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***Research article***

# Climate risk and renewable energy development: the non-linear moderating role of institutional environment

**Xianfeng Luo and Qian Ding***

School of Business, Central South University, Changsha, China

* **Correspondence:** Email: dingqian@csu.edu.cn.

**Abstract:** Using a panel smooth transition regression (PSTR) model, this study investigated the nonlinear impacts of climate risk on renewable energy development (RED) under different regimes of institutional environment, covering the panel data of 85 countries over the period of 2000–2022. The results show that climate risk negatively affects RED, and it exhibits nonlinear transformation characteristics under different regimes. Climate risk has differential impacts on RED in different types of institutional environments; however, the negative impacts of climate risk on RED can be mitigated in a stable economic and financial environment. In addition, the negative effects of climate risk are more pronounced in low-income countries than in high-income countries. Our findings have important implications for addressing the challenges of climate change and achieving sustainable development.

**Keywords:** climate risk; renewable energy development; institutional environment; panel smooth transition regression

**JEL Codes:** F36, Q43, Q54

## 1. Introduction

Excessive use of fossil fuels leading to significant greenhouse gas (GHG) emissions is considered to be highly correlated with the onset of global climate change (Shang et al., 2024). In this context, renewable energy development (RED) has the unique advantage of reducing GHG emissions and fossil energy dependence, making it a key initiative to mitigate climate change (Abban and Hasan, 2021). Therefore, the global climate crisis has put greater demands on RED. However, renewable energy resources are highly vulnerable to unfavorable climatic conditions, making climate risk an important factor affecting RED (Juhola et al., 2024). Given the complex relationship between climate risk and RED, countries are actively adopting policies to drive energy transition, and the effectiveness of these policies largely depends on the institutional environment (Song et al., 2023; Chen et al., 2024b). Consequently, exploring the impact of climate risk on RED and incorporating the institutional environment into the theoretical analytical framework of climate risk-RED can provide unique insights into climate governance of countries, which is essential to effectively respond to climate change, ensure energy security, and achieve sustainable development.

Climate risk refers to the systemic risk posed by severe weather conditions, including climate factors such as extreme weather, natural disasters, and the uncertainty caused by the economic and social transition to sustainable development (Wang and Wang, 2025). According to Acheampong et al. (2021) and Sethi et al. (2020), climate risk has been the greatest threat to human social and economic development for many years, with significant impacts on various industries and markets. In particular, the renewable energy market is not only directly affected by climate risk, but is also a key area for addressing the climate crisis, which makes it an important research focus (Jiang et al., 2025). However, the empirical analyses of existing studies have presented conflicting results. For example, Juhola et al. (2024) revealed that climate risk disrupts the production and supply of renewable energy, which will have a negative impact on RED. Instead, Wen et al. (2023) believed that climate-vulnerable countries are likely to increase green investments and promote RED. This theoretical disagreement implies that there may be unrevealed nonlinear mechanisms between climate risk and RED. Based on this, this study focuses on investigating the nonlinear relationship between climate risk and RED, providing more insight into effectively addressing climate-energy nexus challenges.

Previous studies on the relationship between climate risk and RED have rarely considered the institutional environment. In the midst of the global climate and energy crises, researchers are actively looking for drivers of climate governance goals and the shift to sustainable energy. The role of government policies and actions has come under scrutiny, and the importance of government interventions has been highlighted (Song et al., 2023). Since 2023, 35 countries have adopted new energy regulations that actively promote net-zero emission targets. A favorable institutional environment guarantees the establishment and effective implementation of climate and energy policies through the provision of green financial support and the construction of policy regulatory frameworks (Omri and Ben Jabeur, 2024). Accordingly, we introduce three different institutional environments: economic, financial, and political institutional environments, shedding light for the first time on the different moderating effects of the three institutional environments on the nonlinear relationship between climate risk and RED.

Moreover, existing studies mainly use linear models such as panel regression (Ben Lahouel et al., 2020). However, this approach raises the issue of cross-sectional heterogeneity, which introduces bias in the analysis (Pesaran and Smith, 1995). While fixed-effects modeling can alleviate this concern, the nonlinear characteristics of other parameters across countries cannot be taken into account. Notably, panel smooth transition regression (PSTR) can effectively solve the estimation bias and endogeneity problems caused by linear models. This study innovatively adopts the PSTR model (Fok et al., 2005), which has been widely used to explore energy-related issues (Khezri et al., 2024; Lee et al., 2025). It allows the effects of the explanatory variables on the explained variable to vary in cross-section and time (Jude, 2010). In addition, depending on the threshold level and slope parameter results, it allows the coefficient of the threshold variable to smoothly transition between different regimes (Raza et al., 2020). Therefore, we use the PSTR model to explore the dynamic relationship between climate risk and RED in the context of different institutional environments and attempt to unravel the complexity of the climate risk–RED linkage, filling the existing gap in the literature.

In this study, based on panel data at the global level, we incorporate climate risk, institutional environment, and RED into a unified framework, exploring the nonlinearity of climate risk and RED in different institutional environment regimes. The contributions of this paper are mainly the following: first, existing studies on the interrelationship between climate risk and RED are fragmented and lack systematicity. This study systematically examines the nonlinear relationship between climate risk and RED based on data from 85countries around the world from 2000 to 2022, providing reference and inspiration for countries to cope with the climate crisis and promote RED. Second, we consider whether the impacts of climate risk on RED change in three different institutional environments: the economic, financial, and political institutional environments. This provides new insights for developing better climate adaptation policies and creating a sound institutional environment for the transition to renewable energy. Third, breaking through the limitations of previous literature, using mainly linear models such as panel regression, we introduce the PSTR model, which aims to break through the limitations of traditional linear assumptions and systematically reveal the dynamic threshold effects and district system switching characteristics between climate risk and RED, thus providing a new theoretical explanatory framework for the existing research controversies.

Our study consists of the following sections: in Section 2, literature related to our study is reviewed, and the hypotheses are formulated. Section 3 introduces the PSTR model and explains the research design. Section 4 presents the data and empirical results. The conclusions and recommendations of our study are provided in Section 5.

## 2. Literature review and hypothesis development

Many factors can affect RED. Economic factors such as financial development, foreign direct investment (FDI), GDP, income, and economic growth are widely considered in the existing literature (Akar, 2016; Anton and Nucu, 2020; Bhattacharya et al., 2016; Cherni and Jouini, 2017; Çoban and Topcu, 2013). Yu et al. (2021) found that investment structure greatly benefits RED. Jebli et al. (2016) provided evidence for bidirectional causality between renewable energy consumption and $CO_2$ emissions, non-renewable energy consumption, international trade, and GDP in the long run. Furthermore, human capital, eco-innovation, and energy productivity are identified as determinants of renewable energy generation (Lee and Lee, 2016; Li et al., 2020). Meanwhile, environmental variables such as fossil fuels, population size, $CO_2$ emissions, and environmental degradation are explored in existing research works (Lin and Omoju, 2017; Marques et al., 2010; Romano et al., 2017). In addition, factors from the perspective of institutions and society also attract the attention of researchers, along with corruption, democracy, and institutional quality (Cadoret and Padovano, 2016; Sequeira and Santos, 2018; Uzar, 2020). For instance, Khribich et al. (2021) found that, in the long run, the social development of 27 high-income countries significantly affects their renewable energy consumption.

The impact of climate factors on the energy sector has also attracted the attention of many scholars. On the one hand, climate risk has impacts on the energy expenditure and consumption (Lee et al., 2021). On the other hand, climate risk affects energy supply through energy costs and transportation (Yalew et al., 2020). Therefore, there is no doubt that the energy transition will be affected by climate risk. However, as an important part of the energy transition, the impact of climate risk on RED has been poorly studied. Our study offers a new way of looking at the relationship between them.

The main sources of renewable energy are directly associated with climate variables such as temperature, precipitation, and wind (Contreras-Lisperguer and de Cuba, 2008). Using fossil fuels as a source of electricity generation negatively affects the environment, climate change, and others (Panwar et al., 2011). In this context, the relationship between climate risk and RED deserves further investigation. Climate hazards have implications for the energy system, on both the demand and the supply sides, thus affecting the reliability and performance of the energy system (Cronin et al., 2018; Denholm et al., 2021). As the energy transition process is advancing rapidly, climate change has effects on energy infrastructure investment (In et al., 2022; Jakob and Steckel, 2016). For instance, extremely high temperatures can damage the renewable energy infrastructure (Dell et al., 2014), increasing operational costs, as well as negatively affecting the efficiency of the equipment (Solaun and Cerdá, 2019). Therefore, firms' willingness to RED can be reduced. Other researchers have proposed that climate change can influence a country's inflation and price levels (Chen et al., 2021), international trade (Li et al., 2015), per capita GDP (Lo and Chow, 2015), economic volatility (Gallic and Vermandel, 2020), and inequality and income distribution (Cappelli et al., 2021), among others. These factors are also associated with RED, which is inseparable from macroeconomic conditions. In other words, climate risk can indirectly affect RED by impacting these factors.

Therefore, we propose the first hypothesis of this study:

**Hypothesis 1**: Climate risk hinders RED.

In fact, the relationship between climate risk and RED may not be static and linear, showing dynamic and nonlinear characteristics in different institutional environments. Since both climate change mitigation and RED are dependent on the external environment, researchers have kept an eye on the role of the institutional environment. On the one hand, the institutional mechanism is a main factor for promoting RED (Chen et al., 2021; Uzar, 2020). On the other hand, the institution's quality plays a vital role in governance, social, and economic readiness, helping to mitigate the negative impacts of climate risk (Sarkodie and Adams, 2018). However, there is little literature to distinguish between the impacts of the three different institutional environments of economics, finance, and politics, let alone consider their nonlinear moderating effects, which highlights another outstanding contribution of this study.

First of all, the economic institutional environment expresses cyclical fluctuations in the economy, including booms and recessions (Zhang and Chiu, 2023). Salim and Rafiq (2012) suggested that economic downturns, along with increasing unemployment and declining per capita income, negatively affect renewable energy projects and consumption, which indicates that an unstable economic institutional environment is difficult to support RED. The high input and high cost of RED require the support of a stable economic environment, which can provide adequate capital and more mature technology, thus helping renewable energy facilities withstand climate hazards. Second, the financial institutional environment relates to the availability and value of financial resources in a society. Improvements to the regulatory framework and the financing environment positively affect RED (Opeyemi et al., 2019). When the financial institutional environment is improved, financial institutions with a sound system will fund renewable energy and green technology projects, enabling firms to adopt methods that are energy efficient. Therefore, it can upgrade environmental quality by using fewer fossil fuels and more renewable energy (Diallo and Masih, 2017; Lee et al., 2015). Third, the political institutional environment includes the stability of the political system, the level of effectiveness of government institutions, and the risk of changes in economic policies (Chen et al., 2024a). Su et al. (2021) indicated that the political institutional environment has a positive impact on renewable energy consumption. The findings of Gatzert and Kosub (2017) indicated that both regulatory and policy risk are critical for renewable energy investments. Sequeira and Santos (2018) found that governance can be a key factor that affects renewable energy. Fredriksson and Svensson (2003) also found that renewable energy investments cannot be improved when the political environment is unstable.

Therefore, we believe that the impact of climate risk on RED is characterized by nonlinearity under different institutional environments. Specifically, when the economic institutional environment is favorable, the state can provide more funds to cope with the loss of energy infrastructure caused by climate risk and provide more funds for RED to mitigate the negative correlation between climate risk and RED. When the financial institutional environment is favorable, financial institutions and regulators are able to induce the formation of climate risk management and the transition to low-carbon technologies and production, which is difficult to achieve when the financial institutional environment is poor (Campiglio et al., 2018; D'Orazio and Popoyan, 2019). On the one hand, climate shocks hit the borrowing firms through increasing volatility and bankruptcies, posing a threat to banks. On the other hand, in a stable financial environment, banks can finance more "green" or "brown" projects, mitigating the adverse effects of climate risk on facilitating sustainable development. Financial support is also important for RED as it requires abundant initial investment and high capital costs. When the political institutional environment is stable, a system with a fair legal framework can help drive climate change mitigation measures, such as carbon taxes and emissions optimization, which are often policy-driven (Uzar, 2020). An unstable political institutional environment may increase the costs of addressing climate change risk. In sum, the negative impact of climate risk on RED is more profound in bad institutional environments than in good ones, showing a nonlinear character.

From the above analyses, we formulate Hypothesis 2:

**Hypothesis 2**: The institutional environments have a nonlinear moderating effect on the relationship between climate risk and RED.

## 3. Methodology and data

### *3.1. Econometric model*

Most researchers adopt the panel threshold regression (PTR) model developed by Hansen (2000) to conduct nonlinear research between variables and obtain the threshold value in studies related to the environment, energy, economy, etc. The PSTR model is an extension of the PTR model, allowing continuous and smooth nonlinear transition of parameters as the transition variable changes, and controlling the cross-sectional heterogeneity of panel data. The general form of the two-regime PSTR model is as follows (Ullah et al., 2021):

$$y_{i,t} = \mu_{i,t} + \beta_0 x_{i,t} + \beta_1 x_{i,t} g\left(q_{i,t}; \gamma, c_j\right) + \varepsilon_{i,t} \tag{1}$$

where i=1, …, N, t=1, …, T represents the panel's country and time dimensions, respectively; $\mu_i$ is the fixed effect; and $\varepsilon$ is the error term. The transition function $g\left(q_{i,t}, \gamma, c_j\right)$ is a continuous and bounded logical function, the value of which changes continuously from 0 to 1. When it approaches 0, the model is in the low regime; when it approaches 1, the model is in the high regime; $q_{i,t}$ is the threshold variable; $\gamma$ is the slope parameter, indicating the speed of transition function switching from one regime to another, that is, the smoothness of the transition; $c$ is the location parameter, representing the threshold for transition. Therefore, we use the PSTR model to explore the nonlinearity between climate risk and RED under the two-regime institutional environment. First of all, we need to define a two-regime PSTR model with fixed effects. The Equation (2) is given below:

$$\begin{aligned} \mathrm{RED_{i,t}} &= \mu_i + \alpha_0 \mathrm{RED_{i,t-1}} + \alpha_2 \mathrm{CMV_{i,t}} + \alpha_3 x_{i,t} \\ &+ \left(\beta_0 \mathrm{RED_{i,t-1}} + \beta_2 \mathrm{CMV_{i,t}} + \beta_3 x_{i,t}\right) \mathrm{g}\left(\mathrm{RISK_{i,t}}; \gamma, c_j\right) + \varepsilon_{i,t} \end{aligned} \tag{2}$$

where $RED$ represents renewable energy electricity generation, $RED_{i,t-1}$ indicates renewable energy electricity generation lags one stage; $RISK$ means the country risks indices, indicating the institutional environment; and $CMV$ denotes the climate vulnerability index, that is, the climate risk. $x_{i,t}$ represents a collection of control variables, including GDP per capita (LGDP), foreign direct investment (FDI), net inflows, coal consumption (COAL), and $CO_2$ emissions (LCOE); i=1, …, N; t=1, …, T. N means the country, and T means the time period (2000–2022). In accordance with (Fouquau et al., 2008), we adopted the following logistic transition function:

$$g\left(RISK_{i,t}, \gamma, c_j\right) = \frac{1}{1 + \exp\left[-\gamma\left(RISK_{i,t} - c_j\right)\right]} \tag{3}$$

From what we have shown above, $c$ is the location parameter, and $\gamma$>0 indicates the slope of transition function. When $\gamma \to \infty$, the transition function will convert into an indicator function. Only when $\gamma \to 0$, the PSTR model becomes a fixed effect model. The coefficients of RED and CMV vary with the transition from low regime ($\alpha_2$) to high regime ($\alpha_2 + \beta_2$). The threshold parameter changes with the country and time in the PSTR model. Equation (4) shows the relationship between RED and CMV changing with time (t) and country (i).

$$\frac{\partial RED_{i,t}}{\partial CMV_{i,t}} = \alpha_2 + \beta_2 g(RISK_{i,t}; \gamma, c_j) \tag{4}$$

Referring to the study of (Gonzalez et al., 2017), we need to test the nonlinear relationship between RED and CMV, that is, if it is reasonable for this study to use the PSTR model to analyze their relationship. The null hypothesis is as follows: $H_0$: linear model with individual effect ($\gamma = 0$); and $H_1$: PSTR with two regimes ($\gamma = 1$). In $H_0$: $\gamma = 0$, $SSR_0$ can explain the sum of squared residuals, and in the alternative hypothesis $H_1$: $\gamma = 1$, $SSR_1$ can be used to explain its sum of squared residuals. Because there are unknown uncertainty parameters under the null hypothesis, the tests above are nonstandard. A situation is proposed to overcome this problem: by replacing the transition function $g\left(q_{i,t}, \gamma, c_j\right)$ by the first-order Taylor expansion around $\gamma = 0$, then we will get a regression equation as follows:

$$y_{i,t} = \mu_i + \beta_0^* x_{i,t} + \beta_1^* x_{i,t} q_{i,t} + \cdots + \beta_m^* x_{i,t} q_{i,t}^m + \mu_{i,t}^* \tag{5}$$

Here, the parameters $\beta_0^* \ldots \beta_m^*$ are multiples of $\gamma$ and $\mu_{i,t}^* = \mu_{i,t} + R_1 \beta_{i,t}^* x_{i,t}$, where $R_1$ denotes the remainder of Taylor expansion. Thus, the testing $H_0$: $\gamma = 0$ in equation (3) is similar to testing $H_0^*$: $\beta_0^* = \cdots = \beta_m^* = 0$ in Equation (5). We use three statistics to test the hypothesis of linearity: the Wald test (LM), the Fisher test (LMF), and the likelihood ratio test (LRT) (Ben Cheikh et al., 2021).

$$\text{Wald Test} = \text{LM} = \frac{\text{NT}(\text{SSR}_0 - \text{SSR}_1)}{\text{SSR}_0} \tag{6}$$

$$\text{Fisher Test} = \text{LMF} = \frac{\frac{\text{SSR}_0 - \text{SSR}_1}{\text{K}}}{\frac{\text{SSR}_0}{\text{NT} - \text{N} - \text{K}}} \tag{7}$$

$$\text{LRT Test} = \text{LRT} = -2[\log(\text{SSR}_1) - \log(\text{SSR}_0)] \tag{8}$$

where $K$ represents the number of dependent variables, and $N$ is the number of countries. The LMF can be seen as an approximate F (K, NT-N-K) distribution, while LM and LRT can use a $x^2(K)$ distribution to explain. If the null hypothesis ($H_0$: $\gamma = 0$) cannot be rejected, the model is linear, implying that there is nonlinearity between RED and CMV. If the null hypothesis is rejected, we will accept the alternative hypothesis ($H_1$: $\gamma = 1$) and conclude that the number of transition function ($\gamma$) is 1 for the PSTR model with two regimes.

### *3.2. Data specification*

To investigate the relationship between climate risk and RED under different institutional environments, this study constructs a database of 85 countries from 2000 to 2022. The RED level is measured by renewable energy electricity generation in a natural logarithm (Song et al., 2022), which comes from the International Renewable Energy Agency (IRENA). Following prior studies (Cevik and Jalles, 2022a; Jia and Li, 2020; Nguyen et al., 2021), we adopt the Notre Dame Global Adaptation Index (ND-GAIN), which was developed by the University of Notre Dame, to measure the level of climate risk. The ND-GAIN Index covers the vulnerability of different countries to climate change and their readiness to increase resilience (Ul-Haq et al., 2024). Since we focus only on a country's level of climate risk and not on its adaptive readiness, we chose vulnerability as the independent variable in this paper. As a common measure of climate risk, climate vulnerability has been widely used in recent studies (Cevik and Jalles, 2023; Wen et al., 2023; Ren et al., 2025). While these studies focus on exploring the linear relationship between climate risk and green investment or innovation, this paper uses the PSTR model to explore the nonlinear impact of climate risk on RED. The vulnerability index reflects trends in the exposure of human societies to the negative impacts of climate change, as well as the overall susceptibility to climate-related disruptions of a country (Cevik and Jalles, 2022b), ranging from 0 to 1. We multiply it by 100 in this study (CMV). As for the institutional environment, with reference to Wang et al. (2022), we adopt the International Country Risk Guide (ICRG) risk data. There, we choose four of these indices to describe the multi-dimensional risks of countries, including economic risk (ER), financial risk (FR), political risk (PRR), and composite risk (CR). A higher risk rating is associated with a lower country risk and a better institutional environment. We take the natural logarithm of country risk ratings in this study.

We also consider four control variables from different aspects. Specifically, regarding the economic aspect, there are GDP per capita in natural logarithm (LGDP) (Sadorsky, 2009), measured in 2015 current US$, foreign direct investment, and net inflows (FDI, % of GDP) (Doytch and Narayan, 2016). From an energy perspective, we use coal consumption (COAL, quad Btu) (Apergis and Payne, 2014). In addition, we consider $CO_2$ emissions (LCOE, kt) as a natural environment factor (Sadorsky, 2009). These data are obtained from the World Bank's Development Indicators (WDI) database, except for the data on coal consumption, which are downloaded from the United States Energy Information Administration (EIA). The information on all variables is shown in Table 1. The observations of all samples are 1955. The minimum RED is 0.000, while the maximum is 14.771. This result suggests there are some countries maintaining a relatively low level of renewable energy generation, while the mean of this variable is 8.512, which means most countries have great RED. In addition, the mean of CMV is 40.788, which suggests many countries are sensitive to climate change, while its standard deviation is 8.062, indicating that this indicator is highly volatile.

**Table 1.** Descriptive statistics.

| Variables | RED | CMV | CR | ER | FR | PRR | LGDP | FDI | LCOE | COAL |
|---|---|---|---|---|---|---|---|---|---|---|
| Obs. | 1955 | 1955 | 1955 | 1955 | 1955 | 1955 | 1955 | 1955 | 1955 | 1955 |
| Mean | 8.512 | 40.788 | 4.248 | 3.558 | 3.614 | 4.204 | 25.191 | 2.539 | 240.847 | 13.176 |
| Std. Dev. | 2.350 | 8.062 | 0.130 | 0.155 | 0.148 | 0.185 | 1.895 | 14.078 | 1027.984 | 84.272 |
| Min. | 0.000 | 25.133 | 3.595 | 2.582 | 2.442 | 3.484 | 20.381 | −360.353 | 0.402 | 0.000 |
| Max. | 14.771 | 61.913 | 4.526 | 3.882 | 3.893 | 4.550 | 30.521 | 252.920 | 12621.600 | 965.000 |

Notes: RED, LGDP, CR, ER, FR, and PRR are in natural logarithms; we multiply COAL by 10; we multiply CMV by 100; we use raw data for FDI and LCOE. Table 2 indicates the pairwise correlations between all variables. From this table, we can see that RED and institutional environment (CR, ER, FR, PRR) all have a significantly negative relationship with climate vulnerability (CMV). These results imply that if a country faces a lower climate risk, its renewable energy is more developed.

**Table 2.** Pairwise correlations.

| | RED | CMV | CR | ER | FR | PRR | LGDP | FDI | LCOE | COAL |
|---|---|---|---|---|---|---|---|---|---|---|
| RED | 1 | | | | | | | | | |
| CMV | −0.410*** | 1 | | | | | | | | |
| CR | 0.346*** | −0.698*** | 1 | | | | | | | |
| ER | 0.282*** | −0.510*** | 0.824*** | 1 | | | | | | |
| FR | 0.210*** | −0.214*** | 0.553*** | 0.521*** | 1 | | | | | |
| PRR | 0.294*** | −0.714*** | 0.876*** | 0.545*** | 0.154*** | 1 | | | | |
| LGDP | 0.692*** | −0.589*** | 0.510*** | 0.467*** | 0.438*** | 0.349*** | 1 | | | |
| FDI | −0.046*** | −0.095*** | 0.126*** | 0.110*** | 0.004*** | 0.132*** | 0.016*** | 1 | | |
| LCOE | 0.334*** | −0.100*** | 0.095*** | 0.119*** | 0.221*** | −0.017*** | 0.397*** | −0.017 | 1 | |
| COAL | 0.285*** | −0.067*** | 0.065*** | 0.093*** | 0.191*** | −0.036 | 0.312*** | −0.016 | 0.989*** | 1 |

Notes: RED, LGDP, CR, ER, FR, and PRR are in natural logarithms. P-values are in parentheses. ***, **, and * indicate the 1%, 5%, and 10% significance levels, respectively.

## 4. Empirical results and discussion

### *4.1. Nonlinear test*

The panel smooth transition regression (PSTR) model tests if there are nonlinear relationships between the variables. In this study, we use three statistics, LM, LMF, and LRT, to test the nonlinear relationships for the four models we have built. In these models, we use country risks as thresholds (Ben Cheikh et al., 2021). The results are shown in Table 3. Obviously, when $H_0$: $r=0$vs $H_1$: $r=1$, the null hypothesis of linearity of Models (1)–(4) can be significant rejected. This suggests that there are nonlinear relationships between RED, climate risk, and institutional environment, implying that it is reasonable for this study to use the PSTR model. From the results, we can see that there is at least one transition function. In other words, Models (1)–(4) have at least two regimes. After testing the nonlinear relationship, we refer to the method provided by (Gonzalez et al., 2017), finding that the four models have an optimal threshold parameter, namely m=1. As such, we use the two-regime model to complete our study. Depending on whether the values of transition variables (RISKi,t) are lower or higher than the estimated threshold values (c), we can get two regimes. The first is the low regime, when RISKi,t is lower than c, meaning that countries are in an unstable institutional environment. The second is the high regime, for when countries are in a stable institutional environment. The transition functions are also different in the two regimes. Specifically, they approach 0 in the first regime and 1 in the second regime.

**Table 3.** Tests for the nonlinearity of the PSTR model for the full sample.

| Threshold variables | CR | ER | FR | PRR |
|---|---|---|---|---|
| Models | (1) | (2) | (3) | (4) |
| $H_0$: $r=0$vs $H_1$: $r=1$ | | | | |
| LM | 18.627$^{***}$ | 9.214$^{***}$ | 5.769$^{*}$ | 24.180$^{***}$ |
| | (0.000) | (0.010) | (0.056) | (0.000) |
| LMF | 8.980$^{***}$ | 4.420$^{**}$ | 2.763$^{*}$ | 11.691$^{***}$ |
| | (0.000) | (0.012) | (0.063) | (0.000) |
| LRT | 18.717$^{***}$ | 9.236$^{***}$ | 5.777$^{*}$ | 24.331$^{***}$ |
| | (0.000) | (0.010) | (0.056) | (0.000) |

Notes: r is the number of transition functions. P-values are in parentheses. *** indicates the 1% significance level.

### *4.2. The estimated results of the PSTR model*

From Table 4, we can see that the estimated results of the core explanatory variable (CMV) are significantly negative, but the magnitudes of the coefficients are different which suggests that climate risk has a two-regime impact on RED in different degrees of institutional environment. On the one hand, the slope parameter (γ) of the PSTR model indicates the continuity and smoothness of the transition function. On the other hand, it also implies the transition speed from one regime to another. Specifically, the smaller the slope parameter (γ), the more continuous and smooth the transition function is, and the slower it switches from one regime to another. For the financial institutional environment, the impact of climate risk on RED switches more quickly and less smoothly from low regime to high regime than under the economic and political environment. We can see from the results that, no matter what type of institutional environment we use as a threshold variable, when it is less than the location parameter (4.5139, 3.5472, 3.5881, and 4.4921, respectively), climate risk will have a significantly negative impact on RED, which support hypothesis 1.

The results after adding the control variables are displayed in Table 5. Composite risk represents the overall risk of countries as well as the overall institutional environment. The higher the composite risk, the more stable the national environment. For the national institutional environment as a threshold, after switching to the high regime, the impact becomes insignificantly negative. This result indicates that, in an unstable national institutional environment, climate risk negatively affects RED, while in a stable national institutional environment, the negative effects disappear. This reflects that the improvement of the national institutional environment will mitigate the impairment of RED by climate risk. The reason may be the fact that, when a country is exposed to a higher climate risk, the instability of the economy and society will lead to a decline in economic activities, less willingness to invest in energy infrastructure, and more difficulties with energy transition (Cevik and Jalles, 2022a; Ciccarelli and Marotta, 2024; Dell et al., 2014). With the institutional environment improving, countries will pay more attention to the risks of climate change and issue corresponding environmental policies. Transitioning to a green economy increases financing for green projects (Wen et al., 2021). Therefore, the adverse impacts of climate risk on RED can be mitigated. Hypothesis 2 is validated.

**Table 4.** Estimated results of the PSTR model for the full sample.

| Dependent variable | RED | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Threshold variables | CR | | ER | | FR | | PRR | |
| Regimes | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime |
| Models | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| CMV | −0.2044*** | −0.0538** | −0.2161*** | −0.0095*** | −0.2245*** | −0.0086*** | −0.1905*** | −0.0311* |
| | (−15.2756) | (−2.2949) | (−15.9332) | (−2.9828) | (−16.5045) | (−3.4662) | (−13.7950) | (−1.7727) |
| $RED_{i,t-1}$ | 0.1283*** | 10.0668 | 0.0999*** | 0.0292* | 0.1120*** | 0.0220** | −0.1724 | −0.5018 |
| | (7.2262) | (−0.7910) | (6.6222) | (2.0332) | (8.5601) | (1.8525) | (−0.4903) | (−1.5381) |
| Controls Included | NO | NO | NO | NO | NO | NO | NO | NO |
| Observations | 1955 | | 1955 | | 1955 | | 1955 | |
| Location parameters, c | 4.5139 | | 3.5472 | | 3.5881 | | 4.4921 | |
| Slope parameters, γ | 9.0315 | | 128.1217 | | 32.3584e+05 | | 9.3074 | |

Notes: ***, **, and * indicate the 1%, 5%, and 10% significance levels, respectively. The T-statistic are in parentheses.

With the economic institutional environment as a threshold variable, after switching to the high regime, the impact also becomes insignificantly negative, indicating the nonlinear moderating effect of the economic institutional environment. When the economic environment is unstable, with the increase in unemployment and decrease in per capita income, the harm of climate change to the renewable energy infrastructure can be mitigated in time because of sufficient capital and renewable energy investments. In a stable economic institutional environment, the economic vitality can be released, and economic development can be improved (Ibrahim et al., 2018). In this case, there will be a greater focus on sustainable development and more funding for climate change mitigation.

With the financial institutional environment as a threshold variable, different from the results above, the impact becomes significantly positive after switching to the high regime. This indicates that, as the financial institutional environment improves, the climate risk will first hinder and then improve RED. As mentioned before, climate risk obstructs RED by undermining financial stability. A stable financial institutional environment is associated with the stability and flexibility of financial systems. Financial support is crucial to RED as it requires abundant initial investment and a high capital cost (Kim and Park, 2016). Apart from that, renewable energy technology and further RED also need financing from financial markets (Zhang, 2020). Therefore, as the financial institutional environment becomes more stable, climate risk could instead facilitate RED.

**Table 5.** Estimated results of the multivariate models for the full sample.

| Dependent variable | RED | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Threshold variables | CR | | ER | | FR | | PRR | |
| Regimes | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime |
| Models | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| CMV | −0.1126*** | −0.0031 | −0.1215*** | 0.0053 | −0.1239*** | 0.0130*** | −0.1019*** | −0.0783** |
| | (−6.2845) | (−0.4018) | (−6.8462) | (1.2584) | (−6.9825) | (3.2414) | (−5.4363) | (−2.0124) |
| $RED_{i,t-1}$ | 0.0301* | 0.0814*** | 0.0450*** | 0.0628*** | 0.0404*** | 0.0933*** | 0.1180*** | −0.1376*** |
| | (1.9400) | (3.7002) | (2.7050) | (3.0721) | (2.9913) | (3.2643) | (6.0983) | (−3.0358) |
| LGDP | 0.4573*** | −0.0409** | 0.3977*** | −0.0354*** | 0.4797*** | −0.0697*** | 0.3202*** | 0.0882 |
| | (11.3233) | (−2.3529) | (10.1747) | (−3.1454) | (12.0045) | (−5.1595) | (8.0706) | (1.6071) |
| FDI | −0.0033 | 0.0037 | −0.0009 | 0.0009 | 0.0000 | 0.0002 | 0.0011 | −0.0019 |
| | (−1.4259) | (1.3801) | (−0.3426) | (0.3382) | (0.0083) | (0.0677) | (0.4435) | (−0.4099) |
| LCOE | −0.0002 | 0.0007 | 0.0011* | −0.0006** | 0.0010* | −0.0004 | 0.0005*** | 0.0006 |
| | (−0.2596) | (1.1682) | (1.8900) | (−1.0149) | (1.9312) | (−0.8542) | (3.3831) | (0.3088) |
| COAL | 0.0047 | −0.0113 | −0.0146* | 0.0086*** | −0.0452*** | 0.0380*** | −0.0063*** | −0.0125 |
| | (0.4603) | (−1.1426) | (−1.7536) | (1.0428) | (−4.2862) | (3.7083) | (−3.2485) | (−0.5091) |
| Observations | 1955 | | 1955 | | 1955 | | 1955 | |
| Slope parameters, γ | 61.3976 | | 117.6450 | | 43.4645 | | 11.8494 | |
| Location parameters, c | 4.1781 | | 3.5372 | | 3.5934 | | 4.4492 | |
| AIC | −1.2727 | | −1.2464 | | −1.2947 | | −1.2508 | |
| BIC | −1.2327 | | −1.2064 | | −1.2548 | | −1.2108 | |
| RSS | 535.6324 | | 549.9120 | | 523.9381 | | 547.4997 | |

Notes: ***, **, and * indicate the 1%, 5%, and 10% significance levels, respectively. The T-statistic are in parentheses.

With the political institutional environment as a threshold variable, in the low regime, the estimated coefficient is significantly negative, which suggests that, in an unstable political institutional environment, climate risk has adverse impacts on RED. An unstable political institutional environment has serious problems with corruption, government instability, lack of democracy, and so on (Junxia, 2019). These problems result in indifference in dealing with climate risk and climate change mitigation policies, and projects cannot be proposed. Also, in an unstable political institutional environment, markets and governance will become less efficient, increasing the costs of RED (Fredriksson and Svensson, 2003). However, when the political institutional environment is being favorable, the effect of climate risk on RED remains negative, although the absolute value of the coefficient is smaller, suggesting that the effectiveness of the political institutional environment needs to be further explored.

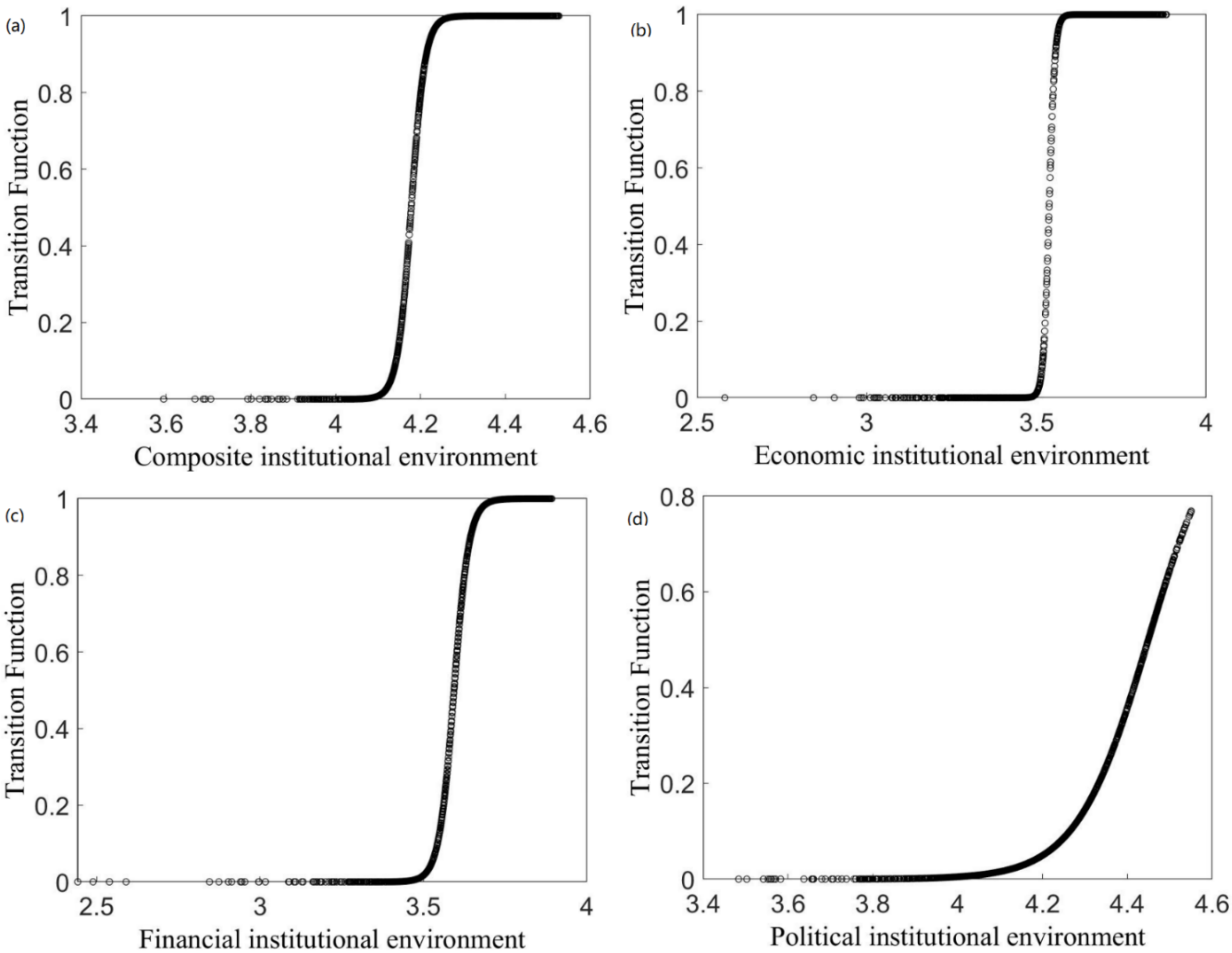


**Figure 1.** Estimated transition functions of the renewable energy development PSTR model with control variables. (a) The composite institutional environment as a threshold. (b) The economic institutional environment index as a threshold. (c) The financial institutional environment index as a threshold. (d) The political institutional environment index as a threshold. (Note: y axis is the transition function, and x axis is the transition variable.)

Combining the information from Table 5 with that of Figure 1 (the transition function of climate risk to RED), we learn the following information: first, with the national institutional environment and the financial institutional environment as thresholds, as climate risk increases, the transition function value shifts smoothly and continuously from 0 to 1. When the national and financial institutional environments are in the low regime below the thresholds (4.1781, 3.5934), the impact on RED shows a significant dampening effect as climate risk increases. Second, with the economic institutional environment as a threshold, as climate risk increases, the transition speed of the transition function is faster. Third, with the political institutional environment as a threshold, it appears that the transition function does not switch to 1 as the climate risk increases, further suggesting that the moderating effect of the political institutional environment is ineffective.

When considering the impacts of four control variables, we get the following information: when taking a country's economic factors (LGDP and FDI) into consideration, from the estimated coefficients shown in Table 6, we can see that LGDP positively affects RED when the institutional environment is stable, and negatively affects RED when it turns to unstable. This is because, with the development of the economy, income and awareness of sustainable development increases. As a result, countries and individuals are able and more willing to invest in renewable energy generation.

**Table 6.** Estimated results of the multivariate model for low income countries.

| Dependent variable | RED | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Threshold variables | CR | | ER | | FR | | PRR | |
| Regimes | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime |
| Models | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| CMV | $-0.1031^{***}$ | $0.0247^{***}$ | $-0.1065^{***}$ | $0.0250^{***}$ | $-0.1067^{***}$ | $0.0241^{***}$ | $-0.1024^{***}$ | $0.0297^{**}$ |
| | (−5.8642) | (3.1204) | (−5.7578) | (4.3680) | (−5.8079) | (3.3209) | (−5.9557) | (2.1960) |
| $RED_{i,t-1}$ | $0.0416^{***}$ | $0.0512^{**}$ | $0.0661^{***}$ | 0.0014 | $0.0490^{***}$ | $0.0580^{*}$ | $0.0435^{***}$ | $0.0716^{**}$ |
| | (2.7985) | (2.1934) | (3.6918) | (0.0611) | (3.1438) | (1.6679) | (2.9322) | (1.9616) |
| Controls Included | YES | YES | YES | YES | YES | YES | YES | YES |
| Observations | 1219 | | 1219 | | 1219 | | 1219 | |
| Slope parameters, γ | 75.2293 | | 54.9405 | | 25.6661 | | 25.4764 | |
| Location parameters, c | 4.1828 | | 3.5329 | | 3.6038 | | 4.1828 | |

Notes: ***, **, and * indicate the 1%, 5%, and 10% significance levels, respectively. The T-statistic are in parentheses. Economies are divided among income groups according to 2020 gross national income (GNI) per capita, calculated using the World Bank Atlas method. The groups are: low income, $1,045 or less; middle income, $1,046 to $12,695; and high income, $12,696 or more. Due to the small samples of middle income, we included it in the high-income countries.

*4.3. Heterogeneity analysis*

It is worth noting that the impacts of climate risk on RED in different institutional environments have the potential to vary with the income level. Thus, in this study, we classified the sample countries into low-income and high-income countries to test the influence of economic development on the empirical results. These two groups all passed the nonlinearity tests of the PSTR model.

**Table 7.** Estimated results of the multivariate model for high income countries.

| Dependent variable | RED | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Threshold variables | CR | | ER | | FR | | PRR | |
| Regimes | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime | Low-Regime | High-Regime |
| Models | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
| CMV | −0.2136*** | −0.0594** | −0.2265*** | −0.0966*** | −0.1974*** | −0.1251** | −0.1064 | −0.1082 |
| | (−4.3844) | (−2.3825) | (−4.4725) | (−4.4260) | (−4.5583) | (−2.3919) | (−0.7933) | (−0.7378) |
| $RED_{i,t-1}$ | 0.2113*** | −0.1833*** | 0.1259*** | −0.0786* | 0.0677*** | 0.0444 | 0.9244*** | −0.9606*** |
| | (4.2702) | (−3.8816) | (3.9360) | (−1.9156) | (3.4061) | (0.6154) | (4.9459) | (−4.8420) |
| Controls Included | YES | YES | YES | YES | YES | YES | YES | YES |
| Observations | 736 | | 736 | | 736 | | 736 | |
| Slope parameters, γ | 1.0086e+05 | | 45.9310 | | 279.0746 | | 9.3831 | |
| Location parameters, c | 4.3458 | | 3.6963 | | 3.7583 | | 4.1555 | |

Notes: ***, **, and * indicate the 1%, 5%, and 10% significance levels, respectively. The T-statistic are in parentheses. Economies are divided among income groups according to 2020 gross national income (GNI) per capita, calculated using the World Bank Atlas method. The groups are: low income, $1,045 or less; middle income, $1,046 to $12,695; and high income, $12,696 or more. Due to the small samples of middle income, we included it in the high-income countries.

Table 6 and Table 7 show the results of heterogeneity analysis. From the results we have obtained, we can see that the results of low-income and high-income countries are apparently different from each other. In unstable institutional environments of low-income countries, climate risk still has negative impacts on RED. With the improvement of the institutional environment, the relationship between these two variables can become positive. Low-income countries are more susceptible to climate risk than high-income countries (Kahn et al., 2021). In a better institutional environment, when exposed to climate risk, they are more able and willing to take more aggressive measures to mitigate its negative effects and reduce $CO_2$ emissions to prevent greater climate risk in the future. It can be seen from the above analysis that in a stable institutional environment, climate risk can have positive impacts on RED (Wu and Broadstock, 2015).

Comparing the estimated results of low-income countries with high-income countries, the results show that, in most situations of institutional environment, the estimated coefficients of climate risk and RED are significantly negative, which indicates that climate risk has a negative impact on RED in high-income countries. Thus, the moderating role of the institutional environment is more pronounced in low-income countries. In addition, whether for low-income countries or high-income countries, the relationship between climate risk and RED is nonlinear.

### *4.4. Robustness test*

#### 4.4.1. Substitution of explained variable

In order to further explore whether the nonlinearity between climate risk and RED is robust, we replace the core explained variable renewable energy generation with renewable energy capacity, with the results shown in Table A.2. In Model (1), the estimated coefficient of CMV is significantly negative. However, it becomes insignificant in Model (2). The results above indicate that the effect of climate risk on renewable energy capacity becomes insignificant after entering a stable national institutional environment, which are basically consistent with the baseline results, indicating that our regression results are robust and our conclusions are valid.

#### 4.4.2. Exclusion of the effects of the COVID-19

Considering that shocks from external events may affect the results of this paper, this section excludes the 2019 and 2020 samples. COVID-19 was initially reported on December 31, 2019, in Wuhan, China, and rapidly spread globally. It is clear that when the 2019 and 2020 samples are removed, climate risk still suppresses RED when the institutional environment is unstable, while this effect becomes insignificant when the institutional environment is stable, so the institutional environment still has a significant moderating effect.

#### 4.4.3. CMV lagged one period regression results

Referring to Zhao and Guo (2023), in the established PSTR model, endogenous risk exists if there is a bidirectional causal relationship between climate risk and RED. To reduce endogenous risk, we drop the climate risk lag by one cycle (L.CMV). Since L.CMV affects CMV, and RED in the current period cannot affect L.CMV, this approach mitigates to some extent the potential endogenous risk due to the existence of bidirectional causality. Table A.3 presents the regression results for CMV lagged by one period. The results show that the coefficients are significant even after accounting for endogeneity.

#### 4.4.4. Two-step system GMM estimates

Although the PSTR model can effectively solve the biased estimation and endogeneity problems caused by the linear regression model (Ullah et al., 2021), the reverse causality problem may still exist as RED has the ability of mitigating climate risk by significantly reducing $CO_2$ emissions. According to Ben Lahouel et al. (2022), we add the quadratic term of climate risk as an additional explanatory variable to the model and consider the dynamic panel model using the systematic generalized method of moments (Syst-GMM). This method has an outstanding advantage of circumventing potential endogeneity and reverse causality (Blundell and Bond, 1998). The results are shown in Table A.5.

From the results, we find that the p-values of AR(1) and AR(2) both imply first-order autocorrelation exists for the perturbation term, but not for the second-order autocorrelation. Furthermore, the Hansen test values are not significant, indicating that there is no overidentification problem. The results also show that the coefficients of CMV and its quadratic term CMV2 are significantly negative and positive, respectively, thus there is a nonlinear relationship between climate risk and RED, which demonstrates the rationality of choosing a PSTR model. In addition, climate risk still has a negative impact on RED after excluding the effect of reverse causality. Therefore, our results are robust.

## 5. Conclusions and recommendations

Using annual data ranging from 2000 to 2022, this study adopts three types of institutional environments (economic, financial, and political) as threshold variables and builds a PSTR model to explore the nonlinear relationship between climate risk and RED. We also classify the full samples into low-income and high-income countries to test whether the impacts of climate risk on RED will change with economic development level.

The main findings of this study are the following: first, climate risk hinders RED. This means the risks raised by climate change will obstruct RED. However, their relationship exhibits nonlinear transformation characteristics in different regimes of institutional environment. Second, institutional environment plays a moderating role on the relationship between climate risk and RED, while the moderating effects show heterogeneity under different types of institutional environments; particularly in a stable financial and economic institutional environment, the negative nexus between climate risk and RED can be weakened. Third, compared to high-income countries, climate risk disproportionately affects RED in low-income countries.

From the above conclusions, we can make the following recommendations: first of all, since climate risk negatively affects RED, it is necessary for governments to plan climate change mitigation and energy transition strategies. Specifically, governments should encourage conventional banks to develop green credit and urge them to provide easier access to investment financing for renewable energy companies with good environmental performance. In addition, as institutional environment moderates the negative nexus between climate risk and RED, policymakers should take the institutional environment into account when formulating climate and renewable energy policies to propose climate and energy policies that can be put into practice and ensure policy effectiveness, especially in low-income countries. For low-income countries, due to their growth-oriented policy and underdeveloped institutional environments, an incremental reform path that combines market-driven and institutional safeguards should be adopted. For example, a synergistic mechanism can be established between renewable energy quota systems and green certificate trading to guide power companies to increase the proportion of clean energy consumption and promote RED through the dual-wheel drive of mandatory and voluntary markets.

In addition, with well-established financial institutions and high levels of government stability, countries are more likely to attract investments from companies that focus on environment protection, thereby weakening the negative effects of climate risk. Therefore, for countries with poor institutional environments, the focus should be on improving the stability of the financial and political institutional environments, so as to provide strong institutional safeguards for climate governance and energy transition. Specifically, these countries need to strengthen the regulatory function of central banks, adopt appropriate monetary policies to prevent excessive inflation or deflation, accelerate financial innovation, and improve financial management mechanisms. Countries with better financial and political environments should give full play to institutional synergies and build a policy framework that deeply nests climate goals and governance effectiveness. These countries can establish a dynamic linkage mechanism between carbon tax revenues and renewable energy investments. At the regulatory level, a regulatory framework for environmental risks could be established on the basis of the well-established rule of law to strengthen the regulation of pollution emissions.

Moreover, the prevention of long-term corruption and monitoring mechanisms are required for the assurance of policy implementation and the improvement of government credibility. Investors should pay more attention to green technology innovation and transit their capital from the traditional fossil energy industry to the new energy industry for longer-term growth. Furthermore, sustained business models can be built by business leaders to mitigate climate risk and support RED. Lastly, countries need to take targeted measures to mitigate climate risk and promote RED in accordance with their levels of economic development. For example, China and India, which are fast-growing economies, should balance the relationship between environmental protection and economic development, promote the development of green finance, and subsidize new energy enterprises. Finally, it is necessary to balance the relationship between market-driven and government intervention and actively promote market-oriented RED with the main focus on raising the green awareness of all economic actors, and then promote climate action and RED with government support.

## Author contributions

Xianfeng Luo: writing—original draft preparation conceptualization and supervision. Qian Ding: reviewing, editing, methodology, data collection and reviewing.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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## Conflict of interest

All authors declare no conflicts of interest in this paper.

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