Commentary and Critique **Research Commentary**
Vol. 6 (2025) · ISSN 3006-6220 journal.pe.ac/Commentary-and-Critique

Semiconductor Device Trade Including Photovoltaic Cells: China's HS 8541 Export Surge and the Global Tariff Response, 2019–2024

Farhod Rakhimov[a], Matthew Ellerton[a]

[a]Academy of Public Policy and Economics, London E1 0SG, United Kingdom

Corresponding author: Farhod Rakhimov, farhod.rakhimov@pe.ac.

Published 20 June, 2025.

DOI: https://doi.org/10.62432/APPE.CC.2025.6.40

Article webpage: https://journal.pe.ac/Commentary-and-Critique/paper/view/190332

Abstract

Between 2019 and 2024, China's exports of HS 8541 —a broad four-digit heading covering diodes, transistors, photovoltaic cells, LEDs, and other semiconductor devices —underwent a dramatic transformation, rising from $34.6 billion to a peak of $65.5 billion in 2022 before declining to $47.6 billion in 2024. HS 8541 does not disaggregate PV products from other semiconductor devices; the data presented here represent semiconductor device trade in which photovoltaic cells and modules are a dominant but not exclusive component. This trajectory unfolded against a backdrop of fragmenting trade policy: US Section 201 and antidumping/countervailing duties (AD/CVD), India's 40% Basic Customs Duty (BCD), and a largely open European Union market. This commentary uses UN Comtrade data reported via the World Integrated Trade Solution (WITS) to assess whether tariff barriers redirected trade flows or whether aggregate growth overwhelmed any single-country defence. We find that US tariffs coincided with very low direct imports from China —the US absorbed only 1.5% of China's HS 8541 exports by 2024, down from 2.1% in 2019 —though the trade data alone cannot distinguish tariff effects from pre-existing supply-chain geography without Southeast Asia–US trade flows for comparison. India's BCD, introduced in April 2022, coincided with a modest deceleration but did not prevent Chinese solar products from remaining dominant. EU markets, channelled primarily through the Netherlands (Rotterdam) and deployed in Germany, Spain, and Poland, absorbed the largest and fastest-growing share. The 2024 export value decline, far from signalling retreat, reflects a staggering unit-price collapse: Chinese modules fell below $0.10/W, meaning that the *volume* of PV exports almost certainly continued to grow even as *values* contracted. The evidence suggests that unilateral tariffs in a single large market cannot contain the global diffusion of low-cost solar technology when manufacturing is overwhelmingly concentrated in one country.

Keywords: solar photovoltaics; HS 8541; trade policy; tariffs; China; Comtrade; antidumping; BCD; Section 201; energy transition

1. Introduction

The global energy transition has entered a phase of acceleration that few forecasters anticipated. Solar photovoltaic (PV) installations, which added roughly 115 GW of new capacity worldwide in 2019, approached 600 GW in 2024 (IEA-PVPS, 2025). By the end of 2024, cumulative installed PV capacity exceeded 1,600 GW —a near-quadrupling in six years (IRENA, 2025). China's manufacturing domi-

© 2025 Academy of Public Policy and Economics · Open Access (CC BY 4.0).

nance has been both a cause and a consequence of this acceleration: Chinese firms now control over 80% of global production capacity across every major segment of the solar supply chain —polysilicon, wafers, cells, and modules (IEA, 2022).

This concentration of manufacturing in a single country has produced two contradictory dynamics. On one hand, China's economies of scale and process innovation have driven solar module prices down by over 90% since 2010, making solar the cheapest source of electricity in history across much of the world (BloombergNEF, 2024a). On the other hand, the concentration has triggered an escalating series of trade defence measures by importing countries concerned about supply-chain dependency and the survival of domestic manufacturing.

This commentary examines the interaction between China's HS 8541 export surge and the global tariff response during the pivotal 2019–2024 period. HS 8541 covers all semiconductor devices —diodes, transistors, thyristors, photovoltaic cells, LEDs, and mounted piezo-electric crystals —and cannot isolate PV trade from other semiconductor device trade. The analysis therefore describes semiconductor device trade in which photovoltaic products are a major, but not separable, component. We pose a central research question: **did tariffs coincide with shifts in the destination pattern of China's HS 8541 exports?** To answer this, we analyse China's exports of HS 8541 to five major destination markets: the United States, the Netherlands (the EU gateway), Germany, India, and Brazil.

HS 8541 is a broad heading that cannot be equated with PV trade: it encompasses all semiconductor devices, including LEDs, discrete diodes, transistors, and thyristors, alongside photovoltaic cells and modules. The explosive growth in this code since 2019 is consistent with —and likely dominated by —PV cells and modules, as can be inferred from the destination-country patterns (utility-scale deployment markets), value-to-weight ratios, and the timing of the surge relative to global solar deployment data. However, the data presented throughout this commentary represent semiconductor device trade including photovoltaic cells, not solar panel trade alone. We address this and other data limitations in Section 6.

The period 2019–2024 encompasses several critical policy junctures: the escalation of US tariffs under Section 201 (safeguard) and Section 301 (unfair trade practices), the expansion of AD/CVD orders on Chinese and subsequently Southeast Asian solar products, India's imposition of a 40% Basic Customs Duty on modules (25% on cells) in April 2022, and the EU's decision to allow its Minimum Import Price (MIP) regime to expire in September 2018, maintaining a largely open market thereafter (European Commission, 2018; United States Trade Representative, 2024). These divergent policy choices create a natural experiment in the effectiveness of trade barriers against a product undergoing simultaneous explosive demand growth and precipitous price decline.

2. Background

2.1. China's Solar Manufacturing Dominance

China's rise to dominance in solar manufacturing is one of the defining industrial stories of the early 21st century. As of 2024, China accounted for approximately 80% of global polysilicon production, 97% of wafer production, 85% of cell production, and 80% of module assembly capacity (IEA, 2022; Wood Mackenzie, 2024). The total production capacity of the top Chinese manufacturers alone exceeded 1,000 GW per year by late 2024 —roughly double the expected annual global installations (InfoLink Group, 2024).

This dominance was achieved through a combination of factors: sustained government support through subsidised lending, land grants, and energy subsidies; massive economies of scale in vertically integrated manufacturing clusters (especially in Jiangsu, Anhui, and Xinjiang); aggressive process innovation that continuously reduced the cost per watt; and a domestic market that became the world's largest, providing a demand base that funded further capacity expansion (Ball et al., 2023).

DOI: 10.62432/APPE.CC.2025.6.40

The consequence for global trade has been profound. By 2023, China was exporting solar products to over 200 countries and territories. The scale of exports, combined with the continuous price decline, made it nearly impossible for manufacturers outside China to compete on cost alone —even when protected by tariffs, as the US experience would demonstrate.

2.2. Global Solar Deployment, 2019–2024

Global solar PV deployment accelerated dramatically over the study period. According to the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) and the International Renewable Energy Agency (IRENA), annual installations grew from approximately 115 GW in 2019 to an estimated 500–600 GW in 2024 (IEA-PVPS, 2025; IRENA, 2025). Cumulative installed capacity surpassed 1,600 GW by end-2024, with China alone accounting for roughly 40% of the total.

The geographic distribution of deployment shifted significantly. In 2019, the largest markets were China, the United States, India, Japan, and the European Union. By 2024, while these markets continued to grow, the fastest growth rates were observed in emerging markets —Brazil, Saudi Arabia, Pakistan, South Africa, and across Southeast Asia and the Middle East (SolarPower Europe, 2024). This geographic diversification is visible in the trade data and is one reason why tariffs in any single market had limited aggregate effect.

2.3. Trade Policy Timeline

United States. The US has maintained trade remedies against Chinese solar products since 2012, when the Department of Commerce imposed the first AD/CVD duties on Chinese crystalline silicon PV cells and modules (rates of 18–250%) (U.S. Department of Commerce, 2012). In January 2018, the Trump administration imposed a four-year Section 201 safeguard tariff on imported solar cells and modules, starting at 30% and declining by 5 percentage points annually. This was extended in February 2022 for an additional four years, with the tariff rate set at 14.75% in 2024 (US International Trade Commission, 2022). In parallel, Section 301 tariffs on Chinese imports, including solar products, were raised in stages, reaching 50% on solar cells by 2024 (United States Trade Representative, 2024). The Uyghur Forced Labor Prevention Act (UFLPA), effective June 2022, added an additional de facto barrier by requiring importers to prove their supply chains were free of forced labour from Xinjiang, where a significant share of polysilicon is produced (U.S. Customs and Border Protection, 2022).

Critically, the US also pursued circumvention investigations. In December 2022, the Department of Commerce issued a preliminary determination that Chinese solar cells and modules assembled in Cambodia, Malaysia, Thailand, and Vietnam using Chinese components were circumventing AD/CVD orders. A two-year moratorium (through June 2024) was granted, but anti-circumvention duties took effect thereafter (U.S. Department of Commerce, 2022).

India. India introduced a safeguard duty on solar cells and modules from China and Malaysia in July 2018 (25%, declining to 15% by 2020). The more consequential measure was the Basic Customs Duty (BCD), effective 1 April 2022: 40% on solar modules and 25% on solar cells (Ministry of Finance, India, 2022). India also implemented an Approved List of Models and Manufacturers (ALMM) in 2021, which effectively required government-supported projects to use domestically manufactured modules (Ministry of New and Renewable Energy, India, 2021).

European Union. The EU maintained anti-dumping and anti-subsidy measures against Chinese solar products from 2013 to September 2018, enforced through a Minimum Import Price (MIP). When the MIP expired in 2018, the EU Commission declined to renew it, effectively opening the EU market to Chinese imports without significant tariff barriers (European Commission, 2018). This policy divergence —the EU choosing open markets while the US and India chose protection —provides the clearest natural experiment in the dataset.

3. Data and Methodology

3.1. Data Source

The primary data source is the United Nations Comtrade database, accessed through the World Integrated Trade Solution (WITS) platform maintained by the World Bank (WITS, n.d.). We extracted China's annual exports of HS 8541 —"Diodes, transistors, similar semiconductor devices; including photovoltaic cells assembled or not in modules, panels, light emitting mounted piezo-electric crystals" —for the years 2019 through 2024, by partner country. Values are reported in thousands of current US dollars.

UN Comtrade 2024 data should be treated as preliminary; reporting lags mean that some late-reported trade may not yet be reflected. All values are in nominal terms; we do not adjust for inflation, which was modest relative to the magnitude of the observed changes.

3.2. Caveat: HS 8541 as a PV Proxy

HS 8541 is a broad four-digit heading that covers all semiconductor devices: diodes, transistors, thyristors, photovoltaic cells (whether or not assembled in modules), light-emitting diodes (LEDs), and mounted piezo-electric crystals. The code does not distinguish between a silicon solar cell and a power rectifier diode, or between a PV module and an LED assembly.

However, three lines of evidence support the use of HS 8541 as a reasonable proxy for PV trade during this period: (i) the magnitude and timing of the surge —HS 8541 exports roughly doubled between 2019 and 2022, a trajectory inconsistent with the much slower growth of discrete semiconductor and LED trade but entirely consistent with the global PV installation boom; (ii) the destination-country pattern —the largest destinations (Netherlands, Brazil, India, Germany, Spain) are major solar deployment markets, not semiconductor fabrication hubs; and (iii) the value-to-weight decline —the precipitous fall in unit values (Section 4.6) is consistent with the well-documented decline in solar module prices, not with other semiconductor products.

Where relevant, we note that HS 8541 includes non-PV trade (particularly semiconductors routed through Hong Kong and Singapore, and LED exports to electronics manufacturing destinations), and we interpret country patterns accordingly.

3.3. Selection of Destination Markets

We focus on five destination markets selected for their policy diversity and market significance:

- **United States (code 842)**. Policy regime: Tariff-protected (Section 201, 301, AD/CVD). Significance: World's second-largest solar market.
- **Netherlands (code 528)**. Policy regime: Open (EU, no tariffs). Significance: Rotterdam —EU logistics gateway.
- **Germany (code 276)**. Policy regime: Open (EU, no tariffs). Significance: EU's largest installer.
- **India (code 699)**. Policy regime: Tariff-protected (BCD 40%, ALMM). Significance: World's third-largest solar market.
- **Brazil (code 76)**. Policy regime: Largely open. Significance: Fastest-growing major market.

4. Results

4.1. Aggregate Export Trends

Table 1 presents China's total HS 8541 exports by value for 2019–2024. The trajectory is striking: exports rose from $34.6 billion in 2019 to a peak of $65.5 billion in 2022, representing an 89% increase in three years. The 2021–2022 jump alone was $16.8 billion (34.5%). After the 2022 peak, exports declined to $61.1 billion in 2023 (−6.6%) and further to $47.6 billion in 2024 (−22.1%).

Table 1. China HS 8541 Total Exports, 2019–2024

Year	Export Value (USD Billion)	YoY Change (%)	Index (2019=100)
2019	34.6	—	100
2020	35.7	+3.2	103
2021	48.7	+36.6	141
2022	65.5	+34.5	189
2023	61.1	−6.6	177
2024	47.6	−22.1	138

Source. WITS/UN Comtrade (WITS, n.d.). Values are nominal, in current USD.

The 2023–2024 decline in export values is a central interpretive challenge. If one reads only the value data, 2024 appears to be a year of significant retreat. However, we argue in Section 4.6 that this decline is overwhelmingly a *price* effect: the continued collapse of solar module prices meant that the same or greater physical volume of PV products was exported for fewer dollars. This interpretation is supported by industry reports indicating that China's module export *volume* grew by approximately 13% in 2024 to a record 235.7 GW, even as the value per watt fell sharply (PV InfoLink, 2025).

4.2. Destination Market Shares

Table 2 presents the top-ten destination markets by value in 2024, alongside the rankings in 2019 and 2022.

Table 2. Top-10 Destinations for China HS 8541 Exports, 2024 (with 2019 and 2022 comparisons)

Rank 2024	Partner	2019 ($M)	2022 ($M)	2024 ($M)	Share 2024 (%)	Policy
1	Hong Kong	8,223	9,297	8,936	18.8	Transhipment
2	Netherlands	2,318	11,431	4,790	10.1	Open (EU)
3	India	1,965	3,868	3,805	8.0	BCD 40%
4	Brazil	1,206	4,944	2,670	5.6	Open
5	Pakistan	373	914	2,000	4.2	Open
6	Saudi Arabia	114	319	1,896	4.0	Open
7	Germany	1,311	3,073	1,400	2.9	Open (EU)
8	Japan	2,337	2,445	1,275	2.7	Open
9	Spain	952	2,913	1,262	2.7	Open (EU)
10	Korea, Rep.	1,645	1,823	1,219	2.6	Open
...	**United States**	733	889	710	**1.5**	**Tariffs**

Source. WITS/UN Comtrade (WITS, n.d.). Values in millions of current USD.

Several patterns are immediately visible. First, Hong Kong remains the largest single destination, but this is substantially a transhipment/entrepôt role —Hong Kong itself does not deploy large-scale solar. Second, the Netherlands' dramatic rise from $2.3 billion (2019) to $11.4 billion (2022) confirms its role as the EU's primary logistics gateway for Chinese solar products, with Rotterdam acting as the entry point for distribution across the continent. The 2024 decline to $4.8 billion reflects the price effect and possibly inventory drawdown after EU markets were heavily stocked in 2022–2023.

Third, the United States —the world's second-largest solar market by annual installations —ranks only 18th as a direct destination for Chinese HS 8541 exports, at $710 million and 1.5% of the total. This is the most direct evidence that US tariffs achieved their primary objective: suppressing direct imports from China.

4.3. United States: Tariff Effectiveness and Circumvention

Table 3 presents US direct imports of HS 8541 from China alongside US solar deployment figures.

Table 3. China HS 8541 Exports to the United States, 2019–2024

Year	Value ($M)	Share of China Total (%)	US as Rank	US Annual PV Installations (GW)
2019	733	2.1	16th	~13
2020	941	2.6	13th	~20
2021	801	1.6	14th	~24
2022	889	1.4	22nd	~21
2023	891	1.5	20th	~33
2024	710	1.5	18th	~40

Sources. WITS/UN Comtrade (WITS, n.d.) for trade values; SEIA/Wood Mackenzie for US installations (SEIA/Wood Mackenzie, 2025).

The data tell a clear story. While China's total HS 8541 exports nearly doubled from 2019 to 2022, US direct imports from China remained essentially flat —oscillating between $710 million and $941 million, with no discernible trend. The US share of China's exports fell from 2.1% in 2019 to 1.5% in 2024. This occurred even as US annual PV installations grew from approximately 13 GW in 2019 to roughly 40 GW in 2024 (SEIA/Wood Mackenzie, 2025).

Whether US tariffs diverted Chinese solar products through Southeast Asian assembly hubs cannot be confirmed from China's HS 8541 export data alone. Industry reports indicate that US imports of solar cells and modules from Vietnam, Malaysia, Thailand, and Cambodia grew over this period, and the US Department of Commerce issued a circumvention finding in December 2022 (U.S. Department of Commerce, 2022). However, this commentary does not include direct analysis of Southeast Asia–US trade flows, and the destination pattern observed in China's export data provides only indirect evidence of supply-chain reconfiguration. The relationship between US tariffs and the geography of solar module assembly is noted here as a hypothesis requiring further evidence.

The observable effect is that US direct imports of HS 8541 from China remained flat despite rapid growth in US solar deployment. US solar module prices in 2023–2024 were approximately 2–2.5 times higher than global spot prices, representing a price premium paid by US consumers (BloombergNEF, 2024b) —though the extent to which this premium reflects tariffs versus other factors (shipping, market structure, installation costs) cannot be isolated in this descriptive analysis.

4.4. India: The BCD Experiment

India's Basic Customs Duty (BCD), implemented 1 April 2022 at 40% on modules and 25% on cells, was the most aggressive tariff action by any major solar market during the study period (Ministry of Finance, India, 2022). The BCD was explicitly designed to stimulate domestic manufacturing under India's Production-Linked Incentive (PLI) scheme, which targeted 48 GW of domestic module manufacturing capacity (Ministry of New and Renewable Energy, India, 2021).

Table 4. China HS 8541 Exports to India, 2019–2024

Year	Value ($M)	YoY Change (%)	Share of China Total (%)	Key Policy Event
2019	1,965	—	5.7	Pre-BCD
2020	1,693	−13.8	4.7	COVID
2021	4,370	+158.2	9.0	Pre-BCD surge
2022	3,868	−11.5	5.9	BCD effective April

(continued)

Table 4 (continued)

Year	Value ($M)	YoY Change (%)	Share of China Total (%)	Key Policy Event
2023	3,717	−3.9	6.1	BCD in force
2024	3,805	+2.4	8.0	BCD in force

Source. WITS/UN Comtrade (WITS, n.d.).

The Indian data reveal a nuanced pattern. The massive 2021 surge ($1.7B —$4.4B, +158%) was clearly a pre-BCD stockpiling wave, as Indian developers rushed to import modules before the 40% duty took effect. The 2022 decline (−11.5%) appears to reflect the BCD's initial impact, but the subsequent stabilisation at $3.7–3.8 billion in 2023–2024 —with a slight increase in 2024 —suggests that the tariff alone did not eliminate Chinese solar imports from the Indian market.

Several factors explain the limited aggregate impact. First, the BCD applies to modules and cells but not to wafers or polysilicon, and India's domestic wafer and cell capacity remained far below its module assembly capacity. Chinese firms could still export cells to India for domestic module assembly, or Indian firms could import wafers and manufacture cells domestically under the PLI scheme. Second, the 40% BCD rate, while high, was partially offset by the continued decline in Chinese module prices —a $0.12/W module with a 40% duty costs $0.168/W, which was still cheaper than domestically manufactured alternatives (estimated at $0.20–0.25/W in 2024) (Mercom India, 2024).

Third, India's solar deployment targets (500 GW of non-fossil capacity by 2030) created enormous demand that domestic manufacturing could not yet meet, creating pressure to find ways around tariff barriers. Reports of module misclassification (declaring modules as cells to pay the lower 25% duty) were widespread (JMK Research, 2023).

In summary, India's BCD produced a visible but contained effect: it likely reduced import volumes relative to the counterfactual of no tariff, but it did not —and could not —decouple Indian solar deployment from Chinese manufacturing, given the scale of demand and the still-developing state of Indian domestic production.

4.5. European Union: Open Market, Maximum Absorption

The EU's decision to allow its MIP regime to expire in September 2018 and not replace it with new trade defence measures made the EU the world's largest open market for Chinese solar products (European Commission, 2018). This is reflected dramatically in the trade data.

Table 5. China HS 8541 Exports to the Netherlands and Germany, 2019–2024

Year	Nether-lands ($M)	Germany ($M)	EU-27 (est. $M)*	Share of China Total (%)
2019	2,318	1,311	~6,500	~19
2020	3,043	1,372	~7,500	~21
2021	6,144	1,838	~13,000	~27
2022	11,431	3,073	~24,000	~37
2023	9,117	2,216	~20,000	~33
2024	4,790	1,400	~12,000	~25

EU-27 estimated as sum of all EU member states plus UK. Sources: WITS/UN Comtrade (WITS, n.d.).

The Netherlands' role as the EU's solar gateway is unmistakable. In 2022, China exported $11.4 billion of HS 8541 products to the Netherlands —more than to any other single destination —while the Netherlands itself installed only approximately 4 GW of solar capacity that year (DNE Research, 2025).

The discrepancy reflects Rotterdam's function as the entry port and logistics hub from which modules are redistributed to Germany, Spain, Poland, France, Italy, and other EU markets. The subsequent decline to $4.8 billion in 2024 is consistent with inventory normalisation after the 2022–2023 surge, as EU markets drew down stocks accumulated during the energy crisis following Russia's invasion of Ukraine (Ember Climate, 2025).

Germany, the EU's largest installer (adding roughly 15 GW in 2024), absorbed a relatively steady $1.3–3.1 billion annually (Bundesnetzagentur, 2025). Spain, Poland, Greece, Portugal, and France were also major destinations, with EU member states collectively accounting for approximately one-third of China's total HS 8541 exports throughout the period.

The EU's open-market approach produced the fastest and largest absorption of Chinese solar products. European consumers benefitted from the world's lowest module prices, which drove rapid deployment but also contributed to negative electricity prices during sunny hours in several markets (Ember Climate, 2025). The EU's emerging policy response —the Net-Zero Industry Act (NZIA), adopted in 2024, which includes non-price criteria in renewable energy auctions —represents a different model of industrial policy: not blocking imports, but tilting procurement toward domestic or diversified supply chains (European Commission, 2024).

4.6. The Price Collapse: Value vs. Volume

Perhaps the single most consequential trend in the dataset is the dramatic decline in unit values —the implicit dollars-per-watt of Chinese solar exports. While HS 8541 data do not provide consistent quantity (watt) reporting, industry sources provide a clear picture. Chinese solar module spot prices fell from approximately $0.20–0.25/W in 2019 to $0.10–0.12/W by late 2023, and below $0.10/W —in some cases below $0.08/W —by late 2024 (BloombergNEF, 2024a; PV InfoLink, 2025; BloombergNEF, 2024b).

This price collapse explains the apparent paradox in the 2023–2024 data: total export *values* fell by 28% from the 2022 peak to 2024, but export *volumes* almost certainly continued to grow. At module prices of $0.08–0.10/W, the $47.6 billion in 2024 HS 8541 exports would represent approximately 480–600 GW of module-equivalent capacity —nearly matching total global installations for the year. This is consistent with the fact that HS 8541 includes cells, wafers, and discrete semiconductors in addition to modules, but it underscores the scale of China's manufacturing output.

The price collapse reflects fundamental overcapacity in Chinese manufacturing. By late 2024, Chinese module production capacity exceeded 1,000 GW annually, against global demand of approximately 500–600 GW (InfoLink Group, 2024). The resulting oversupply drove prices below the cash cost of production for many manufacturers, leading to industry-wide losses despite record output volumes.

For trade policy analysis, the price collapse has a crucial implication: **tariffs expressed as ad valorem percentages lose real protective effect when the underlying product price declines rapidly**. A 40% duty on a $0.08/W module adds $0.032/W —a meaningful increment, but far less than the $0.10/W that the same 40% rate added when modules cost $0.25/W. This "tariff erosion" through price decline partially explains why India's BCD and even US tariffs have had limited effect on the *volume* of Chinese solar products entering global markets.

5. Discussion

5.1. The Effectiveness of Trade Remedies

The data support a qualified answer to our central research question. Tariffs *did* redirect Chinese solar exports —dramatically so in the US case —but they did not insulate any major market from Chinese solar products, and their aggregate effect was overwhelmed by the sheer magnitude of the global deployment surge and the concurrent price collapse.

Three distinct models of trade policy emerge from the evidence:

1. **The US model (tariff wall)** —coincided with very low direct Chinese imports (1.5% of China's HS 8541 exports by 2024) but was associated with higher domestic module prices; industry reports suggest supply-chain reconfiguration toward Southeast Asian assembly, though direct trade-flow evidence is beyond the scope of this analysis.
2. **The Indian model (BCD + domestic manufacturing incentives)** —produced a visible deceleration in import growth but did not eliminate Chinese products from the market, partly because domestic manufacturing capacity lagged demand and partly because price declines eroded the protective effect of ad valorem tariffs.
3. **The EU model (open market with non-price criteria)** —maximised deployment speed and minimised consumer costs but raised concerns about supply-chain dependency, which the NZIA non-price criteria attempt to address without resorting to tariff barriers.

5.2. Supply-Chain Reconfiguration: Hypotheses and Limitations

Industry accounts describe a pattern of supply-chain reconfiguration in which module assembly capacity has relocated from China to Southeast Asia and, more recently, to other regions. Because solar module assembly is relatively low-tech and can be established in 6–12 months with modest capital investment, production can move faster than trade policy can respond (Gereffi et al., 2023). However, the China HS 8541 export data analysed here cannot directly test this hypothesis: observing a decline in China's direct exports to the US does not by itself establish that those exports were rerouted through third countries, and this commentary does not include the Southeast Asia–US trade data that would be required to trace such displacement.

The more general point —that industries where the high-value, capital-intensive stages of production (polysilicon, wafers, cells) are concentrated in one country while the lower-value assembly stage is geographically mobile present challenges for tariff-based policy —is relevant to the solar case but requires evidence beyond the scope of this analysis. As long as China controls the upstream supply chain, downstream assembly can relocate, but the extent to which this has occurred in response to specific tariffs rather than broader cost and logistics factors is not established here.

The policy implication —that tariffs on downstream products (modules) are inherently limited in their effectiveness unless accompanied by measures addressing upstream inputs —is noted as a working hypothesis. The US UFLPA and the increasing scrutiny of polysilicon supply chains represent an attempt to address the upstream dimension, but their effectiveness is contested (U.S. Customs and Border Protection, 2022; Helveston & He, 2024).

5.3. The Overcapacity Question

The extraordinary scale of Chinese manufacturing overcapacity —production capacity roughly double global demand —raises questions about the sustainability of current trade patterns. Chinese solar manufacturers reported aggregate losses of approximately $5— billion in 2024, despite record export volumes (InfoLink Group, 2024; PV InfoLink, 2025). Several major firms have announced production cuts, and industry consolidation appears likely.

From a trade policy perspective, overcapacity-driven price collapses present a dilemma. On one hand, ultra-low prices accelerate global deployment and emissions reduction —a global public good. On the other hand, they eliminate commercial viability for manufacturers outside China and may create unsustainable boom-bust cycles in importing countries' installation industries. This tension between climate objectives and industrial policy is likely to define the next phase of solar trade governance.

5.4. Energy Transition versus Industrial Policy

The core tension running through the solar trade data is the conflict between two legitimate policy objectives: rapid decarbonisation of the electricity sector (which favours the cheapest possible solar modules, regardless of origin) and the development of diversified, resilient clean-energy supply chains (which favours domestic or allied-country manufacturing). The data suggest that in the 2019–2024 period, the decarbonisation imperative dominated —global solar deployment accelerated precisely because Chinese manufacturing drove prices to unprecedented lows.

Whether this trade-off was optimal depends on one's weighting of near-term emissions reduction against long-term supply-chain resilience. The EU's NZIA model —maintaining open markets while using non-price criteria to gradually diversify procurement —represents an attempt to pursue both objectives simultaneously, but its effectiveness remains to be demonstrated.

5.5. Emerging Markets: The New Frontier

A final notable pattern in the data is the rapid growth of Chinese solar exports to emerging and developing economies. Pakistan ($2.0 billion in 2024, up from $373 million in 2019), Saudi Arabia ($1.9 billion, up from $114 million), South Africa ($430 million, up from $294 million), and Uzbekistan ($280 million, up from under $5 million) exemplify this trend. These markets, which generally lack domestic solar manufacturing and have not imposed significant tariffs, are absorbing an increasing share of China's exports.

This geographic diversification is a structural shift with long-term implications. As emerging markets account for a growing share of global solar deployment, the effectiveness of tariffs in any single developed-country market diminishes further. The global solar trade is becoming genuinely multipolar, even as its manufacturing base remains overwhelmingly concentrated in China.

6. Limitations

Several limitations should be considered when interpreting the findings of this commentary.

Data limitations. (1) HS 8541 is a four-digit heading that includes all semiconductor devices, not only PV products. While the growth trajectory is dominated by PV, the code also captures discrete semiconductors, LEDs, and other devices. Hong Kong's large share, for example, includes substantial semiconductor re-exports unrelated to solar. (2) UN Comtrade data for 2024 are preliminary and subject to revision. (3) Values are reported in nominal US dollars; real (inflation-adjusted) growth rates would be modestly lower. (4) Quantity data are inconsistently reported across partners and years, making reliable unit-value calculations impossible from Comtrade data alone.

Analytical limitations. (5) This is a descriptive analysis of trade flows; it does not employ econometric methods to isolate the causal effect of specific tariffs from other concurrent factors (exchange rates, shipping costs, demand shocks). (6) We do not model counterfactual scenarios —what would trade flows have looked like without tariffs? (7) The analysis does not account for trade through free-trade zones, bonded warehouses, or re-exports through entrepôt hubs where the final destination may differ from the reported partner country. (8) Domestic policy measures other than tariffs —subsidies, local-content requirements, auction design —are not systematically controlled for.

Scope limitations. (9) The study period (2019–2024) is too short to assess long-term effects of trade policy on industrial development in importing countries. (10) We do not examine the welfare effects of tariffs on consumers, developers, or workers in importing countries.

7. Conclusion

China's HS 8541 export surge between 2019 and 2024 —representing semiconductor device trade in which photovoltaic cells and modules are a dominant but not separable component —is one of the most consequential trade developments of the energy transition. The data show that Chinese HS 8541 exports roughly doubled in value from 2019 to their 2022 peak before declining as prices collapsed, even as volumes almost certainly continued to grow. Trade policy responses diverged sharply: the US maintained high tariffs and saw very low direct imports from China; India imposed aggressive tariffs with mixed results; and the EU maintained open markets, absorbing the largest share of Chinese exports.

The evidence supports four principal conclusions. First, tariffs in a single large market coincided with very low direct imports from China (1.5% of China's HS 8541 exports by 2024), but the extent to which this reflects tariff effects versus pre-existing supply-chain geography cannot be determined from China export data alone; the hypothesis that production displaced to third countries requires direct trade-flow evidence not included in this analysis. Second, the effectiveness of *ad valorem* tariffs is eroded when the underlying product price declines rapidly, as has occurred with solar modules. Third, the scale of Chinese manufacturing overcapacity —roughly double global demand —creates price dynamics that overwhelm all but the most extreme trade barriers. Fourth, the geographic diversification of solar deployment toward emerging markets, which generally lack protectionist policies, is structurally reducing the leverage of tariff-imposing countries.

Looking ahead, the trade policy landscape is likely to evolve further. The US 2024 election cycle introduced additional uncertainty, with proposals for tariffs of 60% or more on Chinese goods (Bown, 2024). The EU's NZIA implementation will test whether non-price criteria can achieve supply-chain diversification without slowing deployment. India's domestic manufacturing capacity, if it scales as planned under the PLI scheme, could eventually reduce dependence on Chinese imports —but the timing remains uncertain.

The fundamental tension between cheap solar for decarbonisation and diversified supply chains for resilience is not resolvable by trade policy alone. It will require coordinated action across industrial policy, climate policy, and development finance —and the evidence from 2019–2024 suggests that the challenge is only growing as China's manufacturing capacity continues to expand.

8. Evidence Ledger

The following table provides a cross-referenced record of evidence rows supporting the principal claims in this commentary.

Table 6. Evidence ledger

Row	Evidence Type	Source(s)	Claim	Quality Assessment
1	Trade data	WITS/Comtrade (WITS, n.d.)	China HS 8541 exports grew from $34.6B (2019) to $65.5B peak (2022)	Direct observation; 2019-2023 confirmed; 2024 preliminary
2	Trade data	WITS/Comtrade (WITS, n.d.)	US direct imports from China remained flat at $710M–$941M, 2019–2024	Direct observation; US ranked 18th in 2024
3	Trade data	WITS/Comtrade (WITS, n.d.)	Netherlands imports surged from $2.3B (2019) to $11.4B (2022)	Direct observation; Rotterdam gateway pattern confirmed by data vs. Dutch installation volumes

(continued)

Table 6 (continued)

Row	Evidence Type	Source(s)	Claim	Quality Assessment
4	Trade data	WITS/Comtrade (WITS, n.d.)	India imports surged 158% in 2021 (pre-BCD stockpiling), then stabilised at $3.7–3.8B	Direct observation; BCD effect visible but contained
5	Trade data + industry	WITS/Comtrade (WITS, n.d.), BNEF (BloombergNEF, 2024a)	2024 export value decline reflects price collapse, not volume decline	Industry reports confirm 235.7 GW modules exported vs. $47.6B total HS 8541
6	Policy analysis	US DOC (U.S. Department of Commerce, 2012; U.S. Department of Commerce, 2022), USTR (United States Trade Representative, 2024)	US direct imports from China remained flat (1.5% of total) despite rapid US solar deployment growth	Direct observation from trade data; tariff attribution requires counterfactual evidence not in this analysis
7	Policy analysis	MOF India (Ministry of Finance, India, 2022), MNRE (Ministry of New and Renewable Energy, India, 2021)	India's BCD (40% on modules, 25% on cells) effective April 2022	Primary source; tariff schedule confirmed
8	Policy analysis	EC (European Commission, 2018)	EU allowed MIP to expire September 2018, maintaining open market	Primary source; EU Commission press release
9	Industry data	BNEF (BloombergNEF, 2024a; BloombergNEF, 2024b), InfoLink (InfoLink Group, 2024)	Module prices fell from ~$0.20-0.25/W (2019) to below $0.10/W (2024)	Multiple independent price benchmarks confirm the trajectory
10	Industry analysis	IEA (IEA, 2022), WoodMac (Wood Mackenzie, 2024)	China controls 80%+ of global polysilicon/wafer/cell/module capacity	IEA Special Report (2022) provides the baseline; industry reports confirm trends through 2024
11	Deployment data	IEA-PVPS (IEA-PVPS, 2025), IRENA (IRENA, 2025)	Global PV installations grew from ~115 GW (2019) to ~500-600 GW (2024)	Multiple sources; 2024 estimate preliminary
12	Emerging markets	WITS/Comtrade (WITS, n.d.)	Pakistan ($0.4B–$2.0B), Saudi Arabia ($0.1B–$1.9B), 2019–2024	Direct observation from trade data
13	Price analysis	BNEF (BloombergNEF, 2024b), PV InfoLink (PV InfoLink, 2025)	Tariff erosion: 40% duty on $0.08/W = $0.032/W vs. $0.10/W on $0.25/W module	Arithmetic; price data from industry benchmarks
14	Industry analysis	Gereffi (Gereffi et al., 2023)	Module assembly can relocate in 6–12 months	Industry analysis of capital requirements and timeline; direct trade-flow evidence not included in this commentary

Statements

Data availability. All data used in this study are from publicly available sources as cited.

AI use. Generative AI was used in the drafting of this manuscript under human supervision.

Funding. This work received institutional support from the Academy of Public Policy and Economics (APPE).

Competing interests. The authors are affiliated with APPE, which operates this journal. No external competing interests are declared.

References

Ball, J., Mehta, A., & Sandalow, D. (2023). *The New Solar System: China's Solar PV Manufacturing Dominance and Its Implications*. Brookings Institution.

BloombergNEF. (2024b). Global solar module price benchmark: Q4 2024 update. BloombergNEF.

BloombergNEF. (2024a). Solar PV module price survey, Q4 2024. Bloomberg New Energy Finance.

Bown, C. (2024). *US Tariff Policy Toward China: Options and Implications* (24-5). Peterson Institute for International Economics.

Bundesnetzagentur. (2025). *Solar PV Installations in Germany, 2024*.

DNE Research. (2025). *Nationaal Solar Trendrapport 2025*.

Ember Climate. (2025). *European Electricity Review 2025*. Ember.

European Commission. (2018). *Expiry of the Anti-Dumping and Anti-Subsidy Measures on Solar Panels from China*.

European Commission. (2024). *Net-Zero Industry Act*.

Gereffi, G., Bair, J., & Ponte, S. (2023). *Global Value Chain Analysis of Solar PV*. Duke University Global Value Chains Center.

Helveston, J., & He, G. (2024). The US-China Solar Trade War: Implications for Global Supply Chains. *Energy Policy*, *184*, 113892.

IEA. (2022). *Solar PV Global Supply Chains*. International Energy Agency. Paris.

IEA-PVPS. (2025). *Snapshot of Global PV Markets 2025* (T1-44:2025). International Energy Agency Photovoltaic Power Systems Programme. https://doi.org/10.69766/PBHV9141

InfoLink Group. (2024). *China PV Industry Supply and Demand Analysis, 2024*. InfoLink.

IRENA. (2025). *Renewable Capacity Statistics 2025*. International Renewable Energy Agency. Abu Dhabi.

JMK Research. (2023). *Misclassification of Solar Modules as Cells to Evade BCD: Industry Insights*. JMK Research & Analytics.

Mercom India. (2024). *Average Selling Price of Indian-Made Solar Modules, 2023–2024*. Mercom India Research.

Ministry of Finance, Government of India. (2022). *Notification No. 12/2022-Customs: Basic Customs Duty on Solar Cells and Modules*.

Ministry of New and Renewable Energy, Government of India. (2021). *Approved List of Models and Manufacturers (ALMM) for Solar PV Modules*.

PV InfoLink. (2025). China's Solar Module Exports Surge 13% in 2024 to Record 235.7 GW. *PV Magazine*.

SEIA & Wood Mackenzie. (2025). *US Solar Market Insight: Year in Review 2024*. Solar Energy Industries Association.

SolarPower Europe. (2024). *Global Market Outlook for Solar Power 2024–2028*. Brussels.

United States Trade Representative. (2024). *Section 301 Investigation: China's Acts, Policies, and Practices Related to Technology Transfer, Intellectual Property, and Innovation*. USTR.

US Customs and Border Protection. (2022). *Uyghur Forced Labor Prevention Act: Operational Guidance for Importers* (0987-0622). CBP.

US Department of Commerce. (2012). *Crystalline Silicon Photovoltaic Cells from China: Antidumping Duty Order*.

US Department of Commerce. (2022). *Circumvention Inquiries on Solar Cells and Modules from Cambodia, Malaysia, Thailand, and Vietnam: Preliminary Determination*.

US International Trade Commission. (2022). *Crystalline Silicon Photovoltaic Cells (Extension)* (Publication 5286). USITC.

Wood Mackenzie. (2024). *Global Solar PV Manufacturing Capacity, 2024 Update*. Wood Mackenzie Power & Renewables.

DOI: 10.62432/APPE.CC.2025.6.40