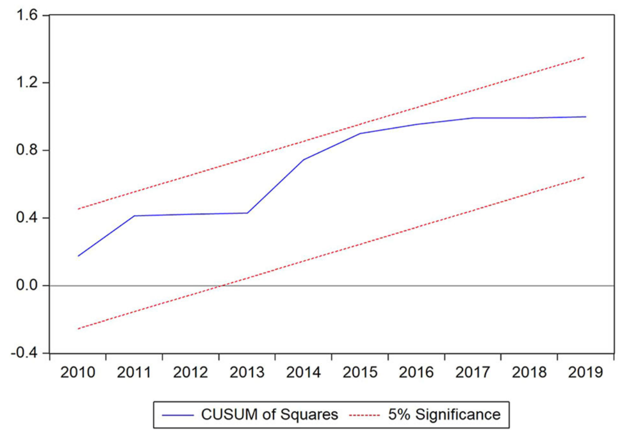

Fig. 3 Cumulative sum of squares of recursive residuals. Source: Author construction (2023).

In exploring driving factors of LNCI, the variables LNPGDP, LNNF, LNQ, and the dummy variable for the year of break DU are used. Considering that carbon emission intensity decreases during the sample period while the GDP per capita continues to increase, only the linear correlation between LNCI and LNPGDP is included to reflect the relationship between economic growth and carbon intensity (Zhang et al., 2014). The findings from the ARDL-ECM model using LNCI as a dependent variable are presented in Table 8.

The long-run findings from the ARDL-ECM model indicate that economic growth and the percentage of non-fossil energy help reduce carbon intensity. The coefficients of LNPGDP and LNNF are −0.8793 and −1.0092, both significant at the 1% level. An increase of 1% of GDP per capita and non-fossil energy share may accompany a 0.8793% and 1.0092% decrease in carbon emission intensity, respectively. The coefficient of LNQ is 0.0584, but it is not significant at the 5% level. Just like the influence of policies in reducing carbon emissions, climate policies have not significantly reduced carbon intensity.

In the short run, energy structure may be the main factor affecting carbon intensity. The coefficient of D(LNNF) is −0.3363, which is significant at the 1% level. This means that an increase in incremental non-fossil energy share may bring a 0.3363% decrease in incremental carbon intensity. Therefore, pursuing faster non-fossil energy development may accelerate the reduction of energy intensity. The estimated ECM(−1) value is −0.5036 and statistically significant at the 1% level. It indicates that the short-term disequilibrium among the variables may be corrected quickly by their long-term cointegration relationship in the previous period.

The robustness of the coefficients, in the long run, can be achieved by Fully Modified OLS and Dynamic OLS. The beauty

Table 8 The long run and short run coefficients with LNCI as the dependent variable.

	Variable	Coefficient	Std. error	*t*-statistic	Prob.
Long run relations	LNPGDP	−0.8793*	0.4539	−1.9375	0.0887
	LNNF	−1.0092**	0.3151	−3.2033	0.0125
	LNQ	0.0584	0.0708	0.8251	0.4332
Short run relations	D(LNPGDP)	0.0082	0.1203	0.0684	0.9471
	D(LNNF)	−0.3363***	0.0711	−4.7328	0.0015
	D(LNQ)	0.0099	0.0078	1.2772	0.2373
	DU	0.1095***	0.0243	4.4967	0.0020
	ECM(-1)	−0.5036***	0.0866	−5.8145	0.0004
	C	5.1381***	0.8864	5.7964	0.0004

***, ** and * indicate significance at the level 1%, 5% and 10%, respectively. "DU" is 0 before 2009 and 1 from 2009.

Table 9 Results from dynamic OLS and fully modified OLS.

Variable	FMOLS		DOLS	
LNNF	−0.4348***	0.0000	−0.4000***	0.0000
LNPGDP	2.6388***	0.0000	2.6394***	0.0000
LNPGDP2	−0.0964***	0.0000	−0.0973***	0.0000
LNQ	−0.0046	0.7408	−0.0027	0.8755
DU	−0.0636**	0.0104	−0.0605**	0.0434
C	−0.4348***	0.0000	−0.4000***	0.0000

*** and ** indicate significance at the 1% and 5% levels.

of the DOLS and FMOLS estimators is that they are free from endogeneity issues, small sample size bias and serial correlation (Ahmad and Du, 2017). For LNNF, LNPGDP and LNPGDP2, the results from DOLS and FMOLS are consistent with the ARDL results in terms of sign and significance (see Table 9). Although the sign of LNQ in the ARDL-ECM model is different from those in the DOLS and FMOLS Models, they are all not significant at the 5% level. Therefore, increasing policy quantity has no significant effect on emission reduction. The results confirm that the initial ARDL model is robust to statistical biases.

Discussion: the regulatory gaps for carbon neutrality

The empirical analysis of this study finds that carbon emissions are mainly affected by economic and technical factors. Climate policies in China have not significantly changed the increasing carbon emissions trend. A green paradox may exist due to defects in policy supply, especially the lack of policy intensity. Instead of providing specific measures to incentivise renewable development, emission control and energy efficiency improvement, an integrated design of climate governance is necessary for improving policy intensity. Climate governance literature has revealed that the rule of law, accountability, and energy justice are crucial to effective governance (Barendrecht, 2011).

The rule of law. The rule of law is an essential requirement of good governance (Yu, 2018). Scholars have demonstrated the significant positive role that strategic framework legislation can play in improving climate policy integration and coherence. For example, the Climate Change Act (CCA) is a key contributing factor to the UK's substantial emissions reductions, notably by helping to accelerate electricity sector decarbonisation (Gransaull et al., 2023).

The international climate architecture is moving towards a nationally determined contribution (NDC) system. Promises regarding emissions are not credible unless the targets and the corresponding measures are provided by law (Eskander et al., 2021). Additional domestic legislation may be required to achieve global climate objectives (Fankhauser et al., 2015). National legislation is crucial because it makes an international agreement more likely and meaningful (Townshend et al., 2013). Climate legislation is harder to reverse than strategy or policy (Dubash, 2020; Iacobuta et al., 2018). Binding legal measures help solve the tragedy of the commons, climate market failure, and climate crisis (Tvarnø, 2020). In addition, specific laws on climate change are more effective than sectoral policies with multiple objectives and a narrower scope (Moore, 2012).

However, China's approach to climate policy reflects a governance system driven more by executive orders than acts of parliament. Legislation and policies directly related to climate change are mainly soft regulations. In terms of controlling greenhouse gases, China can only carry out indirect control according to paragraph 2 of Article 2 of the Atmospheric Pollution Prevention Law through coordinated management of air pollutants and greenhouse gases. This is only an abstract provision, and more detailed institutions for their coordination are absent. Despite China's rapid growth in generation from renewables, output from coal-fired power plants has increased by 330 TWh, or nearly 7%, between 2019 and 2021 (IEA, 2021), presenting a deepening carbon lock-in due to the essential economic role played by the coal industry (Stutzer et al., 2021).

The accountability. Pledges on emissions are not credible unless the targets and related measures are stipulated by law (Eskander et al., 2021). Many countries, such as Britain, France, Denmark, and Germany, have mandated emission reduction or carbon neutrality targets as legal targets. The UK is the first country to adopt national legislation for long-term, legally binding GHG emission reduction targets.

However, China mainly sets emission reduction targets or energy structure transformation targets in policies and plans (Neuweg and Averchenkova, 2017). In 2021, the National Development and Reform Committee (NDRC) declared a "$1+N$" framework for carbon peak and neutrality. "1" refers to Opinions on Completely, Accurately, and Comprehensively Implementing the New Development Concept and Promoting Carbon Peak and Neutralisation. "N" includes the 2021 Action Plan for Carbon Peak Before 2030 and other vital industrial policies, including energy, industry, transportation, and urban and rural construction.

Compared with the statutory targets, the policy-dominated approach is weaker in force, accountability and social impacts. Whether the targets can be achieved is not a matter of law but a matter of political performance. Such targets constitute only political statements intending to reduce emissions (Minnerop, 2020). However, legislation for binding climate targets is challenging due to concerns about economic growth or conflicts of interest. It is suggested that four factors are essential in explaining this: the economy, scepticism about climate science, hegemonic drives and a quest for distributive justice (Nwankwo, 2019).

The energy justice issues. From the perspective of governance, energy justice has significant instrumental values. This is because perceptions of fairness lead social actors to be more willing to accept sacrifices, and perceptions of inequity generate social resistance and make policy implementation more difficult (Meadowcroft, 2009). Climate change can potentially exacerbate societal inequalities in income distribution and access to resources and options. A growing body of research reveals that climate change governance strategies can produce or reproduce (un)just decision-making processes and result in an (in)equitable distribution of climate change risks and resources (Romero-Lankao et al., 2018).

Energy justice should be an inherent component of climate legislation (Barton and Campion, 2019). The normative dimensions of energy justice (distributive, procedural and recognition) provide a framework for transition legislation (Jenkins et al., 2016). Since climate change requires a green energy transition, climate legislation is necessary for a Pareto improvement in the energy transition. Distributive justice is related to the cost and burden share of energy transition. Mitigation measures should not aggravate the disadvantages of the poverty or marginal groups. Procedural justice requires inclusive and democratic energy decisions. Although environmental authoritarianism has proven more capable of responding to China's complex political and ecological pressures (Beeson, 2010), effective public participation is necessary for the sustainability and justice of related institutions (Engels, 2018). A polycentric approach is indispensable to building a shared narrative for fostering the trust and social acceptance of ambitious climate goals (Gillard et al., 2017). Failures of procedural justice can result in discrimination and marginalisation (Sovacool and Dworkin, 2015). Environmental objectives are achieved at a high socioeconomic cost and impose unfair burdens on disadvantaged communities (Lo, 2020).

China's energy justice issues are mainly manifested in two aspects. First, the mandatory energy reform in some areas fails to consider the cost of energy use for low-income groups. Measures for pollution prevention have hindered some small businesses from obtaining income and affected the satisfaction of energy demand for livelihoods. Governance through social movements in China has been criticised since it may break the rule of law during implementation. To implement coal burning control, some local governments have adopted administrative coercive measures to punish residents who violate the ban on coal utilisation. However, article 36 of the Atmospheric Pollution Prevention Law of China only provides that governments at all levels should encourage residents to burn high-quality coal and clean coal and promote the utilisation of energy-saving and environment-friendly stoves.

Second, from the regional development perspective, fossil fuels such as coal are significant to industrial development, involving considerable revenue and employment. Therefore, energy transition means significant industrial changes and the social costs will seriously affect the fairness of the social benefits and risk allocation. The fossil energy industry is estimated to lose approximately 710,000 jobs in 2035, including 450,000 jobs in coal mining and washing and 260,000 jobs in the coal power industry due to energy transition (Zhang et al., 2021).

Energy legislation shall follow technical and economic efficiency principles and security, sustainability, and equity (Natorski and Solorio, 2023). Creating energy transition laws and policies that advance equity and principles of environmental justice is essential for an equitable, sustainable, and just transition (Kennedy, 2022).

Policy implications for improving China's climate governance

Environmental authoritarianism in China has stimulated the booming of climate-related policies at both the central and local levels. However, economic considerations always overtake long-term climate goals and low-carbon investment (Lockwood, 2013). Achieving carbon neutrality requires a high level of policy density and intensity. Combined with the requirements of good governance and experiences of other jurisdictions, China can improve climate policy intensity from the perspectives of the rule of law, accountability and energy transition equity.

Establish a comprehensive climate legislation system. Comprehensive and detailed climate legislation is needed to secure carbon neutrality. China can improve climate change legislation by accelerating the formulation and modification of specific climate and energy laws. The legislation of Climate Change Addressing Law and Energy Law has lasted for around ten years. However, the adoption of the two comprehensive laws remains uncertain. Without mandatory and integrated rules, the rule of law in climate governance is far from achieved. Moreover, existing laws, such as the Renewable Energy Promotion Law, must be modified to meet carbon neutrality requirements. More mandatory provisions should be formulated. In addition, since psychological distance impedes climate mitigation actions (Spence et al., 2012), the confirmation of CO_2 as a pollutant by law can urge people to reduce emissions. Relatively mature institutions, including pollution taxes, can also be directly adapted to carbon emissions.

Formulate binding emission reduction targets. A good climate law contains statutory targets, assigns clear duties and responsibilities, and clarifies the long-term direction of travel (Fankhauser et al., 2018). These obligations are outcome duties that ensure the achievement of a specified outcome (Reid, 2012; Schapper, 2020). The German Climate Protection Act sets long-term reduction targets, including reducing total GHGs by at least 55% compared to the 1990 level by 2030 and realising carbon neutrality by 2050.

However, setting the climate targets in legislation is insufficient for the government to fulfil the responsibility. Binding targets to reduce GHG emissions instead of rhetorical promises are more important (Harris et al., 2013). The guarantee mechanisms are indispensable. Although there are no sanctions regarding the targets, various compliance mechanisms are necessary to secure their achievement, including government procurement and investment, industrial emissions caps, carbon budget management, annual target reviews, and contingency plans for unmet targets (Averchenkova et al., 2021). For example, regarding the carbon neutrality target by 2050, the Constitutional Court in Germany has ruled that the German government should set more precise targets for reducing greenhouse emissions, and the statutory provisions are insufficient to ensure the realisation of carbon neutrality in time. It should be noted that the implementation of binding climate targets requires systemic measures. It is suggested that the correct use of flexibility, together with the proper application of monitoring and enforcement measures, is necessary to secure the pursued outcome (Peeters and Athanasiadou, 2020).

Combine energy justice with regulation efficiency. To promote energy justice, climate change legislation should incorporate considerations of social differences. Interest differences and divergences are potential causes of conflicts (Singleton et al., 2021).

A more inclusive transition is critical for the sustainability of mitigation or adaptation measures. It is suggested that climate policy mixes must ensure a just transition to achieve public support (Andresen et al., 2021). Climate change legislation should balance multiple social, economic, and environmental targets to secure the durable and stable implementation of related measures. For example, the 2020 Denmark Climate Act provides that the realisation of Denmark's climate targets must consider sustainable business development, competitiveness, sound public finances and employment and maintain a strong welfare society where cohesion and social balance are secured (Gregersen and Johnson, 2021).

Lower-income households spend more on emission-intensive products such as heat and power (Buchholz et al., 2019). They are less able to switch to lower emission-intensive substitutes. Groups lacking access to clean energy should be allowed to use traditional energy sources. However, the government should take measures to provide clean energy, prohibit the adoption of compulsory measures to punish the use of conventional energy, and secure residents' basic energy needs for livelihood. Shutting down coal-fired power plants or coal mines will create economic hardship for workers and local governments, and subsidies for new industries should be provided by the central government (Carley and Konisky, 2020).

In addition, decarbonisation in industries should consider the economic influence and carbon footprints of different sectors to realise regulation efficiency. The input–output analysis combined with carbon footprints can provide a primary direction for designing a cost-effective and flexible decarbonisation approach. Specifically, sectors with above-average emissions linkages but below-average production linkages, such as transport and mining, should be constrained first by limiting the scale or levying carbon taxes. For industries with above-average emissions and production linkages, such as metal processing and production, electricity, and chemical fibre, a progressive transition approach is necessary, as the stability of these industries is vital for economic security and social stability (Chang and Han, 2020).

Conclusions

Achieving carbon neutrality has become a priority for China. However, a green paradox still exists. The increase in climate policies has not changed the carbon emission trend. The weakness of policies is one of the reasons for the green paradox. Policy quantity is insufficient for policy effectiveness. More efforts are needed to improve policy intensity. Developments in climate governance theories provide valuable references for strengthening China's climate regulation. Political commitment needs to be confirmed by legislation to ensure its stability, compulsion, and accountability. This will provide reliable legal expectations and guarantees regarding some critical response measures. Since time has become the decisive factor in climate change, climate legislation should be more direct, systematic, and comprehensive, combined with energy justice. Then, climate change governance will be more target-oriented, through which different interests can be negotiated and coordinated.

Moreover, the actual considerations of the government regarding carbon quota allocation and the impacts of different reduction paths still need to be further analysed. Legislations cannot guarantee the effectiveness of implementation. Addressing climate change is a systematic and long-term project. Special climate legislation will face new problems and contradictions during implementation, and settling them once and for all is difficult. Therefore, a dynamic policy and legislation response mechanism is needed.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files.

Received: 14 November 2022; Accepted: 8 November 2023;
Published online: 21 November 2023

References

Ahmad N, Du L (2017) Effects of energy production and CO_2 emissions on economic growth in Iran: ARDL approach. Energy 123:521–537. https://doi.org/10.1016/j.energy.2017.01.144

Andresen S, Bang G, Skjærseth JB et al. (2021) Achieving the ambitious targets of the Paris Agreement: the role of key actors. Int Environ Agreem Politics Law Econ 21:1–7. https://doi.org/10.1007/s10784-021-09527-6

Averchenkova A, Fankhauser S, Finnegan J (2021) The impact of strategic climate legislation: evidence from expert interviews on the UK Climate Change Act. Clim Policy 21(2):251–263. https://doi.org/10.1080/14693062.2020.1819190

Ayalew HA (2013) Determinants of domestic saving in Ethiopia: an autoregressive distributed lag (ARDL) bounds testing approach. J Econ Int Finance 5(6):248–257. https://doi.org/10.5897/JEIF2013.0526

Barendrecht M (2011) Rule of law, measuring and accountability: problems to be solved bottom up. Hague J Rule Law 3(2):281–304

Barton B, Campion J (2019) Energy justice and the design of climate change legislation: avoiding regressive measures. In: Del Guayo I et al. (eds) Energy justice and energy law. Oxford University Press, pp. 203–216

Bauer N, McGlade C, Hilaire J et al. (2018) Divestment prevails over the green paradox when anticipating strong future climate policies. Nat Clim Change 8:130–134. https://doi.org/10.1038/s41558-017-0053-1

Beeson M (2010) The coming of environmental authoritarianism. Environ Politics 19(2):276–294. https://doi.org/10.1080/09644010903576918

Buchholz W, Dippl L, Eichenseer M (2019) Subsidizing renewables as part of taking leadership in international climate policy: the German case. Energy policy 129:765–773. https://doi.org/10.1016/j.enpol.2019.02.044

Cairns RD (2014) The green paradox of the economics of exhaustible resources. Energy Policy 65:78–85. https://doi.org/10.1016/j.enpol.2013.10.047

Carley S, Konisky DM (2020) The justice and equity implications of the clean energy transition. Nat Energy 5(8):569–577. https://doi.org/10.1038/s41560-020-0641-6

Chang N, Han C (2020) Cost-push impact of taxing carbon in China: a price transmission perspective. J Clean Prod 248:119194. https://doi.org/10.1016/j.jclepro.2019.119194

Dubash NK (2020) Climate laws help reduce emissions. Nat Clim Change 10(8):709–710. https://doi.org/10.1038/s41558-020-0853-6

Dubash NK (2021) Varieties of climate governance: the emergence and functioning of climate institutions. Environ Polit 30:1–25. https://doi.org/10.1080/09644016.2021.1979775

Engels A (2018) Understanding how China is championing climate change mitigation. Palgrave Commun 4(1):1–6. https://doi.org/10.1057/s41599-018-0150-4

Eskander S, Fankhauser S, Setzer J (2021) Global lessons from climate change legislation and litigation. Environ Energy Policy Econ 2:44–82. https://doi.org/10.1086/711306

Fankhauser S, Averchenkova A, Finnegan J (2018) 10 years of the UK Climate Change Act. Grantham Research Institute, London

Fankhauser S, Gennaioli C, Collins M (2015) The political economy of passing climate change legislation: evidence from a survey. Glob Environ Change 35:52–61. https://doi.org/10.1016/j.gloenvcha.2015.08.008

Fisch-Romito V, Guivarch C, Creutzig F et al. (2021) Systematic map of the literature on carbon lock-in induced by long-lived capital. Environ Resear Lett 16(5):053004. https://doi.org/10.1088/1748-9326/aba660

Gillard R, Gouldson A, Paavola J et al. (2017) Can national policy blockages accelerate the development of polycentric governance? Evidence from climate change policy in the United Kingdom. Glob Environ Change 45:174–182. https://doi.org/10.1016/j.gloenvcha.2017.06.003

Gransaull G, Rhodes E, Fairbrother M (2023) Institutions for effective climate policymaking: lessons from the case of the United Kingdom. Energy Policy 175:113484. https://doi.org/10.1016/j.enpol.2023.113484

Gregersen B, Johnson B (2021) The measurement and performance of the Danish innovation system in relation to sustainable development. In: Christensen JL, Gregersen B, Holm JR, Lorenz E (eds) Globalisation, new and emerging technologies, and sustainable development. Routledge, Oxon and New York, pp. 252–266

Gu A, Teng F, Feng X (2018) Effects of pollution control measures on carbon emission reduction in China: evidence from the 11th and 12th Five-Year Plans. Clim Policy 18(2):198–209. https://doi.org/10.1080/14693062.2016.1258629

Guo W, Chen Y (2018) Assessing the efficiency of China's environmental regulation on carbon emissions based on Tapio decoupling models and GMM models. Energy Rep 4:713–723. https://doi.org/10.1016/j.egyr.2018.10.007

Harris PG, Chow Y, Karlsson R (2013) China and climate justice: moving beyond statism. Int Environ Agreem Political Law Econ 13:291–305. https://doi.org/10.1007/s10784-012-9189-7
Heggelund GM (2021) China's climate and energy policy: at a turning point? Int Environ Agreem Political Law Econ 21:9–23. https://doi.org/10.1007/s10784-021-09528-5
Heinen D, Arlati A, Knieling J (2022) Five dimensions of climate governance: a framework for empirical research based on polycentric and multi-level governance perspectives. Environ Policy Gov 32(1):56–68. https://doi.org/10.1002/eet.1963
Hübler M, Voigt S, Löschel A (2014) Designing an emissions trading scheme for China—an up-to-date climate policy assessment. Energy policy 75:57–72. https://doi.org/10.1016/j.enpol.2014.02.019
Iacobuta G, Dubash NK, Upadhyaya P et al. (2018) National climate change mitigation legislation, strategy and targets: a global update. Clim Policy 18(9):1114–1132. https://doi.org/10.1080/14693062.2018.1489772
IEA (2021) Global energy review 2021. IEA, Paris
IPCC (2022) Climate Change 2022: mitigation of climate change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York
Jenkins K, McCauley D, Heffron R et al. (2016) Energy justice: a conceptual review. Energy Res Soc Sci 11:174–182. https://doi.org/10.1016/j.erss.2015.10.004
Kennedy EJ (2022) Equitable, sustainable, and just: a transition framework. Arizona Law Rev 64(4):1045–1096
Khan Z, Zhu S, Yang S (2019) Environmental regulations an option: asymmetry effect of environmental regulations on carbon emissions using non-linear ARDL. Energy Source Part A 41(2):137–155. https://doi.org/10.1080/15567036.2018.1504145
Lee HW (2019) Moderators of the motivational effects of performance management: a comprehensive exploration based on expectancy theory. Public Pers Manag 48(1):27–55. https://doi.org/10.1177/0091026018783003
Liu Y, Jiang Y, Liu H et al. (2022) Driving factors of carbon emissions in China's municipalities: a LMDI approach. Environ Sci Pollut Res 29:21789–21802. https://doi.org/10.1007/s11356-021-17277-w
Lo K (2020) Ecological civilization, authoritarian environmentalism, and the eco-politics of extractive governance in China. Extr Ind Soc 7(3):1029–1035. https://doi.org/10.1016/j.exis.2020.06.017
Lockwood M (2013) The political sustainability of climate policy: the case of the UK Climate Change Act. Glob Environ Change 23(5):1339–1348. https://doi.org/10.1016/j.gloenvcha.2013.07.001
Lysack M (2021) Best practices in effective climate policy implementation, governance, and accountability: the UK Committee on Climate Change. In: Mišík M, Kujundžić N (eds) Energy humanities. Current state and future directions. Springer, Cham
Mao X, Yang S, Liu Q, Tu J, Jaccard M (2012) Achieving CO_2 emission reduction and the co-benefits of local air pollution abatement in the transportation sector of China. Environ Sci Policy 21:1–13. https://doi.org/10.1016/j.envsci.2012.03.010
Meadowcroft J (2009) Climate change governance. Background paper to the 2010 World Development Report, policy research working paper 4941. The World Bank
Menzies N, Almuzaini Y, Annandsingh C et al. (2020) World Bank reference guide to climate change framework legislation. World Bank, Washington, DC
Minnerop P (2020) The first German climate case. Environ Law Rev 22(3):215–226. https://doi.org/10.1177/1461452920948626
Moore C (2012) Climate change legislation: current developments and emerging trends. In: Chen W, Seiner J, Suzuki T et al. (eds) Handbook of climate change mitigation. Springer, New York, pp. 43–87
National Bureau of Statistics of China (2022) China statistical yearbook. China Statistics Press, Beijing
Natorski M, Solorio I (2023) Policy failures and energy transitions: the regulatory bricolage for the promotion of renewable energy in Mexico and Chile. NPJ Clim Action 2:8. https://doi.org/10.1038/s44168-023-00039-4
Neuweg I, Averchenkova A (2017) Trends in climate change legislation and policy in China, the European Union and the United States. Edward Elgar Publishing, Cheltenham, MA
Nielsen T, Baumert N, Kander A, Jiborn M, Kulionis V (2021) The risk of carbon leakage in global climate agreements. Int Environ Agreem Political Law Econ 21:147–163. https://doi.org/10.1007/s10784-020-09507-2
Nwankwo CF (2019) Understanding US government reluctance to accept legally binding emissions reduction targets: the import of elite interest convergence. Open Political Sci 2(1):9–20. https://doi.org/10.1515/openps-2019-0002
O'Brien RM (2007) A caution regarding rules of thumb of variance inflation factors. Qual Quant 41:673–690. https://doi.org/10.1007/s11135-006-9018-6
Peeters M, Athanasiadou N (2020) The continued effort sharing approach in EU climate law: binding targets, challenging enforcement? RECIEL 29:201–211. https://doi.org/10.1111/reel.12356
Perron P (1989) The great crash, the oil price shock, and the unit root hypothesis. Econometrica 57(6):1361–1401. https://doi.org/10.2307/1913712
Perron P, Vogelsang TJ (1992) Nonstationarity and level shifts with an application to purchasing power parity. J Bus Econ Stat 10(3):301–320. https://doi.org/10.1080/07350015.1992.10509907
Pesaran MH, Shin Y, Smith RJ (2001) Bounds testing approaches to the analysis of level relationships. J Appl Econ 16:289–326. https://doi.org/10.1002/jae.616
Reid CT (2012) A new sort of duty? The significance of "outcome" duties in the climate change and child poverty acts. Public Law 4:749–767
Ribeiro FDM, Kruglianskas I (2015) Principles of environmental regulatory quality: a synthesis from literature review. J Clean Prod 96:58–76. https://doi.org/10.1016/j.jclepro.2014.03.047
Romero-Lankao P, Burch S, Hughes S et al. (2018) Governance and policy. In: Rosenzweig C, Solecki W, Romero-Lankao P et al. (eds) Climate change and cities: second assessment report of the urban climate change research network. Cambridge University Press, New York, pp. 585–606
Schaffrin A, Sewerin S, Seubert S (2014) The innovativeness of national policy portfolios—climate policy change in Austria, Germany, and the UK. Environ Politics 23(5):860–883. https://doi.org/10.1080/09644016.2014.924206
Schaffrin A, Sewerin S, Seubert S (2015) Toward a comparative measure of climate policy output. Policy Stud J 43:257–282. https://doi.org/10.1111/psj.12095
Schapper A (2020) Book review: climate and energy governance for the UK low carbon transition: the Climate Change Act 2008. Environ Law Rev 22(2):159–161. https://doi.org/10.1177/1461452920932685
Schreurs M (2017) Multi-level climate governance in China. Environ Policy Gov 27(2):163–174. https://doi.org/10.1002/eet.1751
Seto KC, Davis SJ, Mitchell RB et al. (2016) Carbon lock-in: types, causes, and policy implications. Annu Rev Environ Resour 41:425–452. https://doi.org/10.1146/annurev-environ-110615-085934
Singleton BE, Rask N, Magnusdottir GL et al. (2021) Intersectionality and climate policy-making: the inclusion of social difference by three Swedish government agencies. Environ Plan C Politics Space 40(1):180–200. https://doi.org/10.1177/23996544211005778
Sinn HW (2008) Public policies against global warming: a supply side approach. Int Tax Public Finance 15:360–394. https://doi.org/10.1007/s10797-008-9082-z
Sovacool BK, Dworkin MH (2015) Energy justice: conceptual insights and practical applications. Appl Energy 142:435–444. https://doi.org/10.1016/j.apenergy.2015.01.002
Spence A, Poortinga W, Pidgeon N (2012) The psychological distance of climate change. Risk Anal 32(6):957–972. https://doi.org/10.1111/j.1539-6924.2011.01695.x
Steinthorsdottir M, Jardine PE, Lomax BH et al. (2022) Key traits of living fossil *Ginkgo biloba* are highly variable but not influenced by climate—implications for palaeo-pCO_2 reconstructions and climate sensitivity. Glob Planet Change 211:103786. https://doi.org/10.1016/j.gloplacha.2022.103786
Stutzer R, Rinscheid A, Oliveira TD et al. (2021) Black coal, thin ice: the discursive legitimisation of Australian coal in the age of climate change. Humanit Soc Sci Commun 8:178. https://doi.org/10.1057/s41599-021-00827-5
Sun Y, Li M, Zhang M et al. (2021) A study on China's economic growth, green energy technology, and carbon emissions based on the Kuznets curve (EKC). Environ Sci Pollut Res 28:7200–7211. https://doi.org/10.1007/s11356-020-11019-0
Teng F, Wang P (2021) The evolution of climate governance in China: drivers, features, and effectiveness. Environ Polit 30:141–161. https://doi.org/10.1080/09644016.2021.1985221
Townshend T, Fankhauser S, Aybar R et al. (2013) How national legislation can help to solve climate change. Nat Clim Change 3(5):430–432. https://doi.org/10.1038/nclimate1894
Tvarnø CD (2020) Regulating the climate. Copenhagen Business School, Frederiksberg. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3545358. Accessed 15 Oct 2022
Udayanganie D, Charos EN (2017) Trade GDP nexus in Greece: an application of ARDL model. Cyprus J Sci 15:3–28
Van der Ploeg F, Withagen C (2015) Global warming and the green paradox: a review of adverse effects of climate policies. Rev Environ Econ Policy 9(2):285–303. https://doi.org/10.1093/reep/rev008
Wang X (2020) Study on the direct impact of environmental regulation policy on carbon emission intensity in China. J Appl Sci Eng Innov 7:136–142
Wang X, Zhang T, Nathwani J et al. (2022) Environmental regulation, technology innovation, and low carbon development: revisiting the EKC Hypothesis, Porter Hypothesis, and Jevons' Paradox in China's iron & steel industry. Technol Forecast Soc Change 176:121471. https://doi.org/10.1016/j.techfore.2022.121471
Westman L, Broto VC (2018) Climate governance through partnerships: a study of 150 urban initiatives in China. Glob Environ Change 50:212–221. https://doi.org/10.1016/j.gloenvcha.2018.04.008

World Bank Open Data (2023) World Bank, Washington, DC. https://data.worldbank.org. Accessed 21 Apr 2023
Wu J, Zuidema C, de Roo G (2022) Climate policy integration on energy transition: an analysis on Chinese cases at the local scale. Cities 120:103469. https://doi.org/10.1016/j.cities.2021.103469
Xu S (2021) The paradox of the energy revolution in China: a socio-technical transition perspective. Renew Sustain Energy Rev 137:110469. https://doi.org/10.1016/j.rser.2020.110469
Yan Y, Zhang X, Zhang J et al. (2020) Emissions trading system (ETS) implementation and its collaborative governance effects on air pollution: the China story. Energy Policy 138:111282. https://doi.org/10.1016/j.enpol.2020.111282
Yu K (2018) Governance and good governance: a new framework for political analysis. Fudan J Hum Soc Sci 11:1–8. https://doi.org/10.1007/s40647-017-0197-4
Zhang H, Huang X, Zhang D et al. (2021) Evaluating economic and social benefits of accelerated energy transition. Bull Chin Acad Sci 36(9):1039–1048. https://doi.org/10.16418/j.issn.1000-3045.20210813003
Zhang J, Jiang X, Pan X (2019) Regional legislation to address climate change in China: necessity and feasibility. Int J Clim Change Strateg Manage 11(4):536–551. https://doi.org/10.1108/IJCCSM-05-2018-0046
Zhang K, Zhang ZY, Liang QM (2017) An empirical analysis of the green paradox in China: from the perspective of fiscal decentralization. Energy Policy 103:203–211. https://doi.org/10.1016/j.enpol.2017.01.023
Zhang Y, Liu Z, Zhang H et al. (2014) The impact of economic growth, industrial structure and urbanization on carbon emission intensity in China. Nat. Hazards 73:579–595. https://doi.org/10.1007/s11069-014-1091-x
Zivot E, Andrews D (1992) Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. J Bus Econ Stat 10(3):251–270. https://doi.org/10.2307/1391541

Author contributions

SX designed the study, performed data analysis and wrote the manuscript.

Competing interests

The author declares no competing interests.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-023-02381-8.

Correspondence and requests for materials should be addressed to Shengqing Xu.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2023