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Geographical Sciences ARTICLE

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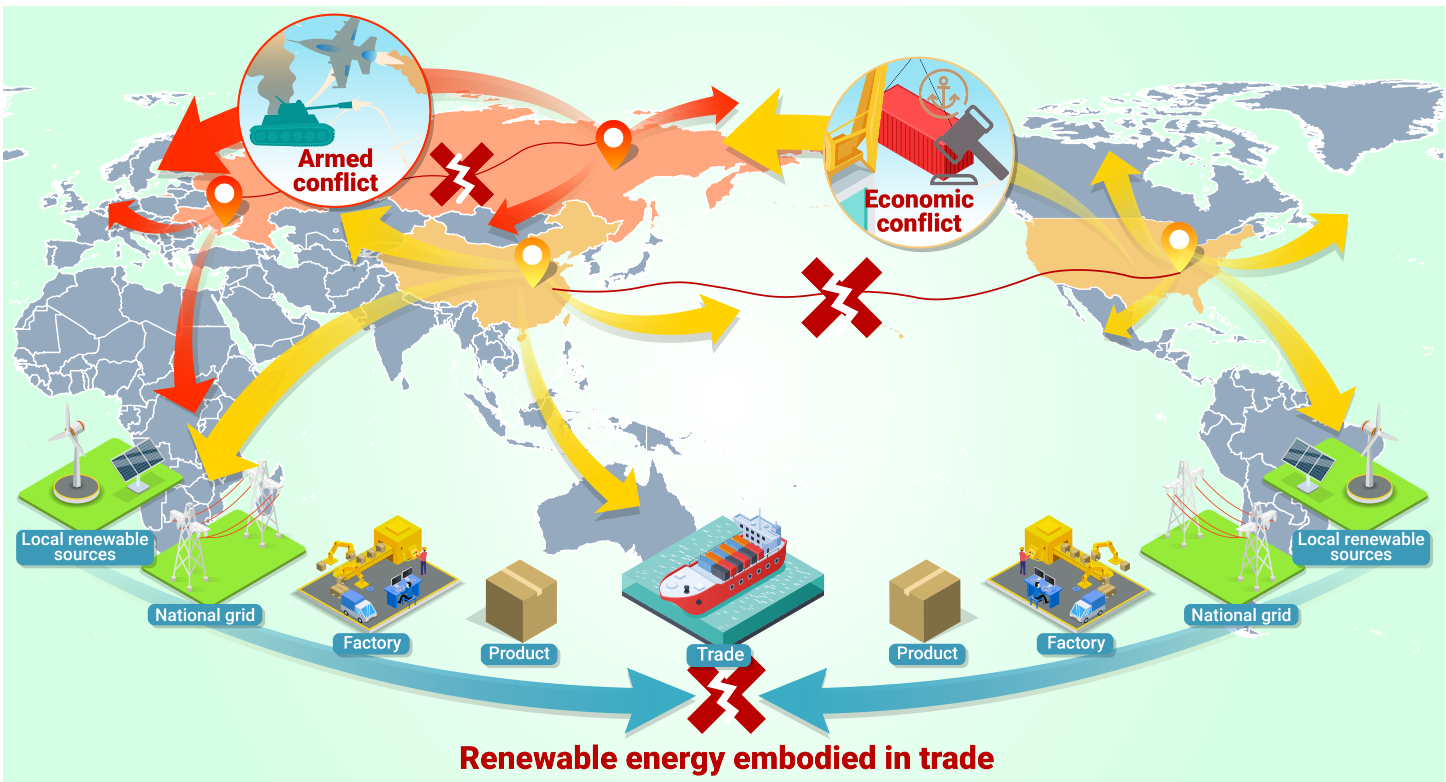
Received: November 4, 2025; Accepted: April 9, 2026; Published Online: April 17, 2026; https://doi.org/10.59717/j.xinn-geo.2026.100218

GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- We develop a Conflict-Supply Chain-Effect (CSE) model to capture the cascading pathways of trade shocks.
- First quantification of embodied renewable energy import losses under geopolitical conflict scenarios.
- Trade disruptions exert uneven direct and spillover effects on conflict and third-party nations.

Threats to energy transition embodied in global supply chains under extreme geopolitical scenarios

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Received: November 4, 2025; Accepted: April 9, 2026; Published Online: April 17, 2026; https://doi.org/10.59717/j.xinn-geo.2026.100218

Citation: Cheng Y., Yang Y., Poon J. P.H., et al. (2026). Threats to energy transition embodied in global supply chains under extreme geopolitical scenarios. *The Innovation Geoscience* **4**:100218.

Geopolitical conflicts may threaten energy transition embodied in global supply chains via disruptions to embodied renewable energy imports (EREM). Current studies predominantly focus on direct shocks to conventional energy trade, largely overlooking the vulnerabilities of EREM and failing to disentangle the cascading transmission pathways of these disruptions. Here, we develop a Conflict-Supply Chain-Effect (CSE) model to quantify EREM change for both conflict participants and third countries under two scenarios: an economic conflict (the China-US trade dispute) and an armed conflict (the Russia-Ukraine war). We find that the China-US dispute reduces global EREM by 4.1%, with the US facing a sharper loss (7.1 Mtoe) than China (1.5 Mtoe). In the Russia-Ukraine scenario, global EREM declines by 8%. Notably, losses from spillover effects are nearly double those from direct effects, causing substantial losses (3.8 Mtoe) even among non-conflict nations. Crucially, we demonstrate that import substitution strategies fail to significantly mitigate these losses; instead, they deepen the hidden dependencies between the US and China and the asymmetric reliance of Russia on sanctioning nations. Our findings underscore that the energy transition transcends environmental concerns to become a complex geopolitical issue and ensuring supply chain resilience is critical for a secure global energy future.

INTRODUCTION

The green transition of the global economy is not only related to local renewable energy production[1,2] but also associated with international trade. As a critical carrier of embodied energy,[3,4] global trade is undergoing a structural shift toward greener energy consumption,[5] making it an essential dimension of the global transition. From 2011 to 2020, renewable energy embodied in global trade surged by 72% while fossil fuel only increased by 2%.[6] This dynamic creates an important mechanism: through international trade, importers acquire not only goods but also the renewable energy embodied in their manufacturing processes, known as embodied renewable energy imports (EREM). In this context, global trade enables a transnational sharing of clean manufacturing and service benefits. This is particularly significant for less developed importers that lack both mature manufacturing capabilities and renewable energy development capacity. However, the stability of accessing this embodied renewable energy is contingent upon the resilience of global supply chains (GSCs), which are increasingly threatened by geopolitical tensions.

Current research on the nexus of geopolitics and energy transition has primarily focused on direct disruption mechanisms. Extensive studies have examined how conflicts physically damage renewable energy infrastructure,[7–9] impose trade barriers on low-carbon technologies like solar PVs,[10–13] and trigger energy price shocks that indirectly affect transition costs.[14,15] For instance, the 2022 Russia-Ukraine war caused a continental energy crisis in Europe with skyrocketing gas and electricity prices, while China-US trade frictions have been quantified to undermine carbon mitigation efforts by restricting solar trade.[10] While these studies provide critical insights into direct impacts, they predominantly treat energy transition disruptions as localized or bilateral phenomena, largely overlooking the cascading effects transmitted through complex GSCs.

To evaluate the cascading effects of conflicts, extensive research has been conducted using diverse analytical frameworks. For example, computable general equilibrium model has been used to assess the broader economic and GHG consequences of conflicts like the China-US trade dispute and the Russia-Ukraine war,[16–18] while others have applied complex network approaches to analyze global energy and food security risks.[19,20] Similarly, input-output model has been widely employed to estimate shocks to embodied energy or embodied carbon trade, considering scenarios of either trade cessation or specific supply chain adjustments.[21–24]

However, regardless of the modeling approach, these studies have primarily concentrated on assessing the aggregate magnitude of impacts. They rarely deconstruct the transmission pathways by distinguishing between direct effects (supply chains directly involving the trade linkages of conflict nations) and spillover effects (cascading to other relevant supply chains). Furthermore, regarding the scope of study, existing literature has heavily prioritized economic impacts and environmental burdens,[16-18,22-23] such as energy consumption, carbon emissions, land use change, and biodiversity loss. Consequently, the redistribution of environmental benefits, specifically EREM, remains largely unexamined. This omission is critical, as EREM constitutes a valuable clean energy asset for importing economies. Thus, its disruption signifies a direct loss of transition benefits, rather than a mere shift in environmental responsibility as typically analyzed in energy or carbon studies.

To bridge these gaps, we develop a Conflict-Supply Chain-Effect (CSE) model by integrating the latest renewable energy satellite data with global multi-regional input-output tables.[6,25] This framework captures how trade shocks translate into EREM fluctuations through different transmission pathways. We apply this model to two representative cases that embody distinct conflict typologies: (1) the China-US trade dispute, representing a systemic economic clash between global dominant manufacturing hubs; and (2) the Russia-Ukraine conflict, exemplifying an armed confrontation involving key resource exporters. These cases differing in both supply chain roles and conflict nature enable us to comprehensively examine how geopolitical tensions disrupt the energy transition embodied in global supply chains.

We simulate complete trade disruptions in both the China-US (CU) and Russia-Ukraine (RU) scenarios to examine extreme cases of geopolitical conflict and their global impacts. In these simulations, we assume that disrupted trade volumes are compensated by domestic substitution, a setting that mirrors the growing trend of supply chain reshoring in major economies. While these extreme scenarios represent upper-bound estimates, this ex-ante design enables robust assessment of maximum risk exposure and establishes early warning benchmarks for EREM vulnerabilities. Furthermore, we model import substitution scenarios to assess EREM vulnerabilities under more realistic trade diversion conditions. Ultimately, our study can provide critical insights for safeguarding the green transition and advancing SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) in a turbulent geopolitical era.

MATERIALS AND METHODS

Data

Our study uses the Eora26 MRIO tables (https://worldmrio.com/)[26,27] and the RE-FEA energy accounts (https://doi.org/10.5281/zenodo.15826919),[6,25]

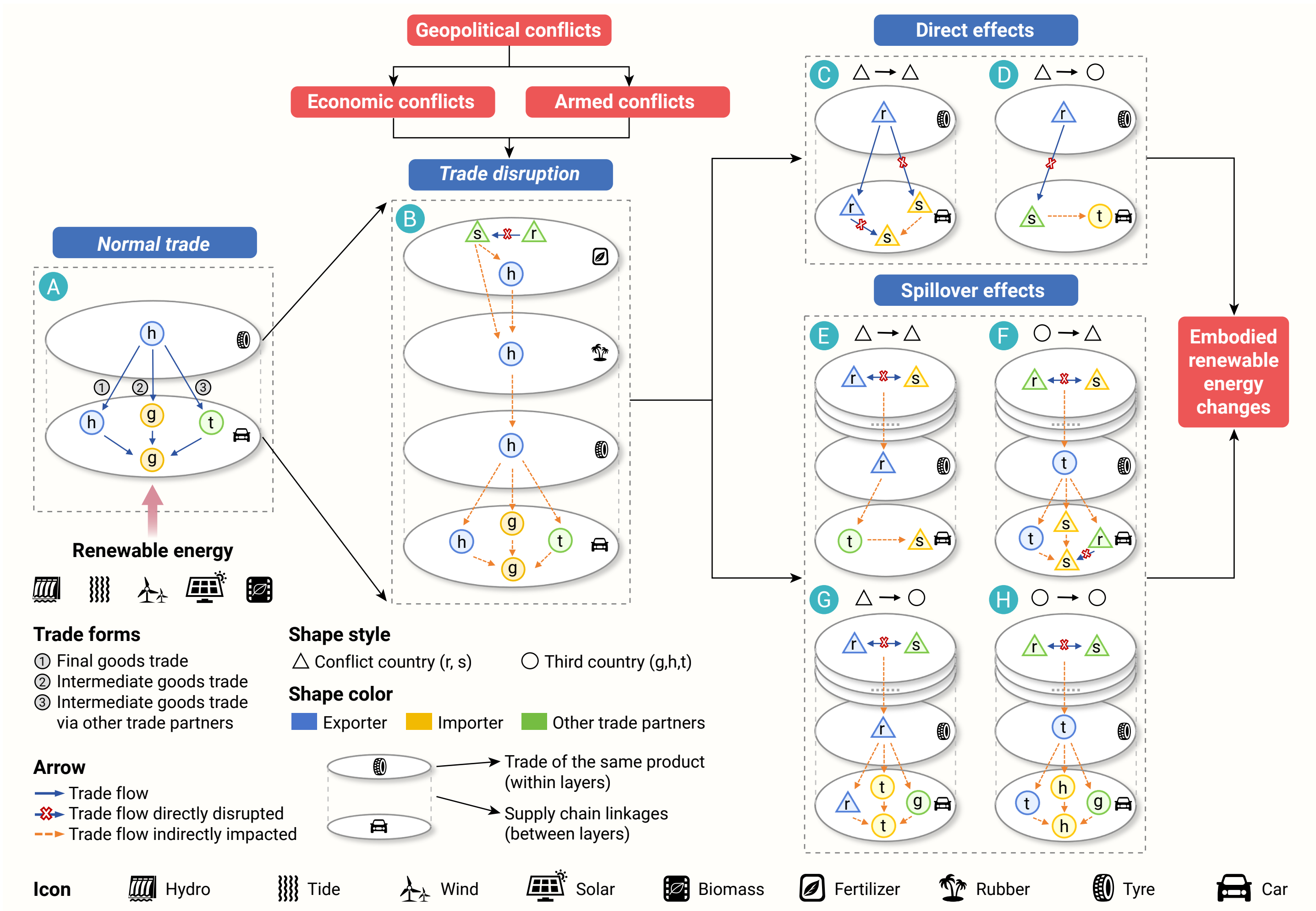

Figure 1. CSE model overview (A) EREM paths under the normal trade scenario. (B) Shock transmission under the geopolitical conflict scenario. (C)~(D) show the EREM changes due to direct effects of conflict. (E)~(H) show the EREM changes due to spillover effects of conflict.

which provide the highest spatiotemporal resolution currently available for renewable energy satellite data. Building on its proven utility in embodied renewable energy research, we apply this framework to analyze 145 countries based on 2021 data (Table S1).

CSE model overview

We develop the CSE model to simulate trade link disruptions between conflict countries and map the transmission pathways of these shocks (Figure 1).

In a normal trade scenario, countries can import renewable energy embodied in trade. Take automobile supply chain as an example (Figure 1A). When country g imports a car, it receives EREM from exporter h through three paths. (1) Direct final goods trade. Country g receives EREM from country h by importing cars. (2) Direct intermediate goods trade. Country g receives EREM from country h by importing tires used in assembling cars. (3) Indirect intermediate goods trade. Country g imports cars from middle country t. As tires from country h is used in country t, country g thus indirectly receives EREM from country h.

Automobile supply chains not only connects country g and h through the trade of cars and tires, but extends to rubber plant and related fertilizer production supply chains in upper stream. Thus, this links countries without direct trade links together (Figure 1B). In geopolitical conflict scenario, we assume r and s are conflict countries and t, h, g are third countries. When trade disrupts between r and s, not only the EREM of them will be impacted, the interconnections of GSCs will further make shocks propagate (as shown by the orange dotted line in Figure 1B) and impact the EREM of third country h and g.

Based on the transmission pathways of shocks in GSCs, we decompose EREM fluctuations into two categories: EREM changes driven by direct effects and those driven by spillover effects.

Direct effects stem from the direct disruption of trade links between conflict countries and encompass two parts: (1) EREM variations in conflict country s sourcing from conflict country r via direct trade (Figure 1C); and (2) EREM variations in third country t sourcing from conflict country r via conflict country s (Figure 1D).

Spillover effects arise from the cascading repercussions of these disruptions and include four parts: (1) EREM variations in conflict country s sourcing from conflict country r via third country t (Figure 1E); (2) EREM variations in conflict country s sourcing from third country t (Figure 1F); (3) EREM variations in third country t sourcing from conflict country r (Figure 1G); and (4) EREM variations in third country h sourcing from third country t (Figure 1H).

Renewable energy extended multi-regional input-output analysis

Multi-region input-output (MRIO) analysis provides a comprehensive and systematic picture of direct and indirect economic linkages among regions and industries. It is widely used to examine the telecoupled impacts along the supply chains induced by various kinds of shocks including trade disputes,[23,28] war[14,29] and climate change.[30,31] Based on renewable energy extended MRIO analysis, embodied renewable energy import (EREM) and export (EREX) among global trade can be calculated.

The equations are expressed as follows.[32–34] There are n regions and k sectors. $x^r((nk) \times 1)$ is a vector with elements x_i^r as the monetary value of total outputs of sector i in region r. $A^{rs}((nk) \times (nk))$ is the coefficient matrix with elements a_{ij}^{rs} as intermediate inputs from sector i in region r into the production of sector j in region s. It's calculated by equation 2, where z_{ij}^{rs} represents the intermediate inputs from sector i in region r to sector j in region s. $Y^{rs}((nk)$

x n) is a matrix with elements y_i^{rs} as the outputs of sector *i* in region *r* to satisfy the final demand of region *s*.

$$\begin{bmatrix} x^1 \\ x^2 \\ \\ x^n \end{bmatrix} = \begin{bmatrix} A^{11} & A^{12} & & A^{1n} \\ A^{21} & A^{22} & & A^{2n} \\ \\ A^{n1} & A^{n2} & & A^{nn} \end{bmatrix} \begin{bmatrix} x^1 \\ x^2 \\ \\ x^n \end{bmatrix} + \begin{bmatrix} y^{11} & y^{12} & & y^{1n} \\ y^{21} & y^{22} & & y^{2n} \\ \\ y^{n1} & y^{n2} & & y^{nn} \end{bmatrix} \quad (1)$$

$$a_{ij}^{rs} = z_{ij}^{rs} / x_j^s \quad (2)$$

Then equation 1 can be simplified as equation 3 and it can be transformed to equation 4， where $(I-A)^{-1}$ is Leontief inverse matrix *L*, with elements *l* reflecting direct and indirect effects from a unit change in final demand.

$$x = Ax + y \quad (3)$$

$$x = (I-A)^{-1} y \quad (4)$$

With the integration of renewable energy data into input-output table, renewable energy embodied in global trade $E^{rs}((nk) \times n)$ can be calculated as equation 5. $\hat{f}((nk) \times (nk))$ is a diagonalized vector with elements f_j^s as the renewable energy intensity of sector *j* in region *s*. It's calculated by equation 6, where d_j^s represents the final renewable energy consumption of sector *j* in region *s*.

$$E = \hat{f} l y \quad (5)$$

$$f_j^s = d_j^s / x_j^s \quad (6)$$

Then the *EREM* and *EREX* of region *r* can be expressed as follows.

$$EREM^r = \sum_{i=1}^{k} \sum_{s=1(s \neq r)}^{n} (E_i^{sr}) \quad (7)$$

$$EREX^r = \sum_{i=1}^{k} \sum_{s=1(s \neq r)}^{n} (E_i^{rs}) \quad (8)$$

Scenario selection

Geopolitical conflicts primarily manifest as economic conflicts and armed conflicts.[35] Both types impose trade shocks and their severity largely depends on the involved nations' roles in global supply chains. For our counterfactual analysis, we select two representative cases: (1) The China-US trade dispute, involving the world's largest (14.2% of global exports) and second-largest (8.5%) trading economies.[36] This case represents not only the most significant ongoing economic war but also a clash between two dominant players in global manufacturing supply chains; and (2) The Russia-Ukraine conflict is the most severe ongoing armed conflict and exemplifies tensions between key actors in resource-based supply chains. Russia is the second-largest gas and third-largest oil exporter, representing 14.8% and 9.9% in global export share in 2023, respectively.[37] Ukraine is a leading exporter of wheat, corn, and sunflower oil, ranking first in global sunflower oil export (46%) in 2021.[38] As energy and food are the most basic inputs in many industries, these two countries are inevitably linked with other countries in GSCs. Furthermore, the conflict's geopolitical tensions have further led 38 countries to sanction Russia by July 2022(Table S2),[39] directly involving more countries' supply chains. Analyzing these distinct cases enables us to encompass diverse shock transmission mechanisms, spanning from bilateral manufacturing shocks to multilateral resource supply disruptions.

Simulation of supply chain reconfiguration under conflict

We assume that r and s are conflict countries, and t is third countries. The reconfiguration proceeds in two stages: (1) trade disruption setup, and (2) re-balancing via substitution.

Trade disruption setup. We assume a complete decoupling, where trade in intermediate and final goods between conflict countries is entirely disrupted. We implement the shock by modifying the technical coefficient matrix *A* and final demand vector *Y*. In the shock phase, these parameters are set to zero.

$$\begin{cases} a_{ij}^{rs} = 0 \\ a_{ij}^{sr} = 0 \end{cases} \quad (9)$$

$$\begin{cases} y_i^{rs} = 0 \\ y_i^{sr} = 0 \end{cases} \quad (10)$$

This operation creates a supply gap (loss of necessary inputs) and a demand surplus (loss of export markets), necessitating a reconfiguration to restore the global input-output balance.

Re-balancing via substitution. To restore the equilibrium condition, we model two reconfiguration strategies. First, we examine domestic substitution, which serves as a theoretical upper bound and reflects the volume effect, capturing the direct changes in EREM resulting from the cessation of original trade routes. (This corresponds to the first two sections of our Results.) Second, to mirror real-world mitigation behaviors, we model import substitution. This strategy captures the structural effect, accounting for EREM changes induced by trade diversion to alternative suppliers with differing renewable energy intensities. (This corresponds to the third section of our Results.)

(1) Domestic substitution

This scenario assumes that conflict nations fill all supply and demand gaps through domestic production both for intermediate inputs and final consumption.

For the target conflict country *r*, the domestic technical coefficient a_{ij}^{rr} is adjusted to absorb the lost inputs from the set of adversary countries *S*:

$$a'^{rr}_{ij} = a_{ij}^{rr} + \sum_{s \in S} a_{ij}^{sr} \quad (11)$$

Similarly, the final demand previously satisfied by imports from adversaries is reallocated to domestic producers. The new domestic final demand y'^{rr}_i for sector *i* is calculated as:

$$y'^{rr}_i = y_i^{rr} + \sum_{s \in S} y_i^{sr} \quad (12)$$

This reconfiguration logic applies symmetrically to both sides of the conflict. While the equations above illustrate the process for country *r* , the same logic applies to the adversary countries *s*. Then the new Leontief inverse $L' = (I-A')^{-1}$ can be calculated.

(2) Import substitution

In this scenario, we assume that substitution occurs primarily through established trade channels. Therefore, the supply gap is reallocated to existing partners proportional to their share in the baseline trade structure.

Let $Loss_{A,ij} = \sum_{s \in S} a_{ij}^{sr}$ be the total coefficient loss for sector *j* in country *r*, then the loss is replaced by imports from available partner countries *p* in the substitution pool *P*. The new coefficient a'^{pr}_{ij} is calculated as:

$$a'^{pr}_{ij} = a_{ij}^{pr} \times \left(1 + \frac{Loss_{A,ij}}{\sum_{p' \in P} a_{ij}^{p'r}}\right) \quad (13)$$

Here, *p* denotes the specific provider being adjusted, while the summation over *p*′ represents the total existing trade volume from the entire pool *P*.

Let $Loss_{Y,ij} = \sum_{s \in S} y_i^{sr}$ be the total loss in final demand. The adjusted final demand y'^{pr}_i is calculated as:

$$y'^{pr}_i = y_i^{pr} \times \left(1 + \frac{Loss_{Y,i}}{\sum_{p' \in P} y_i^{p'r}}\right) \quad (14)$$

The composition of the provider set *P* is defined contextually. In the China-US Scenario, the conflict is bilateral. The substitute provider *p* refers strictly to non-conflict third countries *t*. In the Russia-Ukraine Scenario, for Russia, the pool is restricted to non-sanctioning third countries *t*. For sanctioning nations, the pool includes both non-sanctioning third countries and other sanctioning partners. Following these adjustments, the re-balanced Leontief inverse matrix L′ can be calculated based on the updated technical coefficient matrix A′.

EREM changes decomposition

We quantify the geopolitical impact by calculating the EREM change, defined as the difference between a country's EREM under the conflict scenario and the normal trade scenario. We assume that *r* and *s* are conflict countries, and *t, g, h* are third countries. Structurally, the EREM composes three parts: (1) $\hat{f}_r l_{rs} y_{ss}$ represents EREM through direct intermediate goods trade; (2) $\hat{f}_r l_{rr} y_{rs}$ represents EREM through direct final goods trade; and (3) $\hat{f}_r l_{rt} y_{ts}$ represents EREM through indirect intermediate goods trade from *r* to *s* via third country *t*. The total EREM change arises from the summation of variations in these three components. By analyzing the country interactions within the Leontief inverse matrix *L* and the final demand matrix *Y*, we categorize these variations into changes driven by direct effects and changes driven by spillover effects.

The Leontief inverse matrix *L* is central to this categorization, as its elements reflect the system-wide total output required to meet one unit of final demand. For instance, an element l_{ij}^{rs} represents the total output required from sector *i* in country *r* to satisfy the final demand of sector *j* in country *s*. This metric captures not only the direct inputs but also the infinite series of indirect inputs circulating through domestic and international supply chains. Consequently, when the intermediate input trade between conflict countries *r* and *s* is interrupted, it fundamentally alters the global production topology. This disruption impacts all direct and indirect pathways involving *r* and *s*, causing the elements of the Leontief inverse matrix to shift from their baseline values.

Specifically, we apply this decomposition framework independently to both the domestic substitution and import substitution scenarios. By substituting the distinct Leontief inverse *L* and final demand *Y* matrices derived from each reconfiguration strategy into the equations below, we can obtain scenario-specific EREM variations.

EREM changes driven by direct effects. We attribute the EREM changes resulting from the severance of direct trade links between conflict countries, represented by the elements l_{rs}, l_{sr}, y_{rs} and y_{sr}, to direct effects. These effects impact both the conflict country itself (as shown in Figure 1C and Equation 15) and third countries that rely on downstream inputs from the conflict zone (as shown in Figure 1D and Equation 16).

In these equations, $\triangle E_{de}$ denotes the absolute variation in EREM driven by direct effects. The terms l and *y* denote the elements of the Leontief inverse and final demand matrices in the normal trade scenario, whereas l' and y' correspond to the conflict scenario.

$$\triangle E_{de}^{rs}=(\hat{f}_r l'_{rs} y'_{ss}+\hat{f}_r l'_{rr} y'_{rs})-(\hat{f}_r l_{rs} y_{ss}+\hat{f}_r l_{rr} y_{rs}) \tag{15}$$

$$\triangle E_{de}^{rt}=\hat{f}_r l'_{rs} y'_{st}-\hat{f}_r l_{rs} y_{st} \tag{16}$$

EREM changes driven by spillover effects. The other elements of the Leontief inverse matrix *L*, such as l_{rt}, l_{ts}, l_{th}, are not directly related to the supply chain of the conflict countries, but include the indirect inputs of the conflict countries, are also impacted. For example, country *h* requires inputs from country *t*, which further require inputs from country *r*. Country *r* also require inputs from country *s*. As a result, the entire supply chain from *s*→*r*→*t*→*h* will be affected by the trade disruption between *s* and *r*. We attribute the change of these elements in *L* to the spillover effects of conflict and define $\triangle E_{se}$ as EREM change driven by spillover effects. These effects impact both the conflict country (Figures 1 E-F)(Equations 17-18) and third country Figures 1G-H)(Equations 19-20).

$$\triangle E_{se}^{rs}=\hat{f}_r l'_{rt} y'_{ts}-\hat{f}_r l_{rt} y_{ts} \tag{17}$$

$$\triangle E_{se}^{ts}=(\hat{f}_t l'_{ts} y'_{ss}+\hat{f}_t l'_{tt} y'_{ts}+\hat{f}_t l'_{tr} y'_{rs}+\hat{f}_t l'_{tg} y'_{gs})-(\hat{f}_t l_{ts} y_{ss}+\hat{f}_t l_{tt} y_{ts}+\hat{f}_t l_{tr} y_{rs}+\hat{f}_t l_{tg} y_{gs}) \tag{18}$$

$$\triangle E_{se}^{rt}=(\hat{f}_r l'_{rt} y'_{tt}+\hat{f}_r l'_{rr} y'_{rt}+\hat{f}_r l'_{rg} y'_{gt})-(\hat{f}_r l_{rt} y_{tt}+\hat{f}_r l_{rr} y_{rt}+\hat{f}_r l_{rg} y_{gt}) \tag{19}$$

$$\triangle E_{se}^{th}=(\hat{f}_t l'_{th} y'_{hh}+\hat{f}_t l'_{tt} y'_{th}+\hat{f}_t l'_{tg} y'_{gh})-(\hat{f}_t l_{th} y_{hh}+\hat{f}_t l_{tt} y_{th}+\hat{f}_t l_{tg} y_{gh}) \tag{20}$$

RESULTS

China-US extreme scenario

As the top two largest economies in the world, US and China have developed extensive supply chains between and beyond them. Our simulation of a complete trade disruption showed a 4.1% global EREM decline (from 212.2 to 203.5 Mtoe)(Figure 2A), exceeding UK's total EREM (8.0 Mtoe) under normal trade conditions (Figure S1). Specifically, the direct effects of the conflict caused a massive 9.3 Mtoe decline, while the spillover effect generated via domestic replacement offered only a negligible buffer of 0.6 Mtoe (Figure 2B). This massive disparity indicates that the upstream import demand generated by localized production is far too small to offset the loss of direct trade decoupling.

The contraction of EREM in conflict countries drove the global decline and US was more strongly hit than China. Total EREM losses suffered by US (7.1 Mtoe) and China (1.5 Mtoe) accounted for 98.7% of the global decline (Figure 2A). Specifically, US experienced a 16.5% EREM loss compared to China's 7.3%, reflecting its greater dependence on Chinese EREM (23.4% vs 8.8%, Table S3). In terms of direct effects, the conflict led to a sharp contraction in bilateral EREM flows, with US imports from China decreasing by 7.8 Mtoe and Chinese imports from the US declining by 1.3 Mtoe (Figure 3). However, spillover effects induced divergent trends in EREM imports from third countries for the two nations. On the one hand, the US increased imports from countries such as Canada, Brazil, India, Mexico, and Peru, whereas China's imports from these same nations declined (Figures S2-S3). On the other hand, China expanded its imports from Vietnam, Japan, South Korea, Indonesia, and Australia, while corresponding US imports from these sources decreased (Figures S2-S3). The underlying mechanism involved two opposing forces. Domestic substitution boosted demand for upstream inputs to meet rising internal consumption, while the severance of bilateral trade reduced the need for inputs previously used for exports to the counterpart. Consequently, the import demand generated by domestic substitution shifted toward traditional regional partners. Specifically, the US pivoted to partners in the Americas and the Atlantic, whereas China strengthened linkages within the Asia-Pacific supply chain. This trend suggests an intensified regionalization of global embodied renewable energy trade.

Third-country EREM imports declined by 0.1 Mtoe (Figure 2A), primarily driven by a 0.2 Mtoe reduction in EREM from China via direct effects (Figure 3). This loss stemmed from the disruption of the "China intermediate to US final to third country" pathway. Since US exports heavily incorporated Chinese inputs, the bilateral severance reduced the EREM reaching downstream nations. In contrast, third-country EREM imports from the US dropped only 0.05 Mtoe via direct effects. This fourfold disparity underscores the dominance of the "China-US-third country" chain in the global production network, indicating that a Chinese supply cutoff triggers far greater cascading shocks to third nations than the reverse.

Specifically, EREM change among third countries diverged based on supply chain positioning. EREM fell for economies like Canada, Mexico, and the UK due to their close integration with US supply chains (Table S3). Impacted by direct effects, these nations received less EREM indirectly from China via the US, illustrating that economies positioned downstream of severed trade routes were particularly vulnerable to concealed transmitted shocks. Conversely, EREM rose for countries such as Vietnam, Bangladesh and Thailand. due to spillover effects. China's shift to domestic substitution incorporated more local intermediates, thereby increasing the embodied renewable energy intensity of its exports to these partners.

Russia-Ukraine extreme scenario

In the RU scenario, global EREM declined by 8.0% (17.0 Mtoe). Direct effects caused a 6.0 Mtoe decrease, while spillover effects drove a larger reduction of 11.0 Mtoe (Figure 4A). This pattern contrasted sharply with the China-US scenario where direct effects dominated. The decline stemmed primarily from a steep 8.5 Mtoe drop in EREM from third countries (Figure 4B), with conflict nations accounting for 6.0 Mtoe of this loss (Table S5). Mechanistically, the disruption of supply chains linking third countries to conflict nations and then to counterparts caused a loss of upstream derived demand. This loss outweighed the new upstream demand for third-country inputs generated by domestic substitution for local consumption.

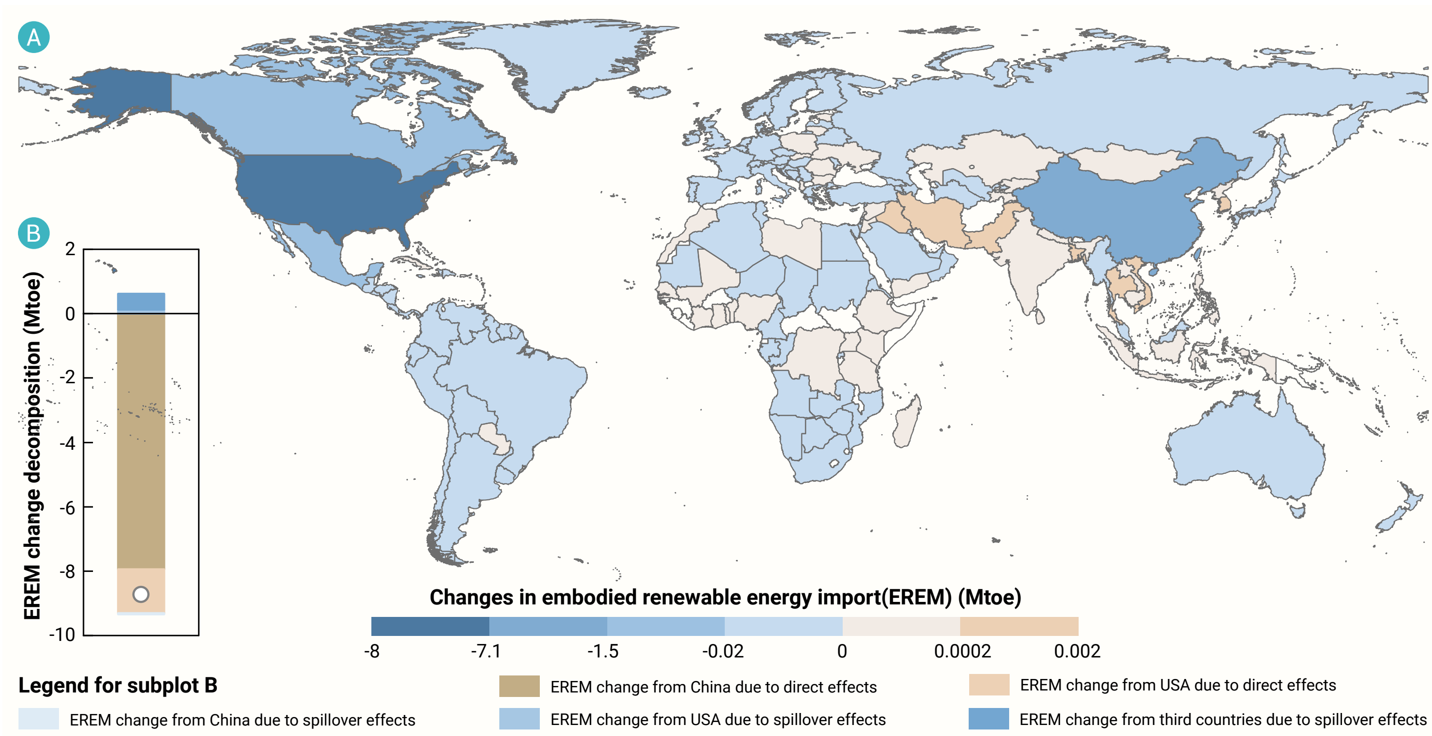

Figure 2. Changes in embodied renewable energy import (EREM) under the China-US domestic substitution scenario (A) Global distribution of EREM variations. Negative values indicate reductions compared to the normal trade scenario. (B) Decomposition of global EREM variations into direct and spillover effects. Scatter points denote net changes.

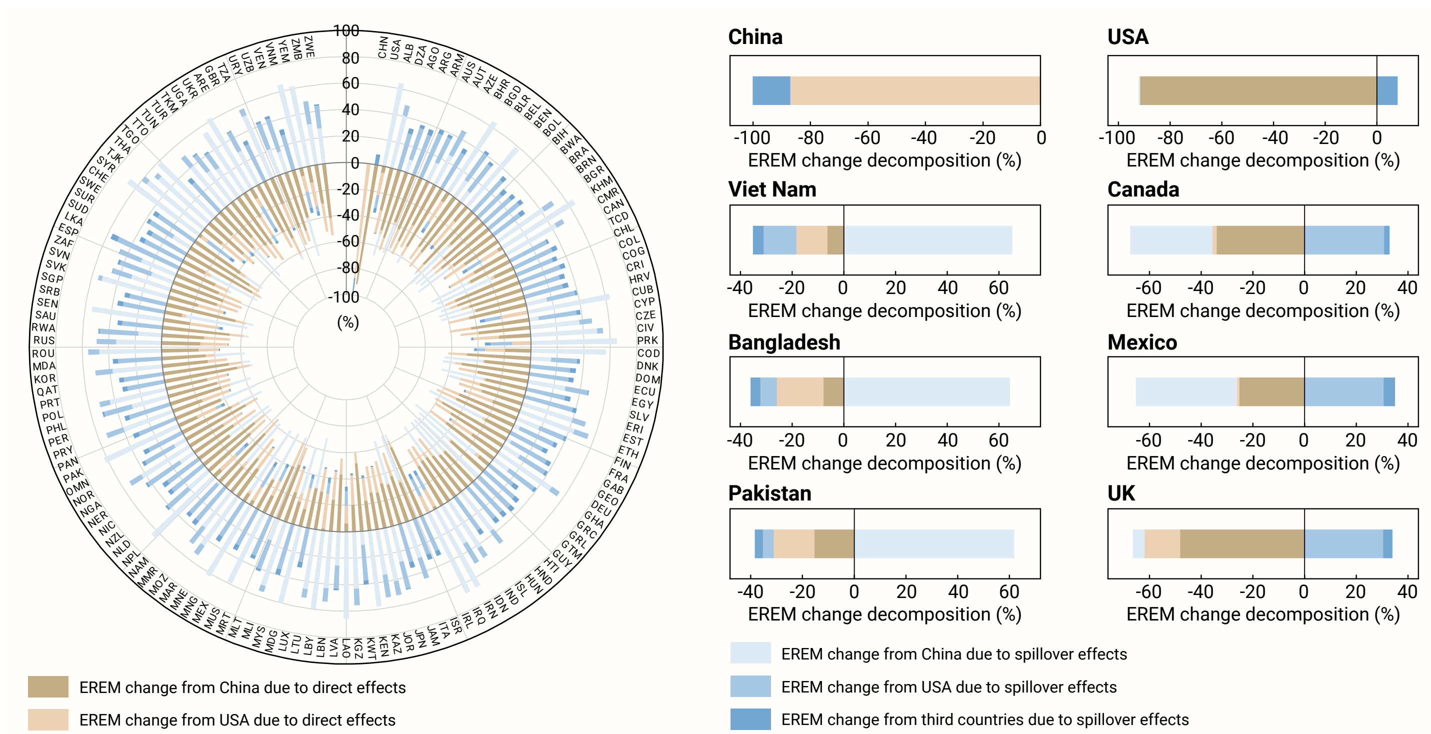

Figure 3. Decomposition of EREM variations into direct and spillover effects for individual economies under the China-US domestic substitution scenario The circular chart presents the standardized decomposition for all countries, while the right-hand panel highlights details for six representative cases. To ensure cross-country comparability, the contributions of direct and spillover effects are normalized: each segment represents the ratio of a specific effect to the sum of the absolute values of all driving effects for that country.

Top EREM losses in the RU scenario occurred in Japan (5.7 Mtoe), the US (2.0 Mtoe), China (2.0 Mtoe), and Russia (1.7 Mtoe) (Figure 4A). Notably, losses in some third countries even surpassed those in conflict nations, underscoring the widespread repercussions of the conflict. The drivers of these losses diverged across nations (Figure 5). Among the top ten affected nations, direct effects drove 83.8%~97.7% of the declines for Russia, Germany, France, and the UK. This specifically reflected sharp drops in Russia's EREM from sanctioning economies including Poland, Ukraine, Germany, Finland, and the US (Table S6), alongside parallel reductions in EREM by Germany, France, and the UK from Russia. As these nations main-

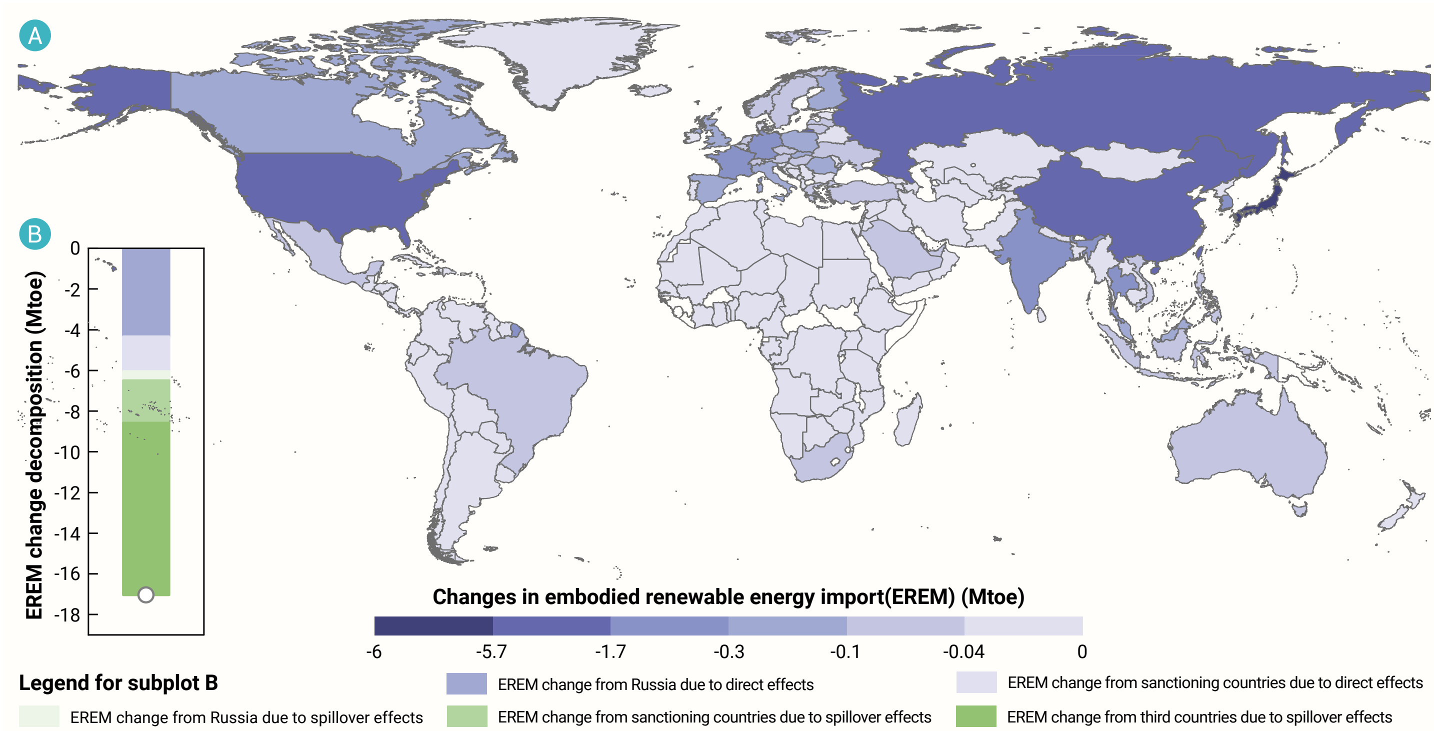

Figure 4. Changes in embodied renewable energy import (EREM) under the Russia-Ukraine domestic substitution scenario (A) Global distribution of EREM variations. Negative values indicate reductions compared to the normal trade scenario. (B) Decomposition of global EREM variations into direct and spillover effects. Scatter points denote net changes.

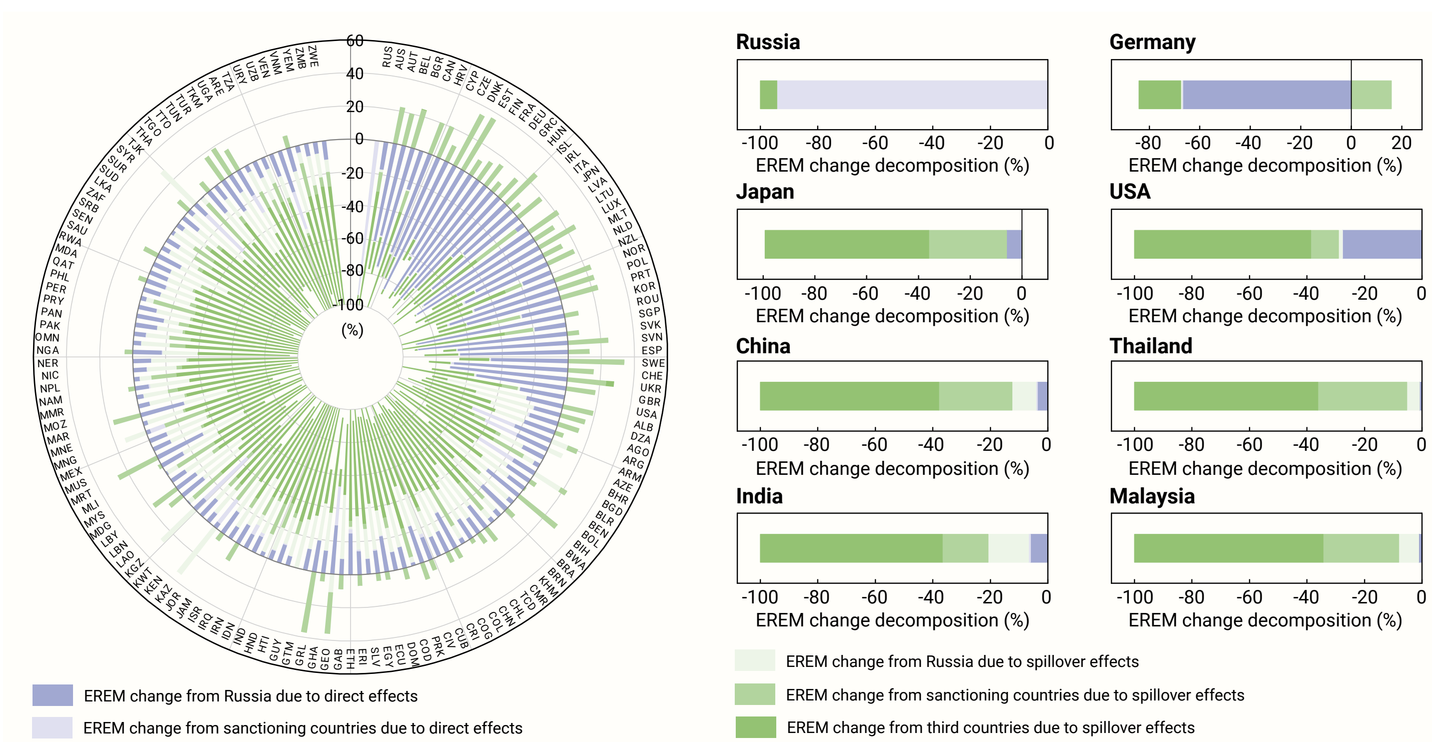

Figure 5. Decomposition of EREM variations into direct and spillover effects for individual economies under the Russia-Ukraine domestic substitution scenario The circular chart presents the standardized decomposition for all countries, while the right-hand panel highlights details for six representative cases. To ensure cross-country comparability, the contributions of direct and spillover effects are normalized: each segment represents the ratio of a specific effect to the sum of the absolute values of all driving effects for that country.

tained intensive bilateral trade in intermediates and final goods, direct severance dominated the total losses. Conversely, spillover effects drove 72.4%~94.0% of the declines in Japan, the US, and South Korea. By disrupting the "third country → Russia → sanctioning country" chain, spillover effects slashed imports from third-party suppliers like China, Brazil, and India (Figure S4). This divergence stemmed from trade structures where Europe's reliance on Russian primary energy involved short supply chains susceptible to direct effects. In contrast, the US, Japan, and South Korea imported Russian industrial materials requiring substantial third-country inputs, exposing them to spillover effects.

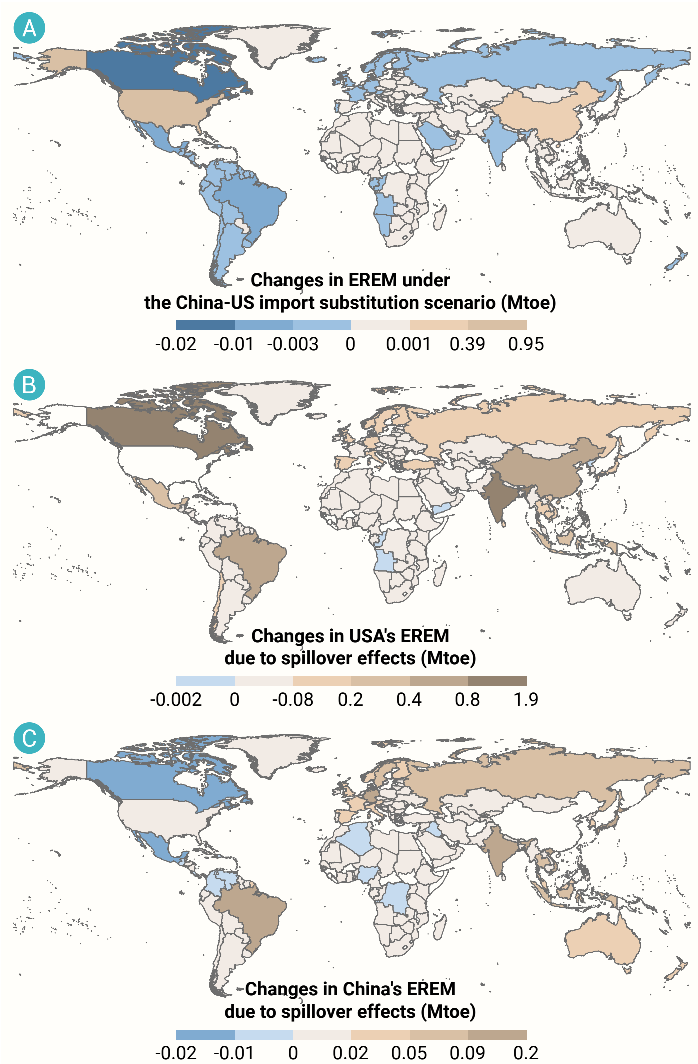

Figure 6. Geographic distribution of embodied renewable energy import (EREM) changes under China-US import substitution scenarios (A) Global distribution of EREM variations under the China-US import substitution scenario. (B) Spatial variations in US EREM sourced from global partners driven by spillover effects. (C) Spatial variations in China's EREM sourced from global partners driven by spillover effects.

The repercussions of the RU scenario extended far beyond conflict participants, causing EREM trade among sanctioning and third countries to decline widely by 3.8 Mtoe, falling from 104.2 Mtoe to 100.4 Mtoe (Figure 4A). Among third nations, Asian economies including China, Thailand, India, Malaysia, and Indonesia suffered the steepest declines. Spillover effects drove substantial reductions in imports by these nations from both other third countries and conflict countries (Figure 5). For instance, spillover effects accounted for 95.9% of China's total loss, primarily reflecting reduced imports from Brazil, India, Russia, the US, and Australia. Mechanistically, although third countries faced no direct conflict, their trade linkages relied on multi-stage indirect production chains involving conflict nations. Consequently, when critical nodes like Russia-Europe trade were severed, the complex long-chain EREM connections established among third countries were inevitably weakened.

Import substitution scenario

EREM variations in the above extreme scenarios stemmed primarily from volume effects where severed bilateral ties directly reduced cross-border flows. Recognizing that nations mitigate shocks via trade diversion, we further analyzed EREM changes under import substitution to examine structural effects. These effects arose from differences in energy intensity and production technology between substitute and original partners. This approach enabled a more accurate assessment of global EREM shifts in real-world conditions and improved the understanding of the mechanism through which geopolitical shocks influence supply-chain-embedded renewable energy.

In the China-US import substitution scenario, global EREM increased slightly by 0.6% (1.3 Mtoe) (Figure 6A). While direct effects caused a 9.1 Mtoe decline, spillover effects from substitution generated a 10.4 Mtoe increase that offset this loss (Table S4). Driven by spillover effects, US's EREM from third countries rose from 33.0 Mtoe to 41.2 Mtoe, sourced largely from India, Canada, and Brazil (Figure 6B). Similarly, China's EREM grew from 18.7 Mtoe to 20.4 Mtoe, primarily from India and Vietnam (Figure 6C). Notably, US's indirect EREM from China via third-country final goods increased from 1.3 Mtoe to 1.7 Mtoe, while China's indirect EREM from the US rose marginally from 0.14 Mtoe to 0.16 Mtoe. These findings indicate that bilateral ties are deeply embedded in global supply chains rather than simple direct links. Consequently, import substitution paradoxically deepened the implicit interdependence between the two nations.

Unlike the China-US scenario, global EREM under RU substitution declined by 0.2% (0.4 Mtoe) (Figure 7A). This occurred because the 5.8 Mtoe loss from direct effects outweighed the 5.4 Mtoe increase from spillover effects (Table S5). Specifically, a 4.2 Mtoe drop in EREM from Russia drove the direct loss. As Russia serves as a key upstream resource exporter, its supply cessation caused widespread downstream shocks. Consequently, only 16 countries, including Russia, the US, and Ukraine, experienced minor EREM increases, while most failed to offset direct losses through spillover contributions (Figure 7A). Results also revealed an asymmetric implicit dependence. Russia's EREM from third countries including China, Vietnam, India, Brazil, and Belarus rose by 2.3 Mtoe (Figure 7B). Concurrently, its indirect EREM from sanctioning nations via the "sanctioning country intermediates→third country final goods →Russia" pathway increased from 0.03 Mtoe to 0.11 Mtoe, indicating a deepened implicit reliance on sanctioning economies. Conversely, sanctioning nations did not exhibit a symmetric implicit dependence on Russia. Their EREM imports increased by 4.3 Mtoe, sourced primarily from China, India, Brazil, Vietnam, and the Democratic Republic of the Congo (Figure 7C). This disparity stemmed from structural trade diversion. Sanctioning nations switched to resource-rich suppliers similar to Russia. As these upstream economies required minimal Russian intermediates, substitution failed to boost Russia's indirect exports to sanctioning nations. In contrast, Russia pivoted to industrial nations dependent on core components from sanctioning economies, paradoxically reinforcing its implicit reliance on them.

DISCUSSION

Our analysis of embodied renewable energy (EREM) losses through the CSE model reveals how geopolitical conflicts propagate risks through global supply chains and threaten global energy transition. These findings extend beyond conventional analyses of visible energy trade by capturing the full scope of renewable energy embodied in manufacturing networks, a dimension previously overlooked despite its significance for both energy transition (SDG7) and sustainable production (SDG12) targets.

We find that the Russia-Ukraine conflict and the China-US trade dispute would reduce global EREM by 8% and 4%, respectively. Notably, in the Russia-Ukraine context, spillover effects are nearly double the direct effects, highlighting that in an era of deeply embedded supply chains, disruptions at key trade nodes generate widespread systemic shocks rather than localized pain. Furthermore, our study reveals that the impact of trade decoupling on energy transition is highly asymmetric. In the China-US scenario, the decline in the US's EREM (7.1 Mtoe) far exceeds that of China (1.5 Mtoe). This disparity underscores that trade decoupling is not merely a geopolitical or economic maneuver but deeply penetrates the environmental domain. Consequently, energy transition has evolved from a purely environmental challenge into a complex geopolitical issue, necessitating diplomatic strategies that explicitly address EREM vulnerabilities embedded in trade networks.

Our research also elucidates the cascading mechanisms affecting third countries, whose vulnerability depends on the intensity of their supply chain linkages with the conflict nations. In the China-US scenario, downstream countries are particularly susceptible to upstream disruptions; thus, a supply cutoff from China generates far greater cascading shocks to third nations than a reciprocal cutoff from the US. Similarly, in the Russia-Ukraine scenario,

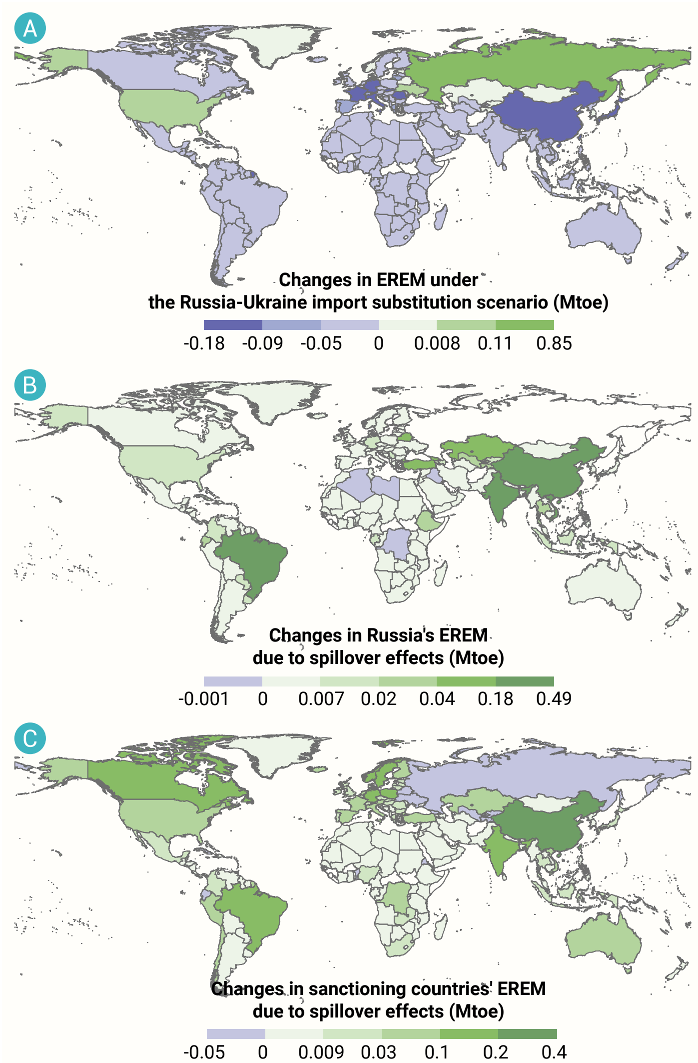

Figure 7. Geographic distribution of embodied renewable energy import (EREM) changes under Russia-Ukraine import substitution scenarios (A) Global distribution of EREM variations under the Russia-Ukraine import substitution scenario. (B) Spatial variations in Russia's EREM sourced from global partners driven by spillover effects. (C) Spatial variations in sanctioning countries' EREM sourced from global partners driven by spillover effects.

spillover effects cause EREM losses in third-party economies like China exceed those of the conflict participants themselves. This suggests that third countries, often innocent bystanders, should actively mediate conflicts to prevent escalation and promote trade diversification to reduce over-reliance on high-risk trade hubs.

To better reflect real-world mitigation strategies, we further examined the potential of import substitution. We find that while import substitution can marginally recover EREM inflows in the China-US scenario, it fails to mitigate losses in the Russia-Ukraine context. Crucially, our analysis exposes a persistent hidden dependency. Even with trade diversion, the US and China remain inextricably linked due to their roles as central nodes in the global manufacturing network. As observed in reality, US friend-shoring efforts often result in increased imports from countries like Vietnam, which in turn rely heavily on Chinese upstream inputs.[40] In contrast, the Russia-Ukraine case exhibits asymmetric dependence driven by a vertical division of labor (resource-technology). While sanctioning nations rely on Russia for resources, Russia depends on them for advanced technologies, which are harder to replace through trade substitution.

We acknowledge two limitations in our approach. First, regarding scenario design, our domestic substitution assumption represents an extreme case (upper-bound estimate), while our import substitution scenario allocates trade proportionally based on historical data. We recognize that these stylized scenarios may not fully capture specific covert evasion tactics, such as the 'refining loophole' where Russian oil is processed and re-exported to Europe via intermediaries like India or Turkey to circumvent sanctions.[41] Nevertheless, our primary objective is to elucidate the transmission mechanisms, specifically direct and spillover effects, and to uncover hidden interdependencies, rather than to fully replicate real-time, complex trade realities. Second, applying national electricity-mix averages to all sectors ignores specific off-grid usage and may lead to an underestimation of embodied renewable energy.[6] Yet, given that off-grid capacity constitutes only 0.3% of the global total and is primarily residential,[42] using national grid data remains the most robust approach for industrial-scale analysis.

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FUNDING AND ACKNOWLEDGMENTS

This work was supported by the Fundamental Research Funds for the Central Universities, the Ministry of Science and Technology of the People's Republic of China (2023YFB3906700), National Natural Science Foundation of China (42571208), Xinjiang Talent Development Fund Project (XJRC-2025-KJ-YJ-CXPT-18). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

C.Y. and Y.Y. designed the study. C.Y. conducted the calculation and analysis. C.Y. wrote the original draft. Y.Y. revised the manuscript and supervised the study. J.P. and L.G. provided comments and contributed to further revisions. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Eora26 MRIO tables are available at (https://worldmrio.com/). RE-FEA energy accounts are hosted at (https://doi.org/10.5281/zenodo.15826919). Code is available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-geo.2026.100218.