International Trade Reduces Emissions through Technology Transfer Led by Key Emitters

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Abstract

The Paris Agreement highlights technology transfer for climate mitigation, yet the disparities in technology ownership and diffusion slow global decarbonization. While trade agreements serve as institutional pathways for technological diffusion, the decarbonization potential of patent transfers remains unassessed. Here using data on carbon emissions, trade, and patents from 1995 to 2023, we evaluate how membership in trade agreements influences global carbon emission through technological accumulation. Our analyses show that while trade agreements have heterogeneous effects on emissions, they lead to a robust 2.8% reduction among key emitters. These reductions are mediated more by cross-border general technology transfers than by specific climate innovation. Scenario analyses further suggest that full technology transferring from key emitters to all their partners could reduce emissions by 587 Mt, equivalent to 1.6% of global emissions in 2021. These results demonstrate that incorporating technology transfer mechanisms into trade agreements is critical for maximizing their decarbonization potential.

Main text

Technological progress is widely recognized as essential to achieving global climate goals[1–3], yet uneven technology transfer and innovation are delaying collective progress toward global emission reductions[4,5]. International Energy Agency (IEA) estimates indicate that advances in clean energy technologies have already avoided around 2.6 Gt CO_2 annually over the past five years[6], underscoring the critical role of innovation in bending emission trajectories. Nevertheless, substantial regional disparities in technological ownership and transfer persist. About 85.7% of methane abatement inventions transfers-out or flow between 2017 and 2019 were confined to developed countries or directed toward China, South Korea and Brazil, leaving other developing countries less involved[7]. This concentration pattern extends to broader climate change mitigation technologies: the top ten inventing countries, largely overlapping with the key emitters responsible for 67.8% of global emissions[8], account for almost 90% of global inventions while most middle-income economies have not caught up[9]. In contrast, emerging and developing economies—where emissions are projected to continue growing through 2050—possess a small fraction of these technologies but face a growing responsibility for mitigation[10,11]. Transitioning toward more technology-intensive industries thus presents a critical opportunity for developing countries to achieve sustainable development[12,13]. Despite this urgent need for effective technology transfer to facilitate emission reduction, existing research has not yet quantified the global emission reduction potential of optimal technology transfer.

While technology transfers through multiple channels, including international trade, foreign direct investment, academic collaboration, and multinational enterprise activity[14–16], international trade provides a particularly powerful pathway. Trade directly integrates into global value chains, thus exerting a broader impact on the carbon emissions through the outsourcing of industries, causing potential carbon leakage[17–22], as evidenced by estimation that complete tariff elimination among Regional Comprehensive Economic Partnership (RCEP) members would increase the yearly global CO_2 emissions from fuel combustion by about 3.1%[22]. Conversely, unlike spontaneous technology diffusion through market mechanisms, trade agreements offer a critical institutional alternative. Deeper regional agreements demonstrate this potential by showing enhanced technology spillovers among member countries[23], embedding legally binding provisions on intellectual property, environmental standards, and technical cooperation that systematically guide technology transfer[24–26]. Nevertheless, how trade agreements shape technology-driven emission reductions, and the extent of their decarbonization potential through patent transfers, remains unexplored.

To fill these gaps, this study develops a multi-stage empirical framework to evaluate the impact of trade agreements on national carbon emissions and to assess the mediating role of technological change. Integrating country-year panel data from 1995 to 2023 for 16 major trade agreements, we estimate the total effect of trade agreements on emissions using a system generalized method of moments (System GMM) with external instruments, test for indirect effects via technology channel with causal mediation analysis, and explore heterogeneity through moderation and stratification. Throughout this analysis, we quantify technology using the cumulative stock of general patents and apply patent families filed in at least two jurisdictions to quantify high-quality climate inventions, and track address changes within these families to represent international technology flows. Finally, we conduct a scenario analysis to quantify potential emissions reductions under three distinct technology transfer regimes. Overall, the study highlights the nuanced role of trade agreements in promoting technology-driven emission reductions and underscores the promising role of technology transfers in global carbon reductions.

Trade agreements and heterogeneous carbon emission impacts

To examine how trade agreements influence carbon emissions through technological channels, we first analyzed emission trends and technological capacity across major trade agreements.

Analysis of emission trends from 1995 to 2023 reveals notable disparities across agreements (**Figure 1**). Countries within the Belt and Road Initiative (BRI) and RCEP experienced significant emissions growth of 127.55% and 165.52%, respectively, largely driven by China's rapid industrialization. In contrast, emissions from agreements such as United States-Mexico-Canada Agreement (USMCA) and the European Union (EU) showed stabilization. Key emitters, defined dynamically as those whose annual emissions exceed 1% of global total in any given year (**Figure 1b**), contribute more than half of the emissions within their respective agreements (Figure S1). Additionally, trade-embodied emissions and its share in total CO_2 emissions stabilized globally (Figure S2 & S3). Meanwhile, the global carbon emission intensity demonstrates a discernible downward trajectory (Figure S4), though per capita carbon emission trends reveal heterogeneous trends (Figure S5).

Technology accumulation serves as a vital indicator of emission reduction potential. The distribution of general patent stocks highlights overlap between countries with high emissions and those with extensive carbon reduction patent portfolios (**Figure 1c**), a pattern mirrored in climate and cross-border patents stock (Figures S6 & S7). The growth trend in cumulative climate (Figure S8) and general patents (Figure S9) within these agreements is like the growth in emissions. Furthermore, overlapping membership, such as Japan in both RCEP and Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP), suggest potential cross-agreement spillover effects.

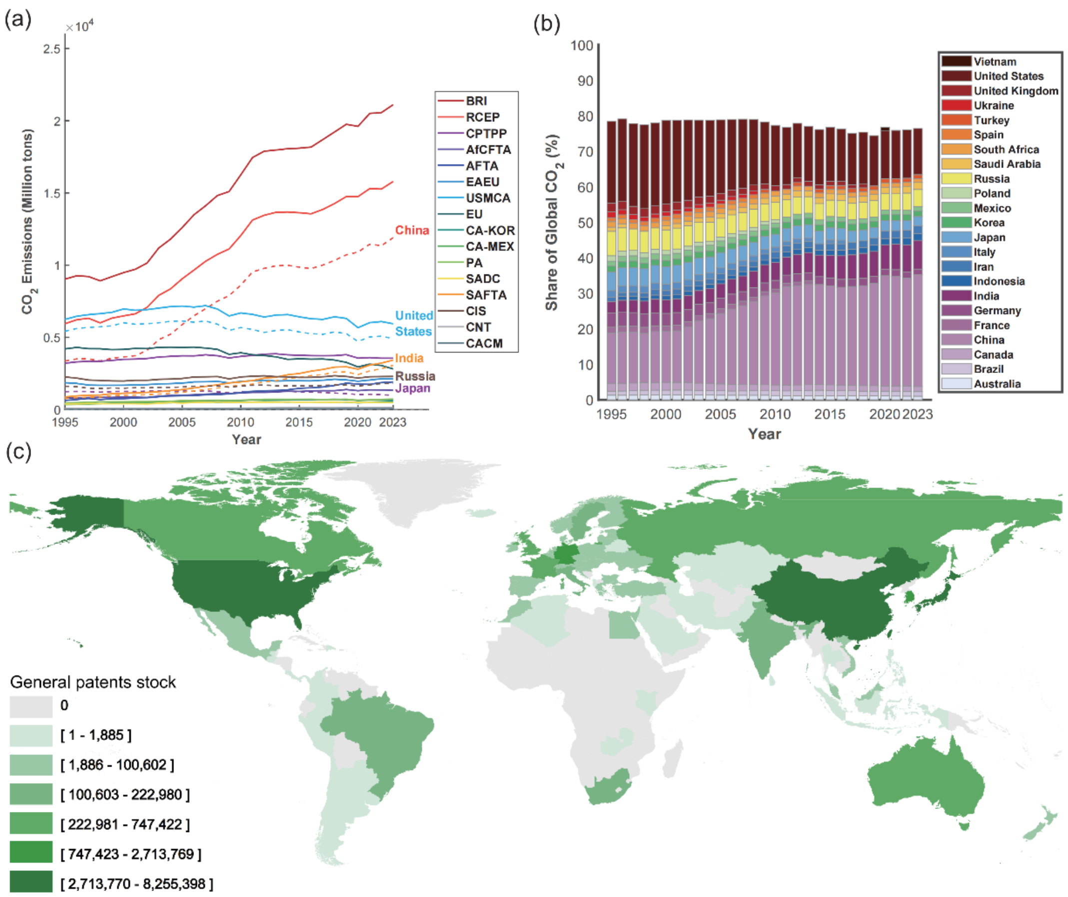

Fig. 1 | The temporal CO_2 emission of trade agreements and key countries. (**a**) Trends in emissions by trade agreements. The solid line represents total carbon emissions. The dotted line indicates the top five key countries (countries with ⩾1% of global carbon emissions in any year). Full agreement names and membership are provided in Table S1. (**b**) Temporal trends in the share of global carbon emissions of key countries. Only years in which a country's emissions exceeded 1% of the global total are shown. (**c**) Cumulative general patents stock as of 2023.

Beyond descriptive trends, we employed a System GMM with external instruments approach to assess the influence of trade agreements on emissions. The results reveal heterogeneity in the impact of different agreements on emissions (**Figures 2a-2d**). The primary results are based on a two-year lag of treatment variable to account for the typical delay between signing and implementation. While overall effects vary in direction and significance across agreements, participation in the EU is associated with a robust and statistically significant reduction in total emissions. Specifically, at a zero-year lag, EU membership reduces emissions by approximately 5.6% (β_1 = –0.056, SE = 0.023, $p < 0.05$). This reduction effect persists across multiple specifications (e.g., β_1 = –0.055, SE = 0.023, $p < 0.05$ at Lag

1). Similarly, the CPTPP agreement shows significant abatement effects ($\beta_1 = -0.359$, SE = 0.158, $p < 0.05$ at Lag 3). However, for many other agreements, the total effect remains statistically insignificant or shows divergent patterns across emission indicators (Tables S2–S8). A supplementary analysis at different lags (0, 1 and 3 years) indicates that impacts appear most pronounced within two years following treatment (Figures S10–S12).

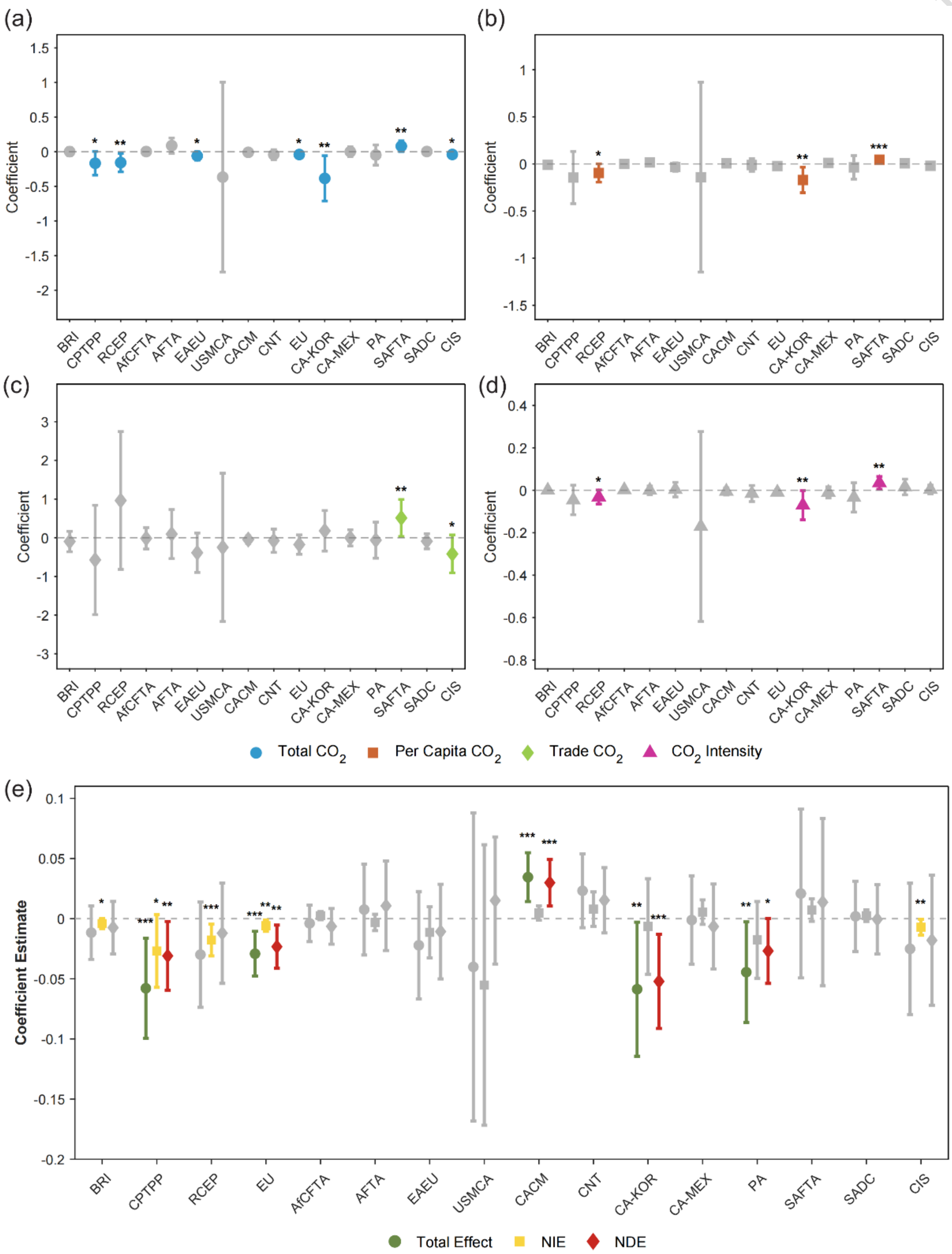

Fig. 2 | Effect of agreement and mediation effect of technology on emissions. (a-d) Treatment effects of agreements on different emission indicators. The results are based on a two-year lag of treatment variable. (**a**) Total CO_2 emissions (n = 4,176 country-year observations). (**b**) Per capita CO_2 (n = 4,176). (**c**) Trade-embodied CO_2 (n = 2,040). Net CO_2 emissions embedded in trade are the net of CO_2 which is imported or exported via traded goods with an economy. (**d**) CO_2 intensity (n = 4,173). (**e**) Mediation effect of cross-border general patent flows on total CO_2 emissions (n = 4,324). The mediation results presented are for the treatment variable with a one-year lag and the mediator with a one-year lag. Data are presented as regression coefficients (point estimates) with error bars indicating 95% confidence intervals (CIs) for the total effects of trade agreements (β_1), as well as the natural indirect effect (NIE), and natural direct effect (NDE) from the mediation model. Statistical significance was assessed using two-sided t-tests; ***p<0.01, **p<0.05, *p<0.1; non-significant results (p⩾0.1) shown in gray. No adjustments were made for multiple comparisons. Exact P-values and test statistics for all estimates presented here are available in the Source Data file.

Cross-border technology transfer partially drives reductions

Although the overall treatment effects are not uniformly robust across all agreements, the subsequent mediation analysis reveals that technology channels may operate as an important pathway. We next investigate whether trade agreements facilitate technological accumulation to achieve indirect emission reductions.

When testing climate technology flow as a mediating variable across the full set of agreements, only the EU exhibited a statistically significant indirect effect ($p < 0.05$) that remained robust across multiple lag combinations (Table S9). For CPTPP and RCEP, significant NIE was observed under specific configurations (i.e., zero-year treatment lag and one-year mediator lag), but these effects were not robust across alternative lag structures (Figures S13–S16). For other agreements and lag specifications, no significant NIE was detected. Similarly, general patent stock, general patent flow, and climate patent stock did not emerge as robust mediators across the full set of analyses. These findings suggest that promoting climate-specific technologies alone may not constitute a sufficiently potent pathway to alter overall emissions through trade agreements.

However, a more nuanced picture emerges when examining specific agreements cross-border general patent flows serve as a statistically significant and robust mediator of emission reductions. For the EU, this channel yields a significantly negative NIE (NIE = –0.006, SE = 0.002, $p < 0.05$) under one-year treatment lag and one-year mediator (**Figure 2e**), and this finding remains robust across multiple lag combinations (Table S10). Notably, RCEP exhibits an even larger indirect effect through this channel (NIE = –0.018, SE = 0.007, $p < 0.01$; Table S11). Significant negative NIEs are also observed for CPTPP, BRI, and Commonwealth of Independent States (CIS), with effects remaining robust across various lag specifications (Tables S12–S14). These results show that cross-border general patent flows emerge as a more robust mediator than climate-specific patents. Moreover, the technology-mediated decarbonization channel exists not only in the EU but also in other agreements.

Reduction effects depend on national absorptive capacity

While mediation analysis reals that climate technology and cross-border technology transfer are potential decarbonization pathways for advanced agreements like the EU, RCEP, CPTPP and BRI, this mechanism remains latent for many other agreements. To investigate this disparity, we conducted moderation and stratified analyses to examine whether pre-existing technological capacity conditions the emissions reduction effects.

The emission-reducing effects of trade agreements are also highly heterogeneous and conditional on countries' initial technological capabilities. In the pooled sample of all countries, the moderation results reveal a robust and significant negative interaction effect between agreement participation and technological stock. The interaction coefficient for cumulative general patents is consistently negative across all lag structures (e.g., β_4 = –0.006, SE = 0.002, $p < 0.05$ at Lag 2; Table S15), indicating that a strong innovation foundation significantly amplifies the emission-reducing effects of joining an agreement. Marginal effect analysis further confirms a distinct threshold effect: agreement participation triggers substantial and robust reductions only for countries above the median technological stock (i.e., 75th percentile), with no meaningful impact for those below it (i.e., 25th percentile). Similar significant moderating effects were found for cumulative climate patents stock (Table S16) and cross-border patent stocks (Table S17).

Stratified analyses further corroborate this capacity-dependent dynamic. When disaggregating by general technology stock (**Figure 3a** & Table S18), countries with higher technological accumulation exhibit significant emission reductions upon any agreement participation (β_5 = –0.024 to –0.028, $p < 0.01$), while those below it show no significant effect. A similar pattern emerges when stratifying by emitter status (**Figure 3b** & Table S19): key emitters exhibit significant 2.8% reductions (β_5 = –0.028 to –0.029, $p < 0.01$), a result we interpret as a proxy for their higher emissions and technological density. A higher cross-border patent flow also links to significant reductions (**Figure 3c** & Table S20). Furthermore, examining technology diffusion roles reveals that both net technology senders and receivers in the climate sector achieve emission reductions (Table S21), suggesting that active participation in the global technology innovation network is essential to realizing emissions reduction co-benefits of trade.

Technology-emissions elasticity estimation further confirms that technology exerts a significant decarbonization effect independent of trade institutional frameworks. Elasticity analysis reveals that cumulative patent stocks significantly reduce emissions with a three to five years lag (Table S22-S23). A 1% increase in total and cross-border patent stocks is associated with a 0.6–0.8% reduction in CO_2, with the maximum effect realized at Lag 5 for both total (φ = -0.007, SE = 0.003, $p < 0.05$) and cross-border patents (φ = –0.008, SE= 0.003 $p < 0.05$).

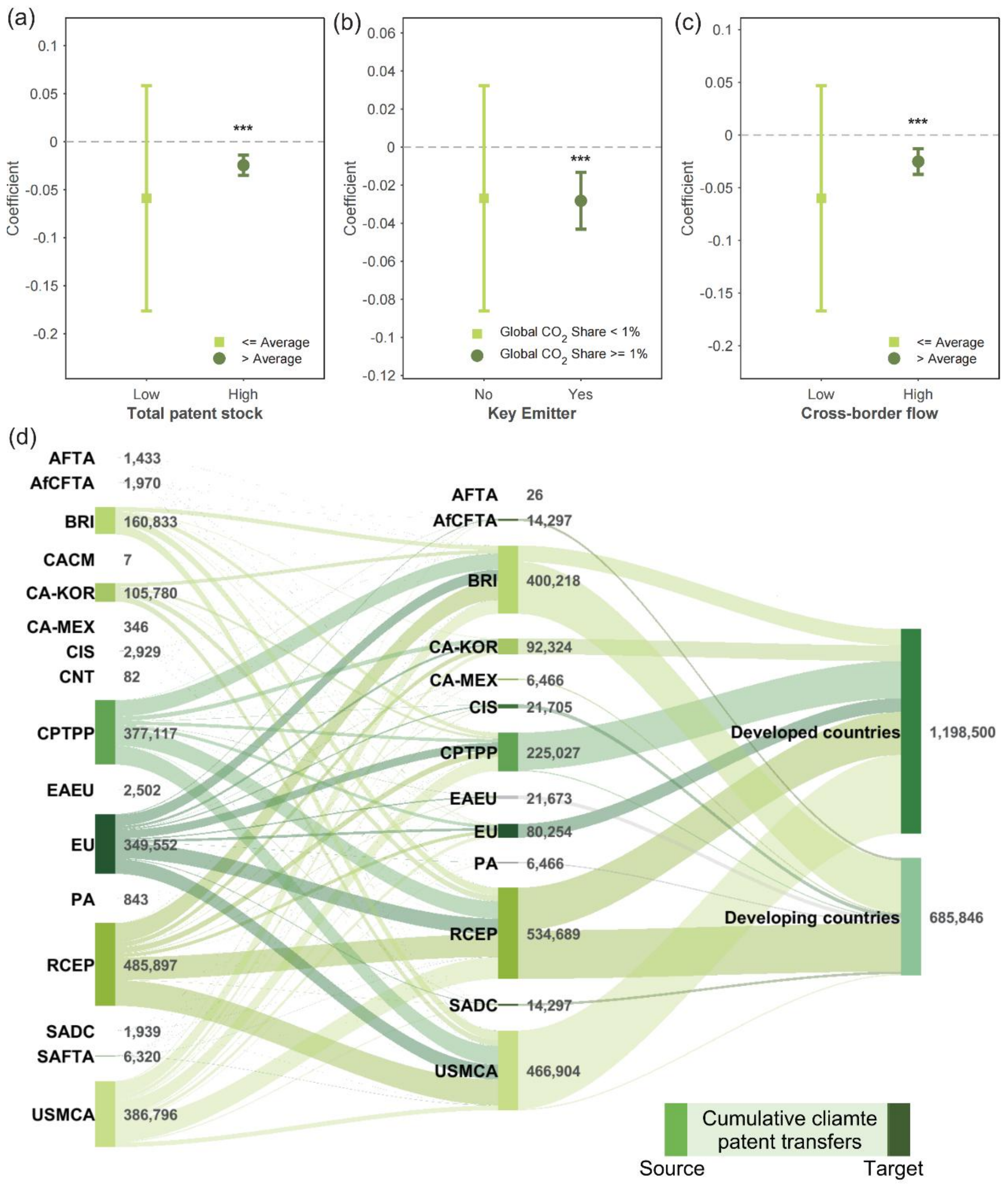

Fig. 3 | Heterogeneous effects and technology transfer patterns. (**a**) Stratified analysis by technology stock levels. Sample sizes: Low stock (n = 2,019 country-year observations), High stock (n = 1,518). (**b**) Stratified analysis by key emitter status. Sample sizes: Non-key emitters (n = 2,976), Key emitters (n = 561). (**c**) Stratified analysis by cross-border flow intensity of general patent. Sample sizes: Low flow (n = 2,324), High flow (n = 1,213). Figures **a** to **c** presented with a two-year lag for the treatment variable. Data are presented as regression coefficients (point estimates) with error bars indicating 95% confidence intervals. Statistical significance was assessed using two-sided t-tests; ***p<0.01, **p<0.05, *p<0.1. Exact P-values and test statistics for all estimates presented here are available in the Source Data file. No adjustments were made for multiple comparisons. (**d**) Flow of cumulative climate patent transfers among trade agreements as of 2021. The diagram shows the source of transfers (left), the recipient (middle), and the economic status of the recipient (right).

Imbalanced technology diffusion limits capacity building

The moderation analysis established that sufficient technological stock is a prerequisite for trade agreements to trigger emission reductions. While domestic innovation is a long-term driver of this stock, international technology transfer serves as a crucial accelerator.

Cumulative cross-border climate patent transfer flows as of 2021 reveal a significant imbalance (**Figure 3d**). Developed economies, which already possess extensive technological capabilities, were the recipients of 1,198,500 climate patents—constituting 63.6% of the total transfers. In contrast, developing countries, where green technologies are most urgently needed, have received only 685,846 patents. Regarding the current landscape of cumulative general patent transfers (Figure S20), the global flow is also dominated by the very agreements—EU, CPTPP, RCEP, and BRI—that our mediation analysis identified as capable of driving reductions through the technology channel. If the intensity of such international transfers could be further strengthened and balanced, it could unlock greater abatement potential.

Even though there are clear provisions within trade agreements aiming to promote technological transfer, intra-agreement technology flows remain constrained, indicating that technology diffusion remains dominated by cross-agreement flows. Direct tests on technology transfers confirm that no agreement promoted intra-agreement climate patent transfers. The limited evidence of direct intra-agreement transfers may be attributable to the private and strategic nature of patent licensing, which is often negotiated bilaterally and may be reported in public data. As such, these findings are interpreted as reflecting the broader role of trade agreements in fostering an innovative environment, rather than their direct effect on specific licensing transactions.

Leader-driven diffusion holds untapped reduction potential

Finally, a series of scenario analyses was conducted to explore the emission reduction potential of technological progress and diffusion within the framework of trade agreements. The 2021 total emissions for each country served as the baseline.

Three scenarios were defined to reflect varied degrees of technological progress and transfer. Scenario 1 ("Idealistic Baseline") assumes all countries achieve a uniform 10% improvement in patent stock. Scenario 2 ("Club-style Convergence") simulates technology diffusion among key emitters within each agreement. Scenario 3 ("Leader-Driven Diffusion") assumes each key emitter transfers its improved technology stock to all partners across its trade networks (see Table S24 for key emitters included in scenario analysis).

Results indicate distinct variation in potential emission reductions across agreements. In terms of percentage reduction (**Figure 4a**), the range of average emission reductions across the three scenarios is –7.9% to –0.1%, with the AFTA exhibiting high relative changes. As for absolute emission reduction potential (**Figure 4b**), agreements with large economic scale (BRI, CPTPP, RCEP) naturally show substantial reduction capacity across all scenarios due to their higher baseline emissions.

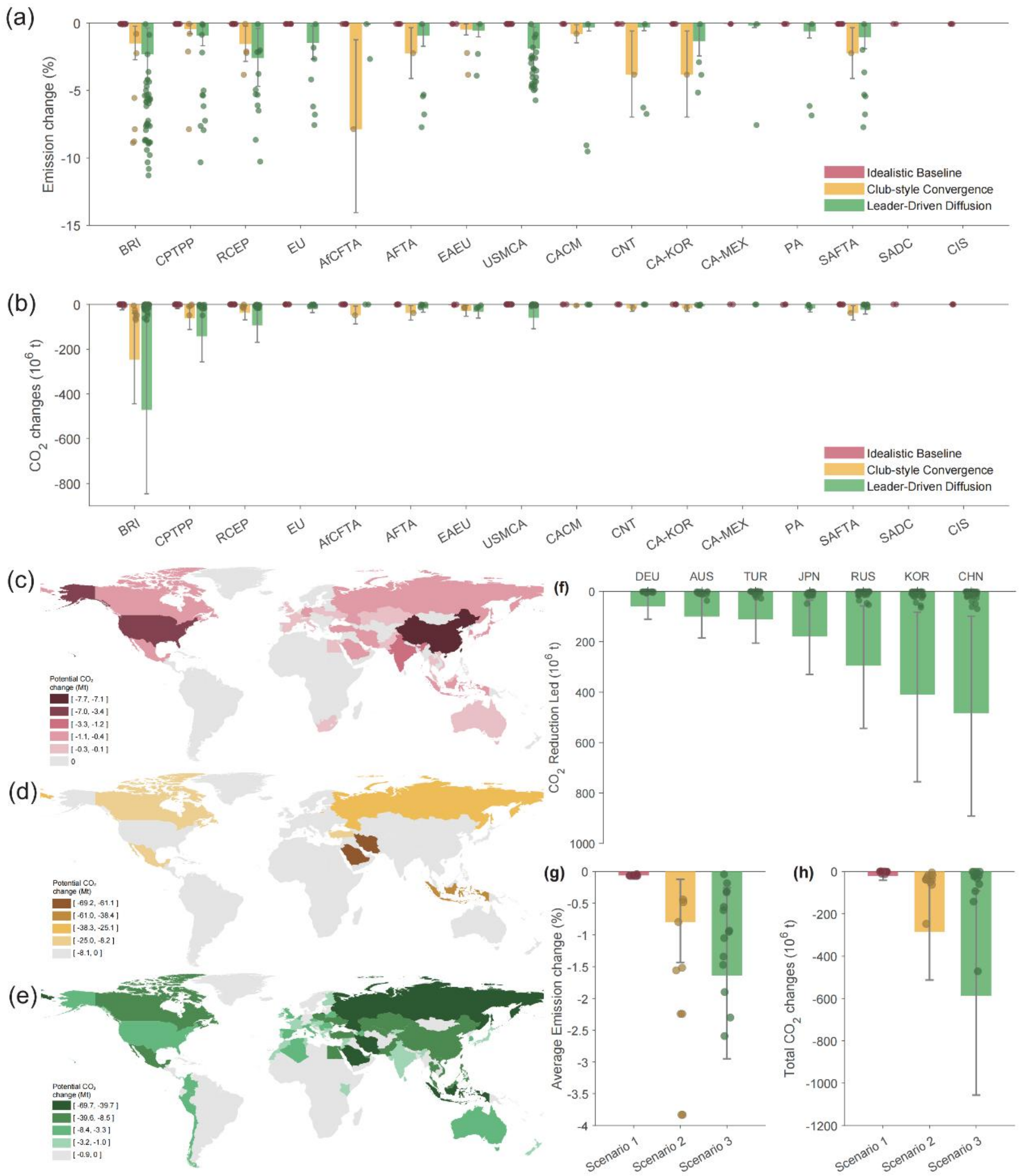

Fig. 4 | Potential carbon reductions under three technology scenarios. (**a**) Percentage of emission reductions per agreement. Bars represent weighted average reductions across member countries (weighted by baseline emissions; measure of center). Individual data points represent country-level percentage reductions; Sample sizes vary by agreement (n, number of countries with non-zero values; see Supplementary Table S25 for details). (**b**) Absolute amount of emission reductions per agreement. Bars represent the sum of country-level reductions. Individual data points represent country-level absolute reductions; Sample sizes as in figure a. (**c-e**) Country-level reductions under Scenario 1 (Idealistic Baseline), Scenario 2 (Club-style Convergence), and Scenario 3 (Leader-Driven Diffusion), with darker shades indicating greater abatement. Gray indicates that data are not available or that the emission reductions are zero. (**f**) Ranking of the key countries' total leadership impact in scenario 3. Bars represent the sum of emission reductions across affected countries (measure of center for aggregated data). Only key countries with emission reduction potential led greater than 50 Mt are shown. Individual data points represent contributions from each affected country. Country codes follow ISO 3166-1 alpha-3 standard.

Sample sizes (n, number of affected countries): DEU (n = 27), AUS (n = 13), TUR (n = 28), JPN (n = 17), RUS (n = 38), KOR (n = 43), CHN (n = 43). (**g-h**) Comparison of the three scenarios (n_{S1} = 16 trade agreements, n_{S2} = 10, n_{S3} = 14). Individual data points represent agreement-level values. Bars show weighted averages (figure **g**) or totals (figure **h**). For scenarios 2 and 3, overlapping memberships may introduce double counting; In such cases, the highest reductions estimate is used. Error bars indicate the 95% confidence interval. Detailed country-level data are provided in Supplementary Table S26.

The country-level analysis in Scenario 3 (**Figure 4f**) identifies China, Korea and Russia as having the highest leadership-driven reduction potentials (483 Mt, 409 Mt, and 295 Mt, respectively). As major emitters and innovation leaders engage in multiple trade agreements, these countries are uniquely positioned to drive substantial regional and global decarbonization through strategic technology transfers.

The comparison of the scenarios reveals distinct patterns in overall reduction potential (**Figures 4g** & **4h**). Scenario 1 achieves a modest global reduction of only 22 Mt (95% CI: [3, 42]). Scenario 2 could reduce emissions by 286 Mt (95% CI: [45, 513]; approximately 0.8% of 2021 global emissions), suggesting that internal technology transfers confined to major emitters have limited effectiveness. In contrast, Scenario 3 offers the highest potential, with reductions reaching 587 Mt (95% CI: [92, 1,056]; approximately 1.6% of 2021 global emissions). However, the spatial distribution of emission reductions varies (**Figures 4c-4e** & Table S26), underscoring that realizing this potential requires moving beyond the facilitation of goods trade to actively promoting technology transfer, thereby building the necessary absorptive capacity in developing member countries.

Discussion and policy implications

This study advances current knowledge by providing the first quantification of the emission reduction potential of technology transfer within trade agreements. While trade is known to affect the environment through scale, composition, and technique effects[27], our analysis further indicates that the technique effect on emissions reduction is primarily driven by the cross-border diffusion of general technological capacity, rather than the promotion of specific climate innovations. This implies that general industrial upgrading serves as a prerequisite for environmental efficiency, enhancing the absorptive capacity necessary to assimilate cleaner production methods[28]. The contrast between the EU (where both climate and general channels work) and other agreements highlights that while general diffusion provides a baseline reduction, while specialized climate technology represents the next frontier of policy integration.

The technology-mediated effect unfolds temporally in distinct phases: initial technological accumulation requires approximately 0 to 2 years, followed by an additional 0 to 2 years needed for this new technology to translate into a measurable reduction in carbon emissions. It is crucial to recognize that this impact represents only the early returns, and the full benefits are realized over a much more extended period as they depend on successful commercialization, widespread adoption, and the gradual replacement of older capital stock[14,29,30]. Spatially, this mediation effect is concentrated in deeply integrated frameworks with meaningful absorptive capacity like the EU, RCEP, CPTPP, and BRI (Table S27), leaving less integrated agreements with insufficient diffusion density to trigger economy-wide decarbonization.

The climate benefits of trade agreements are conditional. While complementary provisions — such as provisions on technical barriers to trade[31], mandatory environmental impact assessments[32], non-regression clauses[33], and the phased removal of fossil fuel subsidies[34] — are vital institutional framework, their effectiveness is often constrained by the absorptive capacity and development priorities[25,28,35]. Our moderation results confirm that the emission-reducing effects are significantly amplified by a country's pre-existing technological stock with stratified analysis showing that key emitters and active participants in the climate technology network drive the observed reductions. Sufficient domestic absorptive capacity is crucial for integrating externally sourced technologies[36,37]. Thus, structural imbalances in technology diffusion not only limit current reductions but actively restrict the accumulation of the very absorptive capacity needed to unlock future benefits.

Scenario analyses quantify the profound opportunity cost of this imbalance. Market-driven "North-North" circulation yields limited gains (Scenario 2), whereas a "Leader-Driven Diffusion" pattern unlocks a maximum reduction potential (Scenario 3). Although idealized, this underscores that unlocking trade's full climate potential hinges on the dual role it plays for these leading nations. On the one hand, trade acts as a catalyst for innovation, creating both the competitive pressure that force surviving firms to accelerate technological upgrading to defend their market share[38,39]. On the other hand, trade can be a pathway for dissemination. The potential for the global benefits of this induced innovation to be realized is contingent upon the willingness of technology leaders to proactively disseminate advancements, in alignment with the cooperative framework for technology transfer delineated in Article 10 of the Paris Agreement[40].

While technology transfer could enhance climate benefits, implementation confronts fundamental trade-offs. For technology leaders, mandatory transfer risk eroding the competitive advantages and decelerating the aggregate pace of global low-carbon innovation. Simultaneously, recipient nations lacking absorptive capacity face dependency traps and prohibitive transaction costs under rigid intellectual property regimes[41,42]. To navigate these barriers, policy frameworks must be designed based on the observed heterogeneity.

First, trade agreements should adopt reciprocal innovation clauses that grant these technology hubs preferential market access in exchange for verified technology dissemination, balancing global diffusion with the innovation rents required to sustain research and development (R&D) incentives.

Second, simple liberalization is insufficient for developing nations. Instead, Aid-for-Trade funds must be explicitly linked to human capital and R&D infrastructure to help recipients cross this threshold and avoid industrial lock-in.

Finally, policy must extend beyond green-only provisions to remove barriers on foundational industrial technologies. Moreover, intellectual property regimes under the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) must accommodate climate needs through flexibility mechanisms that reduce transaction costs without undermining the incentive to innovate[43,44].

Several limitations and sources of uncertainty are acknowledged. First, patents reflect the legal potential for innovation but may overlook informal knowledge spillovers, suggesting our technological effect estimates are conservative. Sensitivity analyses with alternative indicators—such as the Global Innovation Index (GII), R&D expenditure, Total Factor Productivity (TFP), Foreign Direct Investment (FDI), and scientific publications—failed to exhibit significant mediation (Tables S28-S55). This divergence suggests trade agreements primarily catalyze proprietary, commercial technology, though null results may also reflect limited temporal coverage or data gaps in the Global South. Second, while our analysis isolates the effect of trade agreements on innovation, it is acknowledged that even in the absence of trade agreements, climate mitigation technologies can be transferred directly through spontaneous market mechanisms like foreign direct investment and licensing[45,46]. Third, our analysis of 16 plurilateral agreements during 1995–2023 may not generalize to bilateral arrangements or sector-specific agreements. Newer agreements (e.g., RCEP, CPTPP) have limited post-implementation observation, and technology-emission dynamics unfold over decades. Finally, insufficient patent coverage for low-income countries and estimation of average treatment effect may not fully capture the substantial heterogeneity across member countries.

Collectively, these limitations imply that our findings represent a conservative baseline, and the true emission reduction potential of technology transfer through trade agreements is likely to exceed our estimates. Future research should prioritize the use of firm-level data to investigate how intellectual property provisions influence innovation decisions and explore diversified, sector-specific technological transition pathways as granular global data becomes available, providing a more comprehensive understanding of how trade can be leveraged for a just and effective global climate transition.

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Author contributions

J.W., P.W. and L.H. designed the study. J.W. wrote the codes, led the analyses and visualization. S.-C.H., P.H., Y.W. and Y.S. contributed to framing the manuscript. J.W., P.W. and L.H. drafted the manuscript. J.W., P.W., S.-C.H., P.H., Y.W., F.R., Y.W., W.C., J.B., L.H. and Y.S. contributed to the writing, editing, and improving of the paper. L.H. and P.W. supervised and coordinated the overall research.

Competing interests

The authors declare no competing interests.

Figure Legends/Captions (for main text figures)

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Fig. 4 | Potential carbon reductions under three technology scenarios. (**a**) Percentage of emission reductions per agreement. Bars represent weighted average reductions across member countries (weighted by baseline emissions; measure of center). Individual data points represent country-level percentage reductions; Sample sizes vary by agreement (n, number of countries with non-zero values; see Supplementary Table S25 for details). (**b**) Absolute amount of emission reductions per agreement. Bars represent the sum of country-level reductions. Individual data points represent country-level absolute reductions; Sample sizes as in figure a. (**c-e**) Country-level reductions under Scenario 1 (Idealistic Baseline), Scenario 2 (Club-style Convergence), and Scenario 3 (Leader-Driven Diffusion), with darker shades indicating greater abatement. Gray indicates that data are not available or that the emission reductions are zero. (**f**) Ranking of the key countries' total leadership impact in scenario 3. Bars represent the sum of emission reductions across affected countries (measure of center for aggregated data). Only key countries with emission reduction potential led greater than 50 Mt are shown. Individual data points represent contributions from each affected country. Country codes follow ISO 3166-1 alpha-3 standard. Sample sizes (n, number of affected countries): DEU (n = 27), AUS (n = 13), TUR (n = 28), JPN (n = 17), RUS (n = 38), KOR (n = 43), CHN (n = 43). (**g-h**) Comparison of the three scenarios (n_{S1} = 16 trade agreements, n_{S2} = 10, n_{S3} = 14). Individual data points represent agreement-level values. Bars show weighted averages (figure **g**) or totals (figure **h**). For scenarios 2 and 3, overlapping memberships may introduce double counting; In such cases, the highest reductions estimate is used. Error bars indicate the 95% confidence interval. Detailed country-level data are provided in Supplementary Table S26.

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Methods

This study develops a multi-stage empirical framework to evaluate the impact of trade agreements on national carbon emissions and to assess the mediating role of technological change. Integrating country-year panel data from 1995 to 2023 for 16 major trade agreements, sourced from Deep Trade Agreements (DTAs) database, United Nations Commodity Trade (UN Comtrade), and IncoPat patent records, our framework proceeds in four steps: (i) estimating the total effect of trade agreements on emissions using a system generalized method of moments estimator instrumented by a Bartik-style shift-share design; (ii) testing for indirect effects via technology channel with causal mediation analysis; (iii) exploring heterogeneity through moderation and stratification; and (iv) directly quantifying the technology-emissions elasticity to validate the mechanism. Throughout this analysis, we quantify technology using the cumulative stock of general patents and apply patent families filed in at least two jurisdictions to quantify high-quality climate inventions, and track address changes within these families to represent international technology flows. Finally, we conduct a scenario analysis to quantify potential emissions reductions under three distinct technology transfer regimes: an "Idealistic Baseline" of uniform domestic improvement, a "Club-style Convergence" among key emitters, and a "Leader-Driven Diffusion" model where technology leaders disseminate innovations through their trade networks.

Data for evaluating the emission reduction effect and data processing

This study only selected 16 agreements spanning from 1995 to 2023 among all records to conduct the formal analyses, to ensure all these are in force and plurilateral agreements. There are four types of data we use: agreements data, patent transfer flows, terrestrial CO_2 emissions, and bilateral trade flows data.

Data for Trade agreements. Trade agreements data were sourced from the DTAs database (https://datatopics.worldbank.org/dta/table.html). For this study, we restricted our scope to 16 plurilateral major agreements spanning from 1995 to 2023 to ensure the analysis focused on high-impact, multi-country agreements currently in force. For each agreement, the database covers the stated objectives and substantive commitments, as well as aspects relating to transparency, procedures, and enforcement. From this we obtained the current signatories, date of signature, that each agreement contains. Specially, we also took the BRI into account as an emerging type of agreement. Detailed descriptions of the agreements involved are listed in the Supplementary Table S1.

Emission data. Annually carbon emission data of each country was obtained from OWID (https://ourworldindata.org/co2-emissions). OWID provides detailed and long-term datasets on CO_2 emissions, including both production-based and consumption-based metrics. The dataset includes annual CO_2 emissions from fossil fuels, cement production, and land-use changes, extending back to 1750 for some regions. For this study, we focused on the period from 1990 to 2023, taking advantage of the dataset's granularity to analyze emissions trends across different trade agreements and regions. For control variables with incomplete temporal coverage (energy structure from WDI, extending only to

2021), we employed trend extrapolation: values for 2022–2023 were imputed as $\hat{X}_t = X_{t-1} \times (Proxy_t \,/\, Proxy_{t-1})$, where $Proxy$ is the corresponding OWID variable with complete coverage.

Patent data and processing procedure. The patent data utilized in this study came from the IncoPat database (https://www.incopat.com/). To ensure data quality, we filtered for granted invention patents that belong to patent families filed in at least two jurisdictions. This approach mitigates the poor international comparability and wide-ranging quality issues which often associated with single-country filings or large volumes of low-value patents[7]. The included dataset encompasses 32,518,589 granted patents from 1985 to 2024 (see Table S56 for patent retrieval strategy). Using the Cooperative Patent Classification (CPC) system, we further identified climate-related patents under the Y02 categories (technologies or applications for mitigation or adaptation against climate change), which includes subcategories Y02A through Y02W covering climate change mitigation technologies across energy production, buildings, transportation, industrial production, carbon capture, and smart grids.

Each record was assigned to specific countries and years based on the applicant's nationality and the application date. These patent records are then aggregated to track cumulative or annual innovation activities, while cross-border changes in patent family addresses are used descriptively to capture patent transfer flows.

First, the cumulative count of high-quality climate patents was calculated for each country and year reflects its accumulated technological capacity. We constructed three distinct technology stock variables: (1) total patent stock (cumulative count of all CPC-classified patents), (2) cross-border patent stock (cumulative count of patents that have been transferred internationally), and (3) climate patent stock (cumulative count of Y02-classified climate patents). This differentiation allows us to distinguish between domestic innovation capacity and internationally acquired technology. Notably, this measure is based on individual patent records, not the count of families—although the patent family classification serves as the quality filter.

Second, to approximate international patent transfer, we trace address changes of applicants across filings within the same patent family over time. Specifically, following the existing literature and common practices[7,9], a transfer is recorded when a new applicant from a different country enters the family, and the earliest jurisdiction (typically the priority country) is marked as the source of the transfer and subsequent filings within the same family as the recipients. We interpret this as evidence of cross-border transfer or commercialization of proprietary technology. Transfers within the same country are excluded to focus exclusively on international flows. This yields 16,093,291 cross-border patent transfers in total, including 1,630,638 climate-specific transfers between 1985 and 2024. See Figure S21 for the flowchart of patent data processing.

While this method captures formal transfer behavior (i.e., patent assignments), we recognize it does not fully reflect informal knowledge spillovers or technology sharing (e.g., licensing)[16]. As such, we use "patent transfers" as a precise and measurable indicator of a formal channel for technology diffusion, employing it for descriptive flows among agreements and as a dependent variable to directly test the agreement's effect on this channel. In subsequent panel regressions, we use cumulative patent stocks to quantify how these agreements shape the broader technological environment linked to emission outcomes.

Although such patent transfers may also occur independently of trade agreements (e.g., through market-based licensing), we mapped these flows into corresponding trade agreements based on mutual membership status and time, enabling us to evaluate both intra- and inter-agreement patent transfers. In addition, transfers were also categorized by development status: countries classified as high-income were considered developed, while those categorized as low- and middle-income were treated as developing countries. We acknowledge that patent data primarily captures formal technology diffusion (e.g., assignment and commercialization) and may overlook informal knowledge spillovers. While we considered alternative metrics such as GII, R&D expenditure and TFP were considered (see Table S57) we retained patents as the primary metric due to their superior temporal coverage (1995–2023) and granularity (distinguishing climate-specific vs. general technologies). Those alternative indicators serve as the sensitivity analyses for mediation effect.

Trade data. Bilateral trade flows data were obtained from the UN Comtrade database (https://comtradeplus.un.org/). Based on the reporter and partner countries associated with each trade flow record, along with their respective trade agreements, we calculated annual import and export trade value indicators for each country within the scope of each trade agreement. These indicators were then integrated into the panel dataset to enable a more granular analysis of the impact of trade agreements on trade volumes. This methodological approach allows for a detailed examination of trade dynamics at both the national and agreement-specific levels.

The final panel includes data from 1995 to 2023 and covers 201 countries or dependent territories with valid emission and economic data. Of the countries in the study, 145 participated in at least one of the 16 selected trade agreements, 86 have valid data on the number of general patents granted and 85 have valid data on the number of patent transfers.

Empirical framework

This study adopts a multi-stage empirical framework to evaluate how trade agreements affect national carbon emissions, and to assess whether these effects are mediated through technological channel. A central methodological challenge in estimating the effects of trade agreements on emissions is the potential for endogeneity and dynamic feedback. Trade agreement participation is likely non-random, which means countries with specific economic characteristics, environmental priorities, or technological capacities may self-select into certain agreements. Moreover, emissions outcomes from previous periods may influence both current participation decisions and technological accumulation, creating dynamic feedback that can bias standard fixed effects estimators.

To address these concerns, we employ a system GMM estimator (implemented via xtabond2 in Stata) that offers several advantages: (1) it incorporates lagged dependent variables to model emissions dynamics explicitly; (2) it uses internal instruments (lagged levels and differences) to address endogeneity of predetermined and potentially endogenous variables; and (3) it allows incorporation of external instrumental variables to strengthen identification.

Rationale for Instrument Selection. A range of candidate instruments were assessed, incorporating gravity-based predictors, neighbor or partner diffusion measures, and political alignment indices, among others. Most of these instruments did not satisfy the relevance tests (first-stage $F < 10$) (see Table S58). In contrast to the effectiveness of gravity variables in bilateral Free Trade Agreements (FTAs), plurilateral agreements require instruments that capture geopolitical rather than purely economic drivers of participation.

Instrumental variables construction. To resolve the self-selection bias of the treatment variable, we construct interaction-based instrumental variables following the Bartik-style shift-share approach. For each agreement s, the instrument is defined as:

$$Z_{i,s,t} = Share_{i,s}^{pre} \times Shock_{s,t}$$

where $Share_{i,s}^{pre}$ is country i's pre-treatment exposure to agreement s, measured as the average trade share with agreement members during the pre-treatment period 1995–2000. The variable $Shock_{s,t}$ is a binary time-series indicator capturing exogenous geopolitical events that affect the relevance or intensity of agreement participation exogenously to domestic environmental policies (e.g. the 2017 US withdrawal from TPP; See Table S59 for shocks list). The validity of this instrument rests on the exclusion restriction that the interaction of pre-determined trade dependency with external shocks affects emissions only through effective agreement participation. The base-period dependency is measured before most agreements' environmental provisions took effect, mitigating concerns about reverse causality. The external shocks are driven by geopolitical events unrelated to individual countries' environmental policies. For all IV-GMM specifications, we conduct diagnostic tests (Arellano-Bond AR (2) for serial correlation, Hansen J-test for overidentifying restrictions) and focus on results only for specifications that pass both tests.

Estimating the overall effect of trade agreements. Our primary objective is to estimate the average treatment effect on the treated (ATT) of trade agreements on national carbon emissions. The baseline specification is:

$$\ln(Y_{i,t}) = \alpha + \rho \ln(Y_{i,t-1}) + \beta_1 Treated_{i,t-k,s} + X_{i,t}^{'}\delta + \mu_i + \varepsilon_{i,t} \quad (1)$$

In this equation, $\ln(Y_{i,t})$ is the natural logarithm of the carbon emissions outcome for country i in year t. We measure this outcome in several ways based on the data from OWID: total territorial CO_2 emission, which do not account for emissions embedded in traded goods; total territorial CO_2 per capita; net trade embodied CO_2 emission (the net balance of CO_2 imported and exported in traded goods); CO_2

emission intensity, defined as total carbon emission per unit of GDP. α is the constant term. The term $\rho \ln(Y_{i,t-1})$ is the lagged dependent variable that captures emission dynamics and persistence. $Treated_{i,t-k,s}$ is a binary indicator that equals 1 if country i is an active member of a selected agreement s in the year t based on the signing date, and 0 otherwise. Here, $k \in \{0,1,2,3\}$ denotes the lag order to account for implementation delays. Its coefficient, β_1, captures average effect of agreement participation on emissions. Country fixed effects (μ_i) absorb time-invariant heterogeneity. The vector $X_{i,t}$ contains a vector of time-varying control variables to account for potential confounding factors that influence emissions: log GDP per capita; trade openness (the sum of exports and imports as share of GDP), industry structure (industry value added as share of GDP); energy structure (the share of renewables in electricity generation) to account for economic scale, structure, and shifts in the energy system. Equation (1) is estimated using system GMM with the shift-share instruments described above serving as external instruments for the treatment variable.

Causal Mediation Analysis. We further conduct a causal mediation analysis to test general technology and climate technology mediate the relationship between trade agreements and emissions based on the established casual mediation framework[47]. This analysis decomposes the total effect (β_1) into the natural indirect effect operating through the mediator, and the natural direct effect. The core model consists of two equations for the mediator ($M_{i,t}$) and outcome ($Y_{i,t}$):

$$M_{i,t} = \rho_M M_{i,t-l} + \theta Treated_{i,t-k} + X'_{i,t}\delta + \mu_i + \varepsilon_{i,t} \quad (2)$$

$$\ln(Y_{i,t}) = \rho_Y \ln(Y_{i,t-1}) + \tau' Treated_{i,t-k} + \varphi M_{i,t-l} + X'_{i,t}\delta + \alpha_i + \varepsilon_{i,t} \quad (3)$$

where $M_{i,t}$ is the mediator variables in country i at year t. Given the multifaceted nature of technological change, we test multiple mediator variables including cumulative general patent stock, general patent flows, cumulative climate patent stock, climate patent stock, and annual cross-border patent flows. The coefficient θ captures the impact of agreement participation on technological accumulation (Path A). In the outcome equation, τ' represents the NDE—the effect of agreements on emissions not operating through technology, while φ captures the effect of the technology mediator on emissions (Path B). The NIE is quantified by the product of coefficients ($\theta \times \varphi$), denotes the full percentage change in CO_2 emissions attributable to an agreement's influence on technology.

Furthermore, to account for the time it takes for policy to influence innovation and for innovation to impact emissions, we test a range of dynamic lag structures. Specifically, we estimate the mediation effects for various lag combinations of the treatment ($Treated_{i,t-k}$) and the mediator ($M_{i,t-l}$), where lags k and l range from 0 to 3 years. By systematically testing all combinations of treatment and mediator lags, we can identify the time required for an agreement to stimulate technological accumulation and the subsequent time for that technology to translate into a measurable emissions reduction.

Moderation and Heterogeneity Analysis. To understand why the environmental effects of trade agreements are heterogeneous, we conducted a pooled analysis across all agreements to test whether the treatment effect is systematically conditional on general country characteristics.

The primary method for the pooled analysis is to introduce interaction terms into our baseline model. We use the full sample of countries and define the treatment variable, $Any\_Treated_{i,t}$, as a binary indicator equal to 1 if a country is an active member of any of the agreements in year t. The moderation model is specified as:

$$\ln(Y_{i,t}) = \rho \ln(Y_{i,t-1}) + \beta_2 Any\_Treated_{i,t} + \beta_3 Mod_{i,t} + \beta_4 (Any\_Treated_{i,t} \times Mod_{i,t}) + X_{i,t}^{'} \delta + \alpha_i + \varepsilon_{i,t} \quad (4)$$

where $Mod_{i,t}$ is the moderator variable includes continuous measures such as cumulative patent stocks (general, climate and cross border). The coefficient of interest, β_4, captures how the moderator alters the treatment effect.

As a complementary approach, we conduct stratified regressions by re-estimating our baseline specification (Equation 1) on different subgroups.

$$\ln(Y_{i,t}) = \rho \ln(Y_{i,t-1}) + \beta_5 Any\_Treated_{i,t} + X_{i,t}^{'}\delta + \alpha_i + \varepsilon_{i,t} \quad (5)$$

We stratify the sample along several theoretically relevant dimensions: (i) "key emitters" (countries exceeding 1% of global annual emissions) versus others; (ii) general patent stock and cross-border flow (above vs. below average); (iii) technology orientation based on the ratio of outgoing to incoming climate patent transfers, distinguishing technology "net senders" from "net receivers." The entire stratification is predicated on mean split within the $Any_{Treated} = 1$ sample.

Technology-Emissions Elasticity Estimation. To directly quantify the independent effect of technology accumulation on emissions, we further estimate the technology-emissions elasticity without conditioning on trade agreement participation. The specification is:

$$\ln(Y_{i,t}) = \rho \ln(Y_{i,t-1}) + \varphi\, Tech_{i,t-l} + X_{i,t}^{'}\delta + \alpha_i + \lambda_t + \varepsilon_{i,t} \quad (6)$$

where $Tech_{i,t-l}$ represents various technology stock indicators with lag $l \in \{0,1,\ldots,5\}$ years. We test multiple technological measures including annual climate patent flows, cumulative climate patent stock, annual total patent flows, cumulative total patent stock, annual cross-border patent flows, and cumulative cross-border patent stock. The coefficient φ is interpreted as the percentage change in carbon emissions associated with a one-unit increase in log technology stock.

See Table S60 for a comprehensive variable definition table for all key terms and variables used in the analysis.

Uncertainty evaluation. We implement a comprehensive framework to assess uncertainty across statistical estimation, model specification, and scenario projections. Statistical uncertainty is quantified via standard errors and 95% CIs for all coefficient estimates. To address model specification uncertainty, we conduct extensive sensitivity analyses using alternative dynamic lag structures (0–3 years for treatment; 0–2 years for mediators) and various technology indicators (general vs. climate patents; stocks vs. flows), as detailed in Supplementary Tables S27–S54. Finally, we propagate statistical uncertainty into the scenario analysis by using the upper and lower bounds of the 95% CIs of the elasticity estimates to construct error bars for projected emission reductions.

Scenario analysis to quantify CO_2 reduction potential of technical advancement and transfers

To explore the impact of technological progress on emission reduction, we developed a scenario analysis framework. This framework leverages the key parameters estimated from the main empirical models to project emissions reductions under three distinct, policy-relevant scenarios. Due to limitations in the availability of general patent data, we used 2021 as the baseline for scenario modeling to calculate the abatement potential under different scenarios.

Rather than using agreement-specific NIE coefficients, we adopt a unified approach using technology-emissions elasticity coefficient, φ, estimated from the independent technology effect model (Equation 6) using the full sample. This provides a consistent and statistically robust basis for cross-agreement scenario comparisons. Specifically, we employ two elasticity coefficients: Scenario 1 Uses the coefficient for total cumulative patent stock (φ_{total}), representing the reduction of emissions from domestic technological accumulation. Scenarios 2 & 3 uses the coefficient for cumulative cross-border patent stock (φ_{cross}), representing the emissions reduction specifically from internationally transferred technology. For this analysis, we assume that the technology-emissions elasticity (φ) is uniform for all member countries i within a given agreement s. To maximize the estimated emission reduction potential, we choose the coefficient from the lag specification that yields the most negative statistically significant effect while passing all diagnostic tests.

The projected change in CO_2 emissions ($\Delta CO2_i$) for country i in year 2021 under a given scenario is calculated using the following core formula:

$$\Delta CO2_i = CO2_{i,base} \times \left(e^{\varphi \cdot \Delta \ln(Tech_i)} - 1\right) \tag{7}$$

where $CO2_{i,base}$ is the baseline CO_2 emissions of country i in year 2021, and $\Delta \ln(Tech_i)$ is the counterfactual change in the log of its general patents stock under the assumptions of the specific scenario.

To quantify scenario uncertainty, we propagate the statistical error by calculating the upper (pessimistic) and lower (optimistic) bounds of projected reductions using the 95% confidence interval limits of the elasticity coefficient φ. These uncertainty bands are visualized as error bars in scenario comparison figures.

We then designed three scenarios to reflect varying degrees of technological advancement and diffusion:

Scenario 1: Idealistic Baseline. This scenario simulates an idealistic, broad-based improvement in efficiency with which technology translates into emissions reductions. We assume that all countries uniformly improve their patent stock by 10%, representing general advancements in clean energy and industrial efficiency without cross-border transfers.

$$Tech_{i,S1} = 1.1 \times Tech_{i,base} \tag{8}$$

$$\Delta \ln(Tech_{i,S1}) = \ln Tech_{i,S1} - \ln Tech_{i,base} = \ln 1.1 \approx 0.0953 \quad (9)$$

In this scenario, the change in emissions is therefore calculated as:

$$\Delta CO2_{i,S1} = CO2_{i,base} \times \left(e^{\varphi_{total} \cdot \Delta \ln(Tech_{i,S1})} - 1\right) \quad (10)$$

Scenario 2: Club-style Convergence. This scenario simulates optimal technology diffusion among key emitters within each agreement. We assume that all key emitters will improve their patent stock by 10% and subsequently converge to the highest technological level newly observed within their respective agreement. This reflects a dynamic consistent with today's uneven innovation landscape, where gains primarily circulate among major emitters.

$$Tech_{i,key,S2} = 1.1 \times Tech_{i,key,base} \quad (11)$$

Then, all key emitting countries reach the highest cumulative patent level observed within the agreement. For any non-leading key emitter i within agreement s, its technology stock increases from its enhanced baseline level, $Tech_{i,key,S2}$, to match that of the agreement's leader, L, denoted as $Tech_{L,key,S2}$. The corresponding change in the log of technology stock is:

$$\Delta \ln(Tech_{i,S2}) = \ln(Tech_{L,key,S2}) - \ln(Tech_{i,key,S2}) \quad (12)$$

The emissions reduction for each catching-up country is calculated by substituting $\Delta \ln(Tech_{i,S2})$ into the core framework (Equation 7). In this scenario, the change in emissions is therefore calculated as:

$$\Delta CO2_{i,S2} = CO2_{i,base} \times \left(e^{\varphi_{cross} \cdot \Delta \ln(Tech_{i,S2})} - 1\right) \quad (13)$$

Scenario 3: Leader-Driven Diffusion. This scenario quantifies the potential global impact of technology diffusion originating from individual, highly innovative nations ("technology leaders"). For each technology hub, identified as the key emitter with the highest cumulative patents across all agreements it participates in. We assume the leading country L enhances its technology by 10%, and the process for each leading country L is as follows:

$$Tech_{L,S3} = 1.1 \times Tech_{L,base} \quad (14)$$

Subsequently, the leader L is assumed to fully transfer its enhanced technology stock, $Tech_{L,S3}$, to all its partner countries j across all trade agreements in which L participates. For each recipient country j, its technology stock is raised to this new frontier, resulting in a change of

$$\Delta \ln(Tech_{j,S3}) = \ln(Tech_{L,S3}) - \ln(Tech_{j,base}) \quad (15)$$

In this scenario, the change in emissions of each recipient country j is therefore calculated as:

$$\Delta CO2_{j,S3} = CO2_{j,base} \times \left(e^{\varphi_{cross} \cdot \Delta \ln(Tech_{j,S3})} - 1\right) \quad (16)$$

For each leading country L, we further calculate its own emissions reduction from its 10% domestic advancement and sum it with the total emissions reductions achieved by all its partners receiving the technology transfer. This sum represents the total global mitigation potential driven by that single leader. We then rank all identified technology leaders by this total potential to prioritize which countries' leadership in technology diffusion could be most impactful.

Finally, we present bar charts comparing the three scenarios (in both percentage and absolute terms) with uncertainty bands reflecting the 95% confidence intervals of the underlying coefficients, and an overall comparison chart, along with a ranking of the top contributing key emitters across agreements.

Data availability

This study uses data from multiple sources. Country-level CO_2 emissions are obtained from Our World in Data (OWID, https://ourworldindata.org/co2-emissions); macroeconomic indicators such as GDP and population are from the World Bank's World Development Indicators (WDI, https://datacatalog.worldbank.org/search/dataset/0037712/World-Development-Indicators); and information on trade agreements is sourced from the World Bank's Deep Trade Agreements (DTA) database (https://datatopics.worldbank.org/dta/table.html). Bilateral trade flows are retrieved from the United Nations Commodity Trade (UN Comtrade) database (https://comtradeplus.un.org/), and Climate patent records are from IncoPat (https://www.incopat.com/). Due to license restrictions from the providers, the raw trade and patent data cannot be shared. To facilitate reproducibility, the full data processing and analysis codes are available at https://doi.org/10.24433/CO.1738407.v1. The data necessary to reproduce the main results are available via Figshare at https://doi.org/10.6084/m9.figshare.31295878[48]. Background political boundaries used in maps are from Runfola et al. (2020) geoBoundaries: A global database of political administrative boundaries. PLoS ONE 15(4): e0231866 (https://doi.org/10.1371/journal.pone.0231866) published under CC-BY Attribution 4.0 International license (https://creativecommons.org/licenses/by/4.0)[49].

Code availability

MATLAB R2022b was used for data processing and visualization. The analysis for impact of agreements and technology is conducted using Stata 18. All codes in this study are available at https://doi.org/10.24433/CO.1738407.v1[50].

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