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Effectiveness of carbon dioxide emission target is linked to country ambition and education level

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In response to the Paris Agreement, a growing number of countries, 123 in total, have committed to carbon reduction targets. While existing research has assessed various policies' effectiveness in achieving these targets, the potential of the act of goal-setting itself as a policy instrument has been underexplored. Here we leveraged a comprehensive panel dataset spanning 163 countries from 2011 to 2022 and employed a rigorous difference-in-difference model. Empirical findings reveal that both proposing carbon reduction targets and setting higher targets effectively reduce emissions intensity. The mechanism driving the impact of carbon reduction targets on CO_2 emissions centers on the level of education, rather than renewable energy capacity, requiring further investigation to the mechanism. Subsequent analysis establishes connections between target levels and renewable energy capacity. Our results advocate for dynamic updates of carbon reduction targets aligned with renewable energy capacity when formulating climate objectives.

Due to rapid industrialization and the escalating demand for energy, the release of carbon dioxide and other greenhouse gases has played a pivotal role in driving global shifts in temperature. In more specific terms, the human-induced increase in global surface temperatures has amounted to approximately 1.07 °C between the periods 1850–1900 and 2010–2019[1]. This shifting climate landscape ushers in a higher frequency of extreme weather events[2], resulting in property damage[3,4] diminished agricultural productivity[3,5]. Moreover, scientific evidence underscores the detrimental effects of climate change on both physical and mental well-being[6]. To address these challenges, the Intergovernmental Panel on Climate Change (IPCC) has established an ambitious target of limiting global warming to 1.5 °C above pre-industrial levels[7]. To achieve this goal, a reduction of approximately 45% in global net anthropogenic CO2 emissions from 2010 levels is imperative by 2030, with the subsequent achievement of net zero emissions in the latter half of the century[8].

Recognizing the gravity of climate change, national governments worldwide have taken proactive measures. In 2015, 193 parties united in their commitment to combat climate change by signing the Paris Agreement[9]. Signatories to this agreement pledge to submit Nationally Determined Contributions (NDCs) and strengthen their efforts through ongoing progress assessments. By 2022, 147 countries had submitted their first NDCs, with 123 of these nations establishing individual carbon reduction targets in the NDCs (hereinafter referred to as carbon reduction targets). Unlike technical companies that can provide direct technical solutions, governments rely on a range of management tools to meet their carbon reduction objectives. Existing research has delved into policy instruments such as carbon taxes[10,11], emission trading[10,12], and regulatory frameworks[13,14] to effectively attain these goals.

In this context, the concept of goal-setting emerges as a valuable management tool to address greenhouse gas emissions. At the individual level, research has established a strong correlation between self-set goals and personal performance, spanning work-related achievements and academic grades[15–18]. Such goal-setting impacts also extend to organizational performance enhancement[19,20]. While nations can be viewed as aggregations of individuals and entities, limited research has explored the impact of national targets, particularly in the realm of climate governance. Nevertheless, evidence suggests the efficacy of goal-setting in enhancing public administration and policy implementation[21–23]. However, the utilization of goal-setting theory in climate change governance remains underexplored, with recent studies focusing on its application in city-level climate governance[24]. Another study examined the localization of the European Union's sustainable target and found the EU's target had a discursive effect on the national and local levels[25]. Lastly, at the international level, goal-setting policy in the form of Sustainable Development Goals has received

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considerable attention in the area of global governance[26], although empirical evidence to support their effectiveness remains scarce.

This study aimed to solve the following three questions that previous research has failed to answer. First, could carbon reduction targets be conducive to reducing carbon emissions, and does the difficulty of the target affect the effectiveness? Viewing carbon reduction targets as mitigation policies rather than mere objectives, we analyze their impact on emissions, extending goal-setting theory to the national level. Leveraging a panel dataset encompassing 163 countries spanning 2011 to 2022, we assess the influence of NDCs on elevating, diminishing, or leaving carbon emissions unchanged. Secondly, if carbon reduction targets prove effective as policy tools, what mechanisms underlie their impact on emissions? We primarily investigate whether the development of renewable energy could serve as a critical mediator. As renewable energy development is a central strategy for climate mitigation, its role as a mediator aligns with goal-setting theory[27,28]. Lastly, if goal-setting has the potential to enhance emission reduction, how should a country formulate its target? This inquiry examines the key factors shaping existing carbon reduction targets. In doing so, this evaluation offers fresh insights to policymakers on effectively employing carbon reduction targets as policy instruments and explores the viability of goal-setting theory in climate governance.

Results and Discussion

Emission reduction targets effectively reduce carbon emission intensity

In this study, considering data gaps in some of the variables, 163 countries during 2011-2022 are chosen as the research sample to construct panel data. Among them, 123 countries that had at least proposed one carbon reduction target were selected as the treatment group; meanwhile, 40 countries that did not present carbon reduction targets were designated as the control group, shown in Fig. 1.

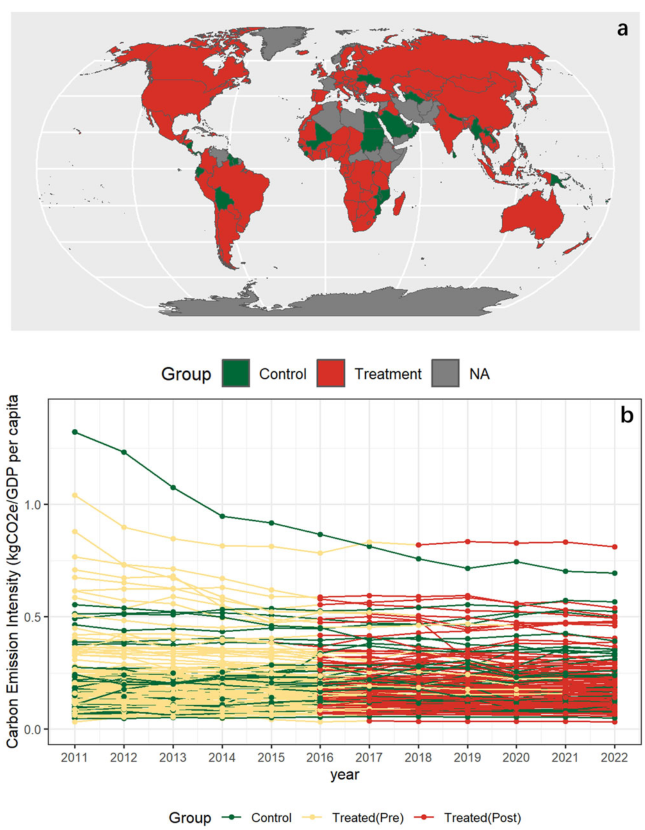

Fig. 1 | The distribution of carbon reduction targets and carbon emissions of 163 countries. a Countries with carbon emission reduction targets over time of control group (green) and treatment group (in red); **b** Carbon emission intensity over time of control group (green) and treatment group (pre in yellow and post in red). Treated (Pre) indicates when a target has not been proposed and Treated (Post) indicates when the target has been proposed.

Considering the diversity in the timing of carbon reduction target proposals across countries, we adopted a two-way fixed effects (TWFE) difference-in-differences methodology to assess the influence of carbon reduction targets on CO_2 emissions intensity. Previous research has pointed out that considerable disparities in treatment timing and its dynamic effect over time may introduce potential bias into the estimates of TWFE[29]. However, in our case, 75 countries in the treatment group proposed their targets in 2016, while 33 countries proposed in 2017 and 15 in other years. Moreover, there is limited variation in treatments at different timings. Thus, the potential bias caused by any staggered treatment periods and inappropriate comparisons is very limited.

CO_2 emissions intensity (*CI*) is measured by carbon emission per GDP per capita. Besides the binary variable (*D*) indicating the emission target, we also consider another variable capture the difficulty of emission target measured by the average reduced emission intensity (*CRT*). Controlled variables include economic development (*PGDP*), economic structure (*IMP*, *SER*, *IND*), education level (*EDU*) and income inequality (*INC*), along with the country-specific constants and year-specific constants. Detailed econometric models and our methodology for constructing our sample can be found in the Methods section.

As shown in Fig. 2, the estimated coefficients for variables *D* and *CRT* exhibited a strong negative significance at the 10% and 1% level. Thus, proposing a carbon reduction target corresponded to an average reduction of 0.0128 kilograms of CO_2 emissions per GDP in the country. Additionally, for the increment of one kilogram in CO_2 emissions per GDP within the annual carbon reduction target, there was a corresponding reduction of 0.230 kilograms in CO_2 emissions per GDP. These findings underscore the substantial efficacy of carbon reduction targets as an impactful policy instrument, transcending symbolic gestures. Notably, higher targets are associated with more profound emission reductions. The GDP per capita and income inequality also had negative and significant coefficients at 5% level.

To validate the applicability of TWFE estimator, we also tested the alternative models. As shown in Supplementary Table 4, only those countries with the implement in 2016 being selected as a single treatment period to perform TWFE regression, the estimated coefficients for *D* and *CRT* remained negative and statistically significant, consistent with the baseline model. Although sample sizes are smaller for other treatment periods, their estimated coefficients also exhibit negativity.

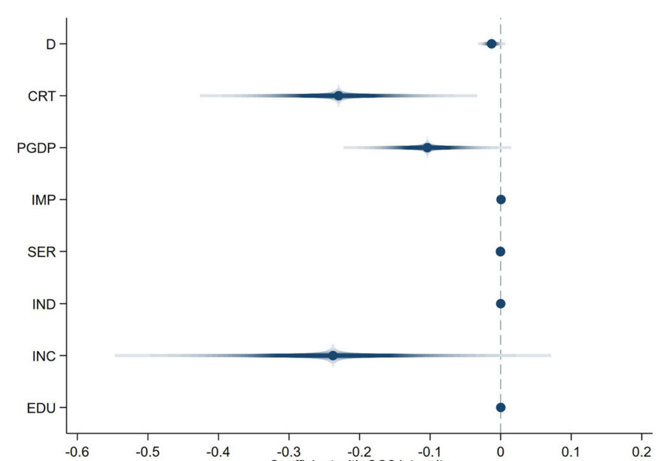

Fig. 2 | Effect of reduction target on carbon emission. Light blue spike line represents the 99% confidence interval. CRT-carbon emission reduction target; PGDP-GDP per capita; IMP-share of import in GDP; SER-share of service sector in GDP; IND-share of industrial sector in GDP; INC-income inequality level; EDU-education level.

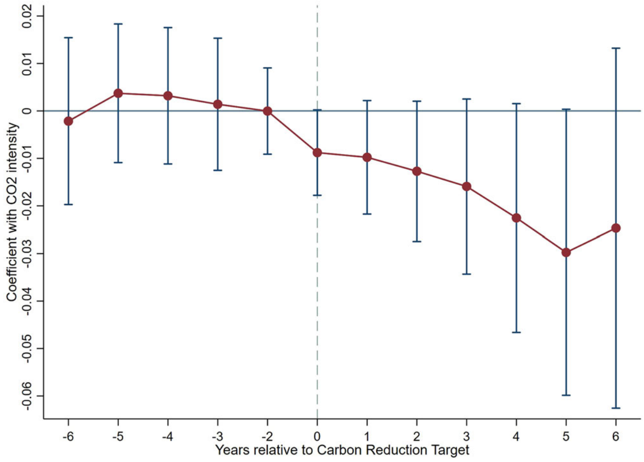

Fig. 3 | Result of parallel trend test. Blue line represents the 95% confidence interval.

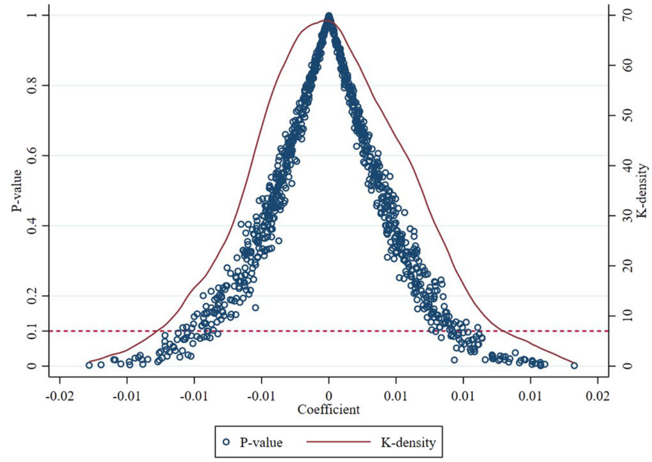

Fig. 4 | Result of placebo test. Red dashed line corresponds to the *P* value of 0.1.

The foundational principle underpinning the application of the difference-in-differences model hinges on the concept of the parallel trend test. Based on the results of parallel trend test, as depicted in Fig. 3 and Supplementary Table 5, the estimated coefficients on the dummy variables showed no significant difference from the base year (zero value) before policy implementation, thus supporting the parallel trend hypothesis. This result indicates that the difference-in-differences model was appropriate to evaluate the treatment effect of policies. In the year of policy implementation, a pivotal shift was discerned, as the coefficients exhibited a marked negative influence. Notably, this impact endured beyond the initial policy enactment, implying a sustained trend in the reduction of CO_2 emission intensity.

The result of placebo test was shown in Fig. 4. Most of estimation coefficients were distributed around 0, with a *p*-values greater than 0.1. Therefore, the placebo carbon reduction target has no significant impact among these 1000 samples. The placebo test consequently passed, and the negative impact of carbon reduction targets on carbon emissions is not accidental.

The robustness of our model was demonstrated through individual control variable elimination (Fig. 5a, b), with *Education* playing a pivotal role. Moreover, modifying the education variable from tertiary enrollment rate to secondary enrollment rate still yielded a significant model outcome (Fig. 5c), thereby reinforcing our study's key conclusion. These results were displayed in Supplementary Table 6. To further test the robustness of the results and eliminate the potential endogeneity of the core independent variable, the result of the lagged test was shown in Supplementary Table 7. The coefficients for variables *D* and *CRT* exhibited a negative significance, basically unchanged compared with the baseline model in Supplementary Table 3, effectively supporting the negative effect of carbon reduction targets on carbon emissions.

The COVID, being a public health crisis, has had a profound impact on the carbon emissions. The results are presented in Supplementary Table 8 to test the potential effects of the COVID. However, it is observed that variables about COVID did not exhibit significant influence. The coefficients of variables *D* and *CRT* demonstrate negative significance and remain largely unchanged compared to the baseline model in Supplementary Table 3, further validating the robustness of the baseline model. The effect of COVID on emission is potentially mediated through economic activities which were already controlled in the model through variable GDP per capita. Furthermore, to gauge the influence of the Ukraine-Russia conflict, we conducted additional tests by excluding the years affected by this significant global event. The regression results presented in Supplementary Table 11 also reinforce the robustness of the baseline model.

The mechanism underlying this phenomenon is likely intricate, but from the robustness test, it appears to be closely linked to education but the causality between education and effectiveness of carbon reduction targets could not be easily concluded based on models available in this study.

We propose potential explanations here. Firstly, a clearly defined carbon reduction target transforms a vague organizational intention into a dedicated consensus, laying the groundwork for systematic and comprehensive action plans. In contrast, without a clear target, carbon reduction's ambiguous nature might clash with the country's economic development goals, leading to conflicts and inefficiencies. By factoring in education, consensus-building could occur at different levels, aligning multiple targets, including economic development, and fostering operational efficiency.

A nationally articulated climate change mitigation target not only establishes explicit expectations but also furnishes governments and enterprises with a strategic framework for action. Education plays a pivotal role in interpreting these expectations across varied tiers. As targets gain clarity, the likelihood of their attainment amplifies, spurring proactive formulation of supportive policies and early innovative action by enterprises. Moreover, measurable national objectives prompt local authorities to actively contribute to carbon reduction, as these targets become metrics for gauging performance and prospects for advancement. Propagation of these targets through media channels heightens environmental consciousness, motivating citizens to adopt eco-friendly lifestyles. Ultimately, carbon reduction targets act as affirmative signals, with education potentially influencing their interpretation, galvanizing a diverse spectrum of stakeholders to engage actively in carbon reduction endeavors, culminating in a remarkable curtailment of CO_2 emission intensity.

However, education, depending on the indicator and content, also has other complicated relationships with climate change. For example, previous research shows that education is associated with energy efficiency education in leftist parties and reduces emissions[30], not through climate targets analyzed in this study. Research also shows that educational attainment is a strong predictor of climate change awareness[31], which might directly affect the population lifestyle and the emission. Therefore, the relationship among education level, climate target effectiveness and emission may not be a straightforward causality.

Renewable capacity is not a mediator

Drawing inspiration from the tenets of goal-setting theory, it becomes apparent that certain goal mediators—such as choice, effort, ability, persistence, and self-efficacy—play a pivotal role in potentially mediating the impact of goals on performance dynamics[27]. Switching our perspective to the realm of carbon emission reduction, the pivotal role of renewable energy in mitigating carbon emissions is a well-established fact[32,33]. The impetus for the development of renewable energy sources is often rooted in the strategic orchestration of corresponding policies. This phase of the analysis tested whether the renewable energy development is the key mediator of the carbon reduction target partially explaining its effect. With historical

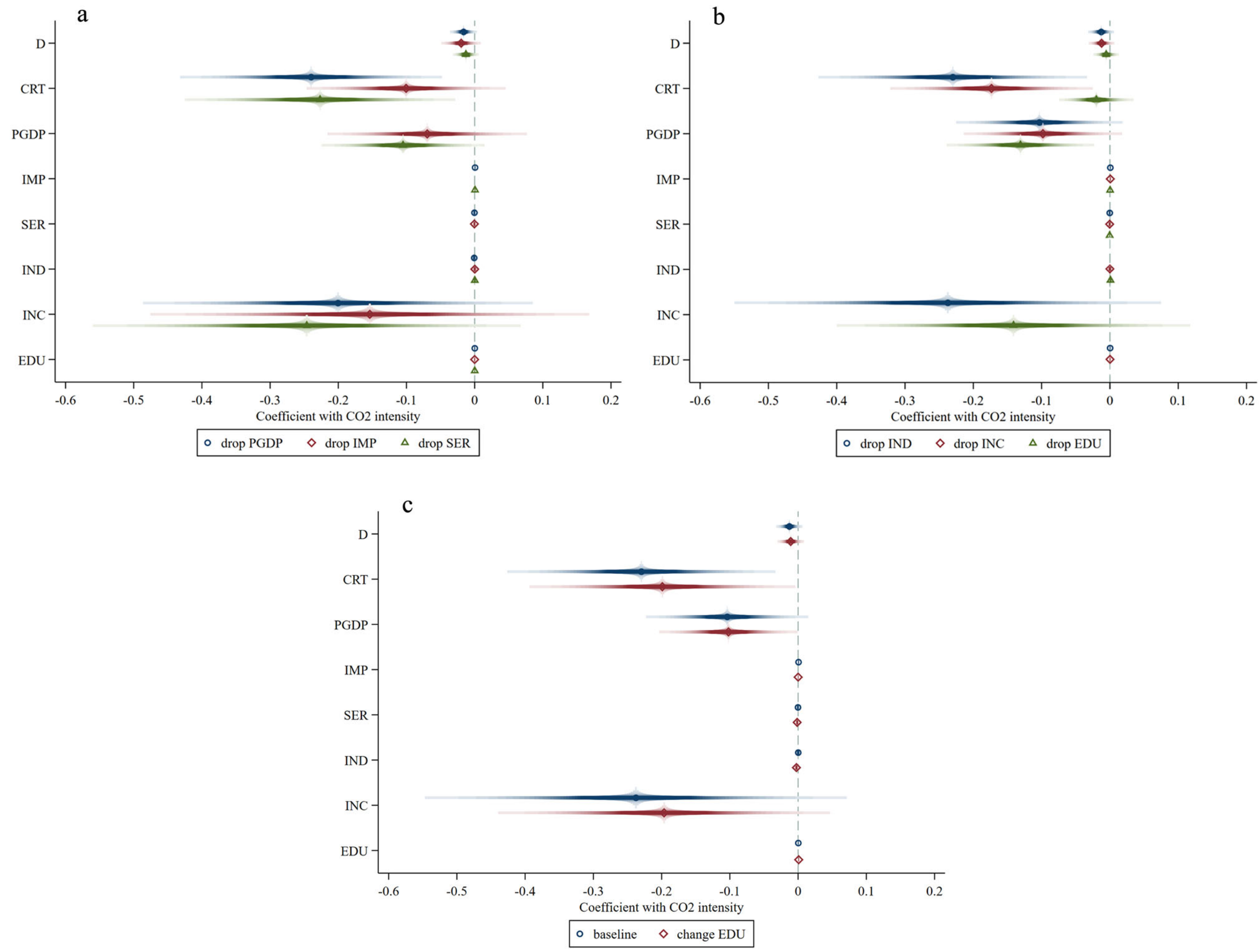

Fig. 5 | Results of robustness test. a Drop PGDP, IMP and SER respectively; **b** Drop IND, INC and EDU respectively; **c** Display the core model with full control variables, and replace tertiary enrollment rate with secondary enrollment rate to represent education level. Light spike line represents the 99% confidence interval. CRT-carbon emission reduction target; PGDP-GDP per capita; IMP-share of import in GDP; SER-share of service sector in GDP; IND-share of industrial sector in GDP; INC-income inequality level; EDU-education level.

renewable installed capacity data from IEA, a classic mediation model is constructed and tested. See more details in the method section. The model result as shown in Fig. 6 and also in Supplementary Table 9, tells that renewable energy installed capacity did not yield a significant association with carbon reduction targets. The percentile confidence interval of indirect effect, (−0.00118, 0.000230), contained zero. The postulation of a mediating role of renewable energy deployment in the relationship between carbon reduction targets and carbon emissions could not be substantiated.

There are several expressions for the underlying assumptions for mediation analysis. Here we describe the assumptions following Acharya, et al.'s approach, two assumptions–sequential confoundedness and no intermediate interactions[34]. The sequential unconfoundedness assumption holds when no omitted variables for the effect of treatment on the outcome and mediator, conditional on the pretreatment confounder, and no omitted variables for the effect of the mediator on the outcome, conditional on the treatment, pretreatment confounders, and intermediate confounder. This assumption is challenging to satisfy in the observational study, so we conducted a sensitivity analysis for assessing how large deviations from this assumption have to be to change the results of our study. As shown in Fig. 7, it indicated that a significant omitted confounder is required to reverse the result of mediating effect test, further supporting that the renewable energy development may not serve as a strong mediator. No intermediate interactions assumption basically assumes that no mediator-outcome confounder is itself affected by the treatment. Although this assumption does not affect the estimation of the direct effect, it is likely that there are other mediators not specified in the model, violating this assumption. Thus, it is possible that the renewable development still acts as a mediator among other mediators while not detected by the current model.

Given the discussion above, a substantive explanation is that some other mediators seem to have an indirect effect on carbon emission. One plausible explanation for these findings is that carbon reduction targets do not always explicitly prioritize renewable energy development. Public sector goal-setting often exhibits complexity, as seen in previous research on the public domain[23]. When these goals lack a specific directive for renewable energy development, it's possible that public sectors may not directly align their efforts in that direction; particularly since renewable energy development is often associated with the private sector in many countries. Furthermore, while renewable energy development remains a pivotal strategy within the energy sector to combat climate change, previous reviews have indicated that numerous countries tend to prioritize enhancing energy efficiency before heavily investing in renewable energy initiatives. This trend has been observed over recent decades[35]. As a result, the intricacies of policy priorities and sector-specific considerations might contribute to the observed lack of a mediating role for renewable energy deployment in the context of carbon reduction targets.

The mediator model also revealed a notable positive and statistically significant relationship between renewable energy capacity and carbon emission intensity. This observation sheds light on previous concerns voiced in the research domain. Specifically, it suggests that the positive impact of renewable energy development on economic growth, alongside an increase

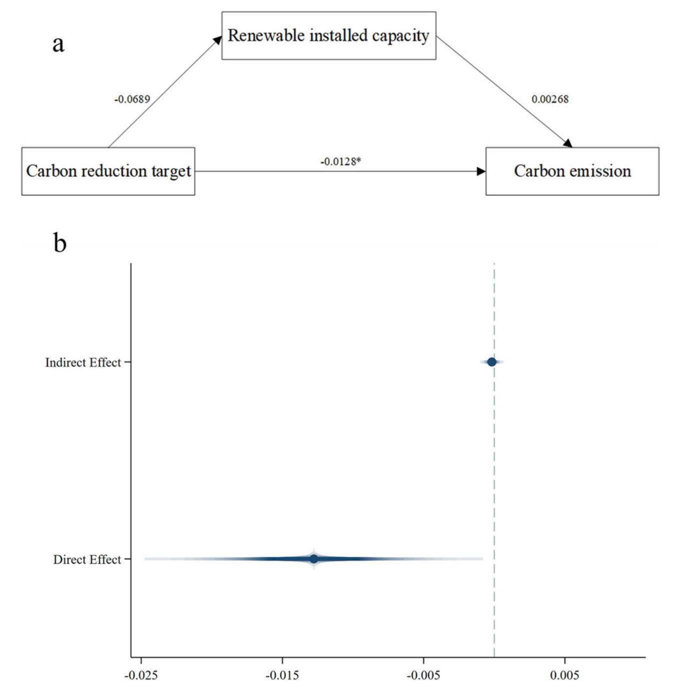

Fig. 6 | Result of mediation effect. a The coefficients of the mediation model; **b** The result of indirect effect and direct effect through a bootstrap test. Light blue spike line represents the 99% confidence interval.

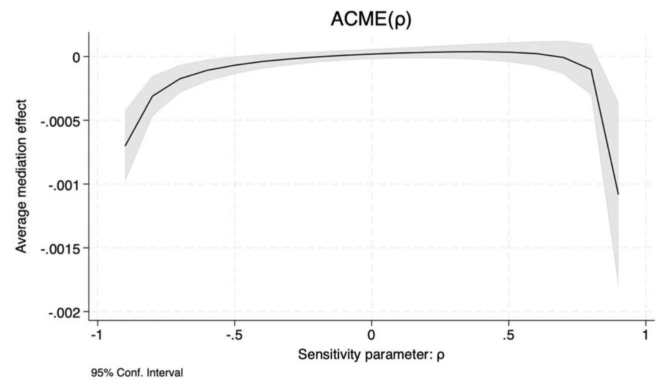

Fig. 7 | Sensitivity analysis. Average causal mediation effect as a function of degree of violation of sequential unconfoundedness assumption. Shaded region shows 95% confidence intervals.

in non-renewable energy consumption, may have partially obscured the mitigation effect of renewable energy on carbon emissions. This phenomenon, which has been discussed in earlier studies[35,36], underscores the complex interplay between renewable energy growth, economic expansion, and carbon emissions.

Furthermore, it's important to acknowledge that the subset of countries demonstrating substantial renewable energy capacity is relatively small within the larger pool of 163 countries. Consequently, the attenuating influence of these countries on overall carbon emissions might be outweighed by the progress of other nations with slower renewable energy development trajectories. Additionally, it's worth noting that ability, a pivotal concept in goal-setting[27], can manifest as both a mediating and moderating factor. Variability in abilities across the diverse landscape of 163 countries, encompassing factors such as technical prowess, developmental costs, and human resource availability for renewable energy initiatives, could further obscure the discernible impact of renewable energy capacity on carbon emissions.

Update the emission reduction target with renewable development

It's imperative to underscore that the establishment of carbon reduction targets necessitates a holistic comprehension of broader socio-economic factors operating at various levels. To unlock the full potential of goal-setting as a policy instrument, particularly in determining the appropriate level of goal difficulty, our analysis extends further. We have introduced an additional model specification designed to unravel the key factors that influence the goal-setting process. These factors encompass dimensions such as income inequality and renewable energy capacity, which wield considerable influence in shaping the formulation of these critical targets. We constructed three models considering different lags when factors affect the difficulty level of carbon emission target. The results of the model can be found in Fig. 8 and Supplementary Table 10.

Renewable energy installed capacity exhibited a positive and significant association with carbon reduction targets at the 5% level in all three models. This result suggests that countries with higher renewable energy capacity are more inclined to set more aggressive carbon reduction targets. One plausible explanation is that higher renewable energy capacity instills confidence in countries, given its efficacy in curbing carbon emissions. This finding underscores the policy implication that carbon reduction targets should be tailored to align with a country's renewable energy capacity. In essence, nations with robust renewable energy capabilities should consider setting ambitious carbon reduction targets, leveraging target-setting as a strategic policy tool for achieving decarbonization goals.

Conclusion

The global drive to address climate change has led to a rising number of countries incorporating carbon reduction targets into their Nationally Determined Contributions (NDCs), a response to the urgency outlined in the Paris Agreement. Amid this context, comprehending the range of policy tools available for encouraging carbon emission reduction becomes imperative. While previous research has predominantly viewed carbon reduction goals as end objectives, a gap persists in our understanding of whether the act of goal-setting itself could function as an effective policy instrument. Drawing from the tenets of goal-setting theory, which posits that goals can enhance performance even within the public sector, this study explores the potential of target-setting as a tool within climate governance.

Our findings underscore that target-setting can indeed serve as a potent policy tool for climate governance. Through a meticulous difference-in-difference model, we establish that proposing carbon reduction targets and their associated difficulty level correlate with a reduction in carbon emission intensity. Notably, this effect persists and intensifies after the policy's implementation.

Surprisingly, our analysis does not reveal a mediating role of renewable energy capacity, often considered a primary measure for emission reduction. Instead, we speculate that the reduction mechanism may involve factors such as improved administrative efficiency and social cohesion, both interwoven with education. However, validation of these hypotheses requires further investigation. Accumulated empirical evidence could pave the way for extending the application of goal-setting theory to the realm of climate governance, especially given the inductive development approach of goal-setting theory[27].

Enhanced alignment with the ambitious 1.5 °C target is conceivable if countries without carbon reduction targets take steps to establish such targets, guiding their emissions reduction efforts. Additionally, countries that have already set targets can adapt and reinforce them based on evolving conditions. Our analysis of influencing factors for target-setting suggests that the difficulty level of targets correlates with renewable energy capacity. Consequently, we recommend that nations with robust renewable energy capabilities consider setting ambitious carbon reduction targets, updating them in tandem with renewable energy growth.

Setting ambitious targets marks just the initial step in the complex journey of climate mitigation, and it is vital to recognize that targets alone do

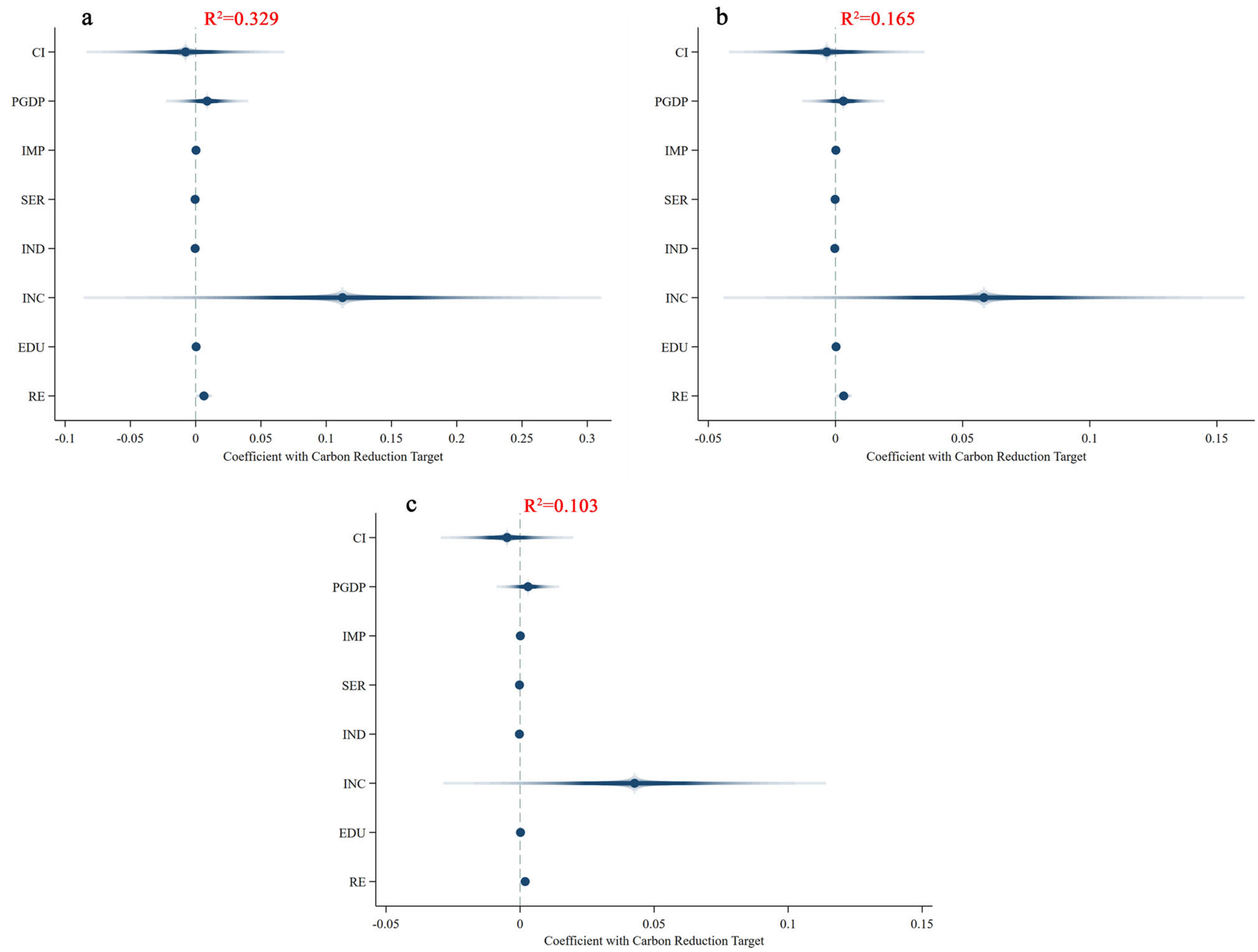

Fig. 8 | Factors affecting target-setting. **a** Using the cross-sectional data of the year when the target was proposed; **b** Using the data from two cross-sections (the year when the target was proposed and the year before the target was proposed); **c** Adopting the data representing three cross-sections (the year when the target was proposed, one year and two years before the target was proposed). Light blue spike line represents the 99% confidence interval. CRT-carbon emission reduction target; PGDP-GDP per capita; IMP-share of import in GDP; SER-share of service sector in GDP; IND-share of industrial sector in GDP; INC-income inequality level; EDU-education level.

not guarantee desired results. Success hinges on the subsequent strategies and policies enacted to attain these goals. Our study does not diminish the importance of these subsequent strategies; rather, it underscores that climate governance and efforts commence at the very moment of goal-setting, not merely after the goals are set.

Furthermore, the process of announcing national targets within the international community entails intricate negotiations and commitments. While our analysis primarily focused on a selection of domestic factors influencing target-setting, it is paramount to emphasize that we do not diminish the paramount importance of international climate negotiations. On the contrary, we firmly believe that our analysis can contribute to these negotiations, reinforcing the foundations of the Paris Agreement. This landmark agreement relies on the collective commitment of nations to submit their targets, and our research aims to enrich this global effort toward a sustainable future.

Our analysis presents certain limitations that warrant further exploration. As with many empirical studies, our research may be susceptible to omitted variables not accounted for in the model, potentially impacting our findings. While the parallel trends test offers evidence of pre-treatment parallel trends, the possibility of endogeneity arising from unobservable factors cannot be entirely ruled out. Future research endeavors could aim to identify suitable instrumental variables to bolster the robustness of our results.

The annual granularity of the dataset prevents the analysis of shorter-term effects, impeding the investigation of interactions between climate targets and other policies. To address this, a more detailed analysis at a finer temporal resolution could examine how different administrative bodies and branches of government respond to national climate targets, shedding light on the potential improvement in administrative efficiency. Moreover, the study's current horizon might not fully encompass the profound impacts of climate targets, given that major projects and policy interventions could extend beyond the time frame of the dataset. Lastly, while we couldn't substantiate the mechanism of carbon reduction targets affecting CO_2 emissions in this analysis, future research might delve into this by incorporating government efficiency data as a reflection of policy response.

Methods

The econometric model

The concept of goal-setting theory has been meticulously nurtured within the domain of industrial/organizational (I/O) psychology, growing from the bedrock of rigorous empirical investigations. Over time, it has ascended to become one of the foremost theories in the expansive realm of I/O psychology. Consistent with a participative goal in the goal-setting theory[27], a multitude of nations have proactively integrated an array of carbon reduction targets into their Nationally Determined Contributions (NDCs) as a direct response to the climate mitigation benchmarks set forth by the IPCC.

Pioneering research has unveiled the far-reaching impact of goal-setting across both individual and organizational strata. Goals function as dynamic motivators, propelling goal performers toward their accomplishment[17–19]. This knowledge underpins our hypothesis that the instrumental role of goal-setting might extend to its utilization as a policy instrument for the reduction of carbon emissions. Beyond the individual and organizational context, goal-setting exhibits a discursive influence at the national level. This influence reverberates through localized policies enacted at both the national and local tiers, all with the shared objective of fostering goal achievement[25]. Concurrently, the efficacy of public policy implementation gains augmentation through the infusion of goal-setting principles[23]. These insights collectively suggest that national-level goal-setting might engender a comparable mechanism, triggering discursive effects that facilitate both policy enactment and goal realization. Further reinforcing the utility of goal-setting, recent findings at the municipal level bolster its standing as a potent tool in the realm of climate governance[24]. On the international stage, the Sustainable Development Goals (SDGs) stand as a premier paradigm for embedding goal-setting into the fabric of global policy and climate governance frameworks[26,37]. This naturally prompts the expectation that SDGs would exert a pronounced influence on nation-level governance dynamics. Emanating from the premise that a nation embodies an amalgam of cities and functions as a principal actor in global governance, the potential impact of national carbon reduction targets on a country's dynamics aligns with similar mechanisms. Anchored in the above analyses, our research endeavors culminated in the formulation of Hypothesis 1 and Hypothesis 2.

Hypothesis 1: Setting a carbon reduction target could have a negative impact on CO2 emission intensity.

Hypothesis 2: A more ambitious target could lead to more reduction in CO2 emission intensity.

Considering the diversity in the timing of carbon reduction target proposals across countries, we adopted a TWFE difference-in-differences methodology to assess the influence of carbon reduction targets on CO_2 emissions. The assessment was grounded in the following regression model:

$$CI_{i,t} = \alpha + \beta_1 D_{i,t} + \gamma CRT_{\mathrm{i,t}} + \delta X_{i,t} + \lambda_t + \mu_i + \varepsilon_{i,t} \quad (1)$$

where CI_{it} represented CO_2 emission per unit of Gross Domestic Production (GDP) in country i during year t. The focal independent variable $D_{i,t}$, constituted a binary variable representing the presence of a carbon reduction target. It held the value of 1 in the years when country i had already put forth its carbon reduction targets, and 0 otherwise. $CRT_{i,t}$ symbolized the complexity of the proposed target, quantified as the annual average emission reduction intensity.

Additionally, $X_{i,t}$ encompassed an array of control variables, described in more details in the following. In parallel, λ_t and μ_i signified sets of year-specific and country-specific variables, capturing fixed effects that accounted for unobservable characteristics varying either across years but not countries, or across countries but not years. In concert, ε_{it} denoted the idiosyncratic error term, manifesting variability across both countries and years.

Mediating effect of renewable capacity

If we consider the viability of the emission reduction target as a policy instrument, the subsequent inquiry revolves around elucidating the underlying mechanisms. Drawing inspiration from the tenets of goal-setting theory, it becomes apparent that certain goal mediators—such as choice, effort, ability, persistence, and self-efficacy—play a pivotal role in potentially mediating the impact of goals on performance dynamics[27]. Switching our perspective to the realm of carbon emission reduction, the pivotal role of renewable energy in mitigating carbon emissions is a well-established fact[32,33]. The impetus for the development of renewable energy sources is often rooted in the strategic orchestration of corresponding policies. Consequently, it stands to reason that when a nation sets a carbon reduction target, it might logically be accompanied by a complementary renewable energy target. This inference leads us to consider renewable energy as a potent mediator—a conscious endeavor by countries to align their actions with the pursuit of carbon reduction targets.

This line of reasoning finds support in prior research, which has underscored that the presence of renewable energy targets effectively expedites the expansion of renewable energy infrastructure[38,39]. Similarly, at the organizational level, investigations have illuminated a noteworthy and affirmative correlation between the adoption of climate change mitigation targets by companies and heightened investments in renewable energy ventures[40]. Building on these insights, we extrapolate that the establishment of national carbon reduction targets could subsequently propel the development of renewable energy sources, thereby engendering a consequential contribution to the overarching objective of curtailing carbon emissions. With these considerations in mind, we posit our Hypothesis 3.

Hypothesis 3: Carbon reduction targets reduce CO_2 emission mediated through renewable installed capacity.

To corroborate Hypothesis 3, as elucidated in the preceding theoretical analysis, we embarked on a mediating effect evaluation. To this end, we adopted the causal steps approach, akin to previous research methodologies[41] that performed a bootstrap test to further ascertain the presence of a mediating effect. To test the veracity of Hypothesis 3, we established additional Eqs. 2 and 3 as outlined below:

$$RE_{i,t} = \eta_0 + \eta_1 D_{i,t} + \gamma CRT_{i,t} + \delta X_{i,t} + \lambda_t + \mu_i + \varepsilon_{i,t} \quad (2)$$

$$CI_{i,t} = \varphi_0 + \varphi_1 D_{i,t} + \varphi_2 RE_{i,t} + \gamma CRT_{i,t} + \delta X_{i,t} + \lambda_t + \mu_i + \varepsilon_{i,t} \quad (3)$$

Where $RE_{i,t}$ was the renewable energy capacity as the mediating variable, and other variables were set as in Eq. 1. The coefficient β of Eq. 1 was the total effect of the independent variable $D_{i,t}$ on the dependent variable $CI_{i,t}$. Meanwhile, the coefficient η_1 in Eq. 2 was the effect of the independent variable $D_{i,t}$ on the mediating variable $RE_{i,t}$. The coefficient φ_2 in Eq. 3 was the effect of the mediating variable $RE_{i,t}$ on the dependent variable $CI_{i,t}$ after controlling for the effect of the independent variable $D_{i,t}$. In addition, the coefficient φ_1 was the direct effect of the independent variable $D_{i,t}$ on the dependent variable $CI_{i,t}$ after controlling for the effect of the mediating variable $RE_{i,t}$. Together, Eqs. 1–3 were meticulously formulated to scrutinize and validate the premises of Hypothesis 3.

Model about how targets are determined

Should goal-setting emerge as a potent policy tool for climate governance, a consequential inquiry emerges: how should these targets be established in practice? We duly acknowledge that the process of target setting is a complex endeavor involving meticulous research and intricate negotiations. Nevertheless, distilling a subset of factors that exert influence on the goal-setting process can provide invaluable insights for informed policymaking. With the intent of unraveling the key determinants that shape the establishment of carbon reduction targets, we devised the ensuing model for comprehensive evaluation.

$$CRT_i = \alpha + \beta X'_i + \mu_i + \varepsilon_{it} \quad (4)$$

where CRT_i was the intensity of carbon reduction target proposed by country i, described in more detail in the following. X'_i are a series of control variables which include carbon emission intensity CI_i, renewable energy capacity RE_i and other control variables as in Eq. 1 except CRT. Considering that goal-setting is influenced by more than just the data from the year when the target was proposed, we created three models to facilitate comparison. The first model took the cross-sectional data of the year when the target was proposed, while the second model used the data from two cross-sections (the year when the target was proposed and the year before the target was proposed), and the last model adopted the data representing three cross-sections (the year when the target was proposed, one year and two years before the target was proposed).

Data description

CO_2 emission intensity (*CI*) was measured by CO2 emission per GDP (kg CO2e per USD). This particular approach, focusing on emission intensity rather than absolute emissions, serves to account for the influences of various factors intricately linked with population growth and economic development. Data pertaining to CO_2 emissions intensity across the span of 163 countries and the years spanning 2011 to 2022 was meticulously sourced from EDGAR (Emissions Database for Global Atmospheric Research) Community GHG Database[42]. Within this dataset, we successfully compiled a comprehensive set of 1884 country-year observations, encompassing instances of limited data availability.

The term *DID* (Difference-in-Differences) is encapsulated by the dummy variable $D_{i,t}$ which signifies the presence of carbon reduction targets. Specifically, for the control group, $D_{i,t} = 0$ while for the treatment group, $D_{i,t} = 1$ in when country *i* had already introduced carbon reduction targets, and $D_{i,t} = 0$ otherwise. As previously indicated, the treatment group encompasses countries that have submitted NDCs (Nationally Determined Contributions), while the control group comprises nations that did not submit NDCs during the research timeframe. It's noteworthy that countries submitting NDCs without explicit targets were excluded from the analysis, leading to a final count of 117 countries in the treatment group and 46 countries in the control group. We have also acknowledged U.S.'s $D_{i,t}$ and *CRT* about its withdrawal from and rejoining of the Paris Agreement and changed the values of these variables accordingly.

CRT constitutes a continuous treatment parameter, signifying the complexity of the target. It operates in conjunction with the primary independent variable $D_{i,t}$ to offer a more nuanced insight into how the target's intricacies influence carbon emissions. This variable is defined as the annual average emission reduction intensity (ω) as depicted in Eq. 5, in which ω_a symbolizes the carbon emission intensity in the year of target proposal *a* and ω_b denotes the carbon emission intensity in the target year *b*.

$$\omega = \left(\omega_a - \omega_b\right)/(b - a) \tag{5}$$

For the control group, $CRT_{it} = 0$. For the treatment group, $CRT_{it} = \omega$ in the years when country *i* had already proposed the carbon reduction targets and $CRT_{it} = 0$ otherwise. This continuous treatment variable possesses the capacity to effectively encapsulate the range of variations in target difficulty, thereby reflecting a pivotal aspect of the goal-setting theory.

For numerous countries, the computation of carbon reduction can be directly deduced from the figures outlined in the NDCs. For targets that deviate from a "business-as-usual" scenario within the NDCs, carbon emission forecast data were sourced from Liu and Raftery[43]. The carbon emission intensity for the target year was determined by dividing carbon emissions for the said year by the projected GDP for that period. The GDP projections were drawn from the Centre for Economics and Business Research[44].

The mediating variable was designated as renewable energy installed capacity (*RE*). This encompassed a spectrum of renewable sources, including bioenergy, solar energy, wind energy, hydropower, geothermal energy, and marine energy. Our data collection spanned the period from 2011 to 2022 across 163 countries, utilizing the comprehensive renewable energy capacity figures furnished by the International Renewable Energy Agency[45].

The vector of control variables, $X_{i,t}$, has several components. The first component is economic development, quantified through GDP per capita (*PGDP*). Prior investigations have underscored the influence of economic growth relative to population expansion on carbon emission intensity[46–48]. Three further variables about economic structure (*IMP*, *SER* and *IND*), respectively corresponding to import share, the size of the service sector and the industry sector have been proven to affect emissions significantly. Previous research has indicated that trade openness and foreign direct investment can elevate emissions through pollution-intensive investments[49,50]. Meanwhile, reduced reliance on the industry sector and a flourishing service sector have been linked to emissions reduction[13,51]. Another variable about education, (*EDU*), quantified by the gross enrollment ratio of tertiary education, plays a pivotal role. This ratio signifies total enrollment in tertiary education relative to the corresponding population age group. Earlier studies on the influence of advanced human capital, peroxided by the number of tertiary schooling years, exert a negative effect on CO_2 emissions[52]. Enhanced education is linked to environmental awareness, driving the adoption of eco-friendly technologies[53], as well as fostering innovative approaches to energy consumption and technology development[54]. All the above five variables were retrieved from the World Development Indicators database[55].

The final control variable, income inequality (*INC*), gauged by the share of pre-tax national income among the top 10% of equal-split adults, was derived from the World Wealth and Income Database[56]. Addressing the complex relationship between inequality and carbon emissions, prior studies have yielded divergent outcomes; nevertheless, the effect is statistically significant and should be controlled. Some researchers reported a positive relationship between inequality and carbon emission[57,58]; contrariwise, others found that when income was more evenly distributed, the poor had a higher propensity to consume energy and other products, leading to an increase in total carbon emissions[59]. Meanwhile, some scholars argued that the link between inequality and carbon emissions might not be linear and might also vary with the degree of inequality[60,61].

Descriptive statistics

Given the multifaceted nature of our variables, the possibility of interdependency issues necessitated scrutiny. Our investigation encompassed descriptive statistics and correlation analyses, detailed in Supplementary Table 1 and Supplementary Table 2. Correlation coefficients remained below 0.6, with the exception of *PGDP* and *EDU* which reached 0.740. The variance inflation factors were less than 6, with the exception of *PGDP* which reached 0.740, indicating that the problem of multicollinearity among the study variables is not a concern.

Within the scope of variables and data availability, our study harnessed a total of 1173 complete observations across year-country combinations. While some variables experienced missing data, our dataset robustly captures global emissions trends. From 2011 to 2022, the 1173 year-country observations accounted for approximately 90% of global carbon dioxide emissions during all the period.

Applicability test

Our analysis commenced with the application of various regression methodologies—pooled regression (OLS), fixed-effect model (FEM), and random-effect model (REM)—utilizing STATA. As a precursor, we subjected the fixed-effect model (FEM) to an F test, resulting in a *P* value of 0.0000 (< 0.05), indicating the substantial rejection of the null hypothesis "H_0: all $u_i = 0$", and FEM was significantly better than OLS. LM test of REM regression yielded a *P* value of 0.0000 < 0.05, which also supported rejecting the null hypothesis "H_0: all $\sigma_u^2 = 0$" and indicating that the pooled regression should not be used. The result of the Hausman test had a P value of 0.0000, which robustly rejected the null hypothesis of "difference in coefficients not systematic." This outcome indicated that the fixed-effect model should be used. By generating time dummy variables and testing the joint significance of time dummy variables (a P value of 0.0021 < 0.05), we rejected the null hypothesis of "no time effect" and determined that the time fixed effect should be included in the model. Therefore, a two-way fixed effects model was finally used.

Parallel trend test

The foundational principle underpinning the application of the difference-in-differences model hinges on the concept of the parallel trend test. Within this study's framework, we operate under the presumption that the carbon emission intensity of both the treatment group and control group countries followed parallel trajectories prior to the implementation of national carbon reduction targets. This supposition of parallel trends is scrutinized via the event study approach, akin to methodologies adopted in prior research endeavors[62–64]. A certain year before the policy or the current period of target implementation needs to be selected as the baseline reference period to encapsulate the foundational disparity between the geographical domains where the event transpired and where it did not. Thus, we embarked on estimating the subsequent equation:

$$CI_{i,t} = \alpha + \sum_{\tau=-6,\tau\neq-1}^{3} \beta_\tau Dummy_{i,\tau} + \gamma CRT_{i,t} + \delta X_{i,t} + \lambda_t + \mu_i + \varepsilon_{it} \quad (6)$$

Within Eq. 6, the policy variable stands as a relative temporal construct, characterized by the temporal distance from the policy intervention within the respective time interval. This configuration captures the fluctuation in policy effect in the period τ preceding or ensuring the implementation of the treatment. For the control group, the dummy variable is designated as 0, whereas for the treatment group, *Dummy* adopts a value of 1, indicating that the policy was enacted τ years ago or will be enacted after τ years; otherwise, its value remains at 0. Since the carbon emission intensity in the current period of policy effective date may already be affected by the carbon reduction targets, the first year preceding the policy instead of the current period of policy is taken as the base period. We dropped the first lagged year $Dummy_{i,1}$ representing the first year preceding the policy and considered it as baseline reference period, which could avoid the multi-collinearity. The remaining variables echo the composition of Eq. 1. Consequently, the regression coefficient β_τ of *Dummy* when $\tau < 0$ signifies statistical insignificance, affirms a lack of meaningful difference from the baseline period and thereby corroborates the tenets of the parallel trend hypothesis.

The placebo test

The placebo test is an analysis conducted using a "false" dummy variable of carbon reduction target to test whether the reduction of carbon emission intensity reduction could be significantly affected. If it is still significantly negative, it indicates that the effect of carbon reduction target in the benchmark regression is not reliable and may be caused by other unobservable factors. In order to further rule out the effect of other unknown influential factors, the placebo test was conducted through 1000 times of random sampling. Each time, 117 countries were randomly selected using the "sample" command in STATA from all samples as the "false" treatment group, and the remaining 46 countries were used as the control group. The corresponding target proposal time of each treatment group was also randomly generated, indicating that a new treatment group was constructed with randomly selected countries and proposal times. The value of "false" dummy variables is then set according to the treatment groups and proposal times.

Data availability

The authors declare that all the data used in this analysis could be found at (https://doi.org/10.6084/m9.figshare.21748160). Specifically, the data for emission intensity can be found at https://edgar.jrc.ec.europa.eu/. National Determined Contribution data can be found at https://unfccc.int/NDCREG. Future GDP forecast can be found at https://cebr.com/service/macroeconomic-forecasting/. Historical renewable capacity data can be found at https://www.irena.org/Data/Downloads/IRENASTAT. Historical GDP per capita, GDP share of different sectors, and education level data can be found at https://databank.worldbank.org/reports.aspx?source=World-Development-Indicators. The income inequality data can be found at https://wid.world/data/.

Code availability

All custom code used to generate results that are reported in this paper and central to its main claims are available on Figshare (https://doi.org/10.6084/m9.figshare.21748160). The analysis was carried out using STATA.

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References

1. Lenssen, N. J. et al. Improvements in the GISTEMP uncertainty model. *J. Geophys. Res.: Atmos.* **124**, 6307–6326 (2019).
2. Diffenbaugh, N. S. et al. Quantifying the influence of global warming on unprecedented extreme climate events. *Proc. Natl Acad. Sci.* **114**, 4881–4886 (2017).
3. Hsiang, S. et al. Estimating economic damage from climate change in the United States. *Science* **356**, 1362–1369 (2017).
4. Liu, J., Hertel, T. W., Diffenbaugh, N. S., Delgado, M. S. & Ashfaq, M. Future property damage from flooding: sensitivities to economy and climate change. *Clim. Change* **132**, 741–749 (2015).
5. Elliott, J. et al. Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proc. Natl Acad. Sci.* **111**, 3239–3244 (2014).
6. Watts, N. et al. Health and climate change: policy responses to protect public health. *Lancet* **386**, 1861–1914 (2015).
7. IPCC. Summary for Policymakers. In *Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (eds Masson-Delmotte, V. et al.) 3–24 (Cambridge University Press, Cambridge, UK and New York, NY, USA, 2018). https://doi.org/10.1017/9781009157940.001.
8. IPCC, 2022: Summary for Policymakers. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Shukla, P. R. et al) (Cambridge University Press, UK and New York, NY, USA 2022). https://doi.org/10.1017/9781009157926.001.
9. Framework Convention on Climate Change. *Adoption of the Paris Agreement*, UN FCCC, 21 sess, Agenda Item 4(b), FCCC/CP/2015/L.9/Rev.1 (UN FCCC, 2015).
10. Fang, K. et al. How can national ETS affect carbon emissions and abatement costs? Evidence from the dual goals proposed by China's NDCs. *Resour. Conserv. Recycl.* **171**, 105638 (2021).
11. Kanudia, A. & Shukla, P. Modelling of uncertainties and price elastic demands in energy-environment planning for India. *Omega* **26**, 409–423 (1998).
12. Zhang, S., Wang, Y., Hao, Y. & Liu, Z. Shooting two hawks with one arrow: could China's emission trading scheme promote green development efficiency and regional carbon equality? *Energy Econ.* **101**, 105412 (2021).
13. Eskander, S. M. & Fankhauser, S. Reduction in greenhouse gas emissions from national climate legislation. *Nat. Clim. Change* **10**, 750–756 (2020).
14. Fankhauser, S., Gennaioli, C. & Collins, M. Do international factors influence the passage of climate change legislation? *Clim. Policy* **16**, 318–331 (2016).
15. Locke, E. A. Motivation through conscious goal setting. *Appl. Prev. Psychol.* **5**, 117–124 (1996).
16. Locke, E. A. & Bryan, J. F. Grade goals as determinants of academic achievement. *J. Gen. Psychol.* **79**, 217–228 (1968).
17. Locke, E. A., Cartledge, N. & Koeppel, J. Motivational effects of knowledge of results: A goal-setting phenomenon? *Psychol, Bull.* **70**, 474 (1968).
18. Latham, G. P. & Kinne, S. B. Improving job performance through training in goal setting. *J. Appl. Psychol.* **59**, 187 (1974).
19. Nahrgang, J. D. et al. Goal setting in teams: The impact of learning and performance goals on process and performance. *Org. Behav. Hum. Decis. Process.* **122**, 12–21 (2013).
20. Porter, R. L. & Latham, G. P. The effect of employee learning goals and goal commitment on departmental performance. *J. Leaders. Org. Stud.* **20**, 62–68 (2013).

21. Latham, G. P., Borgogni, L. & Petitta, L. Goal setting and performance management in the public sector. *Int. Public Manage. J.* **11**, 385–403 (2008).
22. Taylor, J. Goal setting in the Australian public service: Effects on psychological empowerment and organizational citizenship behavior. *Public Admin. Rev.* **73**, 453–464 (2013).
23. Van der Hoek, M., Groeneveld, S. & Kuipers, B. Goal setting in teams: Goal clarity and team performance in the public sector. *Rev. Public Pers. Admin.* **38**, 472–493 (2018).
24. Hofstad, H., Millstein, M., Tønnesen, A., Vedeld, T. & Hansen, K. B. The role of goal-setting in urban climate governance. *Earth Syst. Govern.* **7**, 100088 (2021).
25. Shrestha, S. & Haarstad, H. Do EU goals matter? Assessing the localization of sustainable urban logistics governance goals in Norwegian cities. *Cities* **137**, 104317 (2023).
26. Biermann, F., Kanie, N. & Kim, R. E. Global governance by goal-setting: the novel approach of the UN Sustainable Development Goals. *Curr. Opin. Environ. Sustain.* **26**, 26–31 (2017).
27. Locke, E. A. & Latham, G. P. The development of goal setting theory: A half century retrospective. *Motiv. Sci.* **5**, 93 (2019).
28. Seijts, G. H. & Latham, G. P. Learning versus performance goals: When should each be used? *Acad. Manage. Perspect.* **19**, 124–131 (2005).
29. Baker, A. C., Larcker, D. F. & Wang, C. C. Y. How much should we trust staggered difference-in-differences estimates? *J. Financ. Econ.* **144**, 370–395 (2022).
30. Wang, Q.-J., Feng, G.-F., Wang, H.-J. & Chang, C.-P. The influence of political ideology on greenhouse gas emissions. *Glob. Environ. Change* **74**, 102496 (2022).
31. Lee, T. M., Markowitz, E. M., Howe, P. D., Ko, C.-Y. & Leiserowitz, A. A. Predictors of public climate change awareness and risk perception around the world. *Nat. Clim. Change* **5**, 1014–1020 (2015).
32. Akimoto, K. et al. Estimates of GHG emission reduction potential by country, sector, and cost. *Energy Policy* **38**, 3384–3393 (2010).
33. Jin, T. & Kim, J. What is better for mitigating carbon emissions—Renewable energy or nuclear energy? A panel data analysis. *Renew. Sustain. Energy Rev.* **91**, 464–471 (2018).
34. Acharya, A., Blackwell, M. & Sen, M. Explaining causal findings without bias: detecting and assessing direct effects. *Am. Polit. Sci. Rev.* **110**, 512–529 (2016).
35. Ang, B. W. & Su, B. Carbon emission intensity in electricity production: A global analysis. *Energy Policy* **94**, 56–63 (2016).
36. Dong, K., Dong, X. & Jiang, Q. How renewable energy consumption lower global CO2 emissions? Evidence from countries with different income levels. *World Econ.* **43**, 1665–1698 (2020).
37. Fukuda-Parr, S. Global goals as a policy tool: intended and unintended consequences. *J. Hum. Dev. Capab.* **15**, 118–131 (2014).
38. Maulidia, M., Dargusch, P., Ashworth, P. & Ardiansyah, F. Rethinking renewable energy targets and electricity sector reform in Indonesia: A private sector perspective. *Renew. Sustain. Energy Rev.* **101**, 231–247 (2019).
39. Yin, H. & Powers, N. Do state renewable portfolio standards promote in-state renewable generation?. *Energy Policy* **38**, 1140–1149 (2010).
40. Wang, D. D. & Sueyoshi, T. Climate change mitigation targets set by global firms: Overview and implications for renewable energy. *Renew. Sustain. Energy Rev.* **94**, 386–398 (2018).
41. MacKinnon, D. P., Fairchild, A. J. & Fritz, M. S. Mediation analysis. *Ann. Rev. Psychol.* **58**, 593 (2007).
42. Risquez Martin, R. et al. GHG emissions of all world countries. (Luxembourg, 2023).
43. Liu, P. R. & Raftery, A. E. Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 C target. *Commun. Earth Environ.* **2**, 1–10 (2021).
44. CEBR. WORLD ECONOMIC LEAGUE TABLE 2022, https://cebr.com/wp-content/uploads/2022/01/WELT-2022.pdf (accessed 2022).
45. IRENA. IRENASTAT Online Data Query Tool, <https://pxweb.irena.org/pxweb/en/IRENASTAT> (accessed 2022).
46. Sheng, P., Li, J., Zhai, M. & Huang, S. Coupling of economic growth and reduction in carbon emissions at the efficiency level: Evidence from China. *Energy* **213**, 118747 (2020).
47. Stern, D. I. The rise and fall of the environmental Kuznets curve. *World Dev.* **32**, 1419–1439 (2004).
48. Roberts, J. T. & Grimes, P. E. Carbon intensity and economic development 1962–1991: A brief exploration of the environmental Kuznets curve. *World Dev.* **25**, 191–198 (1997).
49. Salman, M., Long, X., Dauda, L., Mensah, C. N. & Muhammad, S. Different impacts of export and import on carbon emissions across 7 ASEAN countries: A panel quantile regression approach. *Sci. Total Environ.* **686**, 1019–1029 (2019).
50. Wang, Q. & Zhang, F. The effects of trade openness on decoupling carbon emissions from economic growth–evidence from 182 countries. *J. Clean. Prod.* **279**, 123838 (2021).
51. Yi-hua, Y., Xin-ye, Z. & Li, Z. Carbon dioxide emission and economic development: A panel data analysis. *Econ. Theory Bus. Manage.* **31**, 72 (2011).
52. Yao, Y., Ivanovski, K., Inekwe, J. & Smyth, R. Human capital and CO_2 emissions in the long run. *Energy Econ.* **91**, 104907 (2020).
53. Furkan, H. B., Rakibul Hasan, K. M. & Uddin, M. J. Greenhouse gas emission, GDP, tertiary education, and rule of law: A comparative study between high-income and lower-middle income countries. *Heliyon* **9**, e16265 (2023).
54. Sarwar, S., Streimikiene, D., Waheed, R. & Mighri, Z. Revisiting the empirical relationship among the main targets of sustainable development: Growth, education, health and carbon emissions. *Sustain. Dev.* **29**, 419–440 (2021).
55. World Bank. World Development Indicators, https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD (accessed 2022).
56. WWID. World Inequality Database, https://wid.world/data/ (accessed 2022).
57. Jorgenson, A., Schor, J. & Huang, X. Income inequality and carbon emissions in the United States: a state-level analysis, 1997–2012. *Ecol. Econ.* **134**, 40–48 (2017).
58. Ravallion, M., Heil, M. & Jalan, J. Carbon Emissions and Income Inequality. *Oxford Econ. Pap.* **52**, 651–669 (2000).
59. Langnel, Z., Amegavi, G. B., Donkor, P. & Mensah, J. K. Income inequality, human capital, natural resource abundance, and ecological footprint in ECOWAS member countries. *Resour. Policy* **74**, 102255 (2021).
60. Ehigiamusoe, K. U., Majeed, M. T. & Dogan, E. The nexus between poverty, inequality and environmental pollution: Evidence across different income groups of countries. *J. Clean. Prod.* **341**, 130863 (2022).
61. Grunewald, N., Klasen, S., Martínez-Zarzoso, I. & Muris, C. The trade-off between income inequality and carbon dioxide emissions. *Ecol. Econ.* **142**, 249–256 (2017).
62. Beck, T., Levine, R. & Levkov, A. Big bad banks? The winners and losers from bank deregulation in the United States. *J. Finance* **65**, 1637–1667 (2010).
63. Goodman-Bacon, A. Difference-in-differences with variation in treatment timing. *J. Econom.* **225**, 254–277 (2021).
64. Jacobson, L. S., LaLonde, R. J. & Sullivan, D. G. Earnings losses of displaced workers. *Am. Econ. Rev.* **83**, 685–709 (1993).

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Competing interests

The authors declare no competing interests.

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