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Li, Jun; Li, Jiajia; Guo, Kun; Ji, Qiang; Zhang, Dayong

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# ARTICLE

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# Policy spillovers from climate actions to energy poverty: international evidence

Jun Li<sup>1,2</sup>, Jiajia Li<sup>3,4</sup>, Kun Guo <sup>ⓑ</sup> <sup>5</sup>, Qiang Ji<sup>6,7⊠</sup> & Dayong Zhang <sup>ⓑ</sup> <sup>8⊠</sup>

Policies to address climate change have been implemented worldwide in recent years. The core of these policies is to control greenhouse gas (GHG) emissions, which primarily stem from the consumption of fossil fuels. Consequently, the implementation of climate policies can affect other energy-related issues, such as energy poverty, a critical element of the UN Sustainable Development Goals (SDGs). This paper uses cross-country data from 2000 to 2020 to study the possible policy spillovers from climate actions to energy poverty. We show that a spillover effect does exist. In other words, a higher number of climate policies is associated with a lower level of energy poverty. The spillover is realized through improvements in energy efficiency, the promotion of renewable energy, and support for innovations. In addition, legislative policies are found to have stronger spillover effects. While the overall policy effects are positive for executive policies, regulations tend to have negative impacts on energy development. There is also evidence demonstrating heterogeneous effects between long-term and short-term policies, and between developed and developing countries. Discovering this spillover effect gives extra motivation for countries to adopt climate policies and actively seek synergies in achieving broader sustainable goals.

<sup>&</sup>lt;sup>1</sup> School of Finance, Zhejiang University of Finance and Economics, Hangzhou, China. <sup>2</sup> Yingyang School of Financial Technology, Zhejiang University of Finance and Economics, Hangzhou, China. <sup>3</sup> College of Economics, Sichuan Agricultural University, Sichuan, China. <sup>4</sup> Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle, Germany. <sup>5</sup> School of Economics and Management, University of Chinese Academy of Sciences, Beijing, China. <sup>6</sup> Institutes of Science and Development, Chinese Academy of Sciences, Beijing, China. <sup>7</sup> School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing, China. <sup>8</sup> Research Institute of Economics and Management, Southwestern University of Finance and Economics, Chengdu, China. <sup>Semanl:</sup> jqwxnjq@163.com; dzhang@swufe.edu.cn

# Introduction

limate change has become the most serious threat to the sustainability of the human race, as reported in the Global *Risks Report 2023* by the World Economic Forum.<sup>1</sup> Despite the ongoing conflict of interests among nations, a global consensus has been slowly established to actively combat climate change. For example, the Paris Agreement was signed by almost all countries worldwide. From developed to developing nations, climate change-related policies have been introduced at an increasing pace. For instance, over seventy carbon pricing initiatives have been implemented globally, according to the World Bank.<sup>2</sup>More than 110 countries, including the world largest emitters, such as China and India, have committed to carbon-neutral targets. The number of countries pursuing these targets is on the rise. Various policies, including legislation, regulations, and strategies, have been implemented to support these climate goals (Eskander and Fankhauser, 2020).

Two important questions arise following these activities: first, can climate actions bring additional benefits to society, for instance, alleviating energy poverty? Second, if the answer to the first question is positive, which type of climate policies are more likely to bring synergies to resolve energy access problems? Bearing these questions in mind, this research performs a crosscountry empirical study using a sample of 75 nations from 2000 to 2020. The first key contribution is to examine whether policy spillover exists from climate actions to energy poverty from an international perspective. Rather than focusing on the impacts of a particular climate policy, the accumulation of policies from various categories is considered. This approach allows us to comment more broadly on the policy spillover effects and to explore differences across policy types. Overall, this work hopes to provide new evidence for policymakers to properly evaluate climate actions. Among different pathways towards a sustainable future, there are potential win-win strategies that should be actively pursued.

Fundamentally, no matter what forms of policies are implemented against climate change, the fundamental issue or objective of these actions is to control GHG emissions (Martin and Saikawa, 2017). Given the fact that these emissions are mainly from the use of fossil fuel energy, transitioning towards a sustainable energy system (Solomon and Krishna, 2011) or using renewable energy (Staples et al., 2017) has become an inevitable option. However, the process of energy transition is fraught with significant challenges (Gillingham and Stock, 2018) and is often related to issues of justice and equity (Carley and Konisky, 2020; Markkanen and Anger-Kraavi, 2019). From this perspective, the impacts of climate change policies are multi-dimensional. Climate actions and policies can affect sustainable development (Swart et al., 2003), improve health conditions through better air quality (Nemet et al., 2010), influence the financial sector (Stolbova et al., 2018), and have spillover effects in many other aspects of the global community.

Referring to energy-related issues, some recent studies point out that the implementation of climate change policies can affect energy poverty (Streimikiene et al., 2020), which is central to the UN SDG target 7–affordable and clean energy. While the world seeks climate solutions, we must realize that a significant share of the population is unable to access modern energy or afford it (Zhang et al., 2019b). IEA (2023), for example, reports about 760 million people without access to electricity, and ~2.3 billion people unable to use clean cooking fuels. These unfortunate figures lead to an urgent need for the international community to respond (Sovacool et al., 2012).

The question is whether and how climate change policies may affect energy poverty. First, by supporting the development of renewable energy, it allows the energy-poor to access electricity (Azad and Chakraborty, 2020). In the past decade, renewable energy, such as solar and wind power, has gained significant financial support. Favorable policies, along with advances in technological progress, have made the renewable energy sector more reliable and economically viable (Adefarati and Bansal, 2019). Second, climate policies can also alleviate energy poverty by improving energy efficiency (Zhao et al., 2022). Green innovation and new technology have changed the way energy is used. Machines are more powerful and less emissive. Third, the development of climate finance provides valuable resources to improve the current energy system (Long et al., 2022). In addition, subsidies to renewable energy and green finance can encourage innovation (Yu et al., 2021), which can further support reducing energy poverty.

In addition to the positive role of climate change policies in resolving energy poverty issues, they can also bring opposite impacts. Belaïd (2022), for example, argues that climate policies, if poorly designed, can worsen energy poverty through the price channel. In other words, energy prices can increase due to climate policy changes, leading to affordability problems. Similar arguments can also be found in Berry (2019) for France, Henry et al. (2021) for Guatemala, and other country-level studies. Carbon tax or environmental restrictions to cope with climate changes can add costs to fossil fuel energy, leading to consequential problems in energy poverty.

Overall, the impacts of climate change policies on energy poverty are not entirely clear, and conclusions from some recent studies are also inconsistent. For example, Chien et al. (2022) estimate the effect of green fiscal policy on energy poverty based on panel data for 2010–2020 in 17 countries. They find that green fiscal policy can reduce energy poverty by improving efficiency. Poblete-Cazenave et al. (2021) evaluate the accessibility of energy services under different climate mitigation policy scenarios in Africa and South Asia. They find that ambitious climate mitigation scenarios cannot fundamentally change access to energy services for households in developing countries.

Arguably, even if policy spillovers exist, not all climate policies can alleviating energy poverty. Authorities should pay attention to their policy mix and incorporate concerns of energy poverty when planning climate actions. Bonatz et al. (2019) explore a policy framework to simultaneously achieve energy poverty alleviation and carbon emissions reduction in the scenario of China. Streimikiene et al. (2020) analyze the energy poverty and climate change mitigation issues in EU households based on a systematic literature review. They argue that it is necessary to adopt more targeted climate change policies to alleviate energy poverty. Economidou et al. (2022) take the European policy designs as an example to show the need for strategic planning of energy and climate policies to achieve a synergetic effect. These studies point to a strand of recent literature explicitly discussing spillovers across different SDGs. Lusseau and Mancini (2019), for example, provide evidence that SDGs and their sub-categories can be used to form an interactive network, and the network differs across nations. Similar works can also be seen in Wu et al. (2022) and Cao et al. (2023), supporting the existence of policy spillovers. They suggest that the synergetic effect is more likely to be achieved with proper policy design.

The remainder of this paper is organized as follows: Section 2 explains the construction of main variables based on relevant literature. Section 3 reports descriptive information on the data, and the empirical models used in the paper. Section 4 reports and analyzes the main results based on the empirical models. Section 5 concludes and discusses the policy implications.

## **Key variables**

Measurement of energy poverty. The concept of energy poverty can be traced back to Lewis (1982), who suggests that the wellbeing of people can be affected by insufficient use of energy. Boardman (1991) follows this logic to introduce the 10% threshold, which is the ratio of energy consumption to household income, as a measure of energy poverty. A household is considered to be in energy poverty if the ratio exceeds 10%, meaning that they cannot afford sufficient energy use, or because of high energy prices, the household must sacrifice other important expenditures to heat their home. In addition to affordable energy use, broader concepts of energy poverty have been developed to incorporate energy access into this framework (Zhang et al., 2019a). Given that most of the developed world has almost 100% access to modern energy, the second dimension of energy poverty is primarily relevant to developing nations (Zhang et al., 2019b). However, this broader concept has led to the development of multi-dimensional energy poverty indices (e.g., Sadath and Acharya, 2017). These measures are often based on fine microlevel or household-level survey data and thus are limited to a smaller sample of countries.

To construct a national-level measurement of energy poverty, while maintaining the multi-dimensional nature of this issue, Banerjee et al. (2021) developed the Energy Development Index (EDI). The EDI measure is designed to encompass the following four dimensions: (1) total primary energy use per capita; (2) renewable energy consumption (percentage of total end-used energy consumption); (3) electric power energy consumption per capita; (4) access to electricity (percentage of the population). Among these factors, a higher level of primary energy use per capita is relevant to affordability, while the renewable energy share indicates cleaner energy use. A higher level of electric power consumption reflects both accessibility and affordability elements, whereas the last factor directly captures energy accessibility in a country. In general, less energy poverty in a country is associated with a higher level of EDI. The measurements of these four dimensions (j) are scaled first (see Equation (1)), and then averaged to get the index for a country *i*.  $E_{i,it}$  refers to the four dimensions of each country *i* in year *t*, where  $EI_{i,it}$  is the scaled measure ranging from 0 to 100, representing the worst to the best in terms of energy development.

$$EI_{j,it} = \frac{E_{j,it} - \min(E_{j,t})}{\max(E_{j,t}) - \min(E_{j,t})} \times 100, i = 1, \cdots, N; j = 1, 2, 3, 4$$
(1)

$$EDI_{it} = \frac{1}{4} \sum_{j=1}^{4} EI_{j,it}$$
(2)

Factors affecting energy poverty. Climate policy has become an important factor related to energy poverty in recent years, attracting more attention. For example, Belaïd (2022) suggests that poorly designed climate policy can exacerbate energy poverty by raising energy prices. Xing et al. (2024) present a stock-flow consistent model examining the economics impacts of varies climate policies. Through simulation, climate policies can have significant economic consequences, for instance, improving general social welfare. Climate policies may also lead to higher risks in financial sector, which requires policymakers to pay further attention. Overall, properly designed climate policies, in their model, can generate positive economic impacts and welfare improvements. Tracing back to the economic literature on climate policy, Jakob et al. (2020) discuss its relationship with economic growth and human well-beings. Their key point is to align environmental stainability with social welfare. Based on

these theoretical discussions, climate policies can be designed to resolve energy poverty issues.

Empirically, Churchill et al. (2022) explore the impacts of climate change on household energy poverty in Australia. Climate risks are found to affect energy poverty in China through technological progress in the renewable energy sector (Lee et al., 2022). The development of this sector can have high exposure to climate policy uncertainties (Ma et al., 2023). Vandyck et al. (2023) argue that climate policies such as carbon pricing can exacerbate energy poverty by raising fuel prices, using the EU climate policies to explore the potential impacts on energy poverty.

To measure climate policy, we follow Eskander and Fankhauser (2020) in using the stock of climate change policies in each country. Two sub-categorical variables are derived according to the issuing authorities: the stock of climate change policies passed by legislative bodies (CP legi) and those passed at executive levels (CP\_exec). Climate change policies can also be divided into categories based on short- or long-term nature of the policies, namely, the stock of climate change policies passed within the previous 3 years (CP\_short), and those implemented more than 3 years ago (CP\_long), respectively. Additionally, Chen et al. (2022) suggest dividing climate change policies into laws, regulations, and strategic policies according to their nature. Laws are generally similar to legislative-level policies, so we treat them in the same way, while policies passed at executive levels can be divided into regulations (Regulation) and strategic policies (Strategy). These different types of policies are also studied in this paper to understand which forms can benefit energy poverty.

Besides climate policies, a wide range of other factors is considered in the existing literature as affecting energy poverty, from economic variables to development issues. These variables will be used as control variables in our empirical model. The choice of these control variables is based on existing studies, such as Chaudhry and Shafiullah (2021); Chen et al. (2022); Eskander and Fankhauser (2020). We limit the choice to (1) the economic development level, or log of per capita GDP (Lgdp), expected to reduce energy poverty; (2) the level of openness, measured by the share of import and export of goods and services to GDP (Open), where a country with strong import and export is expected to have lower energy poverty; (3) the industrial structure (Service), the proportion of the tertiary industry output value, expected to be positively related to EDI; (4) the urbanization level (Urban), the percentage of the urban population, another positive factor to energy development; (5) the labor force participation rate (Labor), or the percentage of labor force participation rate for age 15-64; (6) the age dependency ratio (Dependency), or the percentage of people younger than 15 or older than 64. The impacts of labor force participation and age dependency ratio are not entirely clear and will be discussed with respect to the empirical results. Finally, energy development or poverty is related to climate change. Thus, the last control variable is climate-relevant and measured by abnormal temperature (Tem*perature*), or the difference between annual average temperatures and the long-term (1980-2015) average value.<sup>3</sup>.

#### Model and data

**Model**. To investigate the aforementioned problems, panel fixedeffect models are utilized to analyze the empirical data<sup>4</sup>The baseline model is formulated as follows:

$$EDI_{it} = \alpha + \beta_0 CP_{i,t-1} + \gamma X_{i,t-1} + \theta_i + \eta_t + \varepsilon_{it}$$
(3)

Whereas  $EDI_{it}$  refers to the EDI for country *i* at year *t*.  $CP_{i,t-1}$  is the measure of climate change policies for country *i* at year t - 1.  $X_{i,t-1}$  is the vector of control variables, as explained in section 2.

These explanatory variables are lagged for one-period in all models similar to (Chen et al., 2022). The model controls for country-specific and year-specific fixed effects via  $\theta_i$  and  $\eta_i$ , and  $\varepsilon_{it}$  is the error term. In addition to the model above, we also consider various types of climate policies as discussed above:

$$EDI_{it} = \alpha + \beta_1 CP \, Jegi_{i,t-1} + \beta_2 CP_{-}exec_{i,t-1} + \gamma X_{i,t-1} + \theta_i + \eta_t + \varepsilon_{it} \quad (4)$$

$$EDI_{it} = \alpha + \beta_1 CP \_short_{i,t-1} + \beta_2 CP\_long_{i,t-1} + \gamma X_{i,t-1} + \theta_i + \eta_t + \varepsilon_{it}$$
(5)

Moreover, following Chen et al. (2022), the policies passed at the executive level will be further divided into regulations (*Regulation*) and strategic policies (*Strategy*). These are also examined in the baseline models.

**Data**. The empirical study utilizes annual data from 2000 to 2020 to analyze relevant issues. The primary data source is the World Development Indicators from the World Bank, which provides rich information about national-level socio-economic status. We first calculate the EDI following the methodology outlined by

Banerjee et al. (2021). The cross-country EDIs are depicted in Fig. 1, illustrating the distribution of energy development across all sample countries during the period. From this, we observe that the level of EDI has generally been increasing over time, indicating overall improvements in energy poverty at the international level.

Among all countries in the sample, Iceland has the best level of energy development, or the lowest level of energy poverty, while Norway and Canada took the second and the third places, respectively. However, it is worth noting that many developing countries still experience serious energy poverty in 2020, particularly in regions such as Africa, Southeast and South Asia, Central and South America. As shown in Fig. 2, developed countries are generally in a better position relative to developing countries.

Regarding climate change policies, data is collected from the "Climate Change Laws of the World" dataset, which provides information on the national-level climate change laws and policies. The dataset includes detailed information about the titles, contents, release time, and types of policies. It has been used in recent literature and has proven to be a useful collection of



Fig. 1 Energy development index.



Fig. 2 EDI for developed and developing countries.

climate policies worldwide (e.g., Eskander and Fankhauser, 2020). The original data covers 133 countries, but only 75 of them are used in our analysis due to the availability of information on other variables. Note that the dataset includes both mitigation and adaption policies; of the 2670 items of policies, 1994 are

mitigation policies. Of these mitigation policies, 37% of them are legislative type, or passed by parliaments, while the remainder are in the form of executive orders.

Figure 3 plots the time trend of the implementation of climate change policies over the sample period, by policy types (panel A)



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Table 1 Descriptive statistics.							
Variable	Definition	Obs	Mean	Std. dev	Min	Max	
EDI	Energy Development Index	1505	32.324	8.837	0	83.401	
CP	Stock of climate policies	1505	5.993	6.160	0	51	
CP_N	Average climate policies passed	1505	0.647	1.049	0	10	
CP_legi	Legislative climate policies	1505	3.296	3.236	0	19	
CP_exec	Executive climate policies	1505	2.697	4.229	0	36	
CP_short	Policies passed less than 3 years	1505	1.611	1.915	0	15	
CP_long	Policies passed more than 3 years	1505	3.734	4.404	0	33	
Regulations	Climate-related regulations	1505	1.373	2.501	0	20	
Strategies	Climate-related strategic policies	1505	0.993	1.725	0	15	
Lgdp	Log per capita GDP, (2017 dollar)	1505	10.02	0.837	7.570	11.70	
Open	Imports and Exports (% of GDP)	1505	89.92	57.89	19.56	437.33	
Service	Services, value added (% of GDP)	1505	56.24	10.33	10.86	80.08	
Labor	Labor force participation rate (%)	1505	68.91	9.279	43.64	89.09	
Urban	Percentage of urban population (%)	1505	68.94	17.57	18.20	100	
Dependency	Age dependency ratio (%)	1505	50.17	9.387	16.05	86.59	
Temperature	Abnormal temperature	1505	0.447	0.511	-1.581	2.234	

and by the development status of countries (panel B). It shows that climate change policies have increased rapidly during this period, especially after the 2008 global financial crisis, when the world became more focused on sustainable development and climate change. Among all these policies, legislative policies are relatively stable over the entire sample period, whereas executive policies are more common than in the later stage. Developing countries started at a lower level compared to developed countries, but they have started to catch up and become more active in the recent decade.

For the information of other control variables and their descriptive statistics, please refer to Table 1 for more information. The range of EDI values is from 0 to 83.401, indicating a very large gap between countries in terms of energy poverty. The lowest value is recorded in Bangladesh, with all four dimensions of the EDI construction being the lowest among all countries. Iceland leads all countries with the highest EDI of 83.401. In terms of the number of climate policies, the average number of new policies issued every year is 0.647, and the average stock of climate policies is 5.993.

The correlation matrix of the key variables is presented in Fig. 4, where all the diagonal elements (self-correlation) have been removed. The matrix reveals generally strong correlations among different types of policies. GDP, Urbanization and Labor participation are the top three variables correlated with EDI. For the main climate policy measure (CP), the correlation with EDI is 0.16.

# **Empirical results**

**Baseline regressions**. In this section, we examine the baseline regressions outlined in Equations (3–5) using the sample data. The primary focus of these models is to test whether climate policies can affect energy poverty (EDI) and to determine which types of policies are more effective. Our goal is to identify the overall impacts, as well as the impacts from sub-categories. The results are reported in Table 2. All models presented here include both country-fixed effects and year-fixed effects.

In all models, climate policies are positively associated with EDI, indicating clear evidence of policy spillovers from climate actions to energy poverty. In other words, the adoption of climate policies can benefit a country's energy development. These results are consistent across all sub-categories, though the coefficients show that policies legislated and long-term policy counts have relatively stronger effects compared to those in executive or shortterm counts. This difference can be interpreted as an indicator of effectiveness in policy spillovers. Climate policies passed by legislations tend to be enforced more effectively and thus generate a stronger effect on energy development. These climate policies tend to take a longer time to bring extra benefits to EDI.

An interesting finding (Model 5-6) emerges when dividing executive policies into regulations and strategies. The results indicate that regulations tend to reduce EDI scores, whereas strategies increase them. The rationale behind this is straightforward: regulatory climate policies often suppress the use of fossil fuel energy, leading to lower EDI scores. This is consistent with findings such as those in Belaïd (2022); Vandyck et al. (2023), which suggest that regulations against climate change can induce energy poverty by raising energy prices and other costs. Conversely, strategic climate policies usually emphasize the development of renewable energy or infrastructure, which benefits the general EDI performance of a country. A recent work by Xing et al. (2024) shows that policy mix matters in terms of effectiveness. A poorly designed policy may generate unwanted effects, weakening or neutralizing the initial goals (Chen et al., 2024). Results here also indicate that policymakers need to take a more general view and carefully choose their policy mix.

To illustrate the effect of climate policies on EDI, we hypothetically assume no climate policy and calculate the counterfactual results based on the above regressions. The average differences across countries over time can be seen in Fig. 5. The gap between the scenarios 'without climate policy' and 'with climate policy' widens over time, with the differences being quite significant, around 5% of the average EDI in the sample.

Regarding the effects of other control variables, their impacts are intuitively consistent with expectations. Better economic development, as measured by per capita GDP, is positively and significantly associated with energy development. In other words, rich (developed) countries have better energy development (Simionescu et al., 2023); they tend to consume more energy resources, have better renewable energy development, and have broader access to modern energy forms. Countries with stronger imports and exports are also likely to have stronger energy development. Urbanization, often positively related to economic development and energy infrastructure, is expected to be linked to energy development (Zhao et al., 2022). The dependency ratio, which is often higher for developed nations (Muszyńska and Rau, 2012), becomes a critical issue for these countries. Although this implies a higher dependency ratio is often related to development and thus positively associated with EDI, it is somewhat surprising to see the negative relationship between labor force participation



Fig. 4 Correlation matrix in heatmap.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
СР	0.139*** (0.012)								
CP_legi		0.191*** (0.029)		0.168*** (0.027)		0.144*** (0.027)			
CP_exec			0.138*** (0.016)	0.125*** (0.018)					
Regulations					-0.095*** (0.016)	-0.093*** (0.016)			
Strategies					0.565*** (0.059)	0.53/*** (0.060)	0.400++		0.40.4++
CP_short							0.103** (0.046)		0.104** (0.040)
CP_long								0.180*** (0.018)	0.181*** (0.016)
Lgdp	1.696*** (0.463)	1.998*** (0.546)	1.341*** (0.425)	1.788*** (0.545)	1.073*** (0.395)	1.466*** (0.497)	1.513*** (0.428)	1.688***	1.693*** (0.448)
Open	0.011***	0.010***	0.011***	0.011***	0.007**	0.007**	0.010***	0.012***	0.012***
Service	-0.018 (0.019)	-0.017 (0.019)	-0.024 (0.020)	-0.016 (0.018)	-0.023 (0.016)	-0.016 (0.015)	-0.024 (0.022)	-0.020 (0.019)	-0.018
Labor	-0.077***	-0.075***	-0.091***	-0.075***	-0.082***	-0.069***	-0.089***	-0.082***	-0.078**
Urban	0.044***	0.082***	0.039***	0.048***	0.035***	0.042***	0.067***	0.055***	0.046***
Dependency	0.029***	0.020*	0.040***	0.027***	0.046***	0.034***	0.036***	0.024***	0.025***
Temperature	-0.343 (0.231)	-0.372 (0.244)	-0.338 (0.230)	-0.347 (0.233)	-0.320 (0.235)	-0.328 (0.237)	-0.356 (0.244)	-0.351 (0.226)	-0.343 (0.228)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FÉ	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	1428	1428	1428	1428	1428	1428	1428	1428	1428





Table 3 Further analysis: terms of policies.							
	(1)	(2)	(3)	(4)	(5)	(6)	
CP_legi_short	0.048 (0.046)		0.117*** (0.035)	0.054 (0.045)		0.071 (0.045)	
CP_exec_short	0.144** (0.060)		0.114** (0.054)				
CP_legi_long		0.228*** (0.041)	0.247*** (0.038)		0.212*** (0.036)	0.218*** (0.033)	
CP_exec_long		0.151*** (0.020)	0.140*** (0.016)				
Regulation_short				-0.084* (0.047)		-0.174*** (0.045)	
Strategies_short				0.369** (0.159)		0.440*** (0.114)	
Regulation_long					-0.110*** (0.041)	-0.111*** (0.038)	
Strategies_long					0.702*** (0.086)	0.764*** (0.079)	
Controls	Yes	Yes	Yes	Yes	Yes	Yes	
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	
Ν	1428	1428	1428	1428	1428	1428	
R2 (Within)	0.504	0.518	0.522	0.508	0.537	0.550	
*, ** and *** denotes 10%, 5%,	and 1% level of significance	e, respectively.					

and energy development. Typically, the literature suggests that energy poverty negatively impacts labor force participation (Bakehe, 2022), as poorer access to energy can affect health status and lead to work absences. However, our results show the opposite: a higher labor participation rate is associated with lower EDI performance. This finding is consistent with Chaudhry and Shafiullah (2021), who also identified similar results. Climate itself, as measured by extreme temperatures, has no significant impact on energy development.

**Further investigations**. Building on the baseline regression results, we further explore which types of policies may be more effective in the positive spillovers identified earlier. First, we investigate the short-term and long-term effects. Specifically, we differentiate each policy type by the number of short-term policies (policies introduced within 3 years) and long-term policies (policies introduced more than 3 years ago).

Generally, we expect climate policies to take longer to be effective, as indicated in the baseline regressions. The results, reported in Table 3, align with expectations. For legislative policies, it takes longer to see effectiveness, hence the coefficients for long-term legislative policies are significantly larger than those for short-term ones, where some coefficients of the short-term legislative policies are not significant. A similar pattern is observed for strategic policies, with the coefficients for *Strategies\_long* being almost double those for *Strategies\_short*.

Second, countries have different levels of development and different types of energy poverty. Developing nations, for example, countries in Africa, have much more complicated energy poverty status than wealthy nations. There, even the accessibility to modern energy cannot be easily resolved, and they also have trouble accessing financial resources. On the contrary, developed nations have other major concerns, such as the cost of energy use. In addition, considering that developed countries are the main players in global actions against climate change and tend to have stronger EDI compared to developing nations, it is also interesting to investigate the differences in policy spillovers between developed and developing countries.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Developed	Developing	Developed	Developing	Developed	Developing	Developed	Developing
СР	0.053** (0.022)	0.202*** (0.019)						
CP_legi			0.036 (0.031)	0.370*** (0.041)	-0.040 (0.036)	0.356*** (0.049)		
CP_exec			0.067 (0.045)	0.152*** (0.017)				
Regulations					-0.293*** (0.022)	-0.031 (0.021)		
Strategies					0.703*** (0.155)	0.620***		
CP_short							0.038 (0.044)	0.185*** (0.052)
CP_long							0.081***	0.236*** (0.027)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ν	690	738	690	738	690	738	690	738
R2 (Within)	0.495	0.618	0.495	0.624	0.518	0.669	0.495	0.621

The results dealing with sub-samples according to development status are reported in Table 4. While the results are generally consistent with the baseline regressions in showing that climate policies can generate spillover effects on energy poverty, the implications for developed and developing nations appear to be markedly different. The spillovers of climate policy to energy poverty are significantly stronger for developing countries, which is not entirely surprising given that these countries generally have a smaller number of policies. The marginal effects of introducing more climate policies should, therefore, be larger. This finding provides a stronger incentive for developing countries to actively engage in climate change actions. However, regulations tend to have a more negative impact on the EDI for developed countries, whereas their impact on developing countries is insignificant. To further validate these findings, we also employed an alternative division approach by comparing industrialized countries, specifically the EU/OECD, with other countries. The results, which are similar, are provided in Appendix Table (C5).

**Possible mechanisms.** Upon confirming the existence of policy spillovers from climate policies to the alleviation of energy poverty, there is also great interest in understanding how the system operates. To uncover the underlying mechanisms, this section considers three potential factors and performs relevant empirical tests. These variables are the natural resource rents (NRR) as a percentage of GDP, the share of electricity from renewable energy (Renewable), and a measure of innovation in terms of the number of researchers per million of the population (Innovation).

The rationale behind the selection of these variables is as follows: first, climate policies can improve market efficiency and the productivity of the energy sector (Shen et al., 2021), thereby facilitating energy transition and enhancing energy development (Huang, 2022). Second, climate policies can regulate the use of fossil fuel energy while simultaneously supporting the development of the renewable energy sector, which benefits overall energy development. Third, it is widely accepted that climate policies can promote benefits in the energy sector by supporting innovation (Yu et al., 2021). A few cases can be found in some recent studies to support the arguments above, for instance, Mukhtar et al. (2023) use Sub-Sahara Africa as an example to discuss renewable energy as a possible solution to energy poverty, they suggest that renewable energy development is crucial to achieve the net-zero climate goals, whereas it is a feasible solution to energy poverty. The key problem, though, is the significant cost of investment. Streimikiene et al. (2020) showcase that the EU climate policies can help energy-poor households by prompting energy efficiency technology and renewable energy use. In China, the 2017 green finance pilot policy is found to alleviate energy poverty, by enhancing efficiency and switching to cleaner energy sources (Xue et al., 2023).

Using data from the World Bank's World Development Indicators, we empirically test these channels and report the results in Table 5. A two-step approach is used. Generally, the results align with our expectations and those documented in the literature. As discussed earlier, climate policies can increase NRR, the share of renewable energy, and Innovation, all of which then significantly increase EDI in all specifications. However, it is important to acknowledge that the role of climate policy can be multi-dimensional. In other words, other possible channels exist, especially when investigating different types of policies. For instance, we would expect regulations to suppress the use of fossil fuel energy, leading to negative impacts on EDI, as demonstrated in the earlier analysis.

**Robustness check.** Although the results found in this paper are significant and consistent across different specifications, it is necessary to check for robustness, particularly considering endogeneity. To address this, we perform a simple exercise using an instrumental variable and the 2-stage least square (2SLS) approach. The instrument used here is the *Red List Index*, which shows trends in overall extinction risk for species. It ranges from 0 to 1, with 0 representing all species having goen extinct and 1 representing no risk of extinction in the near future. The index, measuring the risks of biodiversity loss, is not directly related to energy poverty but is relevant to climate policies due to the urgent need to integrate these issues into policy designs (Turney et al., 2020). Following this logic, a country facing a higher exposure to

	(1)	(2)	(3)	(4)	(5)	(6)
	NRR	EDI	Renewable	EDI	Innovation	EDI
СР	0.187*** (0.053)	0.127*** (0.010)	0.129*** (0.023)	0.113*** (0.013)	6.825*** (1.625)	0.190** (0.018)
NRR		0.062*** (0.015)				
Renewable				0.241***		
				(0.037)		
Innovation						0.001**
						(0.001)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Ν	1428	1428	1174	1174	754	754
R2	0.372	0.522	0.540	0.492	0.294	0.517
(Within)						

Table 6 2SLS regression results and additional checks.							
	IV Estimatio	on					
	First Stage	Second stage	(1)	(2)			
	СР	EDI	Access to clean cooking	Access to electricity			
СР		0.414* (0.226)	0.329*** (0.059)	0.136*** (0.036)			
Lgdp	—1.119 (0.741)	2.069*** (0.668)	12.771*** (0.895)	4.890*** (0.779)			
Open	0.003 (0.005)	0.012*** (0.004)	0.021*** (0.006)	0.001 (0.004)			
Service	-0.059** (0.024)	0.000 (0.019)	0.112** (0.051)	-0.080** (0.033)			
Labor	-0.105** (0.040)	-0.045 (0.055)	-0.203*** (0.065)	-0.203*** (0.057)			
Urban	0.186*** (0.047)	-0.021 (0.054)	0.727*** (0.039)	0.233*** (0.020)			
Dependency	0.066** (0.027)	0.019 (0.018)	-0.211*** (0.024)	-0.183*** (0.029)			
Temperature	—0.130 (0.133)	-0.303** (0.146)	0.162 (0.156)	-0.323 (0.239)			
Redlist	36.290*** (10.819)						
Country FE	Yes	Yes	Yes	Yes			
Year FE	Yes	Yes	Yes	Yes			
Ν	1428	1428	1425	1428			
Kleibergen-Paap LM- statistic		11.415***	Stock-Yogo c	ritical values			
Cragg-Donald F-statistic	Wald	16.174	10%	16.38			
Kleibergen-Pa	ap F-statistic	11.251	15%	8.96			

biodiversity risk is more likely to introduce climate-related policies, thus making the index a valid instrument. We use one minus the index as the actual instrument (*Redlist*), which should be positively related to climate policies. The data is collected from the UN SDG website. Results are reported in Table 6.

Note that in Table 6, we also replaced the main dependent variable, EDI, with two single-dimensional energy poverty measures, namely access to clean cooking and access to electricity. Models (1–2) confirm the baseline regression results. Turning to the IV regression results, the 2SLS estimation strongly supports

the baseline regressions. The underidentification test, Kleibergen-Paap LM-statistic, is statistically significant, and the Cragg-Donald Wald statistic exceeds the 15% Stock-Yogo critical value, indicating no weak identification problem. The Kleibergen-Paap F-statistic also validates this finding. In other words, the choice of IV is appropriate.

## **Conclusions and implications**

Addressing climate change is presently the most important issue for the international community and will continue to be in the future. Taking action is costly and requires substantial resources, heavily reliant on government support. Consequently, climate policies are essential for making progress. After decades of debate and discussion, the world has gradually reached a consensus, and an increasing number of policies have been implemented. While these policies are positive, their effects need to be evaluated. In addition to direct impacts on climate, these policies can also affect other aspects of society through the complex economic system, leading to important questions about the existence of policy spillovers.

This paper aims to explore this line of research, with a special interest in understanding how climate policy may affect energy poverty. Alleviating energy poverty is a crucial target for many countries and is one of the most important parts of the UN SDGs. Intrinsically, climate change and energy use are closely connected, making policy spillovers more likely to exist. Unfortunately, the impacts are not entirely clear, as climate policies can bring both benefits and difficulties. In this paper, we use cross-country panel data to empirically test the possible impacts of climate policies on energy development and explore the detailed mechanisms behind them.

The results can be summarized as follows: First, there is clear evidence that more climate policies are associated with better energy development (or lower energy poverty). Second, the impacts of climate policies are sensitive to the nature of these climate policies. Policies passed by legislative bodies have stronger positive impacts compared to those passed by executive orders. Additionally, we find that climate regulations tend to reduce EDI, whereas strategic policies work in favor of EDI. Third, policy effects take longer to manifest, as demonstrated by stronger effects for longer-term climate policies. The impacts of climate policy are stronger for developing nations relative to developed countries. Fourth, the policy spillovers are shown to be effective through improving efficiency, increasing renewable energy shares, and supporting innovation. Our results are robust to a series of checks.

Several important policy implications can be drawn from this study. The first and most crucial is that recognizing the positive spillovers provides policymakers with an incentive to be more proactive in addressing climate change. Such policy actions can have positive externalities beneficial to other sustainable development goals (SDGs), such as alleviating energy poverty. Second, not all policies against climate change have the same effect. It takes longer for climate policies to generate larger benefits for energy development. Legislative or more formal policies work more effectively towards improvements in energy development. Short-term regulations tend to temporarily deteriorate energy poverty, as these policies often suppress the use of fossil fuel energy. When alternative energy is not fully ready to replace the gap, it can generate negative impacts on energy poverty. Third, given that policy spillovers work more effectively for developing nations, which are more affected by energy poverty, policymakers in these states should be more active. This also provides an important incentive for the international community to further support climate actions in developing nations. Energy market reforms, energy transition, and stronger support for green innovation should be considered by policymakers to further reinforce the benefits of these policies.

While the current study is valuable in revealing the impacts of climate action on energy poverty, a few limitations exist and deserve future investigation. First, the current empirical framework is based on national-level evidence, thus unable to show the very detailed responses at the micro-level, for example, households. This can, of course, be resolved by using survey data, which has been extensively utilized in single-country studies. Lacking a comprehensive and globally representative micro-level survey, however, makes this almost impossible in the current setup. A possible solution is to select representative countries and perform cross-country comparisons, which allow the topic to be extended further. Second, it is also worth noting that the effectiveness of different policy approaches may be affected by the country-specific status. Clearly, the EU and China have no major concerns about energy access, but there is still a significant share of the population in Africa who remains unable to access modern energy. Therefore, the major issue for Africa is how to finance the significant cost of investment, whereas the EU and China need to provide stronger policy support for technological innovation. Third, panel time series models might be useful to explore dynamic patterns, but the time dimension of our sample is rather small, resulting relatively inaccurate estimations. Anyhow, some additional analyses have been added in the appendix. Other possible extensions to the current framework are to include other SDGs and expand the scope of this research, for instance, Li et al. (2024).

#### **Data availability**

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

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#### Notes

- 1 https://www.weforum.org/reports/global-risks-report-2023.
- 2 https://carbonpricingdashboard.worldbank.org/.
- 3 The choice of these control variables is justified by the relevant literature, which are listed in Table A2 in the appendix.
- 4 Panel unit root tests are applied to all variables to check stationarity; the results are reported in Appendix Table B3 and all variables are stationary. To further justify the

use of panel fixed-effect models, a series of statistical tests against alternative models are given in the Appendix Table B4, which shows the superiority of fixed-effect model.

#### References

- Adefarati T, Bansal RC (2019) Reliability, economic and environmental analysis of a microgrid system in the presence of renewable energy resources. Appl Energy 236:1089–1114
- Azad R, Chakraborty S (2020) Green growth and the right to energy in India. Energy Policy 141:111456
- Bakehe NP (2022) Energy poverty: consequences for respiratory health and labour force participation in cameroon. J Environ Econ Policy 11:235–247
- Banerjee R, Mishra V, Maruta AA (2021) Energy poverty, health and education outcomes: evidence from the developing world. Energy Econ 101:105447
- Belaïd F (2022) Implications of poorly designed climate policy on energy poverty: global reflections on the current surge in energy prices. Energy Res Soc Sci 92:102790
- Berry A (2019) The distributional effects of a carbon tax and its impact on fuel poverty: a microsimulation study in the French context. Energy Policy 124:81–94
- Boardman, B. Fuel poverty: from cold homes to affordable warmth. (1991)
- Bonatz N, Guo R, Wu W, Liu L (2019) A comparative study of the interlinkages between energy poverty and low carbon development in china and germany by developing an energy poverty index. Energy Build 183:817–831
- Cao M, Chen M, Zhang J, Pradhan P, Guo H, Fu B, Li Y, Bai Y, Chang L, Chen Y (2023) Spatio-temporal changes in the causal interactions among sustainable development goals in china. Humanit Soc Sci Commun 10:1–9
- Carley S, Konisky DM (2020) The justice and equity implications of the clean energy transition. Nat Energy 5:569–577
- Chaudhry SM, Shafiullah M (2021) Does culture affect energy poverty? evidence from a cross-country analysis. Energy Econ 102:105536
- Chen P, Wu Y, Meng J, He P, Li D, Coffman D, Liang X, Guan D (2022) The heterogeneous role of energy policies in the energy transition of asia–pacific emerging economies. Nat Energy 7:588–596
- Chen Y, Zhang D, Guo K, Ji Q (2024) Emission trading schemes and cross-border mergers and acquisitions. J Environ Econ Manag 124:102949
- Chien F, Hsu C-C, Zhang Y, Tran TD, Li L (2022) Assessing the impact of green fiscal policies and energy poverty on energy efficiency. Environ Sci Pollut Res 29:4363–4374
- Churchill SA, Smyth R, Trinh T-A (2022) Energy poverty, temperature and climate change. Energy Econ 114:106306
- Economidou M, Ringel M, Valentova M, Castellazzi L, Zancanella P, Zangheri P, Serrenho T, Paci D, Bertoldi P (2022) Strategic energy and climate policy planning: lessons learned from european energy efficiency policies. Energy Policy 171:113225
- Eskander SM, Fankhauser S (2020) Reduction in greenhouse gas emissions from national climate legislation. Nat Clim Change 10:750–756
- Gillingham K, Stock JH (2018) The cost of reducing greenhouse gas emissions. J Econ Perspect 32:53–72
- Henry CL, Baker JS, Shaw BK, Kondash AJ, Leiva B, Castellanos E, Wade CM, Lord B, Van Houtven G, Redmon JH (2021) How will renewable energy development goals affect energy poverty in guatemala? Energy Econ 104:105665
- Huang S-Z (2022) The effect of natural resources and economic factors on energy transition: new evidence from china. Resour Policy 76:102620
- IEA. Sdg7: data and projections. Technical report, IEA, Paris. (2023)
- Jakob M, Lamb WF, Steckel JC, Flachsland C, Edenhofer O (2020) Understanding different perspectives on economic growth and climate policy. Wiley Interdiscip Rev: Clim Change 11:e677
- Lee C-C, Yuan Z, Lee C-C, Chang Y-F (2022) The impact of renewable energy technology innovation on energy poverty: does climate risk matter? Energy Econ 116:106427
- Lewis, P. Fuel poverty can be stopped. National Right to fuel campaign, pp 40 (1982)
- Li X, An L, Zhang D, Lee C-C, Yu C-H (2024) Energy access and female labor force participation in developing countries. Renew Sustain Energy Rev 199:114468
- Long S, Lucey B, Kumar S, Zhang D, Zhang Z (2022) Climate finance: what we know and what we should know? J Clim Financ 1:100005
- Lusseau D, Mancini F (2019) Income-based variation in sustainable development goal interaction networks. Nat Sustain 2:242–247
- Ma Y-R, Liu Z, Ma D, Zhai P, Guo K, Zhang D, Ji Q (2023) A news-based climate policy uncertainty index for china. Sci Data 10:881
- Markkanen S, Anger-Kraavi A (2019) Social impacts of climate change mitigation policies and their implications for inequality. Clim Policy 19:827–844
- Martin G, Saikawa E (2017) Effectiveness of state climate and energy policies in reducing power-sector co2 emissions. Nat Clim Change 7:912–919
- Mukhtar M, Adun H, Cai D, Obiora S, Taiwo M, Ni T, Ozsahin DU, Bamisile O (2023) Juxtaposing sub-sahara africa's energy poverty and renewable energy potential. Sci Rep. 13:11643

- Muszyńska MM, Rau R (2012) The old-age healthy dependency ratio in europe. J Popul Ageing 5:151–162
- Nemet GF, Holloway T, Meier P (2010) Implications of incorporating air-quality co-benefits into climate change policymaking. Environ Res Lett 5:014007
- Poblete-Cazenave M, Pachauri S, Byers E, Mastrucci A, van Ruijven B (2021) Global scenarios of household access to modern energy services under climate mitigation policy. Nat Energy 6:824–833
- Sadath AC, Acharya RH (2017) Assessing the extent and intensity of energy poverty using multidimensional energy poverty index: empirical evidence from households in India. Energy Policy 102:540–550
- Shen Y, Su Z-W, Malik MY, Umar M, Khan Z, Khan M (2021) Does green investment, financial development and natural resources rent limit carbon emissions? a provincial panel analysis of china. Sci Total Environ 755:142538
- Simionescu M, Radulescu M, Cifuentes-Faura J, Balsalobre-Lorente D (2023) The role of renewable energy policies in tackling energy poverty in the european union. Energy Policy 183:113826
- Solomon BD, Krishna K (2011) The coming sustainable energy transition: history, strategies, and outlook. Energy Policy 39:7422-7431
- Sovacool BK, Cooper C, Bazilian M, Johnson K, Zoppo D, Clarke S, Eidsness J, Crafton M, Velumail T, Raza HA (2012) What moves and works: broadening the consideration of energy poverty. Energy Policy 42:715–719
- Staples MD, Malina R, Barrett SR (2017) The limits of bioenergy for mitigating global life-cycle greenhouse gas emissions from fossil fuels. Nat Energy 2:1-8
- Stolbova V, Monasterolo I, Battiston S (2018) A financial macro-network approach to climate policy evaluation. Ecol Econ 149:239–253
- Streimikiene D, Lekavičius V, Baležentis T, Kyriakopoulos GL, Abrhám J (2020) Climate change mitigation policies targeting households and addressing energy poverty in european union. Energies 13:3389
- Swart R, Robinson J, Cohen S (2003) Climate change and sustainable development: expanding the options. Clim Policy 3:S19–S40
- Turney C, Ausseil A-G, Broadhurst L (2020) Urgent need for an integrated policy framework for biodiversity loss and climate change. Nat Ecol Evol 4:996–996
- Vandyck T, Della Valle N, Temursho U, Weitzel M (2023) EU climate action through an energy poverty lens. Sci Rep. 13:6040
- Wu X, Fu B, Wang S, Song S, Li Y, Xu Z, Wei Y, Liu J (2022) Decoupling of sdgs followed by re-coupling as sustainable development progresses. Nat Sustain 5:452–459
- Xing X, Guo K, Zhang D, Ji Q (2024) On the interactive effects of climate policies: insights from a stock-flow consistent model. Appl Energy 358:122664
- Xue Y, Hu D, Irfan M, Wu H, Hao Y (2023) Natural resources policy making through finance? The role of green finance on energy resources poverty. Resour Policy 85:104023
- Yu C-H, Wu X, Zhang D, Chen S, Zhao J (2021) Demand for green finance: Resolving financing constraints on green innovation in china. Energy Policy 153:112255
- Zhang D, Li J, Han P (2019a) A multidimensional measure of energy poverty in China and its impacts on health: an empirical study based on the china family panel studies. Energy Policy 131:72–81
- Zhang T, Shi X, Zhang D, Xiao J (2019b) Socio-economic development and electricity access in developing economies: a long-run model averaging approach. Energy Policy 132:223–231
- Zhao J, Dong K, Dong X, Shahbaz M (2022) How renewable energy alleviate energy poverty? a global analysis. Renew Energy 186:299–311

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### Author contributions

Jun Li: methodology, software, formal analysis, investigation, data curation, writingoriginal draft. Jiajia Li: methodology, formal analysis, investigation, writing-original draft. Kun Guo: methodology, investigation, writing-original draft, project administration, funding acquisition. Qiang Ji: validation, writing-review & editing; validation, supervision, project administration, funding acquisition. Dayong Zhang: conceptualization, visualization, validation, writing-original draft, writing-review & editing; validation, supervision, project administration.

#### **Competing interests**

The authors declare 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

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**Correspondence** and requests for materials should be addressed to Qiang Ji or Dayong Zhang.

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