energies

MDPI

Article

The Impact of U.S. Tariff Barriers on the Global Solar PV Exports from China Under Digitalization

Jing Shuai [1], Yuanyuan Wu [1], Wenjia Wang [1] and Chuanmin Shuai [2,3,*]

[1] Center for Industrial Economic Research, School of Economics, Wuhan Textile University, Wuhan 430200, China
[2] School of Economics, Wuhan Donghu University, Wuhan 430212, China
[3] School of Economics and Management, China University of Geosciences (Wuhan), Wuhan 430074, China
* Correspondence: shuaicm@cug.edu.cn

Abstract

As digitalization reshapes global value chains and trade patterns, China's solar photovoltaic (PV) exports face growing challenges from trade protectionism, particularly U.S. tariff barriers. Despite the strategic importance of solar PV products for the global low-carbon transition, the impact of U.S. tariffs on China's PV trade under digitalized conditions remains insufficiently understood. Using panel data from 2007 to 2024, this study employs Difference-in-Difference (DID) methods to examine how U.S. tariff barriers influence China's solar PV exports and the underlying adjustment mechanisms. The results indicate that (1) U.S. tariff measures imposed on global trading partners significantly reduced China's solar PV exports, with substantial regional heterogeneity; (2) amid rising external policy uncertainty and accelerating global digitalization, China's solar PV export structure has undergone significant adjustment, with exports increasingly directed toward countries with mature and stable PV markets; and (3) global trade policy shocks are contributing to structural adjustments in China's solar PV export markets. Overall, the findings offer empirically grounded evidence and policy insights for optimizing China's solar PV export structure and responding to trade barriers.

Keywords: U.S. tariff barriers; China's solar PV exports; difference-in-difference; digitalization

1. Introduction

Against the backdrop of global efforts to address climate change and promote a low-carbon energy transition, solar PV power has become a crucial component of national energy transition strategies due to its technological maturity and significant emissions-reduction potential. At the same time, digital technology is increasingly integrating into energy production, equipment manufacturing, trade circulation and supply chain management, accelerating the reconfiguration of the global clean energy value chain and reshaping the regional environmental governance landscape [1]. Leveraging a complete industrial chain, large-scale production capacity, and continuous technological advancement, China has developed into the world's largest producer and exporter of solar PV products [2]. According to reports by the International Energy Agency (IEA), China's newly installed capacity in 2025 reached approximately 315 GW, accounting for nearly 67% of global new installations. In addition, based on China Customs data, China's cumulative exports of solar PV modules in 2025 amounted to about 233 GW, representing a year-on-year increase of 2.1%, and reflecting strong competitiveness in the global market. Meanwhile, Chinese solar PV firms are becoming increasingly concentrated in the processing and manufacturing

Check for updates

Academic Editor: Jin-Li Hu

Received: 21 September 2026
Revised: 19 October 2026
Accepted: 19 October 2026
Published: 3 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

segments of the global solar PV value chain [3]. The United States, as one of the major global solar PV markets, exerts a significant influence on China's solar PV exports through both import demand and trade policy adjustments, and it has had a negative impact on China's GDP and the revenue of solar photovoltaic export enterprises [4,5]. In recent years, however, the U.S. has frequently employed anti-dumping, countervailing, and safeguard measures, exposing China's solar PV trade to persistent and institutionalized policy uncertainty. Under the circumstance of digitalization, such trade barriers affect product flows not only through direct tariff costs but also via digital governance tools, such as supply-chain traceability, rules of origin, and industrial security reviews, thereby further amplifying their impact on the global solar PV trade landscape. For China, the solar PV industry is both a critical support for energy transition and the development of strategic emerging industries, as well as a key sector deeply embedded in the global green value chain. In this context, clarifying the actual impact of U.S. tariff barriers on China's solar PV exports under digitalization provides empirically grounded evidence to inform government decisions on optimizing export market strategies and refining trade policies. Moreover, understanding how trade barriers affect the cross-border allocation efficiency of clean energy products is directly relevant to achieving global green transition objectives. Therefore, systematically investigating the effects of U.S. tariff barriers on China's solar PV trade in a digital context is both important and urgently needed.

Against the backdrop of ongoing global digital transformation and the rising tide of trade protectionism, the security of the solar PV value chain has become increasingly prominent, and ensuring supply chain resilience is a critical requirement for guiding future industry development [6,7]. Following the imposition of anti-dumping and countervailing (AD/CVD) measures on PV products, the United States raised tariffs on solar PV imports from most countries except for certain developing economies in 2018—an action that delivered a major shock to the global PV industry chain. China, which accounts for approximately 80% of global PV capacity, bore the brunt of this impact [8]. Subsequently, after President Trump began his second term in February 2025, the United States adopted a series of hardline measures across trade, technology, and supply chains, posing unprecedented systemic challenges to the security and stability of China's PV industry chain [9]. Specifically, "Trump 2.0" represents a continuation and escalation of the 2018 "America First" strategy [10,11], strengthening tariff barriers and trade restrictions, with solar PV products becoming a primary target. Meanwhile, the United States has expanded export controls through the "Entity List" and the "Foreign Direct Product Rule (FDPR)," restricting China's access to key manufacturing equipment and core technologies [12]. In addition, by leveraging tax incentives under the Inflation Reduction Act (IRA), the United States has promoted industrial reshoring and supply-chain reconfiguration, encouraging PV value-chain segments to relocate to the U.S. and its allies, and thereby exacerbating global value-chain fragmentation [13]. Consequently, the year 2018 represents a critical juncture in the implementation of U.S. tariff barriers on solar PV products, as the scope of targeted countries expanded from China alone to most economies worldwide.

Research on trade policy shocks has generally followed two strands. The first emphasizes causal identification of policy impacts, with a large body of literature employing difference-in-difference (DID) and its extensions to identify external shocks. Examples include analyses of the effects of U.S. economic sanctions on the industrial-chain security of Chinese firms from the perspective of outward foreign direct investment [14], spatial DID evaluations of China's grain supply-chain resilience [15], and staggered DID approaches to assess the impact of AD/CVD policies on China's PV exports [16]. The second strand relies on theoretical and statistical modeling: for instance, studies using time-varying parameter autoregressive models have examined the impacts of U.S. trade policy, identifying phased

characteristics in shocks to China's grain prices—namely gradual stabilization, sharp volatility, and deepening impacts [17]—and significant intertemporal heterogeneity in effects on livestock product prices, with pork market stability playing a key role [18].

With respect to the solar PV sector, domestic studies have primarily focused on anti-dumping and countervailing (AD/CVD) measures. Using network analysis to examine EU and U.S. AD/CVD actions against Chinese PV products, some studies find sharp declines in solar PV trade among participating countries, accompanied by increases in trade with non-participating countries [19]. Others employ equilibrium models to assess the economic effects of AD/CVD actions, concluding that such measures impose losses on all participants and generate a "lose–lose" outcome [20,21]. A substantial portion of the literature also provides theoretical analyses of trade policy uncertainty, including responses to trade-restrictive measures on solar cells [22,23], as well as media-based analyses of the China–EU PV trade dispute [24]. Research on reciprocal tariffs remains limited and largely theoretical, examining the U.S. approach from dimensions such as positive versus negative, substantive versus superficial, and specific versus universal effects [25], or analyzing ASEAN perceptions and responses, which reveals a mixed strategy of "passive compromise, proactive adjustment, and regional coordination" [26].

International scholarship on trade policy shocks in the solar PV industry is more extensive. Beyond analyses of the effects of AD/CVD actions on China's PV sector [16,27,28] and theoretical discussions of China–U.S. PV disputes [29], studies have examined the broader role of trade barriers. For example, evidence suggests that trade barriers exert a suppressive effect on China's solar PV exports [30]. An analysis of PV-related disputes under the World Trade Organization from 2001 to 2018 finds a close linkage between protectionist policies and export competitiveness [31]. From a sustainable development perspective, other work indicates that additional tariff barriers on solar PV trade could reduce carbon-mitigation potential in 2026 by nearly one-third [32].

In sum, while existing studies have generated rich insights into trade policy shocks, solar PV trade frictions, and industrial-chain security, several limitations still remain. First, this study treats the 2018 U.S. tariff barriers on solar PV exports to most countries as a typical exogenous shock and constructs a DiD model based on China's solar PV export data from 2007 to 2024 in the context of digitalization, in order to identify the actual impact of tariffs on the security of China's solar PV value chain. Second, from a "domestic supply–foreign demand" perspective, this study combines export propensity with country-specific solar PV market demand to characterize how U.S. tariff policies reshape the global market landscape and to reveal the reallocation patterns of China's solar PV exports under conditions of digitalization and systemic risks. Third, in terms of analytical frameworks and perspectives, prior work largely emphasizes protectionist shocks, paying insufficient attention to the roles of regional economic blocs, supply-chain coordination structures, and cross-regional trade relations in PV industry-chain security. Consequently, the mechanisms through which regional communities influence shock transmission and industrial restructuring remain underexplored.

To address these research gaps, this study has made three contributions. (1) It treats the U.S. tariff barriers imposed on solar PV products in 2018 as a quasi-exogenous policy shock and constructs a DID model using China's solar PV export data from 2007–2024 to identify the impact of U.S. tariff barriers on China's solar PV exports. This provides empirical evidence on how external trade policy shocks affect the international market performance of China's solar PV industry. (2) From a "domestic supply–foreign demand" perspective, this study examines the role of destination-market characteristics in shaping China's solar PV export responses to U.S. tariff barriers. By incorporating lagged market performance, solar power generation, solar PV capacity, and export growth, the study

provides evidence on how market conditions and demand potential are associated with heterogeneous export responses following tariff shocks. (3) Situating PV industry-chain security within the broader context of global value-chain restructuring and geopolitical competition, this analysis examines heterogeneous regional economic groupings—including the Belt and Road Initiative (BRI), Asia-Pacific Economic Cooperation (APEC), and the Group of Twenty (G20)—to identify the buffering effects of regional cooperation mechanisms against external shocks, thereby providing policy-relevant evidence on the resilience of global green industry chains.

The remainder of this paper is organized this way: Section 2 presents the theoretical analysis and research hypotheses. Section 3 describes the methodology and data sources. Section 4 reports the empirical results. Section 5 provides heterogeneity analysis. Section 6 is discussion, and finally, Section 7 concludes this study with policy implications.

2. Theoretical Analysis and Research Hypotheses

2.1. Direct Effects

U.S. tariff barriers imposed on solar PV products represent a typical manifestation of trade protectionism. According to trade protectionism theory, a country protects domestic industries by raising tariffs, imposing trade volume restrictions, or tightening regulatory measures, thereby directly altering the relative price structure of imported goods and ultimately deteriorating the terms of trade [33]. Through the price channel, higher tariffs increase importers' marginal costs, reducing the price competitiveness of Chinese and other countries' solar PV products in the U.S. market. Through the demand channel, as import demand is sensitive to price increases, importers tend to reduce procurement volumes, leading to a contraction in imports and, consequently, a decline in solar PV exports to the United States. Through the market-structure channel, elevated tariffs reshape the competitive landscape, facilitating substitution toward U.S. domestic producers or a limited number of countries not subject to tariff barriers [34]. As a result, tariff shocks jointly operate through price, demand, and substitution effects to reduce China's exports to the United States, and may further propagate along global value chains to affect a broader set of countries [30]. Accordingly, this study proposes the following hypothesis:

Hypothesis 1. *U.S. tariff measures will significantly reduce China's exports of solar PV products to other countries.*

2.2. Indirect Effects

Following the imposition of U.S. tariff barriers, the external trade environment facing China's solar PV industry has undergone systemic changes. Tariff hikes not only raise the cost of access to the U.S. market for Chinese solar PV products, but also reshape global propensity and the allocation of solar PV trade. Overall, the underlying mechanisms can be analyzed along two interconnected pathways—"trade regime shocks on the domestic supply side" and "changes in the international demand-side export landscape"—which converge through the channel of trade diversion.

(1) Trade Regime Shocks (Supply Side): Domestic Supply Reallocation and Expectation Adjustments

As the world's second-largest solar PV market, the United States tariff increases on solar PV products not only elevate firms' actual export costs but also significantly alter propensity regarding future demand and the global market structure through heightened institutional uncertainty.

First, from the perspective of institutional shock mechanisms, the solar PV industry is characterized by strong economies of scale, high price sensitivity, and rapid inventory turnover. Tariff uncertainty can be quickly transmitted to firms' export entry decisions and investments in technological innovation through channels such as digital trade platforms [35]. Sudden tightening of trade policy not only raises costs directly but also increases uncertainty about future market conditions, inducing risk-averse behavior among firms and generating a "pessimistic expectation shock" [16,36]. Second, according to the reallocation effect in trade models [37], when expected returns in an export market decline, industries with high fixed costs—such as PV module manufacturing—tend to experience rapid reallocation of export destinations. In response to deteriorating propensity in the U.S. market, Chinese firms adjust their export portfolios to maintain capacity utilization and scale advantages, redirecting exports toward countries and regions with faster marginal demand growth, lower market barriers, and more favorable policy environments [38]. This supply-side response is manifested in trade diversion and export reallocation.

Hypothesis 2. *U.S. tariff measures will increase institutional uncertainty, induce pessimistic export propensity for China's solar PV industry, reduce China's overall PV export value, and promote trade diversion in export destinations.*

(2) Changes in the Export Landscape (Demand Side): Global Demand Reshaping

Concurrently with supply-side shocks, global demand for solar PV products undergoes structural changes driven by trade policy uncertainty and adjustments in national energy policies. From a theoretical standpoint, when a country imposes trade sanctions or tariff measures on multiple trading partners, it distorts global trade structures and thereby affects third countries' demand and supply decisions [39]. In the highly integrated global value chain of the solar PV industry, such distortions may generate cascading effects.

According to real options theory [40], when future policy conditions are uncertain, firms tend to preserve the option to wait by postponing irreversible investments until more information becomes available. Given the large scale of equipment investment and high adjustment costs in the PV industry, heightened uncertainty in global clean energy policies following U.S. tariff increases may lead global investors and downstream installers to delay orders, postpone project implementation, or revise short-term demand forecasts downward, resulting in cyclical fluctuations in global PV demand. Besides, demand-side responses are also shaped by heterogeneity in national energy policy objectives. While solar PV demand is closely linked to energy transition strategies, countries differ substantially in policy intensity, instruments, and implementation timelines. For example, European economies pursue relatively stable yet institutionally complex energy transition frameworks, Middle Eastern countries experience rapid demand growth driven by energy diversification strategies, and emerging economies may exhibit demand volatility associated with policy revisions [41,42]. Consequently, the trade-distorting effects of U.S. tariffs are transmitted through diverse policy channels across countries, leading to heterogeneous adjustments in solar PV demand.

These differentiated responses in the global demand structure ultimately affect both the direction and scale of China's solar PV exports, giving rise to new patterns of trade diversion. Accordingly, this study proposes:

Hypothesis 3. *U.S. tariff barriers will induce changes in global PV market demand, thereby generating trade diversion effects in China's solar PV exports.*

2.3. Regional Heterogeneity

Significant cross-regional differences exist in market size, external dependence, import substitution elasticity, and the degree of integration into the PV industry value chain,

resulting in heterogeneous transmission of U.S. tariff shocks across regions. For instance, emerging Asian economies often exhibit rapidly growing PV demand and limited import substitution capacity, making them more likely to absorb exports diverted from the U.S. market. European countries, by contrast, face strong installation demand alongside complex regulatory systems, and may experience both policy coordination effects and intensified competitive pressures. Meanwhile, geographic distance and logistics costs also shape the direction of export reallocation. Moreover, global trade in solar PV modules displays pronounced polarization, with substantial disparities across countries and regions [43,44].

Hypothesis 4. *The impact of U.S. tariff policies on China's solar PV exports differs significantly across regions.*

2.4. Heterogeneity in Risk-Buffering Capacity Across Regional Economic Blocs

In the meantime, regional economic organizations can function as "buffers" against global trade shocks. According to regional economic integration theory, integration processes enhance members' resilience to external uncertainty through mechanisms such as tariff reductions, standards harmonization, institutional convergence, and industrial chain coordination [45]. Specifically, first, reductions in tariff and non-tariff barriers improve trade facilitation among member economies, tightening internal trade linkages and enabling intra-regional markets to absorb part of the shock arising from unilateral tariffs imposed by external countries. Second, mutual recognition of technical standards and institutional coordination reduce regulatory frictions among members and improve the efficiency of cross-border value-chain operations, enhancing substitutability and flexibility of supply chains when confronted with third-country shocks. Third, intra-regional industrial chain coordination—such as vertical specialization and value-chain embedding—strengthens economies of scale within regional blocs, increasing members' resilience to external policy uncertainty and enabling more stable access to intra-regional demand and investment, thereby reshaping global trade patterns [46,47]. Accordingly, the stability and coordination mechanisms of regional economic cooperation organizations can effectively mitigate the external impact of U.S. tariffs and enhance the import and supply-chain resilience of member economies.

Hypothesis 5. *Membership in regional economic cooperation organizations enhances countries' ability to withstand external trade risks.*

In summary, the technical roadmap of this paper is shown in Figure 1.

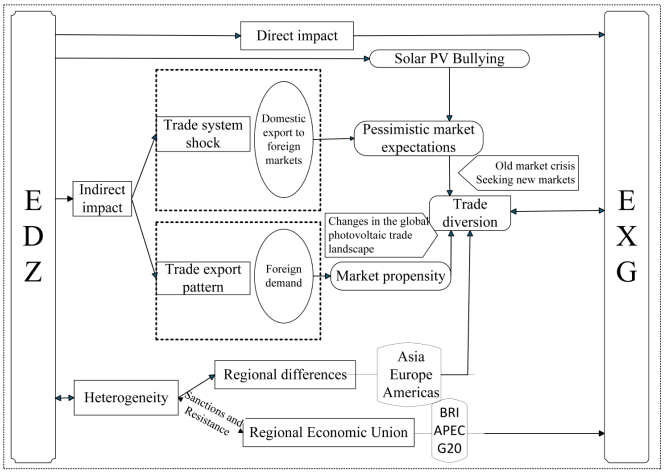


Figure 1. Technology Roadmap.

3. Research Methodology and Data Sources

3.1. Econometric Model

To examine the impact of U.S. tariff barriers on China's solar PV exports, this study employs a baseline DiD model with two-way fixed effects. This baseline specification is designed to capture the combined effect of direct exposure in the U.S. destination and potential effects transmitted through third-country markets. The model is specified as follows:

$$EXG_{it} = \beta_0 + \beta_1 EDZ_{it} + \sum \gamma_i X_{it} + \alpha_i + \delta_t + \varepsilon_{it} \quad (1)$$

where i and t denote country and year, respectively. The dependent variable EXG_{it} represents China's PV exports to country i in year t. The key explanatory variable EDZ_{it} captures the policy treatment effect, and X_{it} is a vector of control variables. α_i and δ_t denote country fixed effects and year fixed effects, respectively, while ε_{it} is the error term. The first difference is at the country level, with 34 treated countries and 15 control countries; the second difference is at the time level, defined by the pre- and post-2018 periods. The sample consists of 34 treated countries whose PV products were subject to the U.S. Section 201 safeguard measure and 15 control countries whose PV products were exempted under the developing-country provision specified in U.S. Note 18(b) of Presidential Proclamation 9693. The complete list of countries and the corresponding classification criteria are reported in Appendix A.

3.2. Explained Variable

The logarithm of China's PV export value is used to capture changes in solar PV exports over the study period. Following existing studies [48,49], HS code 854140 is adopted to measure China's PV export value, Although more detailed classifications are available at the eight-digit level under the EU Combined Nomenclature (CN) and the ten-digit level under the US Harmonized Tariff Schedule (HTS), these classifications do not provide a globally consistent basis for constructing a comparable trade series across all countries in our sample. We therefore retain the six-digit HS classification to ensure international comparability over the study period. With the implementation of HS 2022, the WCO (World Customs Organization: https://www.wcoomd.org/es-es/topics/nomenclature/instrument-and-tools/hs-nomenclature-2022-edition/correlation-tables-hs-2017%E2%80%932022. accessed on 12 November 2020.) correlation table indicates that HS 2017 subheading 8541.40 corresponds to HS 2022 subheadings 8541.41, 8541.42, 8541.43, and 8541.49. To maintain a consistent product scope across HS revisions, we aggregate these four corresponding HS 2022 subheadings and use their combined export value for observations classified under HS 2022. Thus, the dependent variable is constructed at the aggregate product level corresponding to HS 8541.40, rather than treating the four HS 2022 subheadings as separate PV module categories. The logarithm of the resulting export value is then used as the explained variable. To further illustrate the product composition, we conducted an analysis of four corresponding HS 2022 subheadings during the period from 2022 to 2024. During this period, the total export value of HS 8541.42 (unassembled photovoltaic cells) and HS 8541.43 (assembled photovoltaic cells) accounted for more than 90% of the total export value of the four subheadings HS 8541.41, HS 8541.42, HS 8541.43, and HS 8541.49 combined. The more detailed 8-digit harmonized system code (HS 854140) in Jha's research found that it covered over 90% of the EU's import and export trade volume under this code. This result indicates that in the export value covered by these four subheadings in recent years, photovoltaic products have occupied a major share, and thus can be regarded as a reasonable indicator of inter-group trade in photovoltaics [50,51].

3.3. Key Explanatory Variable

The policy shock is assumed to occur in 2018. A dummy variable is constructed based on whether a country's solar PV products are subject to U.S. tariff barriers. Specifically, according to the 201 safeguard document issued by the United States in 2018, if a country's solar PV market is affected, then EDZ_{it} equals 1; otherwise, it takes the value of 0. Here, the US, as the policy enforcer, also has its own photovoltaic market impacted.

3.4. Control Variables

The set of control variables includes economic size (*lngdp*), population size (*lnpop*), international investment activity (*lnfdi*), trade structure (*imports*), and price level (*ppp*), all of which are obtained from the World Bank's World Development Indicators (WDI) database. Controlling for cross-country differences in economic fundamentals, industrial structure, openness, and price competitiveness helps mitigate omitted variable bias and improves the precision of identifying the effect of *EDZ* on *EXG*. To address a small number of missing observations in the dataset, we use linear interpolation based on adjacent years within each country. To assess potential multicollinearity, all explanatory, dependent, and control variables are tested. As reported in Table 1, no multicollinearity concerns are detected. For the variable *lnfdi*, we follow the approach of Levy Yeyati et al. [52] for processing negative values. Please refer to Formula (2) for details.

$$lnfdi = sign(FDI) \cdot log(1+|FDI|) \quad (2)$$

Table 1. Multicollinearity Test.

	VIF	1/VIF
lngdp	5.74	0.174
lnpop	5.66	0.176
ppp	2.86	0.350
imports	1.47	0.682
did	1.27	0.786
lnfdi	1.15	0.866
Mean VIF	3.02	.

Source: results by the authors using Stata 18.0.

3.5. Data Sources

This study uses China's solar PV export data to the top 49 countries along the PV industry chain over the period of 2007–2024 to analyze the impact of U.S. tariff barriers on China's solar PV exports. Specifically, to maximize global geographic coverage across multiple continents, we construct our sample by selecting the top 49 countries ranked by export values during the reference period 2007–2024. Countries with substantial missing data, such as the Democratic People's Republic of Korea, are dropped. A total of 15 country-year observations for solar indicators are imputed using interpolation, representing around 1.70% of the full sample of 882 observations. Export values are obtained from the United Nations Commodity Trade Database (UN Comtrade). The end-of-year net installed solar PV capacity and annual solar PV electricity generation are retrieved from the International Renewable Energy Agency (IRENA) Renewable Energy Statistics database, where installed capacity is measured in gigawatts (GW) and power generation in gigawatt-hours (GWh). The remaining control variables are sourced from the World Bank. All monetary variables are denominated in US dollars. Descriptive statistics are reported in Table 2.

Table 2. Descriptive statistics.

Var Name	Obs	Mean	SD	Min	Max
EXG	882	15.960	3.031	5.861	22.351
EDZ	882	0.270	0.444	0.000	1.000
lnfdi	882	−12.036	18.490	−26.568	30.333
imports	882	45.175	26.058	11.255	208.333
ppp	882	0.545	0.247	0.166	1.588
lngdp	882	26.007	1.519	23.000	31.005
lnpop	882	16.776	1.563	13.854	21.095
EDZ × *solar_cap*	882	3.607	13.770	0	176.843
solar_wh	882	4.957	20.887	0	303.750
export_ex	882	0.412	0.943	0	4.922
EDZ × *export_growth*	882	55.641	148.633	−91.065	945.848

Source: results by the authors using Stata 18.0.

4. Empirical Results

4.1. Baseline Regression

The baseline regression results are presented in Table 3. The coefficient on *EDZ* is consistently negative and statistically significant across all four specifications, indicating that the implementation of U.S. tariff barriers significantly reduced China's solar PV exports to affected countries. As control variables are gradually added, the absolute magnitude of the *EDZ* coefficient changes only moderately, while its sign and statistical significance remain stable, demonstrating the robustness of the estimated policy effect. Notably, after controlling for countries' economic size through lngdp, the absolute value of the *EDZ* coefficient increases slightly, suggesting that differences in economic size may attenuate the estimated policy effect when GDP is omitted. The inclusion of lngdp therefore allows for a more precise estimation of the effect of U.S. tariff barriers.

Table 3. Baseline Regression Results.

	(1)	(2)	(3)	(4)
	EXG	***EXG***	***EXG***	**EXG**
EDZ	−1.152 *** (0.346)	−1.185 *** (0.342)	−1.016 *** (0.350)	−1.016 ** (0.454)
lngdp		1.723 *** (0.386)	1.468 *** (0.508)	1.468 *** (0.536)
lnfdi			0.007 (0.006)	0.007 (0.006)
imports			0.028 *** (0.011)	0.028 ** (0.012)
ppp			1.453 (1.352)	1.453 (1.927)
lnpop			3.270 *** (1.188)	3.270 ** (1.563)
Year Nation	YES YES	YES YES	YES YES	YES YES
Constant	16.271 *** (0.126)	−28.540 *** (10.031)	−78.760 *** (23.485)	−78.760 *** (29.112)
N R^2	882 0.4753	882 0.4861	882 0.4964	882 0.4964

Standard errors in parentheses. ** $p < 0.05$, *** $p < 0.01$. Note: Among them, (4) is clustered at the national level.

The estimated coefficient also indicates a substantial economic magnitude. In column (4), the coefficient on *EDZ* is −1.016. Since the dependent variable is measured in logarithmic form and *EDZ* is a binary variable. This implies that, holding other covariates and country and year fixed effects constant, China's solar PV exports to tariff-affected countries are approximately 63.8% lower than those to the comparison group. This result indicates that the impact of U.S. tariff barriers is not only statistically significant but also economically substantial. In addition, population size and merchandise imports exert significantly positive effects on exports, reflecting the roles of market size, labor endowments, and global value chain linkages.

4.2. Parallel Trends Test

To verify whether the treatment group and the control group followed similar trends prior to the implementation of U.S. tariff measures, the policy variable *EDZ* is decomposed into five leads and five lags around the event. After the implementation of tariff barriers, statistically significant negative effects are observed in the post-treatment periods, except for the third post-treatment period. Although the policy was formally introduced in 2018, the post_2 period (2020) coincided with the global COVID-19 outbreak, which brought widespread disruptions to global supply chains, demand and supply conditions, and cross-border factor flows. This provides a plausible contextual explanation for why the tariff effect is not detectable in that specific year. In addition, relative to many other economies, China adopted comparatively effective pandemic containment policies during this period, which may also help account for the temporary obscuration of the tariff's short-run impact. The parallel trend test results and event-study estimates are presented in Figure 2 and Table 4, respectively.

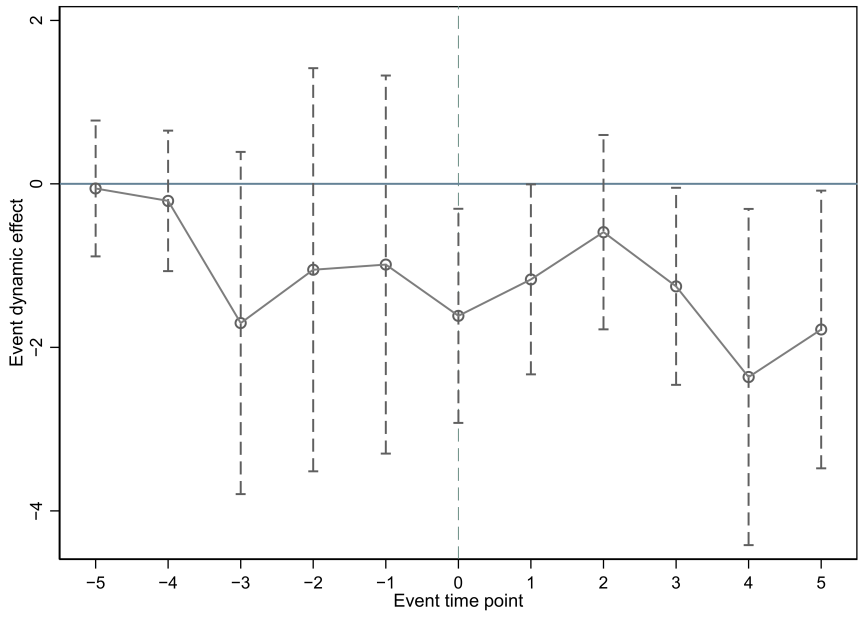


Figure 2. Parallel Trends Test Results.

We note that this interpretation remains suggestive rather than empirically identified. Year fixed effects absorb common global pandemic shocks across all countries, and our baseline specification does not estimate heterogeneous pandemic exposure between treated and control groups. Therefore, we cannot statistically attribute the insignificant estimate in 2020 to differential pandemic effects. Related literature [16] also notes that parallel-trend estimates are affected around 2020 when setting 2012 as the policy shock year, consistent with the view that 2020 represents a period of heightened global economic noise.

Table 4. Event-study regression results.

Year	Time Relative to Treatment	Coefficient	*p* Value	[95% CI]
	pre_5	−0.0556	0.894	[−0.886,0.775]
2014	pre_4	−0.208	0.628	[−1.067,0.651]
2015	pre_3	−1.702	0.109	[−3.795,0.391]
2016	pre_2	−1.050	0.396	[−3.515,1.416]
2017	pre_1	−0.987	0.395	[−3.299,1.326]
2018	current	−1.614 **	0.017	[−2.923,−0.305]
2019	post_1	−1.168 **	0.049	[−2.330,−0.00605]
2020	post_2	−0.590	0.323	[−1.779,0.599]
2021	post_3	−1.253 **	0.042	[−2.458,−0.0481]
2022	post_4	−2.362 **	0.025	[−4.418,−0.306]
2023	post_5	−1.781 **	0.040	[−3.480,−0.0822]
	N	882		
	Joint F-test (pre-treatment coefficients)	$F(5,48) = 0.55$, $p = 0.7398$		

S95% confidence intervals in brackets. ** $p < 0.05$. Note: Clustered at the national level.

4.3. Placebo Test

To further assess the robustness of the model, a placebo test is conducted to rule out spurious significance arising from model misspecification or random factors, thereby ensuring that the estimated effect of *EDZ* is genuine. Specific approach: Randomly select the same number of countries as the benchmark regression sample as the "non-actual treatment group", and generate corresponding dummy variables for non-actual policy shocks. The remaining countries that were not selected are the "non-actual control group". Then, conduct regression according to the benchmark model in Table 3 column 4, repeating this process 500 times. Finally, obtain the estimated coefficients and corresponding *p*-values of 500 non-actual policy shock dummy variables.

As presented in Figure 3, the results show that the distribution of randomly estimated coefficients is largely centered around zero. Compared with the estimated coefficient from the baseline regression (−1.01557), the placebo estimates do not exhibit systematic significance, indicating that the main results successfully pass the placebo test.

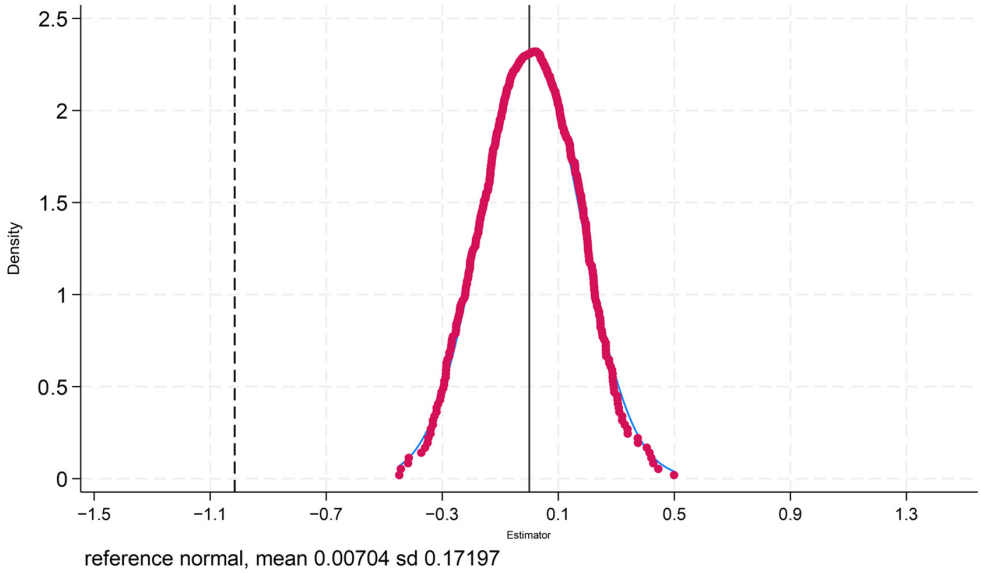


Figure 3. Placebo Test Results. Note: The red dots show the kernel density of coefficient estimates from random permutations. The blue line is the reference normal distribution. The solid black vertical line is our baseline benchmark coefficient, and the dashed black vertical line marks zero.

4.4. Additional Checks

4.4.1. PSM-DID

To address selection bias, this study further employs a propensity score matching difference-in-difference (PSM-DID) approach. Following the empirical strategy of Li et al. [53], we conduct annual matching based on a logit model using the observed characteristics of each country in each year, including *lnfdi*, *imports*, *ppp*, *lngdp*, and *lnpop*. Within each year, a 1:2 nearest-neighbor matching with replacement is performed, with the common-support condition imposed (The balance test is shown in Table 5). Kernel matching and caliper matching are also used as robustness checks. As reported in columns (1)–(3) of Table 6, the coefficients on *EDZ* remain significantly negative, with larger absolute magnitudes than in the baseline estimates, providing further support for the credibility of the results. To further address the issue of selective bias, the text uses the previous period of the policy as the base period for conducting cross-sectional PSM matching. The results are shown in columns (4) of Table 5. The matching results and the selection of covariates are presented in Appendix B.

Table 5. PSM balance test.

Variable	Unmatched Matched	Treated	Control	%bias	|bias|	t	$p > \|t\|$	V(C)
lnfdi	U	−12.599	−11.83	−4.200		−0.550	0.582	1.010
	M	−12.153	−9.652	−13.50	−224	−1.360	0.175	0.840
imports	U	50.17	43.33	25.80		3.480	0.001	1.200
	M	47.46	47.51	−0.200	99.30	−0.0200	0.988	0.28 *
ppp	U	0.574	0.535	16.50		2.080	0.0380	0.65 *
	M	0.573	0.548	10.50	36.50	1.220	0.222	0.940
lngdp	U	26.36	25.88	33		4.300	0.000	0.910
	M	26.34	26.45	−7.400	77.70	−0.760	0.447	0.830
lnpop	U	16.45	16.90	−29		−3.780	0.000	0.910
	M	16.47	16.64	−10.70	63	−1.100	0.274	0.800
Sample	Ps R2	LR chi2	$p >$ chi2	MeanBias	MedBias	B	R	%Var
Unmatched	0.238	244.9	0.000	21.70	25.80	126.9 *	0.41 *	20
Matched	0.0100	6.310	0.277	8.500	10.50	23.60	1.250	20

Standard errors in parentheses. * $p < 0.10$. Note: Clustered at the national level.

Table 6. PSM-DID Checks.

	(1) Nearest Neighbor Matching *EXG*	(2) Kernel Matching *EXG*	(3) Caliper Matching *EXG*	(4) Cross-Sectional Matching (2) *EXG*
EDZ	−2.152 **	−1.348 **	−1.619 **	−1.172 **
	(0.796)	(0.643)	(0.631)	(0.518)
Control Variable	YES	YES	YES	YES
Year	YES	YES	YES	YES
Nation	YES	YES	YES	YES
Constant	−39.243	−80.996 *	−58.684	−69.173 ***
	(55.898)	(47.409)	(45.351)	(24.872)
R^2	0.571	0.489	0.497	0.510
N	257	474	437	576

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Note: Clustered at the national level.

4.4.2. Winsorization

To mitigate the influence of extreme values, all continuous variables are winsorized at the 1% and 5% levels. As shown in columns (1) and (2) of Table 7, the coefficient on *EDZ* remains statistically significant, with an absolute value still exceeding one. This further demonstrates strong robustness of the results.

4.4.3. Excluding the United States

The United States is included in the baseline sample because this study examines the impact of U.S. tariff barriers on China's solar PV exports, including the direct effect on exports to the U.S. market and potential indirect effects on exports to other destination markets. However, these two channels may differ conceptually, and the baseline estimate does not separately identify their effects. To assess whether the main findings are driven primarily by changes in exports to the United States, we re-estimated the baseline model after excluding the United States from the treatment-group sample, while retaining the original treatment and control classifications for all other countries.

Table 7. Additional Robustness Checks.

	(1) 1% Winsorization	**(2) 5% Winsorization**	**(3) Excluding the United States**	**(4) Change the Selected Sample Range**
	EXG	***EXG***	***EXG***	***EXG***
EDZ	−1.042 ***	−1.065 ***	−0.857 **	−0.997 ***
	(0.344)	(0.313)	(0.349)	(0.351)
Control Variable	YES	YES	YES	YES
Year	YES	YES	YES	YES
Nation	YES	YES	YES	YES
Constant	−84.286 ***	−69.772 ***	−80.756 ***	−48.073
	(24.627)	(23.535)	(23.591)	(30.339)
R^2	0.506	0.530	0.495	0.499
N	882	882	882	882

Standard errors in parentheses. ** $p < 0.05$, *** $p < 0.01$. Note: Clustered at the national level.

The column (3) of Table 7 results show that the coefficient on EDZ remains negative and statistically significant after the United States is excluded from the treatment-group sample. This finding indicates that the negative relationship between U.S. tariff barriers and China's solar PV exports is not driven solely by exports to the U.S. market. The main conclusion therefore remains robust when the United States is removed from the estimation sample.

4.4.4. Change the Selected Sample Range

The column (4) of Table 7 results show that the 49 destination countries were selected based on the cumulative value of China's solar PV exports during the entire sample period from 2007 to 2024. Since this selection criterion incorporated the export results observed after the 2018 tariff measures, it may raise concerns about potential post-event sample selection. To address this issue, we conducted additional robustness tests by selecting destination countries solely based on the cumulative export value during the pre-processing period (2007–2017). This alternative standard excluded post-policy export results from the country selection process. There were 7 differences in the baseline sample and the alternative sample (See Appendix B Table A4). The result showed that the coefficient of EDZ remained negative and statistically significant, further enhancing the robustness of the empirical results.

4.5. Mechanism Analysis

To identify whether U.S. tariff measures induce significant trade diversion in China's solar PV exports, this study constructs a unified interaction-term regression framework. The core objective is to assess whether the destination structure of China's solar PV exports is reallocated following the policy shock and to examine whether the economic and structural characteristics of importing countries moderate this reorientation. The empirical model is specified as:

$$EXG_{it} = \beta_0 + \beta_1 EDZ_{it} + \beta_2 EDZ_{it} \times M_{it} + \beta_3 M_{it} + \sum \gamma_i X_{it} + \alpha_i + \delta_t + \varepsilon_{it} \quad (3)$$

where M_{it} denotes alternative moderating variables.

4.5.1. Lagged Market Performance

Following Pan et al. [54] and Wang et al. [55] market propensity are measured by market performance, proxied by the ratio of current-year revenue to the average revenue over the preceding five years. This micro-level expectation measure is extended to the macro level by constructing the ratio of current-year PV export value to the average PV export value over the preceding five years to capture the realized export performance of the solar PV industry. For countries with fewer than five years of observations, the available years of data are used. To mitigate the potential mechanical relationship between the expectation measure and contemporaneous exports, this study uses the one-period lag of lagged market performance as a proxy for market propensity. A higher value indicates more favorable performance for the export market. As shown in Table 8, the interaction term *EDZ* × *L.export_ex* is significantly positive at the 1% level, indicating that favorable lagged market performance can effectively buffer the policy shock. China's solar PV exports thus tend to be directed toward countries with more stable and optimistic lagged market performance.

Table 8. Moderating Effects.

	(1) **EXG**	**(2)** **EXG**	**(3)** **EXG**	**(4)** **EXG**
EDZ	−1.718 ***	−0.842 **	−1.366 ***	−1.346 ***
	(0.42)	(0.358)	(0.373)	(0.372)
EDZ × L.export_ex	0.384 ***			
	(0.116)			
EDZ × export_growth		−0.001 **		
		(0.0005)		
EDZ × *solar_wh*			0.034 *	
			(0.018)	
EDZ × *solar_cap*				0.044 *
				(0.025)
Control Variable	YES	YES	YES	YES
Year	YES	YES	YES	YES
Nation	YES	YES	YES	YES
Constant	−76.635 ***	−79.664 ***	−77.310 ***	−76.851 ***
	(28.490)	(23.718)	(23.22)	(23.307)
R^2	0.498	0.504	0.496	0.507

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Note: Clustered at the national level.

4.5.2. Foreign Market Demand

Table 8 shows that the *EDZ* × *solar_wh* and *EDZ* × *solar_cap* are significantly positive at the 10% level, indicating that the adverse effect of U.S. tariff barriers on China's PV exports is weaker in destination markets with higher solar power generation and greater PV capacity. This suggests that, following the implementation of U.S. tariff measures, China's solar PV exports may be relatively more resilient in markets with more developed PV infrastructure and stronger solar energy deployment. These markets typically have relatively mature PV project pipelines and substantial investment in renewable energy, which may provide more stable demand for imported PV products. For example, Germany, Spain, and Australia represent relatively developed PV markets with established deployment capacity, while Brazil has also become an important large-scale PV market in Latin America. Recent trade patterns provide further contextual evidence: Brazil was the largest destination for China's PV module shipments in the Americas in 2024, while Europe remained an important destination for Chinese solar PV exports.

Meanwhile, the *EDZ*×*export_growth* is significantly negative, indicating that the adverse effect of U.S. tariff barriers is stronger in destination markets where China's solar PV exports had previously grown more rapidly. This finding suggests that markets experiencing rapid expansion in China's solar PV exports may have greater exposure to subsequent trade policy shocks and therefore exhibit larger export adjustments after the implementation of tariff measures. Such markets include emerging PV markets such as India, Pakistan, and Saudi Arabia, which have experienced rapid growth in solar deployment in recent years.

5. Heterogeneity Analyses

5.1. Regional Differences

To further examine whether the effects of U.S. tariff barriers vary across regions, this study divides the sample into three major regions: Asia, Europe, and the Americas. As shown in Table 9, the estimated effects differ across regions, and the pairwise Chow tests indicate that some of these differences are statistically significant.

Table 9. Regional Differences Analysis.

	(1) Asia ***EXG***	**(2) Europe** ***EXG***	**(3) Americas** ***EXG***
EDZ	−1.105 **	−3.153 ***	−3.243 *
	(0.478)	(1.211)	(1.769)
Control Variable	YES	YES	YES
Year	YES	YES	YES
Nation	YES	YES	YES
Constant	−105.268 ***	−48.541	−359.654 *
	(36.331)	(60.899)	(187.636)
R^2	0.514	0.544	0.496
N	450	252	144
N	450	252	144
Chow Test	2.75 *	3.76 **	0.07

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Note: Clustered at the national level. The Chow tests report pairwise differences between regional groups: Asia vs. Europe, Europe vs. Americas, and Americas vs. Asia, respectively. Countries outside Asia, Europe and America were not included in this exercise. This test examines only the between-group differences in the core EDZ coefficients, not a Chow test on all regression coefficients.

The coefficient for Asia is −1.105 and statistically significant at the 5% level, while the coefficient for Europe is −3.153 and statistically significant at the 1% level. The Chow test for the difference between Asia and Europe is statistically significant ($F = 2.75$, $p < 0.1$), indicating that the effect of U.S. tariff barriers on China's solar PV exports differs significantly between the two regions. The coefficient for the Americas is −3.243 and statistically significant at the 10% level. The Chow test between Europe and the Americas is also statistically significant ($F = 3.76$, $p < 0.05$), indicating a significant difference between these two regional groups.

Overall, the results indicate that the impact of U.S. tariff barriers exhibits regional heterogeneity. Significant differences are observed between Asia and Europe and between Europe and the Americas, whereas no statistically significant difference is found between Asia and the Americas. These findings suggest that the effects of U.S. tariff barriers vary across regional markets, although the differences are not uniform across all regional pairs.

5.2. Joint Risk Resilience of Regional Economies

At present, the rise in protectionism has significantly disrupted the trajectory of globalization. The tariffs imposed by the United States on solar PV products exemplify its anti-globalization stance in the new energy sector, aimed at shielding domestic industries and undermining foreign competitiveness through trade barriers. Regional economic integration will have a certain impact on a country's trade exports [56]. Under this circumstance, will there be a significant effect? On the one hand, regional cooperation mechanisms, such as the BRI, APEC, and G20, help maintain the stability of cross-border factor flows through tariff reductions, harmonization of standards, and industrial chain coordination, thereby effectively mitigating uncertainties arising from unilateral policies. On the other hand, regional economic integration enables member states to build more resilient collaborative networks in areas such as new energy transition, green investment, and technology diffusion, thus attenuating the spillover effects of trade protectionist measures by some major economies.

This paper further examines whether regional economic cooperation is associated with differences in the impact of U.S. tariff barriers on China's solar PV exports. The sample is divided according to whether countries are members of the BRI, the APEC, and the G20. As shown in Table 10, the *EDZ* coefficient for G20 members is −1.005 and statistically significant at the 10% level, while the coefficients for APEC and BRI members are −0.378 and −1.033, respectively, neither of which is statistically significant. Although the negative effect remains significant for G20 members, its coefficient magnitude is smaller than that in the benchmark regression, indicating that participation in G20 may partially mitigate the adverse impact of U.S. tariff barriers on China's solar PV exports. This suggests that regional economic cooperation may provide a certain buffering capacity by helping member economies maintain trade connectivity and alleviate the adverse effects of trade protectionism.

To further test the statistical significance of the differences among the groups, we conducted a group difference test based on the interaction terms, as specified in Table 10's notes. For G20 and APEC, the Chow test rejected the null hypothesis of no structural change ($F = 4.37$, $p < 0.05$), and for G20 and BRI, the Chow test also rejected the null hypothesis of no structural change ($F = 3.44$, $p < 0.1$), indicating that there are significant structural differences between these two groups. Overall, these findings suggest that regional economic cooperation may help alleviate the negative impacts of US tariff barriers, although the degree of this buffering effect varies among different regional economic groups.

Table 10. Risk Resilience Capacity of Different Regional Economies.

	(1) G20 *EXG*	(2) APEC *EXG*	(3) BRI *EXG*
EDZ	−1.005 * (0.569)	−0.378 (0.434)	−1.033 (0.634)
Control Variable	YES	YES	YES
Year	YES	YES	YES
Nation	YES	YES	YES
Constant	−61.261 (36.801)	−310.239 ** (133.423)	−59.658 (39.257)
R^2	0.539	0.433	0.497
N	414	252	594
Chow Test	4.37 **	0.65	3.44 *

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$. Note: Clustered at the national level. The detailed classification of countries by BRI, APEC, and G20 membership is provided in Appendix A. The Chow tests report pairwise differences between regional groups: G20 vs. APEC, APEC vs. BRI, and BRI vs. G20, respectively. This test examines only the between-group differences in the core EDZ coefficients, not a Chow test on all regression coefficients.

6. Discussion

The findings of this study engage in a multi-layered dialogue with the existing literature on trade policy shocks, global solar PV value chain adjustment, and regional economic cooperation.

First, with respect to the impact of trade barriers on exports of green energy products, the existing literature has largely focused on anti-dumping and countervailing measures [16], green trade barriers [57], and carbon-related barriers [58]. These studies generally conclude that exogenous policy shocks significantly suppress the cross-border flow of solar PV products, with particularly pronounced effects on upstream manufacturing segments. Our findings regarding U.S. tariff barriers are directionally consistent with this strand of research. However, this study provides a novel evidence on the temporal dimension of policy effects: the impact of the pandemic may have temporarily disrupted the transmission of trade policy effects, resulting in a lack of statistically significant results in 2020.This may reflect that the COVID-19 pandemic could have had some influence on trade policy measures, potentially complicating the interpretation of their effects over time.

Second, with regard to the restructuring of PV export market patterns, existing studies typically emphasize themes such as the "trade diversion effect" [33], "PV value chain reconfiguration" [59], and "overseas technology relocation" [60], arguing that enterprises will actively shift to more complete and stable photovoltaic markets as alternative options under trade frictions. Based on these studies, this paper finds that both the $EDZ * solar_wh$ and $EDZ * solar_cap$ are positively and significantly correlated at the 10% level. This result further indicates that the lagged export performance of importing countries is positively associated with subsequent adjustments in China's PV export structure. This suggests that markets with stronger recent export performance are more likely to remain important destinations during the adjustment of export patterns under trade frictions. By emphasizing the role of lagged market performance, this research expands the literature on global photovoltaic trade and provides additional evidence for understanding the regional differences and structural reconfiguration of China's photovoltaic exports.

Finally, this study provides an empirical test of the role of regional economic cooperation mechanisms, a topic that has received limited attention in the existing literature. While most studies emphasize that regional agreements enhance trade facilitation and attract

foreign investment [61], fewer examine their risk-mitigating function within green energy supply chains. This study reveals that, compared with the BRI, G20 and APEC, the G20 has a weaker ability to buffer the impact of US tariffs on the international photovoltaic market. That is to say, China's export volume to G20 member countries has a significant negative effect. These findings provide empirical support for the recent discussions on regional cooperation and the stability of the global green market.

It is worth noting that this study still has some limitations. Firstly, the data used in this paper are primarily based on country-level solar PV export flows, which limits the ability to capture micro-level firm responses to policy shocks, such as adjustments in product structure or overseas capacity deployment. Future research could integrate enterprise-level data to better identify the micro-dynamics of trade reallocation. Secondly, this paper focuses on export value, while the resilience of the solar PV industrial chain encompasses broader dimensions, including technology, supply-chain networks, and critical raw materials. Future research could combine trade data with global value chain databases to examine how policy shocks propagate across different links. Thirdly, although the market-propensity measure has been replaced with a one-period lagged measure to avoid mechanical overlap with contemporaneous exports, it is still constructed from historical export performance and cannot fully capture forward-looking market propensity. Finally, the HS codes currently used for photovoltaic products still entail certain limitations. Prior to 2022, the six-digit HS codes were not exclusive to photovoltaic modules, as they also covered a portion of LEDs. It was not until the 2022 edition of the HS nomenclature that subheading 8541.40 was split, enabling photovoltaic modules to be classified separately. Therefore, future research can utilize the latest HS coding to achieve more accurate identification and analysis of photovoltaic components. At the same time, independent sources of predictions or indicators of photovoltaic demand expectations can be incorporated to more directly measure market tendencies.

7. Conclusions and Policy Implications

7.1. Research Conclusions

This study examines the impact of changes in the global PV trade environment following the imposition of 2018 Section 201 safeguard by the United States on multiple trading partners on China's solar PV exports. It further investigates the heterogeneous responses of different destination markets to external trade shocks. The main findings are as follows.

(1) U.S. tariff measures imposed on global trading partners significantly reduced China's solar PV exports, with substantial regional heterogeneity. The baseline estimates consistently show negative coefficients for the core policy variable, indicating that U.S. tariff measures not only altered trade relations between the United States and its trading partners but also affected China's solar PV exports through global market linkages and changes in the international trade environment. This finding suggests that, given the high degree of integration and specialization in the global PV value chain, trade restrictions imposed on multiple economies generate significant spillover effects. Chinese PV exporters therefore face not only risks associated with individual markets but also systemic external pressures arising from the tightening of global trade policies. Moreover, the effects differ significantly across regions. The transmission of external policy shocks is also affected by destination-market characteristics, including the level of PV market development, historical market performance, and the growth of China's solar PV exports. Overall, destinations with more mature PV markets and stronger demand foundations exhibit greater resilience to external tariff shocks, whereas markets with more rapid growth in China's solar PV exports are more sensitive to changes in trade policies.

(2) Amid rising external policy uncertainty and accelerating global digitalization, China's solar PV export structure has undergone significant adjustment, with exports increasingly directed toward countries with mature and stable PV markets. The results show that the development and market performance of destination PV markets significantly affect the transmission of tariff shocks. Specifically, the interaction terms between the tariff policy variable and solar power generation, PV capacity, and lagged market performance are 0.034, 0.044, and 0.384, respectively, and are statistically significant. These findings indicate that countries with more developed PV markets and stronger market foundations have greater capacity to absorb external trade policy shocks. Meanwhile, the interaction term between the tariff policy variable and China's export growth to destination markets is −0.001 and statistically significant, suggesting that markets with faster previous growth in China's solar PV exports are more sensitive to external policy shocks. Overall, these findings indicate that China's solar PV exports have undergone a degree of structural adjustment amid rising global trade policy uncertainty, with greater emphasis on destination markets characterized by stable PV demand and relatively mature market conditions, thereby reducing the exposure of export trade to external policy shocks.

(3) Global trade policy shocks are contributing to structural adjustments in China's solar PV export markets. Export responses differ across major economic cooperation frameworks, with distinct estimated coefficients for G20, APEC, and BRI markets, and the formal test of coefficient differences is statistically significant. This finding indicates that changes in global trade policies do not affect all markets uniformly; rather, their effects depend on destination-market characteristics, regional economic linkages, and existing trade relationships. Therefore, strengthening the resilience of China's solar PV exports should not rely solely on the expansion of individual markets. Greater attention should be given to export market diversification, regional trade cooperation, and the diversification of risks across the PV industrial chain.

7.2. Policy Recommendations

Based on the empirical findings, this study proposes the following policy recommendations.

(1) Establish a risk classification and dynamic early-warning system for PV export markets. In response to the spillover effects of U.S. tariff policies on global PV trade, the Ministry of Commerce, customs authorities, and industry associations should establish a dynamic monitoring system covering tariffs, PV demand, installed capacity, and export growth in major destination markets. Markets should be classified into three categories: high-risk markets requiring close monitoring, stable markets, and potential growth markets. For markets with rapid export growth and high sensitivity to policy shocks, early-warning thresholds should be established to encourage firms to reduce excessive dependence on individual markets and avoid concentrated losses caused by sudden changes in external trade policies.

(2) Adopt a differentiated export strategy of "stabilizing mature markets and expanding growth markets." Given the relatively stronger resilience of mature PV markets to external shocks, support should be provided for firms to expand high-efficiency PV modules, energy storage, and integrated energy services in markets such as Europe, Japan, and South Korea, thereby increasing the value added of products in stable markets. For rapidly growing markets in Southeast Asia, the Middle East, and Latin America, firms should strengthen assessments of market access, demand conditions, and trade policies, while expanding market presence through localized sales, after-sales services, and project cooperation rather than relying solely on export volume expansion.

(3) Use regional economic cooperation to mitigate global trade policy shocks. Given the significant differences in export responses across major economic cooperation frameworks,

greater use should be made of platforms such as RCEP, APEC, and the Belt and Road Initiative to promote tariff reductions for PV products, coordination of rules of origin, and mutual recognition of product standards. The Ministry of Commerce, energy authorities, and industry associations could promote information-sharing and dispute-coordination mechanisms for PV trade, while supporting firms in establishing coordinated regional networks covering production, logistics, and project services in key markets. These measures can help diversify market-specific policy risks and strengthen the external resilience of China's PV industry chain.

Author Contributions: J.S.: Software, Writing—review and editing. Y.W.: Methodology, Formal analysis, Writing—Original draft preparation. W.W.: Data curation, Visualization. C.S.: Conceptualization, Funding Acquisition, Supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Key Project of the National Social Science Fund of China (No. 25AGL032): Research on the Governance of Security Risks in China's Solar PV Industry Chain under the background of Trump 2.0.

Data Availability Statement: Data available on request from the authors.

Conflicts of Interest: The authors declare no competing interests.

Appendix A

Table A1. Matched Country Sample and Heterogeneity Group Dummies for DID.

NO.	Nations	Treat	BRI	APEC	G20
1	Argentina	1	0	0	1
2	Australia	1	1	1	1
3	Bahrain	1	1	0	0
4	Bangladesh	1	1	0	0
5	Belarus	1	1	0	0
6	Bulgaria	1	0	0	1
7	Canada	1	0	1	1
8	Chile	1	1	1	0
9	Croatia	1	0	0	1
10	Cyprus	1	0	0	1
11	Czechia	1	1	0	1
12	Estonia	1	1	0	1
13	Greece	1	1	0	1
14	Hungary	1	1	0	1
15	Israel	1	0	0	0
16	Japan	1	0	1	1
17	Kuwait	1	1	0	0
18	Latvia	1	1	0	1
19	Lithuania	1	1	0	1
20	Malaysia	1	1	1	0
21	New Zealand	1	0	1	0

Table A1. *Cont.*

NO.	Nations	Treat	BRI	APEC	G20
22	Oman	1	1	0	0
23	Peru	1	1	1	0
24	Philippines	1	1	1	0
25	Poland	1	1	0	1
26	Qatar	1	1	0	0
27	Rep. of Korea	1	1	1	1
28	Romania	1	1	0	1
29	Saudi Arabia	1	1	0	1
30	Singapore	1	0	1	0
31	Slovenia	1	1	0	1
32	Thailand	1	1	1	0
33	USA	1	0	1	1
34	Vietnam	1	1	1	0
1	Afghanistan	0	0	0	0
2	Brazil	0	0	0	1
3	Cambodia	0	1	0	0
4	Egypt	0	1	0	0
5	India	0	0	0	1
6	Indonesia	0	0	1	1
7	Iraq	0	0	0	0
8	Jordan	0	1	0	0
9	Kazakhstan	0	1	0	0
10	Lebanon	0	1	0	0
11	Nepal	0	0	0	0
12	South Africa	0	1	0	1
13	Sri Lanka	0	1	0	0
14	Ukraine	0	1	0	0
15	Uzbekistan	0	1	0	0

Appendix B

The covariates used in the cross-sectional PSM-DID analysis are divided into two groups. In the first specification, following the conventional approach, all control variables in the baseline model are included as matching covariates. However, because cross-sectional PSM is conducted using data from a single year and the sample contains only 49 countries, including multiple covariates may substantially reduce the number of countries retained after matching, resulting in considerable sample loss. Therefore, in the second specification, we select a smaller set of covariates based on their economic relevance. Specifically, GDP is used to capture differences in countries' economic development and market size; the inflation rate reflects differences in price stability and purchasing power; and net foreign direct investment captures differences in international capital flows, economic openness, and investment environments. This more parsimonious matching specification results

in a more manageable reduction in sample size. Both specifications employ 1:1 nearest-neighbor matching. The corresponding matching results are reported in Tables A2 and A3 of Appendix B. Based on the results of Tables A2 and A3, the second matching result is better. Therefore, in this paper, the second method is presented in the main text.

Table A2. Cross-Sectional PSM-DID Matching Results (1).

Variable	Unmatched Matched	Treated	Control	%bias	|bias|	t	$p > \|t\|$	V(C)
lnfdi	U	−7.394	−18.870	69.700		6.400	0.000	3.95 *
	M	−19.567	−17.114	−14.900	78.600	−1.550	0.123	0.47 *
imports	U	48.718	36.580	50.900		4.760	0.000	2.96 *
	M	41.071	41.360	−1.200	97.600	−0.120	0.907	0.830
ppp	U	0.665	0.389	131.800		12.090	0.000	4.09 *
	M	0.456	0.485	−14.200	89.200	−1.570	0.119	0.46 *
lngdp	U	26.024	25.509	33.700		3.490	0.001	0.860
	M	25.803	25.592	13.800	59.100	1.300	0.197	0.26 *
lnpop	U	16.369	17.563	−83.000		−8.300	0.000	1.230
	M	17.116	17.037	5.5	93.300	0.500	0.619	0.870
Sample	Ps R2	LR chi2	$p >$ chi2	MeanBias	MedBias	B	R	%Var
Unmatched	0.432	260.970	0.000	73.800	69.700	189.4 *	2.32 *	60
Matched	0.079	25.110	0.000	9.9	13.800	67.4 *	1.400	60

Standard errors in parentheses. * $p < 0.10$.

Table A3. Cross-Sectional PSM-DID Matching Results (2).

Variable	Unmatched Matched	Treated	Control	%bias	|bias|	t	$p > \|t\|$	V(C)
lngdp	U	26.174	25.732	29.10		0.94	0.351	0.95
	M	25.644	25.774	−8.5	70.7	−0.32	0.754	0.54
In_inflation	U	25.104	24.352	61.8		1.97	0.055	1.12
	M	24.438	24.533	−7.8	87.4	−0.31	0.759	0.40 *
lnfdi	U	−9.887	−15.814	32.8		1.01	0.319	1.68
	M	−13.688	−14.387	3.9	88.2	0.14	0.893	1.05
Sample	Ps R2	LR chi2	$p >$ chi2	MeanBias	MedBias	B	R	%Var
Unmatched	0.183	11.02	0.012	41.2	32.8	109.3 *	2.18 *	0
Matched	0.002	0.13	0.989	6.7	7.8	10.4	0.70	33

Standard errors in parentheses. * $p < 0.10$.

Table A4. Sample Composition across Alternative Selection Periods.

Nations (2007–2024)	Nations (2007–2018)
Argentina	Afghanistan
Australia	Argentina
Bahrain	Australia
Bangladesh	Bahrain
Belarus	Bangladesh
Bulgaria	Brazil
Canada	Bulgaria
Chile	Cambodia
Croatia	Canada

Table A4. *Cont.*

Nations (2007–2024)	Nations (2007–2018)
Lithuania	Iraq
Cyprus	Chile
Czechia	Croatia
Estonia	Cyprus
Greece	Czechia
Hungary	Egypt
Israel	Greece
Japan	Hungary
Kuwait	India
Latvia	Indonesia
Malaysia	Israel
New Zealand	Japan
Oman	Jordan
Peru	Kazakhstan
Philippines	Lithuania
Poland	Malaysia
Qatar	Mongolia
Rep. of Korea	Myanmar
Romania	New Zealand
Saudi Arabia	Oman
Singapore	Pakistan
Slovenia	Peru
Thailand	Philippines
USA	Poland
Vietnam	Rep. of Korea
Afghanistan	Romania
Brazil	Russia
Cambodia	Saudi Arabia
Egypt	Singapore
India	Slovakia
Indonesia	Slovenia
Iraq	South Africa
Jordan	Sri Lanka
Kazakhstan	Thailand
Lebanon	Türkiye
Nepal	Ukraine
South Africa	United Arab Emirates
Sri Lanka	USA

Table A4. *Cont.*

Nations (2007–2024)	Nations (2007–2018)
Lithuania	Iraq
Ukraine	Vietnam
Uzbekistan	Yemen

References

1. Zhang, S.; Ji, R.; Dou, W.; Hao, Y. As climate risks intensify: How do key digital technologies promote pollution reduction and carbon mitigation? Evidence from China. *Growth Change* **2026**, *57*, e70114. [CrossRef]
2. Shanghai Solar Energy Society. Development status and trends of China's photovoltaic industry. In *Proceedings of the 19th China Symposium on Solar-Grade Silicon and Photovoltaic Power Generation (19th CSPV)*; China Photovoltaic Industry Association: Beijing, China, 2023; pp. 2–24. (In Chinese)
3. Park, S.; Summerfield-Ryan, O. The embodied political ecology of solar energy: Tracing socio-ecological impacts through solar photovoltaic global supply chains. *Energy Res. Soc. Sci.* **2025**, *127*, 104212. [CrossRef]
4. Benguria, F. The global impact of the US–China trade war: Firm-level evidence. *Rev. World Econ.* **2023**, *159*, 827–851. [CrossRef]
5. Panyagometh, K.; Wongsindhuwises, P. China–the United States economic slowdown and their spillovers to ASEAN economies: A GVAR approach with time-varying weights. *Open Econ. Rev.* **2026**, *Advance online publication*. [CrossRef]
6. Wu, D.M.; Wang, C.X. A study of General Secretary Xi Jinping's important discourse on industrial and supply chain security. *Economist* **2025**, *6*, 5–14. (In Chinese)
7. dos Santos Carstens, D.D.; da Cunha, S.K. Challenges and opportunities for the growth of solar photovoltaic energy in Brazil. *Energy Policy* **2019**, *125*, 396–404. [CrossRef]
8. Chadly, A.; Moawad, K.; Salah, K. State of global solar energy market: Overview, China's role, challenges, and opportunities. *Sustain. Horiz.* **2024**, *11*, 100108. [CrossRef]
9. White House. Presidential Memorandum on America First Trade Policy [Memorandum]. Available online: https://www.epi.org/policywatch/presidential-memorandum-on-america-first-trade-policy/ (accessed on 20 January 2025).
10. Chen, J.Y.; Chen, D.B. The impact of Trump's economic and trade protection policy on Sino-US economic and trade relations. *Economist* **2017**, *10*, 96–104. (In Chinese)
11. Zhu, M.; Gong, F.; Yang, S.R. Economic development and strengthening in the era of Trump 2.0. *Stud. Int. Financ.* **2024**, *12*, 6–21. (In Chinese)
12. Capstone, D.C. US–China Tech 2025 Preview: Outlook at a Glance [Policy Preview]. Available online: https://capstonedc.com/wp-content/uploads/2025/05/2025-Preview_us-china_tech.pdf (accessed on 12 May 2025).
13. Bistline, J.E.T.; Wolfram, C. Inflation Reduction Act: Origins, policy implications, and research gaps. *Rev. Environ. Econ. Policy* **2025**, *19*, 258–271. [CrossRef]
14. Han, G.Y.; Cheng, C.L.; Zhu, C. Research on the impact of U.S. economic sanctions on Chinese enterprises' OFDI and industrial chain security. *Asia-Pac. Econ. Rev.* **2025**, *5*, 174–192. (In Chinese)
15. Chen, R.; Wang, Y.F.; Zhang, L.L.; Wang, Q.; Zhang, Y.Q. Resilience and security of China's grain industry chain: Development assessment, spatiotemporal differentiation, and driving mechanisms. *Syst. Eng.-Theory Pract.* **2025**. *Advance online publication*.
16. Lin, B.; Liu, Y. Navigating trade barriers: How anti-dumping and countervailing policies affect outward foreign direct investment of Chinese solar photovoltaic firms. *Energy Policy* **2025**, *206*, 114793. [CrossRef]
17. Deng, J.F.; Zheng, Z.; Shi, J. Time-varying shock effects and policy enlightenment of U.S. trade policy uncertainty on grain prices. *Agric. Econ. Manag.* **2022**, *1*, 79–92. (In Chinese)
18. Hua, J.G.; Feng, M.J.; Sun, W.S. The impact of the uncertainty of US trade policy on the price of Chinese livestock products. *World Agric.* **2022**, *3*, 7–17. (In Chinese)
19. Zhu, X.D.; He, C.F.; Zhu, R.J. How does protectionism change the pattern of the destinations of Chinese photovoltaic export? *Geogr. Res.* **2019**, *38*, 2565–2577. (In Chinese)
20. Tian, K.L.; Yang, C.H. Gain and loss: The dispute of photovoltaic trade between EU and China. *Syst. Eng.-Theory Pract.* **2016**, *36*, 1652–1660. (In Chinese)
21. Hong, J.; Huang, S. An analysis on the economic effects of the AD and CVD duties simultaneously imposed on China's solar energy industry by the U.S. *Econ. Surv.* **2014**, *31*, 49–55. (In Chinese)
22. Hu, X.H.; Chen, L.Z.; Jiang, S.Y. Impacts of trade restrictive measures on strategic emerging industries and policy responses: Evidence from the solar cell industry. *Inq. Into Econ. Issues* **2015**, *2*, 133–139. (In Chinese)

23. Zhang, X.L.; Huang, M.T. Research on the EU's "double-reverse" measures for Chinese photovoltaic enterprises and Chinese coping strategies. *Price Theory Pract.* **2017**, *9*, 128–131. (In Chinese)
24. Wu, Y.L.; Luo, Y.X. Constructing an evaluation model of international trade news dissemination influence: Evidence from the "China-EU photovoltaic trade dispute". *J. Res.* **2015**, *6*, 44–49. (In Chinese)
25. Jiang, L.X. Three dimensions of U.S. reciprocal trade policy and China's response. *J. Int. Relat.* **2022**, *2*, 39–60. (In Chinese)
26. Xing, R. The understanding and response of ASEAN countries to the United States' "Reciprocal Tariffs". *Peace Dev.* **2025**, *5*, 127–156. (In Chinese)
27. Cheng, Y.; Tsang, K. *Trade Policy and Energy Decarbonization: Assessing the Impact of the EU's Trade Defense Measures Against Chinese Solar Panels*; SSRN Working Paper No. 4159388; Edward Elgar Publishing: New York, NY, USA, 2022.
28. Liu, C.S.; Hsiao, C.T.; Chang, D.S. How the European Union's and the United States' anti-dumping duties affect Taiwan's PV industry: A policy simulation. *Renew. Sustain. Energy Rev.* **2016**, *53*, 296–305. [CrossRef]
29. Hughes, L.; Meckling, J. The politics of renewable energy trade: The US–China solar dispute. *Energy Policy* **2017**, *105*, 256–262. [CrossRef]
30. Zhu, X.; He, C.; Gu, Z. How do local policies and trade barriers reshape the export of Chinese photovoltaic products? *J. Clean. Prod.* **2021**, *278*, 123995. [CrossRef]
31. Hajdukiewicz, A.; Pera, B. International trade disputes over renewable energy—The case of the solar photovoltaic sector. *Energies* **2020**, *13*, 500. [CrossRef]
32. Wang, M.; Mao, X.; Xing, Y.; Lu, J.; Song, P.; Liu, Z.; Guo, Z.; Tu, K.; Zusman, E. Breaking down barriers on PV trade will facilitate global carbon mitigation. *Nat. Commun.* **2021**, *12*, 6820. [CrossRef] [PubMed]
33. Tuo, C.J.; Sun, H.; Yang, J.X. Trump 2.0 "Reciprocal Tariffs" and the reshaping of global trade: Trade effects under tariff policy uncertainty. *Consum. Econ.* **2025**, *41*, 19–43. (In Chinese)
34. Chen, W.L.; Wei, H.; Zhou, M.; Huang, J.Z.; Tu, X.Q.; Jia, L.Z.Y. The impact of the United States' reciprocal tariffs on the global economic and trade structure and China's countermeasures. *Int. Bus. Res.* **2025**, *46*, 16–32. (In Chinese)
35. Handley, K.; Limão, N. Policy uncertainty, trade, and welfare: Theory and evidence for China and the United States. *Am. Econ. Rev.* **2017**, *107*, 2731–2783. [CrossRef]
36. Choi, Y.; Cho, S.Y. The effect of foreign competition on firm risk-taking: Evidence from tariff reduction. *J. Bus. Res.* **2024**, *174*, 114532. [CrossRef]
37. Melitz, M.J. The impact of trade on intra-industry reallocations and aggregate industry productivity. *Econometrica* **2003**, *71*, 1695–1725. [CrossRef]
38. Lv, Y.; Zhang, Y.H.; He, M.Y. Impact and countermeasures of the latest U.S. reciprocal tariffs on China's trade. *J. Bus. Econ.* **2025**, *5*, 5–17. (In Chinese)
39. Bown, C.P.; Crowley, M.A. Trade deflection and trade depression. *J. Int. Econ.* **2007**, *72*, 176–201. [CrossRef]
40. Dixit, A.K.; Pindyck, R.S. *Investment Under Uncertainty*; Princeton University Press: Princeton, NJ, USA, 1994.
41. European Council. *European Council (23/24 October 2014) Conclusions*; EUCO 169/14; European Council: Brussels, Belgium, 2014.
42. Mai, T.; Wiser, R.; Sandor, D.; Brinkman, G.; Heath, G.; Denholm, P.; Hostick, D.J.; Darghouth, N.; Schlosser, A.; Strzepek, K. *Renewable Electricity Futures Study: Volume 1. Exploration of High-Penetration Renewable Electricity Futures*; Technical Report NREL/TP-6A20-52409; National Renewable Energy Laboratory: Golden, CO, USA, 2012.
43. Cheng, Y.J.; Liu, X. Dynamic evolution and driving mechanism of global photovoltaic module trade network. *Resour. Sci.* **2023**, *45*, 2322–2340. (In Chinese) [CrossRef]
44. Zhang, M.; Han, M.; Liu, W. Visualizing global photovoltaic supply chains: Dynamics, clusters and drivers. *J. Environ. Manag.* **2025**, *389*, 125919. [CrossRef] [PubMed]
45. Zhang, W.; Cao, S.; Zhang, X.; Qu, X. COVID-19 and stock market performance: Evidence from the RCEP countries. *Int. Rev. Econ. Financ.* **2023**, *83*, 717–735. [CrossRef]
46. Zou, L.; Shen, J.H.; Zhang, J.; Lee, C. What is the rationale behind China's infrastructure investment under the Belt and Road Initiative? *J. Econ. Surv.* **2022**, *36*, 605–633. [CrossRef]
47. Chen, F.; An, P.; Xu, Q.; Jiang, T.; An, H.; Qu, S. Exploring key countries in the tungsten industry chain under the BRI: A spatiotemporal and multilayer trade dependence network perspective. *Resour. Conserv. Recycl.* **2025**, *221*, 108395. [CrossRef]
48. Shuai, J.; Chen, C.; Cheng, J.; Leng, Z.; Wang, Z. Are China's solar PV products competitive in the context of the Belt and Road Initiative? *Energy Policy* **2018**, *120*, 559–568. [CrossRef]
49. Caravella, S.; Crespi, F.; Cucignatto, G.; Guarascio, D. Technological sovereignty and strategic dependencies: The case of the photovoltaic supply chain. *J. Clean. Prod.* **2024**, *434*, 140222. [CrossRef]
50. Jha, V. *Trade Flows, Barriers and Market Drivers in Renewable Energy Supply Goods*; Issue Paper 10; ICTSD: Geneva, Switzerland, 2009.
51. Algieri, B.; Aquino, A.; Succurro, M. Going "green": Trade specialisation dynamics in the solar photovoltaic sector. *Energy Policy* **2011**, *39*, 7275–7283. [CrossRef]

52. Levy Yeyati, E.; Panizza, U.; Stein, E. The cyclical nature of North–South FDI flows. *J. Int. Money Financ.* **2007**, *26*, 104–130. [CrossRef]
53. Li, M.; Zheng, Z.G. Shareholder voting rights delegation in control rights transfer scenarios and corporate performance. *Manag. World* **2024**, *40*, 189–208. (In Chinese)
54. Pan, Y.; Ke, J.J.; Ning, B. Uncertainty shock, government procurement and the resilience of enterprise development. *J. Quant. Tech. Econ.* **2024**, *41*, 193–212. (In Chinese)
55. Wang, Y.L.; Zhao, J.F.; Kong, X.X. Research on the impact of trade friction on the transformation and upgrading of manufacturing enterprises: A quasi-natural experiment based on listed companies in China. *Mod. Financ. Econ.-J. Tianjin Univ. Financ. Econ.* **2025**, *45*, 110–129. (In Chinese)
56. Mamba, E.; Wonyra, K.O.; Evlo, K. Regional (economic) integration, political stability uncertainty and (intra-African) exports. *Econ. Syst.* **2025**, *49*, 101266. [CrossRef]
57. Sun, H.Y.; Dong, G.J. Research on the impact of green trade barriers on the export trade of agricultural products between China and Russia. *Reform* **2019**, *2*, 149–157. (In Chinese)
58. Fu, D.H.; Wang, Y.; Zhang, Y. Carbon barriers in international trade: Development trends, impacts, and China's countermeasures. *Intertrade* **2024**, *4*, 25–35. (In Chinese)
59. Gao, S.; Song, Z. Trade frictions on China's photovoltaic trade and their reshaping effects. *Renew. Energy* **2025**, *244*, 122708. [CrossRef]
60. Jackson, M.M.; Lewis, J.I.; Zhang, X. A green expansion: China's role in the global deployment and transfer of solar photovoltaic technology. *Energy Sustain. Dev.* **2021**, *60*, 90–101. [CrossRef]
61. Zaman, M.; Pinglu, C.; Hussain, S.I.; Ullah, A.; Qian, N. Does regional integration matter for sustainable economic growth? Fostering the role of FDI, trade openness, IT exports, and capital formation in BRI countries. *Heliyon* **2021**, *7*, e08559. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.