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Extent of global decarbonization of the power sector through energy policies and governance capacity

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During the 2007-2008 global financial crisis, many countries enacted clean energy policies as a part of their economic stimulus packages. These policies are believed to have contributed to a significant reduction in the CO_2 intensity of electricity. Here we conduct a retrospective overview and evaluation of energy policies' effectiveness in reducing the CO_2 intensity of electricity. We utilize governance capacity as a measure of policy implementation stringency, and the interaction between governance capacity and the number of categorized policies to adjust policy variables for governance effectiveness. We distinguish between the short- and long-term effects of these policies to investigate the impacts of policy instruments on CO_2 mitigation. The results suggest that the increased policy efforts, when executed with effective governance, have led to long-term cumulative effects. Our findings provide insights into the spatiotemporal dynamics of energy policies in CO_2 mitigation, serving as a reference for policymakers in the post-COVID-19 era.

The lack of decarbonization in the global economy poses significant challenges in adhering to the carbon budget necessary to mitigate climate change. As the primary industrial contributor to CO_2 emissions, the power sector is pivotal in global efforts to combat climate change[1]. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) highlights the urgency of implementing more stringent policies to accelerate the global transition towards a low-carbon future, emphasizing the need for the power sector to fully decarbonize by 2050 to align with the 1.5 °C warming target[2,3]. Policy interventions are widely regarded as crucial for facilitating access to non-fossil fuel, establishing renewable energy infrastructure, adopting clean technologies, and promoting interregional electricity trade, all of which are essential for low-carbon transition of power sector[4,5]. However, the insufficient progress in decarbonizing the global economy and the uneven spatial distribution of CO_2 reduction policies indicate the existence of significant hurdles that still need to be overcome to align CO_2 emissions from the power sector with the ambitious climate targets set amidst the current global energy transition[6]. Thus, understanding the impacts of diverse policies on the decarbonization of the power sector is imperative for designing effective climate mitigation strategies tailored to meet these ambitious goals[7].

Most research based on integrated assessment models is oriented towards ex-ante policy evaluation, focusing on the assessment of possible climate policies before their implementation. This approach aims to predict the effectiveness and feasibility of policies in meeting the 1.5 °C or 2 °C climate targets. Ex-ante evaluation helps stakeholders understand the potential impacts of policies on climate change mitigation, guiding strategic planning towards achieving these ambitious goals[8]. In contrast, ex-post policy evaluation examines the actual effects of climate policy after their implementation. It helps us to assess the successful climate actions in practice rather than climate pledges (political commitments), thus offering insights into which strategies have effectively contributed to climate change mitigation. This retrospective analysis is vital for identifying successful climate policies and understanding the dynamics of policy impacts in real-world settings[8–10]. For example, Pineiro-Villaverde and García-Álvarez analyzed the impacts of wind and solar energy support policies (supply-side policies) and energy tax policies (demand-side policies) on CO_2 intensity of

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electricity in 28 European Union countries over the period of 2000–2019[11]. Sæther investigated the impacts of the emission trading system (market-based policy instrument), feed-in tariff (deployment supporting policy), public environmental R&D expenditure, and technological innovation support policies on CO_2 intensity of electricity in 34 OECD and 5 BRICS countries over the period of 2000-2018[12]. Yi analyzed the impacts of renewable portfolio standards, energy efficiency resource standards, and public benefit funds on CO_2 intensity of electricity across the 48 continental states of the USA over the period of 1990-2008[13]. However, the existing studies have not paid sufficient attention to those energy policies enacted post-Great Recession and their role in decarbonizing the global power sector[1–3]. Notably, since the Great Recession, a growing number of recovery packages have been introduced with the aim of reducing CO_2 intensity in both the economy and the power sector[14]. There is an urgent need to assess the effects of these policies on the energy transition, especially in the context of external shocks such as the global financial crisis and the COVID-19 pandemic. This assessment is essential for refining policy approaches and accelerating progress towards meeting global climate targets[15,16].

In this study, we first present an overview of the spatiotemporal dynamics of climate policy adoption with an emphasis on the power sector. The coverage of policy types includes non-price-based regulatory and planning measures, price-based economic incentives, renewable energy and technology initiatives, fuel choice modifications, electricity substitution, and energy efficiency improvement. The geographical scale of our analysis covers 125 countries/regions worldwide. We compile and group 1,115 energy polices targeted at the power sector of these 125 countries from the International Energy Agency's (IEA) Policies and Measures Database, which consists of four well-established policy databases (see Methods). In order to detect the statistical association between the extent of decarbonization of the power sector and energy policies, we interact the policy variables with governance capacity and distinguish between their short- and long-term policy effects, including 3 sets of policies with 15 governance effectiveness-adjusted policy variables (see Tables 1–2 and Table S2.3). We then adopt a fixed-effect model with alternative settings and a large set of control variables to test the expected association. The model is run on a panel dataset of 125 countries over 2000–2017. These estimations confirm the impacts of governance effectiveness-adjusted policy variables on CO_2 reduction. This study delivers a systematic and comprehensive evaluation of the effectiveness of the climate mitigation policy implementation in reducing CO_2 emissions within the power sector. The analysis spans the period from 2000 to 2017, covering both the pre- and post-global financial crisis eras[7]. The findings shed light on the potential for CO_2 mitigation through newly introduced policies in the aftermath of the COVID-19 pandemic.

Results

Temporal trends in policies targeted the global power sector

Figure 1 shows that a wide range of regulatory and economic incentive measures have been implemented in the global power sector since the financial crisis. The majority (37%) of these policies involve financial mechanisms such as payments, grants, transfers, and taxation. Regulations, codes, and standards are the second most common category of policy, accounting for 25%. Targets, plans, and framework legislation account for 18%, while feed-in tariffs/premiums account for 12% and tax credits, taxes, fees, charges, and exemptions account for 8% (Fig. 1a). Governments prioritized economic incentives, designed regulatory measures, and set targets and plans for power sector during the recovery period of financial crisis (2007-2011).

In terms of renewable energy policies, the vast majority (67%) prefer wind and solar energy. Prior to the global financial crisis, the number of newly enacted solar policies was comparable to the number of wind policies. However, since 2007, there has been a considerable increase in the application of solar policies (Fig. 1b), which has resulted in a significant reduction in the cost of solar PV. As a result, solar PV has achieved a competitive levelized cost of energy (LCOE) about US$0.08/kWh, compared to wind, ranging between US$0.06-0.11/kWh in 2017[17]. Lazard's latest reports on levelized cost of energy also show that the utility-scale solar PV and onshore wind have achieved a minimum LCOE of US$0.024/kWh compared to US $0.064/kWh for coal and US$0.033/kWh for gas combined cycle when taking into account dispatch characteristics in the United States in 2023[18]. Solar PV might be an important driver in lowering CO_2 emissions in the future. Meanwhile, the number of measures supporting hydropower, geothermal, and marine energy has climbed marginally since 2007 (Fig. 1b).

In terms of other technological policy, 45% of newly enacted policies are focused on energy efficiency (Fig. 1c). There was also a major growth in policies relating to technology R&D innovation and combined heat and power projects during the crisis recovery phase. Finally, Carbon Capture, Utilization and Storage (CCUS) and digitization policies have a smaller share during the study period[19]. The global financial crisis provided the opportunity for climate scientists and policymakers to examine and update the energy policy framework of the global power sector[20].

Spatial heterogeneity of policies targeted the global power sector

Figure 2 depicts the spatial variations in the cumulative number of policies on the power sector. Europe and Asia Pacific implemented the greatest number of enacted policies, followed by North America, Central and South America, Africa, Eurasia, and Middle East (see Figs. 2 and S1.1). In Fig. 2a, 1,583 regulatory and economic policies were enacted. The number of regulatory policies outweighed the number of financial policies in China, the United States, and Spain, while financial incentive policies prevailed in Italy, the United Kingdom, and India. China established the largest number of economic and regulatory policies (108), followed by the United States (95), and India (92). In Europe, Italy issued the most economic and regulatory policies (58), followed by Spain (49), and the United Kingdom (42).

In Fig. 2b, 1103 policies on renewables technology were enacted. It is worth noting that renewables policies, particularly those aimed at solar and wind energy, were widely enacted globally. 105 out of 125 countries have solar policies that exceed or equal the number of wind power policies. China implemented the largest number of renewables technology policies (87), followed by Australia (64), and the United States (62).

In Fig. 2c, 492 policies were enacted in other technology group. Specifically, energy efficiency policy accounts for 45% of other technology policy group, combined heat and power for 30%, and technology R&D and innovation for 20%. The United States implemented the largest number of other technology policies (84), followed by Australia (41) and the United Kingdom (39).

However, we find that other technology policies are mainly implemented in countries such as the United States, Australia, Canada, China, India, and European countries. Accordingly, South American, African, Middle Eastern, and Southeast Asian countries all show a lack of other technology policies. This lack of policies may result in the falling behind of electricity generation technologies. Thus, improving energy efficiency and promoting clean R&D innovation could benefit climate mitigation in these regions.

The role of emission-reducing policies in accelerating decarbonization of the power sector

We adopt econometric models to quantify the cumulative effects of policies on the CO_2 intensity of electricity by distinguishing between their short- and long-term effects (see Tables 1–2 and Table S2.3)[21]. Furthermore, because CO_2 reduction depends substantively on the strength of policies and the rigor with which it is implemented, we use the normalized mean of six aggregate governance indicators to represent the strength of policy implementation and take the interaction between this governance capacity measure and the number of policies passed in each year into account[22]. These interaction terms are treated as the governance effectiveness-adjusted policy variables. The correlation coefficient matrix of variables is shown in Supplementary Fig. S2.1. In addition, to ensure the robustness of results, econometric regressions without distinguishing the short- and long-term effects and without considering the governance interaction effects are also

Table 1 | The effects of price-based policies versus non-price policy instruments on carbon intensity of the power sector

Policy type	Independent variables	FE(1)	FE(2)	FE(3)	FE(4)	FE(5)	FE(6)
Governance effectiveness-adjusted, non-price policies	RCS.s×GC		−7.514				
			(4.903)				
	RCS.l×GC		−11.322***				
			(2.665)				
	TPFL.s×GC			−11.516*			
				(6.330)			
	TPFL.l×GC			−15.385***			
				(3.453)			
Governance effectiveness-adjusted, price-based policies	TTFCE.s×GC				−9.101		
					(10.051)		
	TTFCE.l×GC				−24.054***		
					(7.028)		
	FT.s×GC					−12.863	
						(8.975)	
	FT.l×GC					−18.717***	
						(5.975)	
	PFTGT.s×GC						−4.978
							(3.534)
	PFTGT.l×GC						−8.519***
							(1.749)
Control variables	GDP per capita	0.0004	0.001	0.001	0.001	0.001	0.001
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
	Urbanization	−1.054	−0.060	0.315	−0.711	0.293	0.188
		(1.794)	(1.799)	(1.811)	(1.792)	(1.839)	(1.803)
	lag(Pump price for gasoline, 1)	−14.680	−3.159	−5.331	−7.247	−3.915	−0.799
		(12.055)	(12.265)	(12.185)	(12.220)	(12.535)	(12.326)
	Fuel import	1.907***	1.782***	1.909***	1.793***	1.844***	1.842***
		(0.648)	(0.645)	(0.645)	(0.647)	(0.647)	(0.645)
	Fuel export	−0.046	−0.022	−0.040	−0.027	−0.052	−0.022
		(0.275)	(0.274)	(0.274)	(0.275)	(0.275)	(0.274)
	Electricity access	2.895***	2.678***	2.741***	3.138***	2.565***	2.629***
		(0.786)	(0.783)	(0.783)	(0.790)	(0.791)	(0.783)
	Fuel efficiency	−2.766***	−2.736***	−2.724***	−2.717***	−2.683***	−2.788***
		(0.610)	(0.607)	(0.607)	(0.611)	(0.609)	(0.607)
	Fossil capacity load factor	0.382***	0.317***	0.328***	0.340***	0.323***	0.293***
		(0.088)	(0.089)	(0.088)	(0.088)	(0.090)	(0.089)
	Observations	1,836	1,836	1,836	1,836	1,836	1,836
	R^2	0.034	0.046	0.046	0.041	0.040	0.047
	F Statistic	7.613***	8.233***	8.205***	7.298***	7.158***	8.546***

Note: (1) Standard errors in parentheses; (2) Statistical significance levels: $^{***}P < 0.01$ (1% level), $^{**}P < 0.05$ (5% level), $^{*}P < 0.1$ (10% level); (3) GC: governance capacity; (4) FE: fixed-effects model; (5) Fuel export share represents the percentage of mineral fuels, lubricants, and related materials in merchandise exports; (6) Fuel efficiency refers to the average production efficiency of fossil fuel power plants; (7) RCS and TPFL are non-price-based policies, while FT, PFTGT, and TTFCE are price-based policies[24,45].

conducted and the corresponding results are presented in Supplementary Fig. S2.2 and Tables S2.4–S2.7 for comparisons. Notably, we run econometric models for 125 countries worldwide, and their electricity production accounts for 97% of the global total electricity output (see Supplementary Table S2.8).

Ex-post evaluation of price-based versus non-price policies. Because price-based policies and non-price policy instruments utilize distinct approaches to control CO_2 emissions and they address the issues of climate change mitigation through different mechanisms[23,24], we conduct econometric regressions separately for price-based and non-price policy instruments, as shown in Table 1.

The FE(2) column in Table 1 indicates that regulation, codes, and standards (RCS) as a set of non-price policy instrument has exerted a significant long-term mitigation effect, being able to lower the global CO_2 intensity of electricity by 11.322 gCO_2/kWh per unit of policies, while its short-term effect is not statistically significant. Examples of such RCS policies include the solar regulations and standards that United States issued in 2007, which aim to remove barriers and promote the use of solar technologies, and Turkey's commissioning of renewable energy projects in 2016

Table 2 | The effects of renewables technology policies on carbon intensity of the power sector

Policy type	Independent variables	FE(i)	FE(ii)	FE(iii)	FE(iv)	FE(v)	FE(vi)
Governance effectiveness-adjusted policy variables	Hydropower.s×GC		−8.043				
			(9.487)				
	Hydropower.l×GC		−21.931***				
			(5.932)				
	Wind.s×GC			−6.274			
				(5.639)			
	Wind.l×GC			−14.614***			
				(3.112)			
	Solar.s×GC				−9.690**		
					(4.509)		
	Solar.l×GC				−12.651***		
					(2.653)		
	Geothermal.s×GC					−16.689*	
						(9.948)	
	Geothermal.l×GC					−31.123***	
						(6.780)	
	Marine.s×GC						−14.209
							(12.426)
	Marine.l×GC						−26.758***
							(7.079)
Control variables	GDP per capita	0.0004	0.001	0.001	0.001	0.001	0.001
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
	Urbanization	−1.054	−0.323	0.128	0.574	0.011	−0.691
		(1.794)	(1.799)	(1.803)	(1.816)	(1.800)	(1.791)
	lag(Pump price	−14.680	−3.999	−2.187	−4.444	−3.526	−7.492
	for gasoline, 1)	(12.055)	(12.410)	(12.316)	(12.139)	(12.229)	(12.165)
	Fuel import	1.907***	1.795***	1.843***	1.961***	1.839***	1.951***
		(0.648)	(0.646)	(0.646)	(0.644)	(0.644)	(0.646)
	Fuel export	−0.046	−0.017	−0.027	−0.021	−0.033	−0.040
		(0.275)	(0.274)	(0.274)	(0.274)	(0.274)	(0.274)
	Electricity access	2.895***	2.868***	2.630***	2.623***	2.562***	2.648***
		(0.786)	(0.784)	(0.784)	(0.783)	(0.785)	(0.786)
	Fuel efficiency	−2.766***	−2.805***	−2.712***	−2.682***	−2.937***	−2.805***
		(0.610)	(0.608)	(0.607)	(0.607)	(0.608)	(0.608)
	Fossil capacity	0.382***	0.328***	0.288***	0.292***	0.306***	0.335***
	load factor	(0.088)	(0.089)	(0.090)	(0.089)	(0.089)	(0.088)
	Observations	1,836	1,836	1,836	1,836	1,836	1,836
	R^2	0.034	0.042	0.046	0.049	0.046	0.042
	F Statistic	7.613***	7.499***	8.368***	8.792***	8.298***	7.564***

Note: (1) standard errors in parentheses; (2) statistical significance levels: ***$P < 0.01$ (1% level), **$P < 0.05$ (5% level), *$P < 0.1$ (10% level); (3) GC: governance capacity.

to ensure the efficient and effective use of renewables[25]. Notably, the effectiveness of climate policy in reducing CO_2 emissions is highly influenced by a country's governance capacity. Country-specific analysis, not included in Table 1, reveals that countries with good governance capacity, such as Denmark and Austria, achieve more substantial CO_2 mitigation benefits from the implementation of RCS policies over the long term. In contrast, countries with weaker governance capacity, like Iraq and Belarus, see comparatively lesser effectiveness for similar policies.

The FE(3) column reveals both the statistically significant short- and long-term effectiveness of targets, plans, and framework legislation (TPFL) in reducing CO_2 intensity. In more detail, the short-term effect amounts to −11.516 gCO_2/kWh per unit of policies at the 10% significance level and long-term effect to −15.385 gCO_2/kWh per unit of policies at the 1% significance level. Examples of such TPFL policies include India's launch of the Jawaharlal Nehru National Solar Mission in 2010 to promote solar PV, and Germany's amendment of the Renewable Energy Sources Act (EEG) in 2012 to increase the shares of renewables in its electricity supply. Moreover, country-specific analysis indicates that these TPFL policies are more effective in countries with good governance capacity. For example, Canada and Sweden demonstrate greater policy effectiveness compared to countries with weaker governance, such as Iran and Ukraine, for each TPFL policy in the long run.

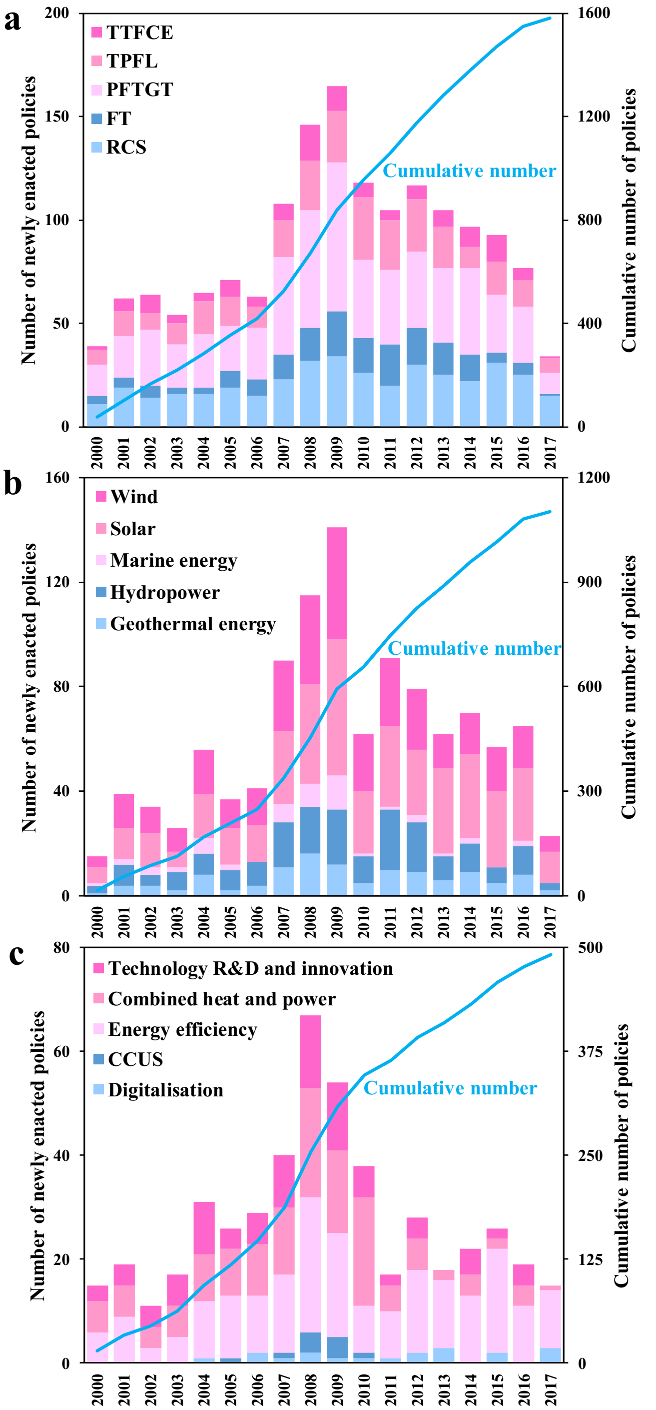


Fig. 1 | Temporal trends in the (cumulative) number of newly enacted policies from 2000 to 2017. a Regulatory and economic instruments. **b** Renewables. **c** Other technologies. Regulatory policies and economic policies are divided into five types. RCS represents regulation, codes, and standards; TPFL represents targets, plans, and framework legislation; FT represents feed-in tariffs/premiums; PFTGT represents payments, finance, transfers, grants, and taxation; TTFCE represents tax credits, taxes, fees, charges, and exemptions. The year was the time that policy went into force. Tables S1.1–S1.9 present national samples of these policies.

For price-based policies, the FE(4) model indicates that policies such as tax credits, levies, charges, and exemptions (TTFCE) have produced statistically significant long-term effect in reducing the CO_2 intensity of the power sector amounting to −24.054 gCO_2/kWh per unit of policies. Illustrative examples of the TTFCE policies include the Netherlands' energy tax exemption to renewable electricity possessing a green certificate in 2005, and the United States' Emergency Economic Stabilization Act of 2008, which extended production tax credits and investment tax credits for renewable energy sources.

The long-term effect of feed-in tariff/premium (FT) policies in lowering the CO_2 intensity of electricity is also statistically significant at the 1% level and amounts to −18.717 gCO_2/kWh per unit of policies, as shown in the FE(5) model. The increasing number and cumulative effect of the feed-in tariff policies during the global financial crisis contributed to the declining levelized cost of renewables and reduced the risk of price volatility (see Figure S3)[17,26]. Similarly, the long-term effect of payments, finance, transfer, grant, and taxes (PFTGT) in reducing CO_2 intensity of electricity is significant at the 1% level and amounts to −8.519 gCO_2/kWh per unit of policies, as presented in the FE(6) column. Illustrative examples of these PFTGT policies include Belgian's launch of an ecological investment incentive for key green high-tech solutions in 2007, the incentives for renewable energy initiatives provided by Luxembourg Ministry of Economy and Foreign Trade in 2010, and Germany's support to investments in battery storage for solar PV household installations in 2016 aiming to improve solar plant grid services. Nevertheless, the short-term effects of these price-based policies are not statistically significant.

In terms of control factors, models in Table 1 show that fuel efficiency significantly contributes to the reduction in CO_2 intensity of electricity, so does pump price for gasoline but show no robust results. In addition, urbanization and exporting energy-intensive products also contribute to CO_2 mitigation but not in a robust way. In contrast, fuel import, electricity access, and fossil capacity load factor (see Figure S4) significantly increase the CO_2 intensity.

Ex-post evaluation of renewables and other technology policies.

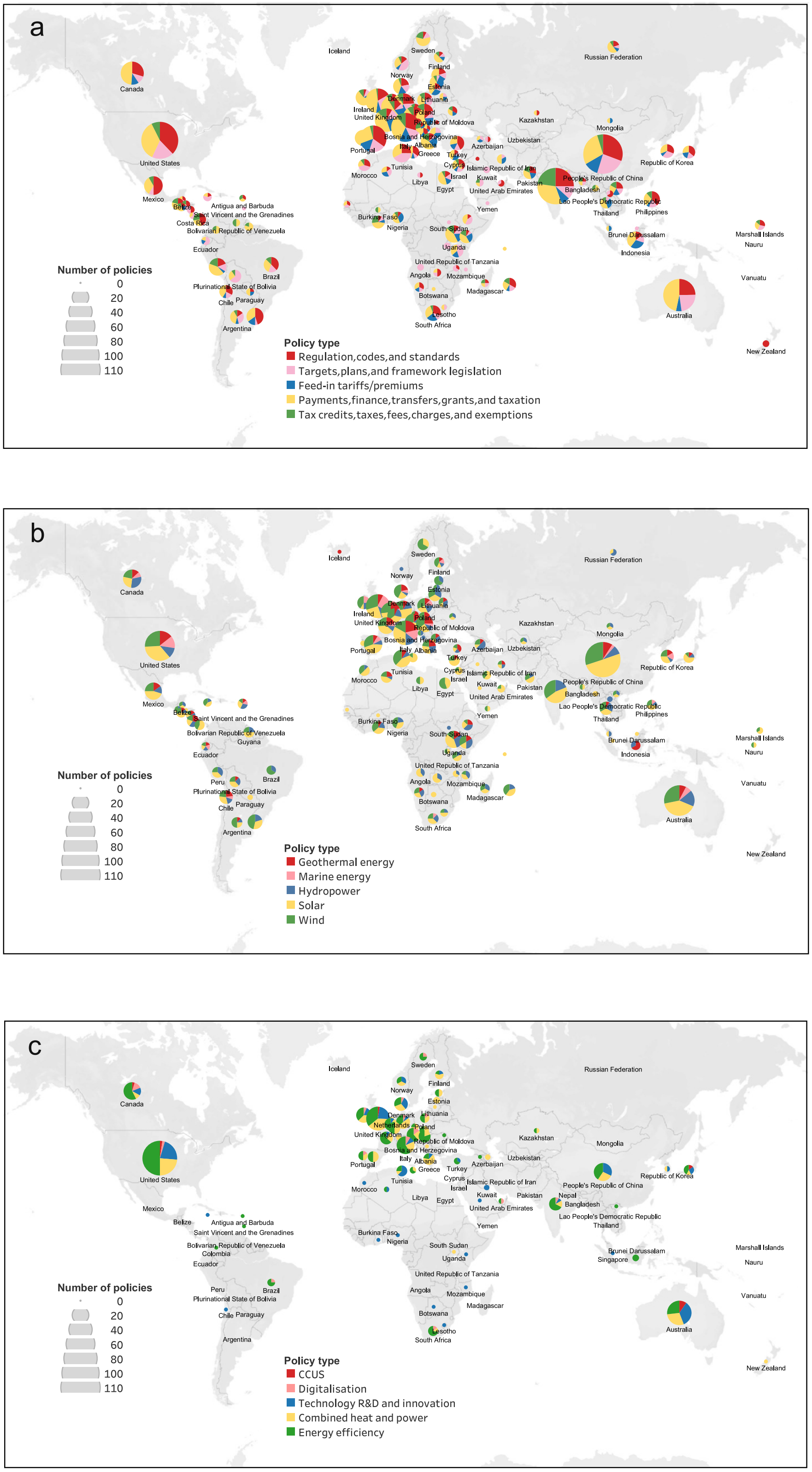
The column FE(ii) in Table 2 indicates that hydropower policies have a significant long-term effect in reducing the CO_2 intensity of the power sector, achieving −21.931 gCO_2/kWh per policy. Similarly, wind and solar PV policies also show significant CO_2 mitigation effects, as shown in FE(iii) and FE(iv), respectively. The International Renewable Energy Agency (IREA) reports that the cost of solar PV has dropped substantially and solar PV nearly achieved price parity with offshore wind since 2014[17]. FE(iii) and FE(iv) show that the marginal contribution of solar PV policies (−12.651 CO_2/kWh per unit of policies) is approaching that of wind power (−14.614 CO_2/kWh per unit of policies) in terms of their long-term effects. With the rapid decline of levelized cost, it can be expected that solar PV policies will become more effective in promoting CO_2 reduction[17]. FE(v) and FE(vi) also reveal the long-term effectiveness of policies promoting geothermal energy and marine energy in CO_2 mitigation, although geothermal and marine energies have not yet been widely used in the global electricity supply. We further examine the impacts of five other available technology policies on CO_2 mitigation in the power sector in Supplementary Table S2.3. Statistically significant long-term CO_2 mitigation effects are detected for policies promoting energy efficiency, Carbon Capture, Utilization and Storage, combined heat and power, technology R&D and innovation, and digitalization[27,28]. This result suggests that a pronounced reduction in CO_2 intensity could be achieved if these technologies were widely adopted in the future.

Discussion

The increasing coal and natural gas consumption made the global power sector even more carbon-intensive from 2000 to 2007. However, countries made great efforts and various policies following the global financial crisis, which broke the balance of the older electricity mix and created opportunities for achieving a rapid decarbonization in the power sector[29].

The spatiotemporal distribution of energy policies targeted at the power sector indicates that CO_2 mitigation strategies may largely differ among countries (see Figs. 1 and 2). It is important to develop and implement customized energy policies that reflect each country's unique climate-related political commitments, energy and economic policy frameworks,

Fig. 2 | Map of the policies by type and cumulative number in the power sector at country level from 2000 to 2017. **a** Regulatory and economic instruments. **b** Renewables. **c** Other technologies. This policy map covers 125 countries.



renewables energy endowments, energy efficiency, clean technology deployment, and R&D innovation. The tailored policy instruments would serve as stable 'wedges' for CO_2 mitigation in a specific country. Moreover, it is at least equally important to strengthen a country's governance capacity. Because good governance can ensure effective enforcement, monitoring, and implementation of clean energy policies. The climate policy instruments implemented by a big country with good governance capacity represent its political commitments to substantially curb its CO_2 emissions, which trigger continuous low-carbon transition in the power sector. By adopting well-designed policy instruments tailored to their specific needs and backed by strong governance capacity, countries can accelerate their progresses towards decarbonizing the power sector and meeting international climate targets[30,31]. In addition, public-private partnerships (PPP) through improving the governance capacity can effectively foster technological innovation, drive investments in low-carbon technologies, and facilitate the deployment of clean energy solutions[32].

Our analysis uncovers a diverse range of policy impacts on the CO_2 intensity of electricity. Notably, while most policies exhibit statistically significant long-term effects that surpass their short-term counterparts in reducing the CO_2 intensity, three groups of policies on targets, plans, and framework legislation (TPFL), solar PV, and geothermal energy demonstrate efficacy in CO_2 mitigation in both the short- and long-terms. The gradual impact of regulatory policies (RCS) is to be expected, as these measures require time to translate into tangible reductions in CO_2 intensity. This gradualism is primarily because regulatory policies often necessitate extensive groundwork, including the establishment of legal frameworks, the promotion of industry compliance, and the facilitation of technological adaptation. Conversely, price-based economic incentive policies, such as feed-in tariffs (FT), payments, finance, transfer, grants, and taxes (PFTGT), and tax credits, levies, charges, and exemptions (TTFCE) should immediately alter the cost-benefit calculations of stakeholders, and thus incentivize relatively swift adoption of greener power-generators and technologies, especially in the realms of solar and wind energy. Surprisingly, the immediate effects of these price-based incentives appear to be insignificant, despite aligning with the anticipated direction of impact. This unexpected finding may be attributed to the limitation of policy-number accounting and suggests a need for further investigation based on monetary scales of these price-based policy.

Our econometric analyses reveal that policies promoting renewable energies such as hydropower, wind power, solar PV, geothermal energy, and marine energy are significantly effective in reducing CO_2 intensity of the power sector over the long term (Table 2). Literature has shown that wind power and solar PV have a lower opportunity cost of lifecycle emissions compared to newly built nuclear, hydro, natural gas, and coal power plants[33]. This advantage positions the most recent global surge in wind and solar PV as a strategic move to prevent CO_2 lock-in, while simultaneously generating employment in the green energy sector and improving air quality and public health.

Our findings also highlight the effectiveness of policies promoting energy efficiency, CCUS, combined heat and power (CHP), technology R&D innovation, and digitalization technology in reducing CO_2 intensity in the long-term. In terms of control variables, improved fuel efficiency significantly contributes to the reduction in CO_2 intensity, while fuel import, electricity access, and fossil capacity load factor are increasing the CO_2 intensity. We deduce that a comprehensive approach involving enhanced production efficiency, the deployment of CCUS technologies, a reduction in fossil capacity load factor, increased adoption of renewable energies, development of combined heat and power systems, and the encouragement of R&D innovation and digitalization, will be pivotal in reducing CO_2 emissions in the power sector. These strategies should be supported by conducive policy framework, financial incentives, and investments in clean technology R&D and innovation. Additionally, reevaluating the operational lifespans of existing power plants and implementing policies for their phase-out or retrofitting could further decrease future CO_2 emissions[34].

Pump prices for gasoline and urbanization play a role in mitigating CO_2 emissions, although their impact is not consistently robust. As international oil prices increase, the widespread adoption of electric vehicles might accelerate the decarbonization of the power sector[35,36]. Recognizing that an increase in fossil electricity consumption in carbon-intensive countries, such as China and India, could impede global decarbonization efforts, it becomes crucial to foster international collaborations. This includes sharing best practices and knowledge, promoting the transfer of low-carbon technologies, and advancing grid integration technologies. Such cooperation will also address technical and regulatory obstacles to integrating renewable energy sources into the electricity grid, facilitating a more sustainable energy future.

The COVID-19 pandemic has introduced increased uncertainty, and the enactment of new emission-reduction policies has disrupted the CO_2 emission trend within the global power sector. We can anticipate a marked decline in CO_2 intensity of electricity over the next 1-2 decades as a result of these efforts in the post-COVID-19 era. However, there is a critical need to thoughtfully design policies for newly built fossil power plants in developing countries, especially in India and China, to ensure a smooth transition to sustainable energy sources[37]. In the ongoing post-COVID-19 era, prioritizing timely and adaptable policies is crucial. This includes implementing green fiscal recovery packages aiming at decoupling CO_2 emissions from economic growth[14,38]. It is also important to evaluate the impacts of the revised policy frameworks on the dynamics of CO_2 emission in the global power sector, considering potential shifts in the energy consumption patterns and behaviors of humans and institutions post-pandemic[14,38–42]. Currently, the priority for policymakers is to carefully upgrade and implement the climate and energy policy frameworks, enhance the resilience of new CO_2 mitigation strategies to future shocks, and foster economic recovery in the short term, while driving the global energy transition to the next level in the medium and long term.

Our study shows a notable increase in policies aiming at reducing emissions since 2017, particularly through technologies such as direct air capture with carbon storage (DACCS) and bioenergy with carbon capture and storage (BECCS), as well as policies related to fuels requiring electricity, such as green hydrogen. While these policies and emerging technologies represent steps in the right direction, they also introduce uncertainty regarding the degree and pace of decarbonization in the global power sector. This uncertainty hinges on the widespread adoption of these technologies and the effectiveness of the measures implemented. However, it is important to acknowledge that these policies and technologies have not yet seen wide adoption and have only had limited impacts up to the end of our study period. Furthermore, each regression includes only a pair of short- and long-term policy variables because of the collinearity of policy variables, as shown in Fig. S2.1. This means that the synergistic effects of different energy policies are overlooked. We apply governance capacity abstracted from WGI as a proxy for the strength and rigor of policy implementation, recognizing its limitations as a true measure of enforcement[43]. Future work should delve deeper into distinguishing the content and focus of individual policies. Additionally, while economic dispatch of the power grid indirectly reduces CO_2 emissions through energy saving, we do not integrate it into this study, potentially leading to an overestimation of the role of declining renewable energy costs in power sector decarbonization. Moreover, our study does not consider the level of technological maturity for scenario analysis, instead focusing more on retrospectively evaluating the effectiveness of climate policy choices by estimating their actual impacts on reducing CO_2 emissions from 2000 to 2017.

Methods

Econometric models

Policy variables. We work with 15 energy policy variables, which can be grouped into three sets as follows: (1) two regulatory ("non-price") types of policies and three economic incentive ("price-based") policies; (2) five renewables technology policies; (3) five other technology policies. The details of these policies are summarized in Tables S2.1 and S2.2.

Governance effectiveness-adjusted policy variables. To investigate the impacts of governance capacity on CO_2 mitigation, we use the normalized mean of six governance indicators g_{it} (namely, voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and control of corruption) to represent the stringency of policy implementation and then interact the governance capacity measure with the enacted policies.

$$g_{it} = \frac{1}{6}\sum_{i=1}^{6}\frac{g_{it} - g_i^{\min}}{g_i^{\max} - g_i^{\min}} \tag{1}$$

The stock of governance effectiveness-adjusted policy variables is rewritten as follows:

$$EP.s_{it} = \sum_{k=1}^{3} ep_{i(t-k)} g_{i(t-k)} \tag{2}$$

$$EP.l_{it} = \sum_{k=1}^{t-4} ep_{ik} g_{ik} \tag{3}$$

In Eq. (2), $EP.s_{it}$ represents the short-term cumulative number of energy policies, which are enacted in year $t-1$, $t-2$, and $t-3$, in country i in year t. In Eq. (3), $EP.l_{it}$ stands for the long-term cumulative number of energy policies enacted before $t-3$ in country i before year t,

Control variables. We include three sets of control variables in our econometric regression models. The first set includes socio-economic factors, namely GDP per capita, urbanization rate, and pump price for gasoline; the second set consists of international energy trade, including fuel import and export shares; the third set contains electricity production factors, including the access to electricity, fuel efficiency, and fossil capacity load factor (see details in Table S2.1).

Modeling the cumulative short- and long-term effects of policies. We use panel data models to investigate the impacts of energy policies on CO_2 intensity of electricity. Notably, the detected effects (in year t) of policies passed in year $t-1$, $t-2$, and $t-3$ can be regarded as the short-term effects, and the detected effects (in year t) of policies passed before $t-3$ can be arguably regarded as the long-term effects, following Eskander & Fankhauser (2020)[22]. We apply this intuitive perspective to distinguish the short- and long-term effects of the stock of policies.

Here, two-way fixed-effect panel regression model is specified as follows:

$$y_{it} = \alpha + \beta_1 \cdot EP.s_{it,\delta} + \beta_2 \cdot EP.l_{it,\delta} + \gamma \cdot CV_{it} + \mu_i + v_t + \varepsilon_{it} \tag{4}$$

where y_{it} represents the CO_2 intensity of electricity in country i in year t. $EP.s_{it,\delta}$ and $EP.l_{it,\delta}$ are the short-term and long-term cumulative number of enacted energy policies in category δ in country i and year t, respectively. CV_{it} denotes a set of control variables. μ_i indicates the country fixed effects and v_t yearly fixed effects.

The estimated CO_2 reduction effect c_{it} for country i with governance level g_{it} in year t is calculated as follows:

$$c_{it} = g_{it} \cdot \beta \tag{5}$$

We use F test and Hausman test to compare the performance of pooling, random-effect, and fixed- effect estimations, the results are in favor of the fixed-effect and therefore, our main results focus on the results of the fixed effect estimations.

Data collection and processing

Policy database. Policy data is collected from IEA's Policies Database[44]. This comprehensive policy database consists of four sub-databases, namely the IEA/IRENA Renewable Energy Policies and Measures Database, IEA Energy Efficiency Database, Addressing Climate Change Database, and Building Energy Efficiency Policies (BEEP) Database[44]. It provides detailed information about energy policy in the power sector at the country level (see Figs. 1 and 2). The whole datasets contain 1,115 energy policies in 125 countries.

Worldwide Governance Indicators database. The CO_2 mitigation effects of various energy policies are influenced by governance capacity of a country. In this study, we construct governance capacity measures based on the Worldwide Governance Indicators database (WGI)[22]. The WGI database is a global compilation of data created by the World Bank, which captures household, business, and citizen perceptions of the quality of governance in more than 200 countries and territories[43]. The WGI reveals the capacity of government to effectively formulate and implement sound policies[43].

Data availability

Energy policy data are publicly available at https://www.iea.org/policies. Worldwide Governance Indicators data are available at https://www.worldbank.org/en/publication/worldwide-governance-indicators. Fuel efficiency data are available at https://unstats.un.org/unsd/energystats/. Fossil capacity load factor data are available at https://www.eia.gov/international/data/world. GDP per capita, urbanization, pump price for gasoline, fuel import, fuel export, electricity access data are available at https://data.worldbank.org/indicator. CO_2 intensity of electricity data is available at https://www.iea.org/data-and-statistics/data-sets?filter=emissions. The default carbon content values are shown in Table S5.

Code availability

We use R software to conduct the econometric regression. The codes are available on Figshare, https://doi.org/10.6084/m9.figshare.25711275.v2.

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References

1. IEA. *CO_2 Emissions from Fuel Combustion In International Energy Agency* (IEA, 2019).
2. Shukla, P. R. et al. (eds.) *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2022).
3. Masson-Delmotte, V. et al. Global warming of 1.5°C. *An IPCC Special Report on the Impacts of Global Warming of 1.5°C* 1 (2018)
4. Bernstein, S. & Hoffmann, M. The politics of decarbonization and the catalytic impact of subnational climate experiments. *Policy Sci.* **51**, 189–211 (2018).
5. Zhang, R. & Hanaoka, T. Cross-cutting scenarios and strategies for designing decarbonization pathways in the transport sector toward carbon neutrality. *Nat. Commun.* **13**, 3629 (2022).
6. Tong, D. et al. Committed emissions from existing energy infrastructure jeopardize 1.5°C climate target. *Nature* **572**, 373–377 (2019).
7. Varro, L., Beyer, S., Journeay-Kaler, P. & Gaffney, K. *Green Stimulus after the 2008 Crisis: Learning from Successes and Failures* (International Energy Agency, 2020).
8. Tol, R. S. The IPCC and the challenge of ex post policy evaluation. Preprint at https://arxiv.org/abs/2207.14724 (2022).
9. Bergquist, P. & Warshaw, C. How climate policy commitments influence energy systems and the economies of US states. *Nat. Commun.* **14**, 4850 (2023).
10. Martin, G. & Saikawa, E. Effectiveness of state climate and energy policies in reducing power-sector CO2 emissions. *Nat. Climate Change* **7**, 912–919 (2017).
11. Pineiro-Villaverde, G. & García-Álvarez, M. T. Impact of clean energy policies on electricity sector carbon emissions in the EU-28. *Energies* **15**, 1040 (2022).
12. Sæther, S. R. Climate policy choices: an empirical study of the effects on the OECD and BRICS power sector emission intensity. *Econ. Anal. Policy* **71**, 499–515 (2021).
13. Yi, H. Clean-energy policies and electricity sector carbon emissions in the US states. *Utilities Policy* **34**, 19–29 (2015).
14. Pollitt, H., Lewney, R., Kiss-Dobronyi, B. & Lin, X. Modelling the economic effects of COVID-19 and possible green recovery plans: a post-Keynesian approach. *Climate Policy* **21**, 1257–1271 (2021).
15. The politics of energy security. *Nat. Energy* **8**, 1047–1047 (2023)
16. Aklin, M. & Urpelainen, J. *Renewables: The Politics of A Global Energy Transition* (MIT Press, 2018).

17. IRENA. *Renewable Power Generation Costs in 2021* (International Renewable Energy Agency, 2021).
18. LAZARD. *Lazard's Levelized Cost of Energy Analysis* (LAZARD, 2023).
19. Huang, C. & Lin, B. Promoting decarbonization in the power sector: How important is digital transformation? *Energy Policy* **182**, 113735 (2023).
20. Bank, W. *Crisis within a Crisis? How the Financial Crisis Highlights Power Sector Vulnerabilities in Europe and Central Asia Region* (World Bank, 2010).
21. Chen, P. et al. The heterogeneous role of energy policies in the energy transition of Asia–Pacific emerging economies. *Nat. Energy* **7**, 1–9 (2022)
22. Eskander, S. M. & Fankhauser, S. Reduction in greenhouse gas emissions from national climate legislation. *Nat. Climate Change* **10**, 750–756 (2020).
23. Allcott, H. & Mullainathan, S. Behavior and energy policy. *Science* **327**, 1204–1205 (2010).
24. Pizer, W. A. Choosing price or quantity controls for greenhouse gases. In *The RFF Reader in Environmental and Resource Policy* (ed. Oates, W.), 245–254 (Routledge, 2010).
25. Ari, I. & Yikmaz, R. F. The role of renewable energy in achieving Turkey's INDC. *Renew. Sustain. Energy Rev.* **105**, 244–251 (2019).
26. OECD. *Renewable Energy Feed-in Tariffs* (Organization for Economic Co-operation and Development, 2022).
27. Lehmann, P. & Söderholm, P. Can technology-specific deployment policies be cost-effective? the case of renewable energy support schemes. *Environ. Resource Econ.* **71**, 475–505 (2018).
28. Nuñez-Jimenez, A., Knoeri, C., Hoppmann, J. & Hoffmann, V. H. Beyond innovation and deployment: modeling the impact of technology-push and demand-pull policies in Germany's solar policy mix. *Res. Policy* **51**, 104585 (2022).
29. Bersalli, G., Tröndle, T. & Lilliestam, J. Most industrialised countries have peaked carbon dioxide emissions during economic crises through strengthened structural change. *Commun. Earth Environ.* **4**, 44 (2023).
30. Axsen, J., Plötz, P. & Wolinetz, M. Crafting strong, integrated policy mixes for deep CO2 mitigation in road transport. *Nat. Climate Change* **10**, 809–818 (2020).
31. van den Bergh, J. et al. Designing an effective climate-policy mix: accounting for instrument synergy. *Climate Policy* **21**, 745–764 (2021).
32. Pattberg, P. Public–private partnerships in global climate governance. *Wiley Interdisciplinary Rev.: Climate Change* **1**, 279–287 (2010).
33. Jacobson, M. Z. *100% Clean, Renewable Energy and Storage for Everything* (Cambridge University Press, 2020).
34. Cui, R. Y. et al. Quantifying operational lifetimes for coal power plants under the Paris goals. *Nat. Commun.* **10**, 1–9 (2019).
35. Bataille, C., Sawyer, D. & Melton, N. *Pathways to Deep Decarbonization in Canada* (Sustainable Development Solutions Network, 2015).
36. Hannula, I. & Reiner, D. M. Near-term potential of biofuels, electrofuels, and battery electric vehicles in decarbonizing road transport. *Joule* **3**, 2390–2402 (2019).
37. Myllyvirta, L., Yu, A., Champenois, F. & Zhang, X. *China Permits Two New Coal Power Plants Per Week in 2022* (Centre for Research on Energy and Clean Air, Global Energy Monitor, 2023).
38. Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J. & Zenghelis, D. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Rev. Econ. Policy* **36**, S359–S381 (2020).
39. Bertram, C. et al. COVID-19-induced low power demand and market forces starkly reduce CO_2 emissions. *Nat. Climate Change* **11**, 193–196 (2021).
40. Liu, Z., Ciais, P., Deng, Z. & Schellnhuber, H. J. Near-real-time monitoring of global CO emissions reveals the effects of the COVID-19 pandemic. *Nat. Commun.* **11**, 5172 (2020).
41. Liu, Z., Ciais, P., Deng, Z., Davis, S. J. & Chevallier, F. Carbon Monitor: a near-real-time daily dataset of global CO_2 emission from fossil fuel and cement production. *Sci. Data* **7**, 392 (2020).
42. Davis, S. J. et al. Emissions rebound from the COVID-19 pandemic. *Nat. Climate Change* **12** (2022)
43. Kaufmann, D. & Kraay, A. *The Worldwide Governance Indicators* (World Bank, 2023).
44. IEA. *Policies Database* (International Energy Agency, 2022).
45. Grodecka, A. & Kuralbayeva, K. *The Price vs Quantity Debate: Climate Policy and the Role of Business Cycles* (University of Oxford, 2014).

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Author contributions

X.P., L.S., K.F., and K.H. conceived the original idea and designed the research. X.P. drafted the initial manuscript. X.P., H.Z., J.L., C.Z., D.Z, H.C., R.L., and Z.X. were responsible for writing method, collecting the raw data, and creating the figures. X.P., L.S., K.F., and K.H. analyzed the results and commented on the discussion. All the authors contributed to writing, revising, and discussing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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