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The Janus-Faced Role of Renewable Energy Development in Global Carbon Reduction Under Renewable Energy Policies

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Key Points:

- Renewable energy policies (REPs) cut global carbon emissions, mainly via regulatory, economic, and R&D policies
- REPs' carbon reduction boosted by robust infrastructure, anti-corruption, and law adherence
- Renewable energy development has a Janus-faced impact on REPs' carbon reduction effect

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Abstract The global-scale empirical analysis of how renewable energy policies (REPs) affect carbon emissions and the mediating role of renewable energy development (RED) in this mechanism remains underexplored. To fill this research gap, we extracted and organized REPs data from IEA's databases for 135 countries until 2018 and conducted empirical analyses of these issues. We find that: (a) REPs significantly reduce global carbon emissions, especially through regulatory, economic, and R&D policies. (b) REPs' effectiveness in mitigating carbon emissions is enhanced by robust energy infrastructure, strong control of corruption, and adherence to the rule of law. Besides, the balance of REPs types does not influence their efficiency, but REPs prioritizing certain renewable energy (RE) types aligns better with carbon reduction goals. (c) RED displays a Janus-faced influence on REPs' carbon reduction effect—renewable energy consumption (REC) positively mediates it, whereas renewable energy share (RES) exerts a negative mediation. Specifically, REC consistently reduces carbon emissions, while RES initially increases and then decreases carbon emissions, exhibiting an inverted U-shape. (d) The initial rise in carbon emissions with RES is due to the low substitution of RE for fossil energy and the country-specific heterogeneity in organizational, geographic, industrial, economic, demographic, and temporal factors.

Plain Language Summary This study looked at how renewable energy policies (REPs) help lower carbon emissions worldwide and the role of renewable energy development (RED) in this process. We used data from the International Energy Agency on 135 countries up to 2018. Our findings show that REPs are effective in reducing carbon emissions, particularly through laws, economic incentives, and research and development. The success of these policies is better in countries with strong energy infrastructure, good governance, and rule of law. Interestingly, not all types of REPs are equally effective; those focusing on specific types of renewable energy (RE) align more closely with carbon reduction goals. We also discovered a dual role of RED in this scenario. While the use of RE helps lower emissions, just increasing the share of RE in the overall energy mix can initially lead to more emissions before eventually decreasing them. This increase at first happens because RE doesn't immediately replace fossil fuels and because countries are different in terms of their organization, geography, industry, economy, population, and changes over time.

1. Introduction

Climate change, driven by human activities and fossil fuel combustion, threatens ecosystems, human health, and the global economy (Perga et al., 2023). The Intergovernmental Panel on Climate Change reports that human-generated greenhouse gas (GHG) emissions, mainly CO_2, have raised the global temperature by about 1.0°C since the pre-industrial era, requiring urgent mitigation actions (Zhang et al., 2023; C. Zhu et al., 2022). Renewable energy (RE) offers a clean and sustainable alternative to fossil energy (FE), reducing CO_2 emissions and decoupling economic growth from GHG emissions (Kebede et al., 2022). Transitioning to RE sources such as solar, wind, hydro, geothermal, and bioenergy can decarbonize the energy sector and foster sustainable development and a low-carbon economy (Alt et al., 2024).

Despite its benefits, renewable energy development (RED) faces several barriers. The intermittency of RE sources like solar and wind challenges grid stability and energy storage (Blondeel et al., 2024), and immature technologies in RE areas, such as advanced biofuels and ocean energy, limit large-scale use (J. J. Liu et al., 2022). High initial costs deter RE investments, especially in financially constrained developing countries (Steffen, 2020), and market distortions like fossil fuel subsidies reduce RE competitiveness (Mutezo & Mulopo, 2021).

Additionally, insufficient policy support and regulatory frameworks impede RE technology investments (Sadiq & Chidi, 2024), either by increasing risks, reducing returns, or both (Polzin et al., 2019). This challenge is exacerbated in countries with dominant state-owned energy sectors or lacking climate commitment (Newell & Phillips, 2016). For example, in Kenya, although the government implemented RE policies, the feed-in tariff for solar power was set too low compared to other energy sources due to the country's dependence on its prevailing energy regime, thereby failing to attract sufficient solar power investments (Newell & Phillips, 2016).

Addressing barriers to renewables, REPs play a key role in promoting technology development and integration into the grid, fostering investment stability, innovation, and public acceptance (Mercure et al., 2021), driving industry growth, and aiding the shift to a low-carbon energy system (Gielen et al., 2019). Three policy types are prevalent: command-and-control regulations (CCRs), market-based incentives (MBIs), and voluntary-based approaches (VBAs) (Mungai et al., 2020; X. Zhao et al., 2019). CCRs, like renewable portfolio standards and net metering, mandate RE use and facilitate grid integration (Li et al., 2022; Zhou & Solomon, 2020). MBIs, including feed-in tariffs and tax credits, incentivize investments by offsetting the environmental costs of fossil fuels (Neves et al., 2020). VBAs, such as green procurement and eco-labeling, enhance consumer awareness and promote eco-friendly practices (Takahashi, 2021).

The consensus on REPs is that they positively influence RED, boosting aspects including RE consumption (Saint Akadiri et al., 2019), production (Y. Zhao et al., 2013), and share (Carley, 2009). Regarding RED's impact on climate change, studies at global (Strandsbjerg Tristan Pedersen et al., 2021), regional (Sadiq & Chidi, 2024), organizational (Xu et al., 2022), national (Stock & Sovacool, 2024), and micro scales (Fan et al., 2024) have examined its effect on carbon emissions. While Berrill et al. (2021) found that renewable energy consumption (REC) can increase emissions, others, like Rehman et al. (2022), observed a decrease. However, few studies, such as Chiu and Chang (2009), have focused on the renewable energy share (RES) and its threshold effect on emissions reduction in OECD countries. This suggests that the path from REPs to RED and then to carbon emission reduction is critical, but existing literature rarely empirically validates this pathway's feasibility globally, particularly the direct impact of specific types of REPs (like CCRs, MBIs, and VBAs) on carbon emissions. Therefore, we posit **Hypothesis 1**: *REPs can reduce carbon emissions, with RED mediating this effect*.

RED encompasses both increases in RE consumption and the share of renewables. Many countries have set ambitious RED targets in these aspects. For instance, China aims to reach up to 1 billion tons of standard coal in REC by 2025 and increase RES to 25% by 2030 (NDRC, 2021). Similarly, the EU targets achieving up to 1,236 GW in renewable capacity (EMBER, 2022) and a 45% RES by 2030 (EU, 2023). We observe that current studies on the carbon emission impacts of RED primarily assess REC (Saint Akadiri et al., 2019; Y. Zhao et al., 2013), often overlooking RES, particularly the distinct carbon reduction effects and the underlying reasons for these differences between REC and RES. It's notable that the implications of REC and RES on carbon emissions differ subtly. Since REC produces minimal emissions, it theoretically and empirically offsets carbon emissions from FEC (Berrill et al., 2021). However, an increase in REC does not necessarily imply a corresponding rise in RES due to uncertainties in energy mix and structure changes (Chiu & Chang, 2009). Consequently, the carbon emission impacts of increasing RES might diverge from those of REC, warranting further investigation. York (2012) argue that efficient substitution of RE for FE contributes to carbon emission reduction. Specifically, with the increasing cost competitiveness and efficiency of RE technologies, renewables can serve as viable substitutes for fossil fuels, resulting in reduced demand for coal, oil, and natural gas (Adua et al., 2021). Therefore, the carbon reduction effects from RED hinge on the efficiency of renewables' substitution effects on FE. Based on this, we posit **Hypothesis 2**: *The mediating effects of RED can be influenced by the substitution effect of RE on FE*.

In addition, numerous studies have highlighted the time lag effects of RED in mitigating carbon emissions, which is attributed to the time-consuming processes involved in developing RE infrastructure and implementing supportive policies (Ölz, 2011). Habiba et al. (2022) suggest that the carbon reduction effect of RED would be more pronounced in the forecast period beyond 5 years compared to the first 5 years. Hence, we propose **Hypothesis 3**: *The carbon reduction potential of RED will progressively strengthen over time*. Plus, due to substantial heterogeneity across countries (Lefevre et al., 2022), the carbon reduction effects of renewables may differ. Thus, we posit **Hypothesis 4**: *The impact of RED on carbon emissions varies due to heterogeneity across countries*.

The three hypotheses (**H2–H4**) show that the carbon reduction effects of RE are not consistent but vary with spatio-temporal disparities. This may contribute to a non-linear relationship between RED and carbon emissions rather than a simple linear connection. Moreover, some literature argues that a limited RED contributes little to reducing carbon emissions in the global energy system (Timilsina et al., 2011), whereas regions with a high RED tend to experience carbon reduction (Hu et al., 2018). Hence, we propose **Hypothesis 5**: *An inverted U-shaped relationship exists between RED and carbon emissions.*

Beyond RED, there are other critical pathways through which REPs impact carbon emissions. First, energy infrastructures, including transmission networks, grid integration, and storage, are vital for large-scale renewable technology deployment (Jacobson et al., 2015). Enhanced infrastructure facilitates efficient RE distribution, augmenting fossil fuel displacement and reducing emissions (Krausmann et al., 2020). Second, stable political environments are crucial for the design and enforcement of REPs (Aklin & Urpelainen, 2013). Transparent regulations, long-term goals, and consistent government support foster conditions conducive to renewable investment, thus lowering emissions (Maulidia et al., 2019).

Additionally, balanced policy designs among different policy types are highlighted (Schmidt & Sewerin, 2019), suggesting that leveraging each type's strengths while addressing their limitations is vital for extensive renewable deployment and climate change mitigation (Jenkins, 2014). In contrast, focused policy designs targeting specific barriers or renewable aspects can be effective in certain contexts, like prioritizing specific technologies or addressing market failures (Sovacool, 2009). Therefore, these factors significantly influencing the carbon reduction efficiency of REPs warrant further exploration.

In summary, existing literature lacks a comprehensive understanding of the impacts and mechanisms of renewable energy policies (REPs) on carbon reduction at the global scale. Our study addresses three critical gaps in REPs research. First, we quantify the impact of REPs on carbon emissions. Previous literature predominantly relies on qualitative analysis, with Schmidt and Sewerin (2019) being the first to propose a quantitative approach. However, their work lacks further empirical analysis. We bridge this gap by extracting and analyzing REP data from the IEA's database for 135 countries until 2018, offering the first empirical assessment of global REPs effects on carbon emissions. Second, while existing research extensively examines the influence of REPs on RED or RED's impact on carbon emissions, the role of RED in REPs-driven emission reductions remains understudied. Our research elucidates the Janus-faced mediating role of RED in this process, highlighting its complex implications for carbon emission reduction. Third, we address the oversight in the literature regarding RES as a key facet of RED in influencing carbon emissions. By differentiating the effects of RES and REC, our analysis provides a nuanced understanding of their respective impacts and underlying mechanisms on carbon emissions. Clarifying the differences between REC and RES provides policymakers with insights for a more comprehensive assessment and setting of RE targets.

The paper proceeds as follows. Section 2 describes the methodology and data. Section 3 reports the results. Section 4 discusses the results. The final section makes a conclusion.

2. Methodology

2.1. Model

2.1.1. Assessing Impacts of REPs on Carbon Emissions

We construct an empirical analysis of the impact of REPs on carbon emissions. Regarding the control variables, we refer to the three important variables in the IPAT model (Ehrlich & Holdren, 1971)—economic, technological, and demographic factors—and further consider industrial structure and foreign direct investment. The baseline model is defined as:

$$\ln CE_{it} = \alpha_0 + \beta_1 REP_{it} + \gamma controls_{it} + \delta_t + \eta_i + \varepsilon_{it} \quad (1)$$

Where i and t represent country and year, respectively, CE denotes CO_2 emissions, and REP stands for renewable energy policy intensity. α_0 is the constant term and γ corresponds to the control variable coefficient. δ_t is the unobserved time effect, while η_i refers to the time-invariant country-specific effect, capturing persistent national differences like climate, location, and natural resources. Finally, ε_{it} represents a random error term.

We also model the six distinct REP types as follows:

$$\ln CE_{it} = \alpha_0 + \beta_1 P\_RI_{it} + \beta_2 P\_PS_{it} + \beta_3 P\_EI_{it} + \beta_4 P\_RD_{it} + \beta_5 P\_VA_{it} + \beta_6 P\_IE_{it} + \gamma controls_{it} + \delta_t + \eta_i + \varepsilon_{it} \quad (2)$$

The error structure is characterized by heteroskedasticity, autocorrelation (up to a certain lag), and potential group correlations, as outlined by Driscoll and Kraay (1998). This leads to within-group autocorrelation, between-group heteroskedasticity, and cross-sectional correlation. To mitigate these issues, we adopt Driscoll-Kraay standard errors, which are robust for panel data with extensive temporal and cross-sectional variations. Following Ayhan and Elal (2023), these standard errors are applied to our fixed-effects regressions.

2.1.2. Mediating Effect of RED

The primary goal of REPs is to improve RED (including REC and RES), ultimately aiming to reduce carbon emissions. Understanding how RED acts as a mediator in this context is essential for assessing the efficacy of REPs in emission mitigation.

Our mediation analysis follows the Baron and Kenny (1986), involving three steps: Initially, we establish a relationship between the independent variable (*REP*) and the dependent variable (*lnCE*), as shown in Equation 1. Next, we explore the relationship between REPs and the mediator—RED (including REC and RES), as indicated in Equation 3.

$$RED_{it} = \alpha_0 + \beta_1 REP_{it} + \gamma controls_{it} + \delta_t + \eta_i + \varepsilon_{it} \quad (3)$$

Finally, we conduct multiple regression analyses with both REP and RED influencing carbon emissions, as depicted in Equation 4:

$$\ln CE_{it} = \alpha_0 + \beta_1 REP_{it} + \beta_2 RED_{it} + \gamma controls_{it} + \delta_t + \eta_i + \varepsilon_{it} \quad (4)$$

If RED significantly impacts carbon emissions while accounting for REPs, and REPs' influence on carbon emissions diminishes or becomes insignificant, it indicates the full mediating role of RED.

This three-step mediation approach, widely recognized across various fields (VanderWeele, 2016), has limitations, such as the presumption of normality and the lack of a direct test for indirect effect significance. To address these limitations, we employ the bootstrapping method with 500 replications, as Preacher and Hayes (2008) suggested, providing a more robust analysis of the mediation effects.

2.1.3. Relationship Between RED and Carbon Emissions

Existing research on the relationship between RED and carbon emissions has been contentious, with studies indicating both linear Rehman et al. (2022) and inverted U-shaped associations Chiu and Chang (2009). To further clarify this relationship, we introduce the square term of RED into Equation 4, resulting in Equation 5:

$$\ln CE_{it} = \alpha_0 + \beta_1 REP_{it} + \beta_2 RED_{it} + \beta_3 {RED_{it}}^2 + \gamma controls_{it} + \delta_t + \eta_i + \varepsilon_{it} \quad (5)$$

2.1.4. Heterogeneity Analysis

This study hypothesizes that the impact of REPs on carbon emissions is significantly shaped by global disparities in energy infrastructure, political institutions, and policy designs (Breetz et al., 2018). These variations, influenced by economic development stages, government capacities, and sociopolitical contexts, crucially affect policy effectiveness in emission reduction (Cherp et al., 2018). Recognizing these factors as moderators, we integrate them into our benchmark model to assess their impact on policy outcomes. The interaction effect is modeled as follows:

$$\ln CE_{it} = \alpha_0 + \beta_1 REP_{it} + \beta_2 M_{it} + \beta_3 REP_{it} \times M_{it} + \gamma controls_{it} + \delta_t + \eta_i + \varepsilon_{it} \quad (6)$$

Where M is the Moderator and the β_3 represents the coefficient of the interaction effect. We emphasize that all variables in the interaction effect are centered in our analysis, which reduces multicollinearity and facilitates interpretation.

2.2. Variable Selection and Data Sources

2.2.1. REPs

The original REPs data obtained from the IEA's Policies and Measures Databases (IEA, 2023) covers 135 countries (see Table A1) with 2,153 REPs until 2018. These policies are classified into six types (Economic instruments, R&D, Regulatory instruments, Policy support, Voluntary approaches, Information and education) and seven targets (Geothermal, Solar, Wind, Bioenergy, Hydropower, Ocean, Multiple RE Sources). Invalid policies like "unknown," "under view," or "planned" were excluded, resulting in over 1,900 policies with clear classifications on type and implementation. For mixed policies with various types, we assign weighted values to each. However, the limited availability of historical data for some variables may compromise reliability, possibly impacting the accuracy and robustness. Therefore, our study primarily concentrates on the 2000 to 2018 period.

This study's key variable, renewable energy policy (*REP*), is measured based on the approach of W. Liu et al. (2019), utilizing the annual cumulative count of a country's REPs as the indicator. This count is a proxy for governmental commitment to RE, where a higher number of policies suggests a stronger dedication to its development, potentially enhancing investment, innovation, and awareness (Del Río, 2012; Polzin et al., 2015). This method offers a quantifiable means to assess and compare policy environments across countries.

2.2.2. Control Variables

Our study utilizes control variables based on the IPAT model, including economic development, technological innovation, and demographic factors, supplemented by industrial structure and foreign direct investment, as commonly used in literature. Economic development is gauged by GDP per capita (constant 2015 US$), technological innovation by the count of journal articles, demographic factors by population size (PS), and industrial structure by the industrial output's GDP share. These data are sourced from the World Bank. Logarithmic transformations standardize these variables, addressing data skewness and variance stabilization, minimizing outliers, and enhancing interpretability and linear relationships.

2.2.3. Heterogeneity Factors

Our heterogeneity analysis (Section 2.1.4) focuses on energy infrastructure, institutional factors, and policy designs. Energy infrastructure level (EIL) is measured by the proportion of electric power transmission and distribution losses, reflecting the efficiency and quality of a country's electricity infrastructure (Bhattacharyya, 2012). Institutional factors include control of corruption (CC) and rule of law (RL) from the World Bank, capturing the exercise of public power for private gain and societal rule adherence, respectively. The above data are from the World Bank. For policy designs, we analyze the targeted nature of policy implementation. We employ policy type balance and policy target balance indices (Schmidt & Sewerin, 2019) to assess targeting in policy types and targets. These indices range from 0 to 1, with higher values indicating a more balanced policy mix, while lower values suggest a greater concentration. The calculation formulas are as follows:

$$BA_{type} = 1 - Simpson_{type} = 1 - \frac{\sum_{m=1}^{6}\left(policy_{type\_m}\left(policy_{type\_m} - 1\right)\right)}{\sum policies \times \left(\sum policies - 1\right)} \tag{7}$$

$$BA_{tar} = 1 - Simpson_{tar} = 1 - \frac{\sum_{n=1}^{7}\left(policy_{tar\_n}\left(policy_{tar\_n} - 1\right)\right)}{\sum policies \times \left(\sum policies - 1\right)} \tag{8}$$

Where the terms $policy_{type\_m}$, $policy_{tar\_n}$, and *policies* stand for policy types, policy targets, and total policies, respectively. The indices BA_{type} and BA_{tar} represent the balance of REP type and target, respectively.

The paper's framework and variable descriptive statistics are presented in Figure 1 and Table 1, respectively.

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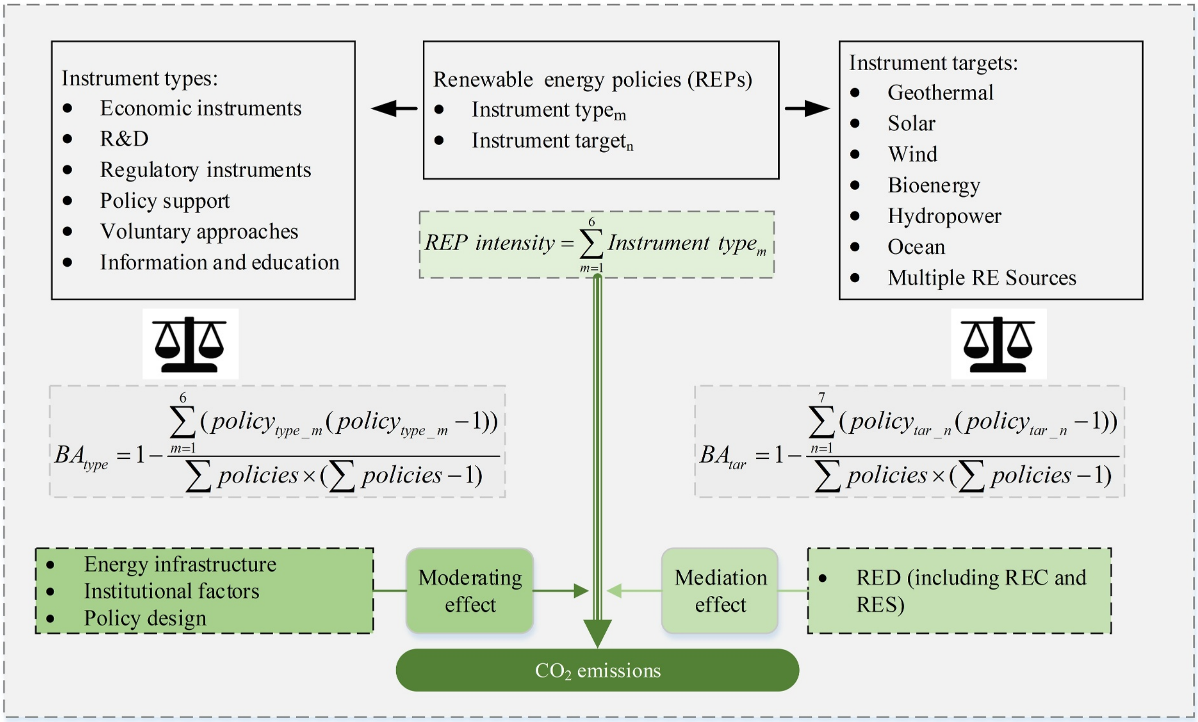

Figure 1. Framework of this paper.

3. Results

3.1. Carbon Reduction Effects of REPs

We investigated the impact of REPs intensity on global carbon emissions and the carbon reduction effects of different policy instruments. As shown in Table 2, regardless of the presence or absence of control variables, the enforcement of REPs significantly reduces carbon emissions after accounting for individual and time effects. The result shows that each unit increase in global REP intensity brings about a 0.29% abatement in carbon emissions worldwide, indicating the significant carbon reduction effects of REPs. Regarding the carbon reduction effects of specific REPs, we found that mandatory approach—Regulatory instruments (*P_RI*), and market-based instruments—Economic instruments (*P_EI*) and R&D policies (*P_RD*) can significantly reduce carbon emissions. This suggests that policies oriented toward mandatory compliance and market incentives exhibit favorable carbon reduction effects. However, Policy support (*P_PS*), Voluntary approaches (*P_VA*), and Information and education (*P_IE*) showed no significant carbon reduction effects.

3.2. Robustness Analyses

Our study performed several robustness checks on the effectiveness of REPs (Table 3). First, we replace the dependent variable *lnCE* with carbon intensity (*lnCI*) (Model 1) and energy consumption (*lnEC*) (Model 2), respectively. Second, we substitute certain independent variables, such as replacing population density (*lnPD*) with population size (*lnPS*) and the proportion of industrial output (*lnIS*) with the proportion of industrial employment (*lnIS2*) (Model 3).

Third, we include additional variables in the benchmark model that may also affect carbon emissions: EIL and energy structure (Model 4). Energy infrastructure level refers to the quality and availability of facilities and services required to distribute and utilize energy effectively. A well-developed infrastructure can contribute to increased energy efficiency and reduced carbon emissions (Tong et al., 2019). On the other hand, energy structure denotes the composition of a country's energy supply, including the mix of renewable and non-renewable sources. Increasing RES can reduce carbon emissions by replacing fossil fuel-based energy generation (Jacobson et al., 2015). The influence of energy infrastructure level (*lnEIL*) on carbon emissions is captured using the

Table 1
Descriptive Statistics

Variable	Description	Obs	Mean	Std.Dev.	Min	Max
lnCE	Carbon emissions	2,565	9.84	2.65	−4.61	16.15
REP	Renewable energy policy intensity	2,565	12.40	19.75	0	168
P_RI	Regulatory instruments	2,565	2.36	3.76	0	38
P_PS	Policy support	2,565	3.10	4.43	0	62
P_EI	Economic instruments	2,565	4.69	7.75	0	55
P_RD	R&D policy	2,565	1.17	3.08	0	29
P_VA	Voluntary approaches	2,565	0.33	1.08	0	10
P_IE	Information and education policy	2,565	0.76	2.48	0	32
lnPGDP	GDP per capita	2,565	8.57	1.79	−4.61	11.63
lnJA	Number of scientific research papers	2,565	6.25	3.30	−4.61	13.18
lnIS	Industrial output to GDP ratio	2,546	3.24	0.39	1.85	4.48
lnPS	Population size	2,565	16.00	2.04	9.19	21.06
lnFDI	Foreign direct investment	2,546	−12.19	16.86	−26.56	25.90
RE	Renewable energy share	2,565	29.00	27.41	0	98.34
lnEIL	Transmission loss rate	1,661	2.35	0.61	0.14	4.29
lnES	Fossil fuel consumption ratio	1,741	3.81	1.72	−4.61	4.61
lnPD	Population density	2,565	4.17	1.39	0.44	8.98
lnIS2	Industrial employment ratio	2,470	2.93	0.51	−0.92	3.70
lnEC	Energy consumption	1,751	2.95	1.90	−4.02	8.02
CC	Control of Corruption	2,548	0.07	1.02	−1.71	2.47
RL	Rule of Law	2,554	0.08	0.99	−2.32	2.13
BA_{type}	Type balance of REPs	1,974	0.73	0.20	0	1
BA_{target}	Target balance of REPs	2,054	0.60	0.30	0	1

Table 2
The Carbon Reduction Effects of Renewable Energy Policies

Variable	Model (1)	Model (2)	Variable	Model (3)
REP	−0.0086*** (0.001)	−0.0029*** (0.001)	*P_RI*	−0.0231*** (0.007)
lnPGDP		−0.2915* (0.139)	*P_PS*	0.0190** (0.007)
lnJA		0.3874*** (0.072)	*P_EI*	−0.0058* (0.003)
lnIS		−0.2746** (0.099)	*P_RD*	−0.0299*** (0.006)
lnPS		2.1146*** (0.289)	*P_VA*	0.0178 (0.017)
lnFDI		−0.0016* (0.001)	*P_IE*	0.0278 (0.020)
Constant	9.5434*** (0.002)	−22.8933*** (3.865)	Constant	−22.5276*** (3.938)
			Controls	Yes
Individual effect	Yes	Yes	Individual effect	Yes
Time effect	Yes	Yes	Time effect	Yes
Within R^2	0.0829	0.2956	Within R^2	0.2982
N	2,565	2,527	*N*	2,527

Note. The values in parentheses represent Driscoll-Kraay standard errors; ***, **, and * denote significance at 1%, 5%, and 10% levels; subsequent tables follow the same conventions.

Table 3
Results of Robustness Analysis

Variable	Model (1) $Y = lnCI$	Model (2) $Y = lnEC$	Model (3) replace X	Model (4) add X	Model (5) winsorize	Model (6) lagged X	Model (7) GMM
REP	−0.0028*** (0.000)	−0.0008*** (0.000)	−0.0030*** (0.001)	−0.0018*** (0.000)	−0.0040*** (0.000)	−0.0031*** (0.001)	−0.0033*** (0.001)
lnEIL				−0.0068 (0.011)			
lnES				0.7585*** (0.048)			
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Within R^2	0.2188	0.6230	0.3007	0.7119	0.4509	0.2691	–
N	2,527	1,732	2,451	1,632	2,527	2,394	2,394

Note. Regarding the tests for IVs in the GMM model, the Kleibergen-Paap rk LM statistic is 142.387 with a p-value of 0.000; The Kleibergen-Paap rk Wald F statistic is 4,864.755, exceeding the 10% maximal IV size of 19.93; The Hansen J statistic is 0.9689.

transmission loss rate, where lower losses indicate higher energy infrastructure levels. The energy structure is represented by the proportion of fossil FEC (*lnES*). Fourth, winsorizing, a common method for addressing extreme values to reduce the impact of outliers and improve the validity of estimates, is applied to the 1% and 99% percentiles of the data (Model 5). Fifth, to address the potential endogeneity issues, such as reverse causality, we implement a one-period lag on all explanatory variables (Model 6).

As shown in Table 3, the robustness checks provide evidence that the negative relationship between *REP* and the dependent variables (carbon emissions, carbon intensity, and energy consumption) remains consistent across different model specifications. This suggests that the main findings of our analysis are robust and not sensitive to the choice of dependent variables, control variables, or lagged variables.

Finally, this study employs the Generalized Method of Moments (GMM) to verify the robustness of our results. We use the first-order lag of *REP* and the interaction term between the lagged *REP* and carbon emissions in 1990 as two instrumental variables for *REP*. Using the lagged policy as an instrument is justified, as it is expected to correlate with the current REP but remain uncorrelated with the error term in the equation. As for the latter instrument, a country's historical carbon emissions may influence the intensity of its REP development, while past emissions are unlikely to affect the current error term significantly. Hence, historical carbon emissions can serve as a reasonable instrument. Due to data availability, the earliest obtainable data on carbon emissions are from 1990. Then, we construct interaction terms between the 1,990 carbon emissions and time-varying variables (lagged *REP*) as instrumental variables. Aside from theoretical feasibility, it is crucial to acknowledge that the validity of these instruments depends on the assumption that they are uncorrelated with the error term in the carbon emissions equation, which may not always hold in practice. To test the validity of the instruments, we must perform underidentification tests to examine the correlation between the instruments and the endogenous explanatory variables, weak identification tests to identify potential weak correlation issues, and over-identification tests to assess the instruments' effectiveness. As seen in Model 7, both the under-identification and weak identification tests significantly reject their respective null hypotheses, indicating that the instruments are correlated with the endogenous explanatory variables and that there are no weak correlation issues. Finally, the Hansen J test statistic for the overidentification tests is greater than 0.1, implying that the null hypothesis of instrument validity cannot be rejected. In conclusion, after testing, the instruments employed in this study were reasonable and effective. Additionally, the GMM results are consistent with our benchmark model.

3.3. Heterogeneity Analyses of REPs on Carbon Emissions

To reveal the heterogeneity of REPs across different geographical contexts, the impacts induced by REPs have been analyzed with a detailed consideration of disparities in energy infrastructure and political institutions using moderating models.

Table 4
Heterogeneity Analyses of Renewable Energy Policies on Carbon Emissions

Variable	Model (1) *EIL*	Variable	Model (2) *CC*	Model (3) *RL*	Variable	Model (4) BA_{type}	Model (5) BA_{target}
REP	−0.0008*** (0.000)	*REP*	−0.0016** (0.001)	−0.0015** (0.001)	*REP*	−0.0028*** (0.001)	−0.0059*** (0.002)
lnEIL	0.0439** (0.015)	*CC*	−0.0483 (0.091)		BA_{type}	0.1788 (0.141)	
REP × *lnEIL*	0.0022*** (0.000)	*REP* × *CC*	−0.0024*** (0.001)		*REP* × BA_{type}	0.0167 (0.016)	
		RL		−0.1921* (0.102)	BA_{target}		0.0070 (0.037)
		REP × *RL*		−0.0017** (0.001)	*REP* × BA_{target}		0.0157** (0.006)
Controls	Yes		Yes	Yes		Yes	Yes
Individual effect	Yes		Yes	Yes		Yes	Yes
Time effect	Yes		Yes	Yes		Yes	Yes
Within R^2	0.6080		0.2366	0.2302		0.3625	0.3729
N	1,646		2,510	2,516		1,959	2,039

As shown in Table 4, the transmission loss rate by the power grid of each country was adopted to depict the variations in energy infrastructure levels (EIL). We found that both EIL and its interaction term with REPs were positively correlated with the amount of carbon emissions, indicating that high-quality infrastructure construction and operation are crucial for enhancing the positive impact of REPs on carbon emission reductions. An efficient and well-integrated infrastructure system facilitates increased penetration of RE sources, reducing carbon emissions.

Furthermore, the effectiveness of REPs, as measures mainly enforced by the government, relies heavily on the features of political institutions. Therefore, we employed two indicators to portray the characteristics of political institutions from both the implementation enforcement and implementation efficiency perspectives. Specifically, CC captures the perception of the degree to which public authority is employed for personal advantage, providing insight into governmental executive capability. Rule of law (RL) captures the perception of how much agents trust and adhere to societal rules, thus being suitable for depicting the implementation efficiency of REPs. Models 2 and 3 illustrate the role of political conditions in moderating the positive impact of REPs on carbon emission reduction. We found that both *CC* and *RL* promoted the carbon reduction effects of REPs. On the one hand, effective corruption control measures are beneficial for improving resource allocation efficiency and sustaining a competitive environment, both of which contribute to the effectiveness of REPs in reducing carbon emissions. On the other hand, the abidance of individuals by the rules and their confidence in the rules allowed them to create an atmosphere that can drive investment, innovation, and RE market growth, leading to reduced carbon emissions.

Moreover, we analyzed the role of policy mix design features, where the effects of policy type balance and target balance on the effectiveness of REPs on emission reductions. The impact of the balances in policy types is statistically insignificant, implying that the intensity differences of policy instruments across different types do not significantly impact the overall carbon reduction effectiveness of REPs. In contrast, the significant interaction term of *REP* and policy target balance (0.0157**) indicates that a balanced target design in REPs may suppress the emission reduction effects of REPs. This result implies that the target design of REPs is more effective in concerning one specific area. Therefore, a biased and unbalanced target design in REPs is necessary to achieve effective emission abatement.

3.4. Mediating Effects of RED on Carbon Emissions

The purpose of REPs is to support the development, deployment, and diffusion of RE technologies, which is beneficial for improving RED in a national energy system. Accordingly, this study utilized RES and REC as indicators to analyze the mediating role of RED in the carbon reduction effects of REPs, respectively. To mitigate the dependency on the assumption of normal data distribution, we conducted bootstrapping with 500 replications to obtain robust standard errors. Then, we employed three mediation tests (Sobel, Aroian, and Goodman) to examine the significance of mediation effects. Table 5 shows that all tests validate the mediation effect of RES

Table 5
Mediation Effect Results

Variable	Model (1) $Y = lnCE$	Model (2) $Y = lnREC$	Model (3) $Y = lnCE$	Model (4) $Y=RES$	Model (5) $Y = lnCE$	VIF test Variable	$Y = lnCE$	$Y = lnCE$
REP	−0.0029*** (0.001)	0.0030*** (0.001)	−0.0014*** (0.000)	0.0331*** (0.009)	−0.0044*** (0.001)	*REP*	1.64	1.57
						lnREC	3.05	
lnREC			−0.1063*** (0.020)			*RES*		1.52
						lnPGDP	1.83	1.87
RES					0.0452*** (0.012)	*lnJA*	2.63	3.38
						lnIS	1.22	1.4
Controls	Yes	Yes	Yes	Yes	Yes	*lnPS*	3.76	3.28
Individual effect	Yes	Yes	Yes	Yes	Yes	*lnFDI*	1.20	1.12
Time effect	Yes	Yes	Yes	Yes	Yes	Mean	2.19	2.02
Adjusted R^2	0.9423	0.9912	0.9966	0.9779	0.9472			
N	2,527	1,732	1,732	2,527	2,527			

Note. (a) The models employ 500 bootstrap standard errors; all three mediation tests, Sobel, Aroian, and Goodman, have passed at 1% significance level and (b) Although collinearity between REP and RED exists to some extent due to their close relationship, the variance inflation factors (VIFs) for all variables are below 5, indicating no severe multicollinearity.

and REC at the 1% significance level, verifying **Hypothesis 1**: *REPs can reduce carbon emissions*, *with RED mediating this effect*.

It can be observed that the implementation of REPs positively enhances REC (0.0030*** in Model 2) and RES (0.0331*** in Model 4), which indicates REPs' benefits in catalyzing the global energy transition. This aligns with W. Liu et al. (2019)'s view that REPs positively influence RE development. However, we found that the impacts of REC and RES on carbon emissions are diametrically opposed. Specifically, an increase in REC is associated with a reduction in carbon emissions (−0.1063*** in Model 3), whereas RES can accelerate national carbon emissions (0.0452*** in Model 5). The former finding aligns with a substantial body of empirical research, which argues that RED can mitigate carbon emissions globally (Jebli et al., 2020), regionally (Wang et al., 2020), and at the individual country level (Dong et al., 2018). The latter finding, however, has been less observed by scholars. Therefore, to deepen our understanding of this phenomenon and validate hypotheses **H2–H4**, we further investigated the underlying causes contributing to the carbon-increasing effects of RES from three perspectives: (a) the limited substitution effects of RE on FE; (b) the lag effects of RES on carbon reductions; and (c) the country-specific heterogeneity of RES on carbon reductions.

3.4.1. Substitution Effects of RE on FE

To confirm **Hypothesis 2**: *The mediating effects of RED can be influenced by the substitution effect of RE on FE*, we adopted York's method (York, 2012) and investigated the substitution effect of RE on FE from both production and consumption perspectives. On the production side, we used per capita RE power generation (*REG*) and per capita FE power generation (*FEG*) as independent and dependent variables, respectively, while on the consumption side, we adopted per capita REC (*REC*) and per capita fossil fuel consumption (*FEC*). Theoretically, if RE proportionately replaces FE, the substitution coefficients of *REG* on *FEG* or *REC* on *FEC* should be less than −1. This implies that, with constant energy consumption, each unit of produced or consumed RE can substitute more than one unit of FE. A coefficient between −1 and 0 indicates partial substitution, where RE just partially displaces FE. A positive coefficient implies that RE fails to replace FE and accelerates FE consumption.

In the regression models, we analyzed the scenarios with and without controlled variables separately, where the controlled variables align with the benchmark model. As shown in Table 6, from the energy consumption perspective, the coefficient of *REC* was −0.09 with a significance of 1% level (Model 2), indicating a negligible substitution effect where one unit of renewables consumption only substituted less than 0.1 unit of FEC.

Table 6
Analyses of Substitution Effects

Variable	Model (1) $Y = FEC$	Model (2) $Y = FEC$	Model (3) $Y = FEG$	Model (4) $Y = FEG$
REC	−0.1083*** (0.010)	−0.0917*** (0.007)		
REG			4.6004*** (0.506)	4.3765*** (0.565)
Controls	No	Yes	No	Yes
Individual effect	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes
Within R^2	0.0639	0.1919	0.3159	0.5015
N	1,741	1,724	1,247	1,244

Regarding energy production, the coefficient of *REG* is equal to 4.38 (Model 4), indicating that the power generation of one unit of renewables corresponds to an increase of 4.38 units in fossil power generation. This finding means the absence of a substitution effect of RE on FE in the power generation aspect.

In summary, the results support **Hypothesis 2** and suggest that the substitution effect of RE on FE is inefficient from both production and consumption perspectives. This inefficiency is likely a contributing factor to the increase in carbon emissions.

3.4.2. Lag Effects of RED on Carbon Emissions

To validate **Hypothesis 3**: *The carbon reduction potential of RED will progressively strengthen over time*, we introduced lagged terms for the RES indicator ranging from 0 to 12 years in the models. Additionally, we included REC for comparative analysis. As depicted in Figure 2, under a 95% confidence interval, we observed that the carbon reduction effects of REC exhibit an inverted U-shaped trend over a decade, initially increasing slightly before diminishing. The impact on carbon emissions remained significantly negative throughout, indicating that REC's carbon reduction effect is significant both in the short and long term. In contrast, the trend of RES's carbon reduction effect is different. We found a significant increase in carbon emissions attributed to RES in the first 2 years. However, this carbon-increasing effect becomes non-significant from the third to the sixth year, and carbon reduction effects from RES emerge starting from the seventh year, stabilizing in subsequent years. This result confirms our hypothesis, indicating that the early advantages of RE might not be prominent, but in the long term, the carbon reduction potential of RE will gradually emerge.

3.4.3. Heterogeneity of RES on Carbon Emissions

Contrary to REC, the mediation effect of using RES as a proxy for RED does not align with mainstream views. Therefore, we primarily employ RES to represent RED in Hypothesis 4 and 5 to investigate the underlying reasons for this intriguing finding. It is assumed in **Hypothesis 4** that *the impact of RED on carbon emissions varies due to heterogeneity across countries*. Accordingly, we analyzed the carbon reduction effects of RE share from the heterogeneity aspects of economic level (PGDP), industrialization level (PIO), PS, initial carbon emissions (CE0), organizational affiliation, geographical location, and REP starting time. The results are presented in Figure 3: (a) From the socio-economic development perspective, countries with higher levels of industrialization and economic status demonstrate carbon reduction with RES, while lower-level countries show an increase in carbon emissions. (b) Countries with higher populations and initial carbon emissions experience significant carbon reduction with RES. This suggests that countries with relatively higher energy consumption may have greater carbon reduction potential. (c) Considering organizational affiliation, except for the African Union, RES from other organizations (ASEAN, OECD, EU, BRICS, OPEC) achieve significant carbon reductions. (d) Geographically, RES in Asia, Oceania, and the Americas show significant carbon reduction, whereas RES in African and European countries exhibit significant increasing effects. Notably, while EU member states demonstrate carbon reduction effects, non-EU European countries exhibit an increase in carbon emissions, surpassing the impact observed in all European countries. (e) Examining the starting time of REPs, samples with less than 5 years of policy implementation show a carbon-increasing effect influenced by RES, while samples

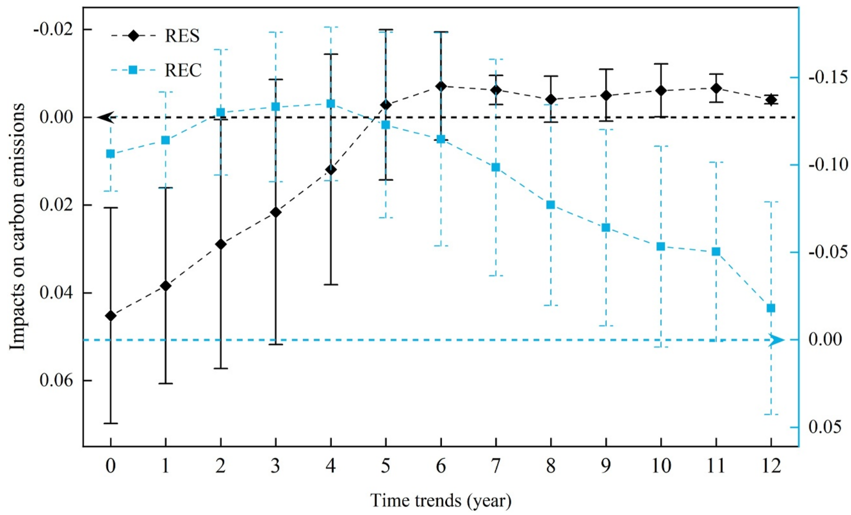

Figure 2. The lag effects of renewable energy share and renewable energy consumption on carbon emissions. Note: Error bars depict the 95% confidence intervals of the estimated coefficients.

with more than 5 years exhibit significant carbon reduction effects. This result aligns with the findings of Habiba et al. (2022) and indicates that REPs need a specific implementation time to enhance the carbon reduction effectiveness of RE.

In conclusion, our results support **Hypothesis 4** and reveal that the impact of RES on carbon emissions exhibits country-specific heterogeneity. Even though RES appears to promote carbon emissions globally across 135 countries, the results might shift due to the impact of heterogeneous factors.

3.4.4. Relationship Between RES and Carbon Reduction

To test **Hypothesis 5**: *An inverted U-shaped relationship exists between RED and carbon emissions*, RE share and its square term are introduced into the mediation model, as shown in Model 2 of Table 7. The result shows an inverted U-shaped relationship between RES and carbon emissions, where the improvements of RES were positively correlated with carbon emissions with the RES below 54% (calculated by the formula of quadratic equations) but changed the role into the negative with the share above 54%. The result validates our hypothesis, indicating that RES may temporarily increase carbon emissions during the initial stages of RE, but it eventually leads to reductions in the high development stage.

4. Discussions and Implications

4.1. The Carbon Reduction Effects of REPs

In recent years, empirical studies delving into the direct impact of global REPs on carbon emissions have been relatively sparse. Our findings indicate that REPs have significant carbon reduction effects globally. Furthermore, we categorized policies into six distinct types and examined the emission reduction efficiency of each category. We found that policies oriented toward mandatory compliance (Regulatory Instruments) and market incentives (Economic Instruments and R&D policies) have demonstrated significant carbon reduction effects. This effectiveness stems from their direct, enforceable nature and financial incentives that compel compliance and spur investment in clean technologies (Downar et al., 2021). Specifically, Regulatory Instruments enforce a legally binding compliance framework through stringent mandates like emission standards and renewable portfolio requirements, yielding carbon reduction effects (Q. Zhu et al., 2022). Economic Instruments, such as carbon taxes and feed-in tariffs, internalize the environmental costs of carbon emissions, enhancing renewable investment attractiveness (Milad Mousavian et al., 2020), and reducing emissions (Metcalf, 2021). R&D policies catalyze innovation by funneling resources into the development of advanced, efficient technologies, thus accelerating the transition to low-carbon solutions (Wu et al., 2020). Conversely, while crucial in cultivating long-term awareness

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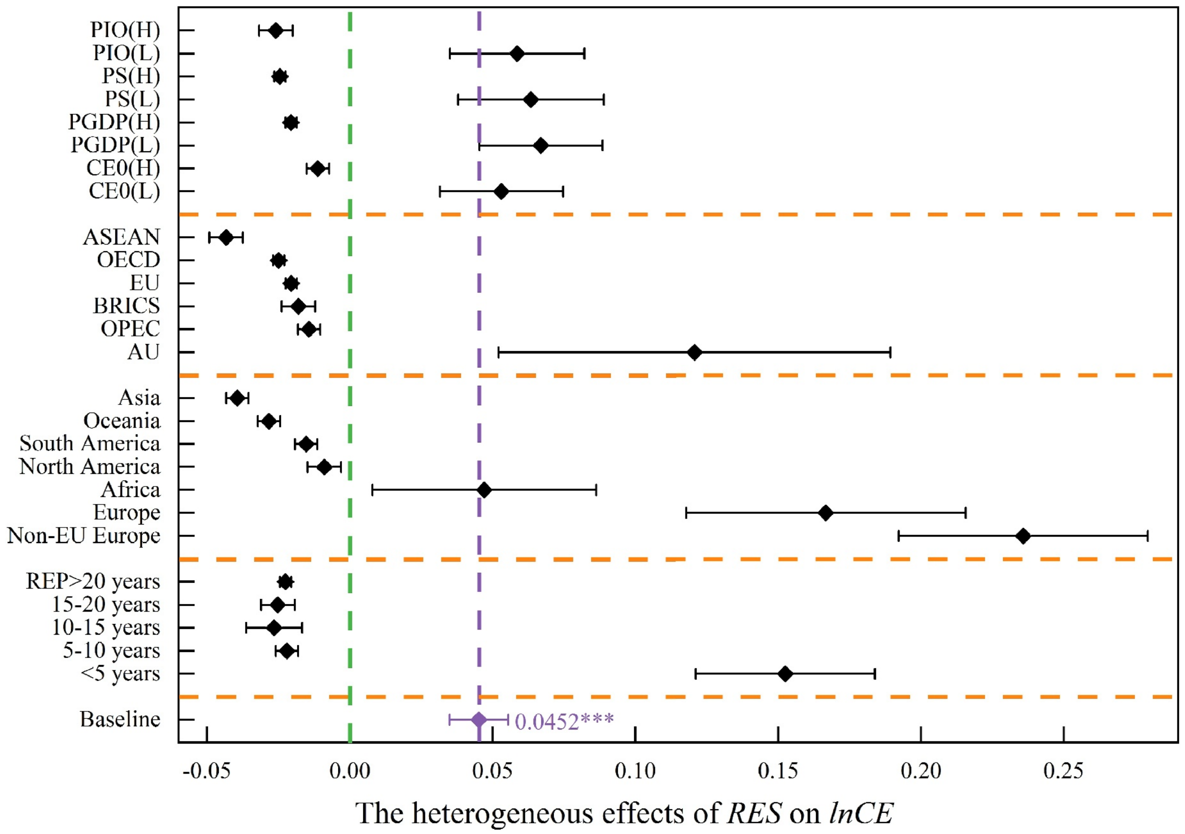

Figure 3. The heterogeneous effects of renewables on carbon emissions. Notes: (a) Error bars depict the 95% confidence intervals of the estimated coefficients. (b) PIO, population size, and PGDP represent per capita industrial output, total population, and per capita GDP, respectively. CE0 indicates carbon emissions at the start of the sample period (in 2000). The indicators use their mean values as thresholds. (c) ASEAN, OECD, EU, BRICS, OPEC, and African Union (AU) represent the Association of Southeast Asian Nations, Organization for Economic Co-operation and Development, European Union, the BRICS countries (Brazil, Russia, India, China, and South Africa), Organization of the Petroleum Exporting Countries, AU. (d) The REPs' development time is the time difference between a country's enactment of the first renewable energy policy and the observed time point in the sample.

and behavioral shifts, Policy Support, Voluntary Approaches, and Information and Education strategies do not demonstrate a significant, immediate impact on carbon emission reduction. The lack of enforceability and direct incentives in these approaches often leads to suboptimal participation and delayed action (de Vries et al., 2012). Policy Support aimed at institutional creation and strategic planning define strategies and outline programs to foster RE. However, their impact require extended periods (W. Liu et al., 2019). Voluntary approaches, relying on societal and cultural shifts, similarly require a lengthy timeframe to achieve functionality due to the bottom-up reform process of emissions reductions driven by individual actions (Arimura et al., 2019). While Information and Education policies provide workforce training and deployment guidelines, they are not directly relevant for stimulating renewable deployment (W. Liu et al., 2019). However, they can indirectly reduce emissions (Ye et al., 2017), by contributing to other mitigation strategies (Smith & Olesen, 2010). Thus, the immediate effectiveness of these three policies necessitates integration with more actionable policy instruments (Feliciano et al., 2014), such as economic incentives and regulatory frameworks (Huang et al., 2021).

In our further analyses, the efficacy of REPs is intricately tied to the dual foundations of a highly efficient energy infrastructure and a robust policy environment (i.e., CC and rule of law). On the one hand, optimal utilization of RE sources hinges on advanced energy infrastructure, including smart grids and decentralized systems, essential for RE efficiency and reliability. On the other hand, the effectiveness of REPs is greatly influenced by a well-established policy foundation, where CC and a strong rule of law create a transparent, stable, and predictable environment for investors and consumers.

Table 7
The Nonlinear Relationship Between Renewable Energy Share and Carbon Reductions

Variable	Model (1) *RES*	Model (2) adding RES^2
REP	−0.0044*** (0.001)	−0.0046*** (0.001)
RES	0.0452*** (0.000)	0.1405*** (0.017)
RES^2		−0.0013*** (0.000)
Turning point of *RES*		54%
Controls	Yes	Yes
Individual effect	Yes	Yes
Time effect	Yes	Yes
Within R^2	0.9472	0.4566
N	2,527	2,527

4.2. REPs' Designs

Besides, our study provided additional insights into how REP's portfolio affects carbon emission reduction trajectories. Schmidt and Sewerin (2019) have innovatively introduced the Gini-Simpson index as a quantitative tool to measure the balance of REP types across nine developed countries. Building upon this, our study incorporates the balance index of REPs for different REP types and RE types. Although Schmidt and Sewerin (2019) argue that a more balanced policy type is likely to be more effective, our findings indicate that the balance of different policy types does not necessarily impact the efficacy of REPs in carbon reduction. Particularly regarding the balance in policy targets, our research highlights the importance of the unbalanced target design in ensuring the positive role of REPs in mitigating carbon emissions. On the one hand, focusing on specific RE sources allows for a more tailored approach where policies can be designed to address the unique challenges and opportunities of each energy type (Kabeyi & Olanrewaju, 2022). This leads to more efficient allocation of resources and more effective problem-solving strategies. On the other hand, in contrast to vast nations like China and the United States, which have the luxury of multiple RE types at their disposal, many countries typically possess only one or a few forms of readily exploitable RE, such as Denmark's wind power (Electricity generation from hydropower in Norway accounts for 95% of its total production (Wikipedia, 2024)), Norway's hydropower (Electricity generation from hydropower in Norway accounts for 95% of its total production (Climate Council, 2022)), Iceland's geothermal resources (Iceland generates almost 100% of its electricity and heat from renewable sources, mainly from hydropower and geothermal energy (World Bank, 2020)), etc. In these countries, a focused approach on exploiting their dominant renewable resources paves the way for developing cost-effective and scalable energy solutions, significantly cutting down the reliance on carbon-intensive fossil fuels. This focused strategy not only optimizes the use of their unique geographical and natural advantages but also exemplifies a strategic alignment with environmental objectives, leading to notable strides in carbon emission reduction.

4.3. Relationship Between RED and Carbon Emissions

Our mediation effect results reveal that REC mediates positively between REPs and carbon reductions during RED, consistent with previous studies (Jebli et al., 2020). However, RES shows a negative mediation effect, suggesting that the RES spurred by REPs may increase carbon emissions. Existing research attributes the carbon-increasing effects of RED to a surge in energy consumption during the early stages of RED (Kabeyi & Olanrewaju, 2022), the crowding out effect on other clean energy sources like nuclear power (X. Zhao et al., 2022), the absence of storage technologies addressing intermittent supply issues (Qudrat-Ullah, 2022), and additional FE consumption to meet peak load requirements (Apergis et al., 2010). Nevertheless, current studies have overlooked some other critical factors. Accordingly, we conducted further analyses in three aspects: First, we found that the carbon reduction effect of RES has a time lag. That is, while RES may initially increase carbon emissions in the short term, it reduces them in the long run. This finding echoes many studies analyzing the nonlinear relationship between RED and carbon emissions Habiba et al. (2022). This is likely because, in the early phases of RED, the substantial energy demand for infrastructure construction can lead to a notable increase in carbon emissions (Timilsina et al., 2011).

Second, we found the substitution of RE for FE was inefficient. From the power generation perspective, RE not only fails to substitute for FE but also requires supplemental FE for electricity generation. Sinsel et al. (2020) note that this inefficiency of substitution effect in renewables, such as solar and wind energy, is due to their reliance on inherently unstable and unpredictable weather conditions like sunlight and wind, thus leading to REG intermittency. Moreover, X. Zhao et al. (2022) suggest that this could result in RE crowding out some low-carbon technologies, including nuclear power, ultimately leading to increased carbon emissions. Adams and Nsiah (2019) argue that grid operators might need to rely on fossil fuel-based power plants to provide backup energy when RE is unavailable due to its intermittent nature, thereby leading to high carbon emissions in the short term. Therefore, promoting demand-side management strategies, such as advanced metering infrastructure, demand response programs, and real-time pricing are capable of achieving dynamic matching of supply and demand by reducing peak demand and supporting the integration of variable RE sources, thus reducing carbon emissions. Energy storage systems, such as pumped hydro storage and batteries, help store excess energy produced during peak generation times and release it when generation is low or demand is high. This helps maintain grid stability and reduce reliance on fossil fuels for balancing the grid.

Third, we observed significant country-specific heterogeneous effects on the carbon reduction efficacy of RES. For instance, countries with higher industrial and economic levels, larger population sizes, and initially high carbon emissions exhibit carbon reduction effects, while other countries do not. This indicates that improving RES can achieve the expected emission reduction effects in economically and industrially advanced countries or those with high energy demands. Moreover, for countries where REPs have been implemented for a longer duration (over 5 years), the emission reduction impact of RES tends to be more significant compared to countries with a shorter duration (under 5 years). This is likely because nations with prolonged REPs have more mature RE technologies, richer implementation experience, and long-term policy support, providing stable expectations and confidence for RE investors (Berg et al., 2020).

These factors contribute to a complex and nonlinear relationship between RES and carbon emissions, which represents an inverted U-shaped relationship. On the one hand, prior to reaching the RES turning point (in the early stages of RED), merely increasing RES in the energy mix without focusing on its substitution efficiency for FE may not reduce carbon emissions in the short term. On the other hand, although solely increasing RES through policies may not immediately achieve energy transformation and carbon reduction goals, the lag effects of REPs and RES on carbon reductions suggest that REPs should focus more on the long-term effects of RED and commit to early planning and sustained efforts. Beyond that, it is noteworthy that over 80% of countries have a RES below the 54% turning point of the inverted U-curve, against a backdrop where global renewables constituted only 19.1% of total final energy consumption in 2020 (IEA, 2022). This suggests that RED in the majority of countries increases their carbon emissions. However, this threshold (54%) serves merely as a rough reference for policymakers, given the substantial country-specific heterogeneity. The actual circumstances in different countries necessitate the consideration of energy demand, energy structure, economic level, etc. For instance, high energy-demand countries like China targeted a relatively lower renewable share of 25% by 2030 (NDRC, 2021), whereas nations predominantly using RE, such as Iceland and Norway (Iceland's RES was 74.3% in 2007, while Norway's RES reached 71.63% in 2022 (Ritchie et al., 2024)), aimed for a relatively higher 67.5% (Rosenberg et al., 2013) and developed regions like the EU set relatively moderate proportion of 45% (In October 2023, the EU Council revised its RE goal to 45% of total energy consumption by 2030, up from the previous 40% (EU, 2023)). Our calculated threshold point suggests that for most countries, the carbon reduction effect of RE requires time to manifest, that is, once RED accumulates to a certain level, the impact of RE on carbon emissions will undergo a qualitative change.

5. Conclusions

Globally, the empirical analysis of REPs' effects on carbon emissions and the mediating role of RED in this mechanism is underexplored. Drawing on REPs data from IEA's databases for 135 countries until 2018, we conducted empirical analyses to fill this research gap. The key findings are as follows:

1. REPs significantly reduce global carbon emissions. Specifically, command-and-control and market-based policies, such as regulatory instruments, economic instruments, and R&D policies, are effective in curbing emissions, while voluntary approaches, along with information and education strategies, show no significant impact on carbon reduction.
2. Heterogeneity analyses of REPs reveal that robust energy infrastructure, strong CC, and adherence to the rule of law enhance the effectiveness of REPs in carbon emission mitigation. Additionally, the balance of different REP types has no impact on the efficiency of REPs; however, a preference for specific RE types more favorably aligns with carbon reduction goals under REPs.
3. In the mediation analyses of RED's impact on REPs' carbon reduction effect, REC exhibits a positive mediation effect, whereas RES shows a negative one. Further investigation indicates that REC can consistently promote carbon emission reduction, while RES follows an inverted U-shaped trajectory with carbon

emissions, initially rising before ultimately decreasing. The initial rise in carbon emissions with an increase in RES is attributed to the insufficient substitution of REC for FEC and RE generation for FE generation. Moreover, due to significant country-specific heterogeneity, the carbon reduction impact of RES varies by organizational affiliation and geographic location; countries with higher industrial and economic levels, larger populations, initially higher carbon emissions, and earlier implementation of REPs exhibit carbon reduction effects, whereas others do not.

Limitations of this study should be acknowledged, offering avenues for future research. First, to thoroughly assess the intensity of REPs, developing an integrated indicator encompassing dimensions such as policy quantity, type, target, coverage, enforcement, and implementation effectiveness would be advantageous. This study, limited by data availability, could not precisely gauge the intensity and actual impact of each policy, relying on cumulative policy quantity from existing literature as a proxy for policy intensity. Second, while this research has delved into the interactions between various factors and REPs, future studies could further explore the synergies between different policy instruments and their interplay with non-RE policies, like land use planning and industrial policy, to provide a more comprehensive view of policy effectiveness.

Appendix A

Table A1 shows the sample countries or regions in this paper.

Table A1
The 135 Countries or Regions Covered in This Paper

1	Albania	28	Croatia	55	Ireland	82	Mozambique	109	Slovenia
2	Algeria	29	Cyprus	56	Israel	83	Myanmar	110	Solomon Islands
3	Angola	30	Czech Republic	57	Italy	84	Namibia	111	South Africa
4	Antigua and Barbuda	31	Congo, Dem. Rep.	58	Japan	85	Nauru	112	South Sudan
5	Argentina	32	Denmark	59	Jordan	86	Nepal	113	Spain
6	Armenia	33	Djibouti	60	Kazakhstan	87	Netherlands	114	Suriname
7	Australia	34	Dominican Republic	61	Kenya	88	New Zealand	115	Sweden
8	Austria	35	Ecuador	62	Kiribati	89	Nicaragua	116	Switzerland
9	Azerbaijan	36	Egypt, Arab Rep.	63	Korea, Rep.	90	Nigeria	117	Syrian Arab Republic
10	Bangladesh	37	El Salvador	64	Lao PDR	91	Norway	118	Tajikistan
11	Barbados	38	Estonia	65	Latvia	92	Pakistan	119	Thailand
12	Belarus	39	Ethiopia	66	Lesotho	93	Panama	120	Tunisia
13	Belgium	40	Fiji	67	Libya	94	Paraguay	121	Turkey
14	Belize	41	Finland	68	Lithuania	95	Peru	122	Tanzania
15	Bolivia	42	France	69	Luxembourg	96	Philippines	123	Uganda
16	Bosnia and Herzegovina	43	Germany	70	Madagascar	97	Poland	124	Ukraine
17	Botswana	44	Ghana	71	Malawi	98	Portugal	125	United Arab Emirates
18	Brazil	45	Greece	72	Malaysia	99	Romania	126	United Kingdom
19	Brunei Darussalam	46	Guatemala	73	Maldives	100	Russian Federation	127	United States
20	Bulgaria	47	Guyana	74	Mali	101	St. Vincent and the Grenadines	128	Uruguay
21	Burkina Faso	48	Honduras	75	Malta	102	Samoa	129	Uzbekistan
22	Burundi	49	Hungary	76	Marshall Islands	103	Saudi Arabia	130	Vanuatu
23	Canada	50	Iceland	77	Mauritius	104	Senegal	131	Venezuela, RB
24	Chile	51	India	78	Mexico	105	Serbia	132	Vietnam
25	China	52	Indonesia	79	Mongolia	106	Seychelles	133	Yemen, Rep.
26	Colombia	53	Iran, Islamic Rep.	80	Montenegro	107	Singapore	134	Zambia
27	Costa Rica	54	Iraq	81	Morocco	108	Slovak Republic	135	Zimbabwe

Abbreviation

CC	Control of corruption
CCR	Command-and-control regulations
EIL	Energy infrastructure level
FDI	Foreign direct investment
FE	Fossil energy
FEC	Fossil energy consumption
FEG	Fossil energy generation
GMM	Generalized method of moments
IS	Industrial structure
JA	Journal articles
MBI	Market-based incentives
PD	Population density
PGDP	GDP per capita
PS	Population scale
RE	Renewable energy
REC	Renewable energy consumption
RED	Renewable energy development
REG	Renewable energy power generation
REPs	Renewable energy policies
RES	Renewable energy share
RL	Rule of law
VBA	Voluntary-based approaches

Data Availability Statement

The data and software utilized in this study are derived from publicly available information and open-source channels.

The original Renewable Energy Policies (REPs) data were sourced from the International Energy Agency's (IEA) Policies Databases, available at https://www.iea.org/policies. Each specific information regarding country, year, status, jurisdiction, type, and sector of each policy can be accessed by following the provided hyperlinks.

Data for all controlled variables (GDP per capita, the count of journal articles, population size, foreign direct investment, and the industrial output's share of GDP) and variables included in the regression analysis (renewable energy share, transmission loss rate, fossil fuel consumption ratio, population density, industrial employment ratio, energy consumption) were obtained from the World Bank Databases, accessible at https://databank.worldbank.org/source/world-development-indicators.

Data on control of corruption and rule of law were sourced from https://databank.worldbank.org/source/world-wide-governance-indicators.

The initial processed data and all codes are available at https://github.com/jessecy1/REPs and archived in Chen and Zheng (2024).

STATA 16, which was utilized for all regression models, can be downloaded from https://www.stata.com/support/updates/stata16.html.

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