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Port-Level Network and Resilience Analysis of the Solar PV Module Import Supply Chain in the United States

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Abstract

The accelerated expansion of solar photovoltaic (PV) adoption in the U.S. has resulted in a significant reliance on international supply chains. This study conducts a comprehensive port-level network analysis of U.S. solar PV module imports to investigate the supply chain resilience and highlight its key vulnerabilities. Utilizing trade data from U.S. International Trade Commission (USITC) for the period 2019-2024, a directed network was established consisting of 177 trade relations connecting 30 exporting countries to 55 U.S. ports, reflecting a total trade value of $80.225 billion. The study results show a considerable concentration risk within the PV module supply chain, where Malaysia, Vietnam, and Thailand dominate the export, and Los Angeles, New York, and Houston-Galveston together manage around 50% of all PV module imports. Centrality analysis revealed that Cleveland and New York have the highest in-degree centrality, demonstrating their vital role as key entrance points. The use of the Infomap algorithm for community detection recognized 34 unique communities, indicating significant imbalances in the distribution of imports that favor major hubs. Lastly, resilience evaluation using disruption simulation uncovers significant vulnerabilities where excluding Los Angeles alone causes a 24.9% reduction in total U.S. PV module imports, whereas the removals of New York and Houston-Galveston result in losses of 13.5% and 12.4%, respectively. This research makes three key contributions: it extends network-based methods to incorporate renewable energy supply chains with port-level analysis; it develops a replicable approach for quantitative resilience evaluation; and it delivers actionable insights to inform energy security policy and infrastructure planning.

Keywords
PV modules; supply chain resilience; port-level network analysis; centrality measures; resilience evaluation

1. Introduction and Background

The global transition toward renewable energy, and its accelerated adoption, has positioned solar photovoltaic (PV) technology as an essential element of sustainable energy infrastructure. In the United States (U.S.), solar capacity has undergone remarkable expansion, with increasing PV panel installations annually in recent years (IEA, 2023). According to the Department of Energy (DOE, 2022) and Feldman et al. (2023), solar energy is the fastest-growing source for electricity generation capacity in the U.S., driven by powerful policy incentives, including the Inflation Reduction Act, as well as the national targets for achieving a carbon-free power sector. This emphasizes that maintaining supply chain stability and resilience for solar PV modules is a commercial requirement and a policy and climate necessity. However, this rapid adoption has created considerable dependencies on international solar PV module supply chains, as domestic production capacity remains insufficient to meet the demand. The U.S. imports 75-84% of its solar PV modules, mainly from Asian markets (DOE, 2022; Feldman et al., 2023), which exposes the solar energy sector to supply chain interruptions that might risk the national energy security and climate objectives.

Recent global events have underscored the fragility of international supply chains. For example, the COVID-19 pandemic, geopolitical conflicts, and natural disasters have frequently indicated how regional disruptions can cascade across supply chains and interconnected networks, resulting in extensive effects on crucial industries (Lücker et al., 2024). In the solar PV sector, supply chain instabilities have resulted in module shortages, increased material prices, and bottlenecks that hinder the global deployment of PV systems (IEA, 2023). The centralized nature of manufacturing capacity in particular regions, along with restricted diversification of supply routes, increases these risks and emphasizes an urgent necessity for an intensive resilience evaluation (Wang & Liu, 2024). Traditional supply chain analysis tends to emphasize country-level trade flows, excluding the fundamental influence of port infrastructure on supply chain resilience (Hosseini et al., 2019; Xu et al., 2020; Lam & Bai, 2016). U.S. ports are crucial gateways for international trade (Bak et al., 2020); however, their vulnerabilities and interdependencies remain insufficiently examined with regard to solar PV module imports. Disruptions related to ports, such as those caused by natural disasters, labor conflicts, infrastructure malfunctions, or security issues, can significantly limit import capacity and affect downstream supply chains (Ivanov, 2020; Zhou et al., 2021).

Network theory has emerged and been used as a powerful framework for studying and analyzing complex supply chain interactions and points of vulnerability. Freeman (1978) and Brandes (2001) developed essential centrality metrics for identifying critical nodes in networks, and subsequent studies, such as Hosseini et al. (2019), Kim et al (2011), Li et al. (2022), and Ma et al. (2024), have modified these centrality metrics for application in supply chains. Solar PV module supply chains (Figure 1) have distinctive and unique structural characteristics, in which the PV module manufacturing process follows a sequential set of steps: polysilicon (Si) production, wafer manufacturing, cell fabrication, module assembly, and PV module distribution (Erol et al., 2024). The linear structure of this supply chain, coupled with the geographic concentration of manufacturing capacity, creates vulnerabilities and weaknesses in the supply chain.

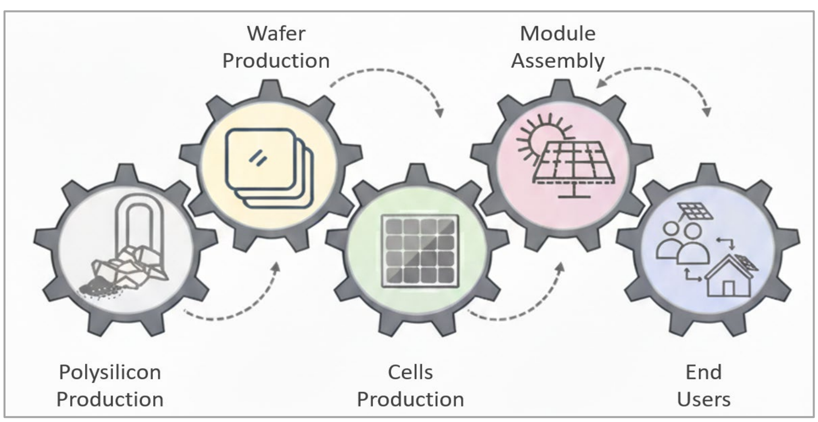

Figure 1. PV Module Supply Chain

Although there is a growing recognition of the renewable energy supply chains and their vulnerabilities and distributions, there are some research gaps that remain. First, most studies explored the national or regional levels, missing the detailed granular port-level dependencies that define import flows (Ma et al., 2024). This limitation is particularly critical because port infrastructure restrictions can introduce bottlenecks to the supply chain. Second, most resilience assessment studies use theoretical frameworks instead of comparative and integrated quantitative modeling and analysis of actual trade data (Ma et al., 2024; Roshani et al., 2024). Although conceptual models offer important insights, they might be unable to adequately capture the complexity of trade flows, seasonal fluctuations, and dynamic supply patterns that reflect the actual nature of supply chains. Although supply chain network resilience is defined as "the ability to anticipate, prepare for, respond to, and recover from disruptions" (Cinti et al., 2024), empirical exploration using real data remains limited. Third, current supply chain network analysis studies have not sufficiently examined the challenges of renewable energy trade. Solar PV module supply chains have a unique structure and their own characteristics. Current research identifies the need to expand polysilicon (Si), wafer, cell, and module manufacturing capacity by 2030 (Erol et al., 2024), but recent studies focus on country-level instead of port-level analysis. This study addresses these gaps by performing a comprehensive port-level network analysis of U.S. solar PV module imports, utilizing real trade data to evaluate this supply chain resilience and recognize key vulnerabilities. The primary objectives are:

(a) to develop and visualize the U.S. solar PV module import supply chain as a directed network utilizing port-level trade data.
(b) to identify primary supplier countries and main U.S. entry ports according to the trade volumes and values; and
(c) to evaluate network resilience through structural analysis and disruption scenario simulations.

This study has several key contributions to supply chain resilience literature. First, it expands network-based methods for supply chain research by recognizing their relevance to renewable energy (i.e., PV module) trade and confirming the significance of port-level analysis. Second, it provides a replicable approach for assessing supply chain resilience along with disruption simulation. Third, the study results provide insights into U.S. energy security policy through determining critical infrastructure dependencies and quantifying potential risks related to import concentration, which provides actionable insights for supply chain diversification initiatives, port infrastructure priorities, and improving emergency backup planning.

This paper is structured into five sections: introduction; the methodology outlines data collection, network construction, network analysis, and resilience evaluation; the results illustrate network visualization, centrality analysis, and simulation results; and the conclusion summarizes key insights and future research directions.

2. Method

The method applied in this study (Figure 2) includes the following steps:

(a) Data Collection: The dataset for this study was obtained from the database of the U.S. International Trade Commission (USITC), selecting 'Imports for Consumption' trade flow data. The dataset collected has 3,548 samples from 2019 to 2024 and was filtered to include Harmonized Tariff Schedule (HTS) commodities like PV cells, PV modules, light-emitting diodes, and semiconductor devices.
(b) Data Cleaning: To ensure completeness and accuracy, the collected dataset was checked for any missing or zero values. Valid and cleaned records were then aggregated annually for the needed analysis.
(c) Network Construction: The dataset was analyzed to identify the top exporters, major U.S. ports, and top trade routes by total trade value. Also, a directed network (Country → Port) was created, consisting of trade value, quantity, and edge weights. Community detection algorithms were applied to identify clusters within the network.
(d) Network Analysis: The network nodes' significance was evaluated by calculating three centrality measures: in-degree centrality (countries shipping to each port), out-degree centrality (major exporting countries), and betweenness centrality (key connectors). This analysis revealed critical hubs and dependencies within the trade network.
(e) Resilience Evaluation: In this step, the top 20 ports were removed from the network to evaluate the network vulnerability and resilience after each port removal. The total import flow was recalculated to recognize the reduction percentage and the impact of port dependency on the PV module network resilience.
(f) Interpretation: The last step involves discussing the study results and providing recommendations for improving the PV supply chain performance.

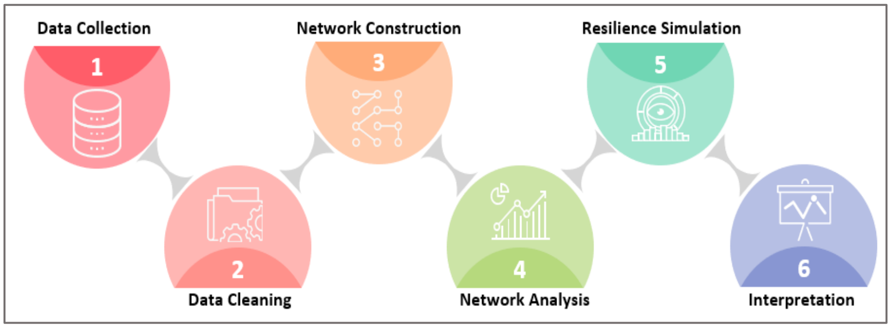

Figure 2. Study Method

3. Results and Discussion

3.1 Network Overview

The constructed port-level for the U.S. solar PV module import network consists of 177 distinct trade relationships connecting 30 exporting countries (source nodes) to 55 U.S. ports (destination nodes) for the period 2019-2024. The network's total trade value for all relationships is $80.225 billion, with a cumulative quantity of 36,847 million units imported from 2019 to 2024. As visualized in Figure 3, the port-level network presents the concentration of flows into a limited number of U.S. ports, with Los Angeles, New York, and Houston-Galveston dominating the structure. This visualization provides the basis for subsequent structural and resilience analyses.

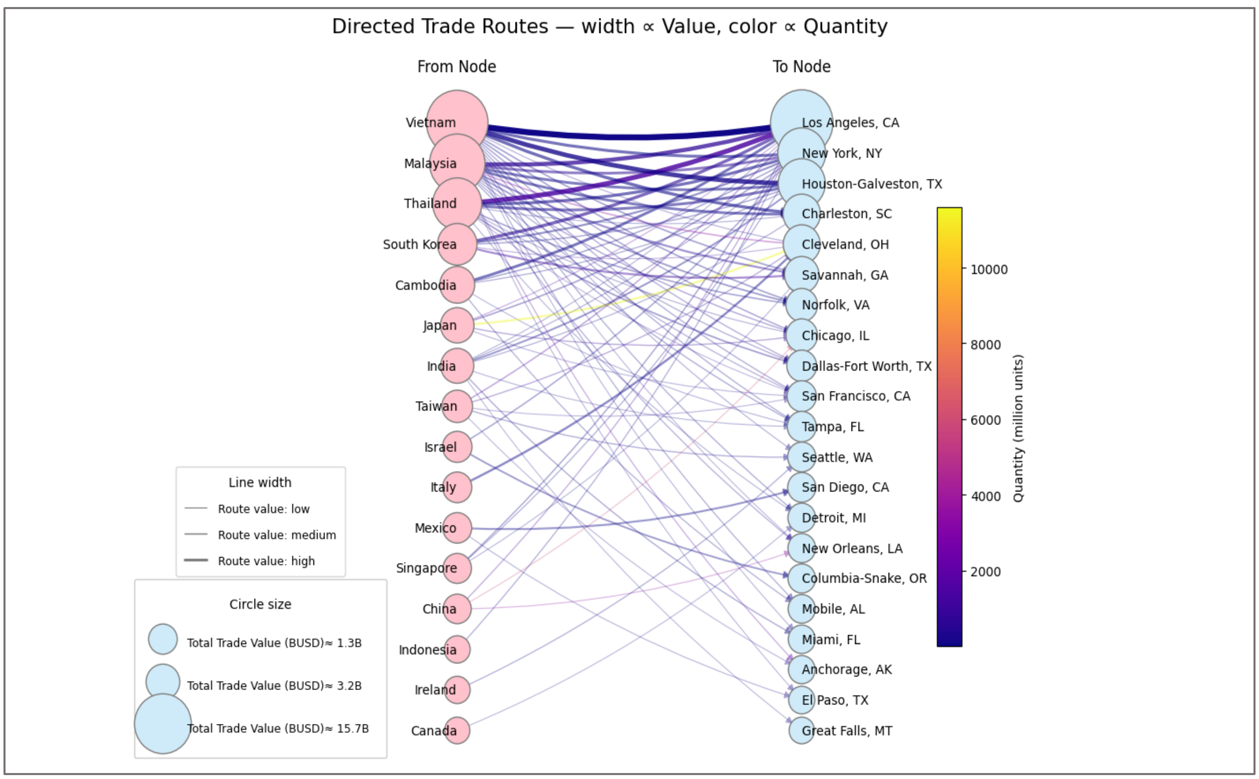

Figure 3. Port-level Network Visualization of U.S. Solar PV Module Imports (2019–2024)

3.2 Trade Flow Analysis

3.2.1 Major Exporting Countries and Primary U.S. Entry Ports

The network analysis revealed only a few countries that export solar PV modules to the U.S. (Figure 4). Malaysia, Vietnam, and Thailand represented the most significant portions, each of which exports to over 20 U.S. ports. This aligns with Erol et al.'s (2024) study, which highlights that global PV production is geographically concentrated in China and a few Asian countries, which leads to supply chain vulnerabilities. Regarding the U.S. side (Figure 5), Los Angeles, New York, and Houston-Galveston collectively handled nearly 50% of total PV module import flows during the study period, highlighting their significance as strategic entry ports. This dominance aligns with Inomata and Hanaka (2024), who highlighted that most global supply chains exhibit network concentration, with manufacturing and trade heavily centered in a few nodes, thereby increasing the risks when disruptions occur.

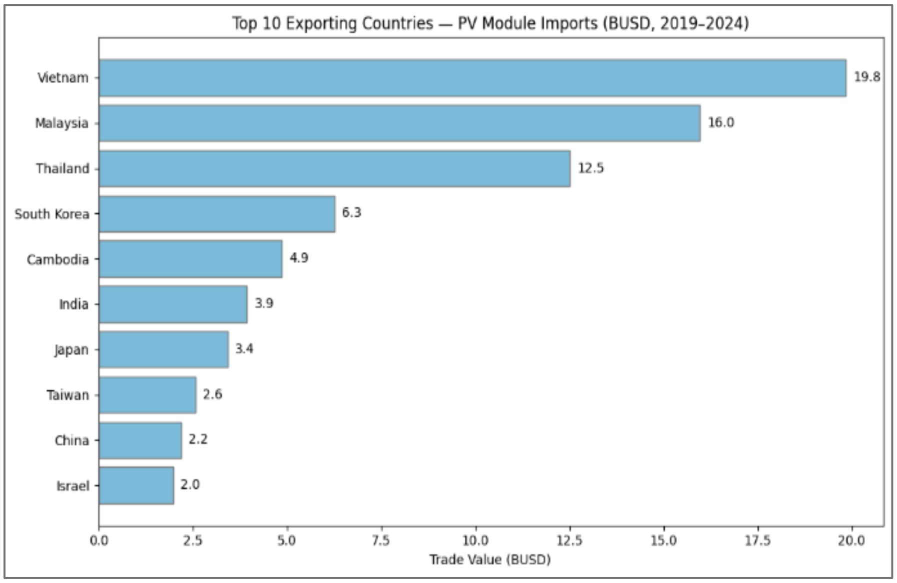

Figure 4. Top 10 Exporting Countries of PV Modules to the U.S., 2019–2024 (BUSD).

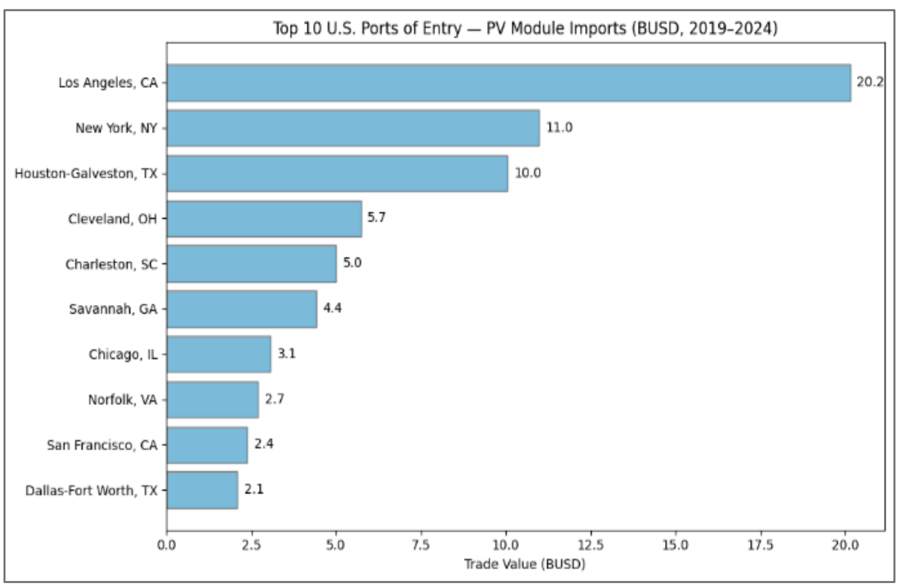

Figure 5. Top 10 U.S. Ports of Entry for PV Module Imports, 2019–2024 (BUSD).

3.2.2 Major Trade Routes and Port Dependence

As per Inomata and Hanaka (2024), network concentration analysis requires dual evaluations, including trade volume and the frequency of interactions among specific routes. Table 1 and Figure 6 present the top 30 trade routes for PV module imports to the U.S. for the period from 2019 to 2024. The results emphasize that such a supply chain is profoundly dependent on a limited number of high-value trade routes. The largest route is from Vietnam to Los

Angeles, with $5.22 billion and more than 74 million units. Collectively, the first five routes listed in Table 1 represent almost one-third of total PV module imports, demonstrating the crucial role of Southeast Asian exporters and U.S. West Coast and Gulf Coast ports. Following the top five routes, significant flows involve Vietnam to Charleston (2.30 BUSD), Thailand to New York (2.19 BUSD), and Vietnam to New York (2.16 BUSD), showing a growing diversification across East Coast ports. Interestingly, the route from Japan to Cleveland is differentiated by a trade value of 1.30 billion USD and an exceptionally large cargo volume of 11,596.9 million units, reflecting distinctive trade patterns in product composition or reporting. In addition, the imbalance between value and quantity across routes suggests possible vulnerabilities, where high volume but low value flows might cause logistical bottlenecks in the case of distribution.

Table 1. Top 30 PV Module Trade Routes by Total Import Value and Quantity, 2019–2024.

#	*From*	*To*	*Trade Value (BUSD)*	*Quantity (M Units)*
1	Vietnam	Los Angeles, CA	5.224	74.412
2	Thailand	Los Angeles, CA	4.034	1,432.92
3	Vietnam	Houston-Galveston, TX	3.783	176.369
4	Malaysia	Los Angeles, CA	3.369	721.378
5	South Korea	Los Angeles, CA	2.393	496.594
6	Vietnam	Charleston, SC	2.302	21.536
7	Thailand	New York, NY	2.186	33.171
8	Vietnam	New York, NY	2.162	25.252
9	Cambodia	Los Angeles, CA	2.027	33.434
10	Thailand	Houston-Galveston, TX	1.978	105.654
11	Malaysia	Houston-Galveston, TX	1.934	31.567
12	Malaysia	Charleston, SC	1.908	21.014
13	Malaysia	New York, NY	1.894	479.058
14	Italy	Cleveland, OH	1.485	17.456
15	Japan	Cleveland, OH	1.303	11,596.89
16	South Korea	Savannah, GA	1.302	988.565
17	South Korea	New York, NY	1.213	8.616
18	Malaysia	Savannah, GA	1.201	474.149
19	Mexico	San Diego, CA	1.164	27.168
20	India	Houston-Galveston, TX	1.038	5.882
21	Israel	Columbia-Snake, OR	0.957	0.3
22	Malaysia	Norfolk, VA	0.902	10.207
23	Thailand	Dallas-Fort Worth, TX	0.841	178
24	Vietnam	Savannah, GA	0.785	49.894
25	Vietnam	Norfolk, VA	0.764	5.998
26	Malaysia	Cleveland, OH	0.745	3,376.04
27	Japan	New York, NY	0.74	215.371
28	Thailand	Norfolk, VA	0.709	6.492
29	Israel	New York, NY	0.659	4.636
30	Taiwan	Los Angeles, CA	0.638	1,322.80

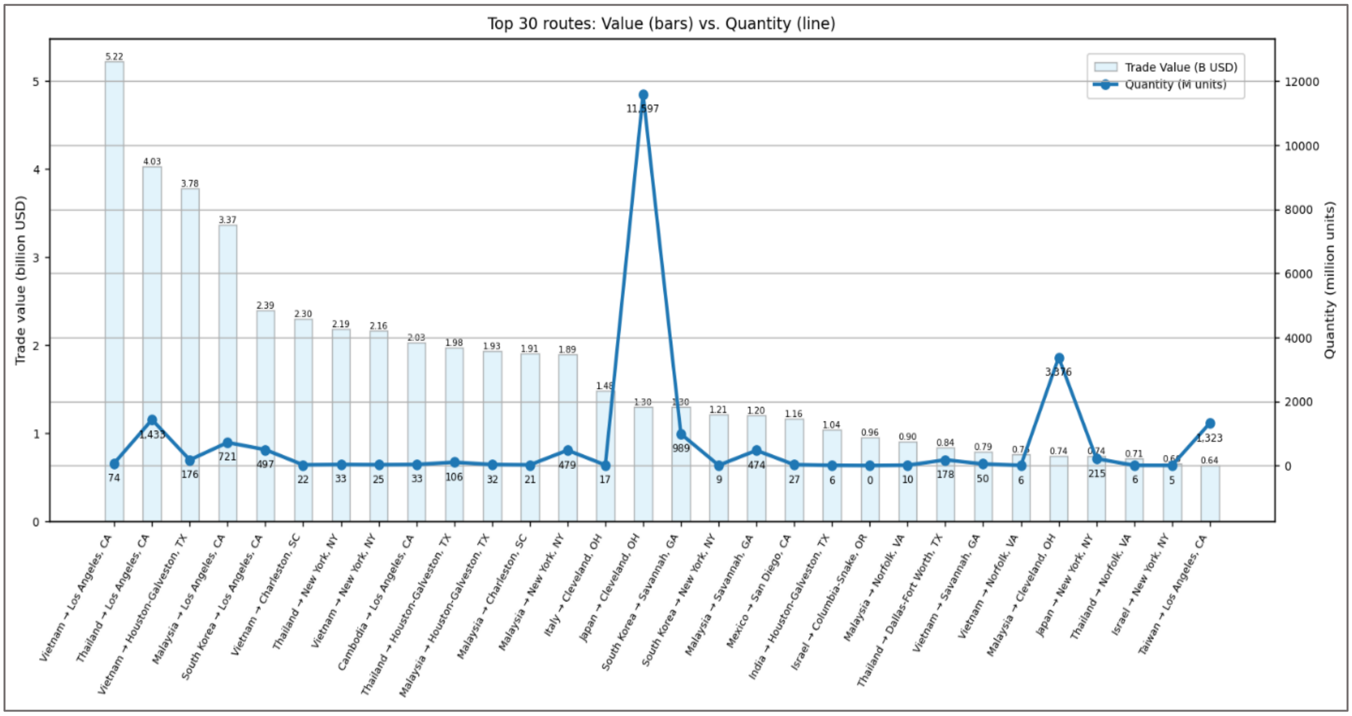

Figure 6. Top 30 PV Module Import Routes: Trade Value (bars, billion USD) Vs. Quantity (line, million units).

3.3 Centrality Analysis

Centrality analysis involves three key measures to provide insights about structural importance, network vulnerabilities, and the key hubs:

(a) In-Degree Centrality (C_{in}): It measures the number of nodes (countries) exporting/sending goods to a given port (Brandes, 2001; Freeman, 1978), such as the Los Angeles and San Diego ports. For a node $\boldsymbol{v}$, the in-degree centrality is calculated as:

$$C_{in}(v) = \frac{d_{in}(v)}{N-1}$$

Where:

- $d_{in}(v)$ is the in-degree of the node v, which consists of the number of incoming edges (i.e., from exporters to a port).
- N is the total number of nodes in the graph (i.e., all exporters and ports).

(b) Out-Degree Centrality (C_{out}): It measures how many ports a particular node (country) exports to (Brandes, 2001; Freeman, 1978). For a node $\boldsymbol{v}$, the out-degree centrality is calculated as:

$$C_{out}(v) = \frac{d_{out}(v)}{N-1}$$

Where:

- $d_{out}(v)$ is the out-degree of the node v, which consists of the number of edges going out (i.e., from a country to ports).
- N is the total number of nodes in the graph (i.e., all exporters and ports).

(c) Betweenness Centrality (C_B): It identifies nodes (countries) that act as bridges or connectors in the network (Brandes, 2001; Freeman, 1978). For a node $\boldsymbol{v}$, the betweenness centrality is calculated as:

$$C_B(v) = \sum_{\substack{s \neq v, \\ t \neq v, \\ s \neq t}} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Where:

- $\boldsymbol{\sigma_{st}}$ is the number of shortest paths from the node $\boldsymbol{s}$ to node $\boldsymbol{t}$.
- $\boldsymbol{\sigma_{st}(v)}$ is the number of paths that pass the node $\boldsymbol{v}$.

Table 2. In-degree and Out-Degree Counts and Centrality Values of U.S. Ports (2019–2024)

In-Degree				Out-Degree			
#	Node	Count	Centrality	#	Node	Count	Centrality
1	Cleveland, OH	14	0.254545	1	Malaysia	23	0.418182
2	New York, NY	14	0.254545	2	Vietnam	22	0.4
3	Los Angeles, CA	13	0.236364	3	Thailand	21	0.381818
4	Chicago, IL	10	0.181818	4	India	15	0.272727
5	New Orleans, LA	10	0.181818	5	Cambodia	14	0.254545
6	San Francisco, CA	10	0.181818	6	China	12	0.218182
7	Savannah, GA	9	0.163636	7	South Korea	8	0.145455
8	Houston-Galveston, TX	8	0.145455	8	Taiwan	8	0.145455
9	Nogales, AZ	8	0.145455	9	Japan	7	0.127273
10	Seattle, WA	8	0.145455	10	Germany	6	0.109091
11	Dallas-Fort Worth, TX	6	0.109091	11	Israel	6	0.109091
12	Detroit, MI	6	0.109091	12	Singapore	6	0.109091
13	Tampa, FL	6	0.109091	13	Indonesia	5	0.090909
14	Charleston, SC	5	0.090909	14	Canada	4	0.072727
15	Mobile, AL	5	0.0909	15	Philippines	4	0.07272

As indicated in Table 2, Cleveland, OH, and New York, NY show the highest in-degree centrality, followed by Los Angeles and Chicago as the primary entry ports for PV modules. This emphasizes a concentration of imports across a few key hubs. For the exporter side, Table 2 also shows that Malaysia, Vietnam, and Thailand dominate the out-degree centrality, highlighting their wide distribution to U.S. ports. Lastly, betweenness centrality values are zero for all ports, indicating that the PV module trade flows are direct (country-to-port); there are no bridging nodes in the network.

3.4 Community Detection

The Infomap algorithm was applied due to its effectiveness for directed and weighted networks. It conceptually aligns best with the study scope, which focuses on analyzing trade-flow resilience, and it detects communities where PV module shipments tend to remain. In other words, it groups ports according to their strong trade connections; therefore, Infomap distinguishes between sub-systems with supply chain disruptions and those where shocks may spill over (Rosvall & Bergstrom, 2008). The results (Figure 7) identified 34 different communities in the U.S. PV module import network. Major communities are concentrated on key hubs such as Los Angeles, New York, and Cleveland, while smaller communities capture more localized flows. The findings show that the network (Figure 7) is unbalanced, where a limited number of large groups of ports handle the majority of the imports, and the remaining are small groups that handle much less trade. This disparity affects the supply chain resilience, in which disruptions in small communities can be contained and controlled; whereas the heavy reliance on a few major hubs means that disturbances at these ports can be propagated rapidly across the supply chain. Likewise, Li et al. (2022) stressed that disruptions at primary hub ports may negatively impact the performance of entire maritime networks.

3.5 Resilience Evaluation

The resilience assessment involves simulating the removal of the major U.S. entry ports to assess the impact on total PV module import flows. With a baseline value of 80.225 BUSD, the results indicate that disruptions at the primary few hubs lead to significant declines in total import value. As Table 3 illustrates, removing Los Angeles alone reduces imports by 24.9%, followed by New York (13.5%) and Houston-Galveston (12.4%). On the other hand, removal of other ports causes less than a 7% drop, and many below 2%. According to Erol et al. (2024) and Zhu et al. (2024), linear and concentrated supply chains allow for vulnerabilities and fragility, and supply chain resilience, on the other hand, requires diversifying capacity over different geographies. Similarly, Inomata and Hanaka (2024), Li et al.

(2022), and Zhu et al. (2024) emphasize that supply systems characterized by repeated reliance and dependence on a limited number of corridors have increased exposure to operational interruptions.

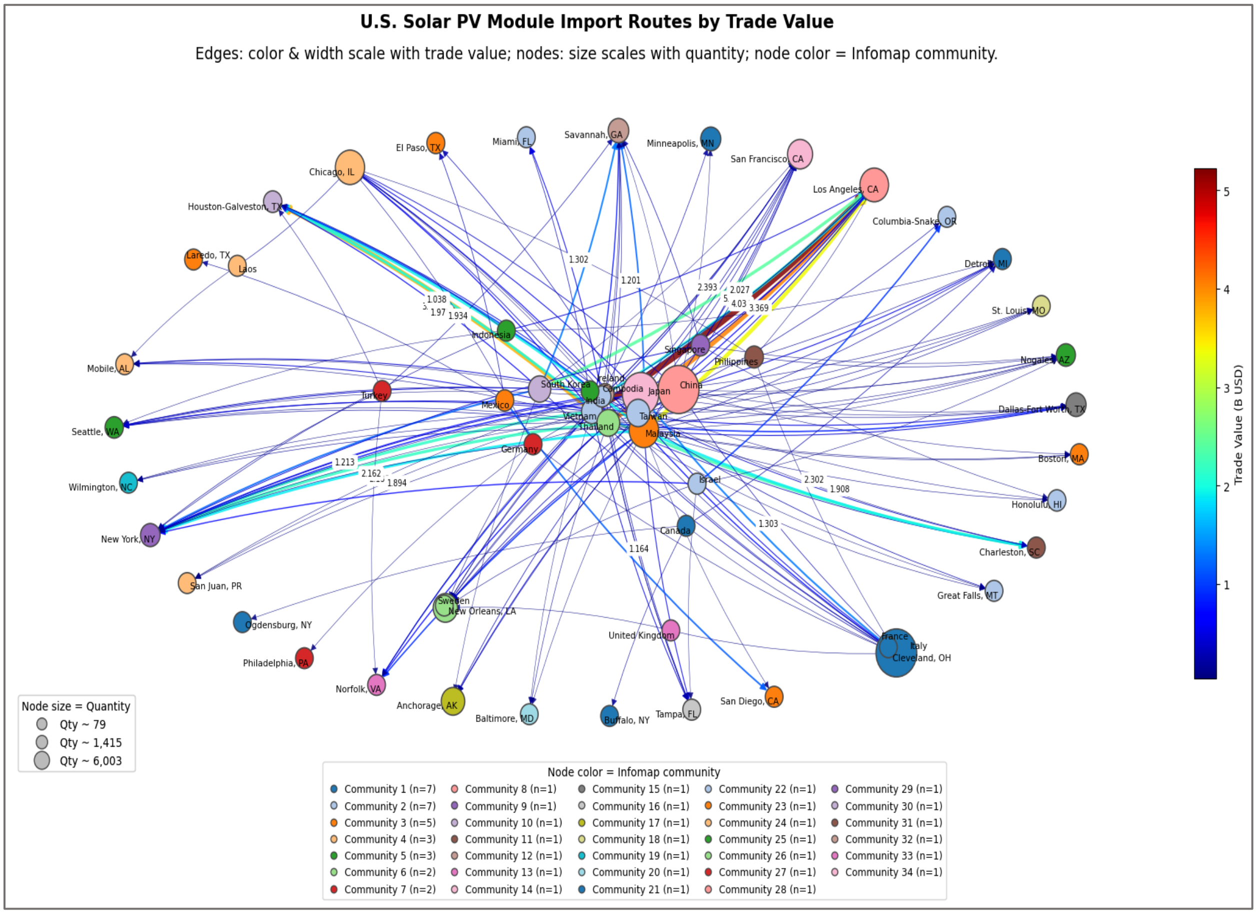

Figure 7. Communities in U.S. PV module import routes.

Table 3. Resilience Evaluation Results

#	Removed Port	Total Import	Percent Drop	#	Removed Port	Total Import	Percent Drop
1	Los Angeles, CA	60.263	24.88%	11	Seattle, WA	78.462	2.20%
2	New York, NY	69.424	13.46%	12	New Orleans, LA	78.573	2.06%
3	Houston-Galveston, TX	70.286	12.39%	13	Tampa, FL	78.625	1.99%
4	Cleveland, OH	74.724	6.86%	14	Detroit, MI	78.881	1.68%
5	Charleston, SC	75.325	6.11%	15	San Diego, CA	79.005	1.52%
6	Savannah, GA	75.952	5.33%	16	Columbia-Snake, OR	79.081	1.43%
7	Chicago, IL	77.311	3.63%	17	Mobile, AL	79.167	1.32%
8	Norfolk, VA	77.71	3.13%	18	Anchorage, AK	79.36	1.08%
9	San Francisco, CA	77.943	2.84%	19	Miami, FL	79.452	0.96%
10	Dallas-Fort Worth, TX	78.239	2.48%	20	Nogales, AZ	79.613	0.76%

Based on the findings from network analysis and resilience evaluation, several actionable insights emerge to improve the energy security policy (Table 3):

(a) Supply Chain Diversification: The significant dependence on a few exporting countries, which are Malaysia, Vietnam, and Thailand in this study, requires a policy that encourages having trade relationships with additional suppliers. The diversification of capacity over various geographies enables mitigating the vulnerabilities in concentrated supply chains (Erol et al., 2024).
(b) Port Infrastructure Investment: Resilience evaluation indicates that the exclusion of Los Angeles alone decreases imports by around 25%. This underscores the necessity of enhancing infrastructure resilience at main ports, while increasing capacity at secondary ports (e.g., Cleveland, Charleston, Savannah).
(c) Strategic Development: It is recommended to encourage imports from underutilized ports, which handled less than 2% of the trade flow (<2% of flows), to mitigate network vulnerability, support regional development, and address the potential risks of network concentration (Inomata & Hanaka, 2024).
(d) Risk Management and Emergency Planning: Because the disruptions at the few ports can be quickly escalated and cascaded, port-disruption scenarios must be incorporated into border resilience strategies. Emergency and safety plans must involve pre-established redirecting processes and backup storage facilities near ports (Ivanov, 2020; Lücker et al., 2024).

4. Conclusion

This study aims to analyze the port-level network of U.S. solar PV module imports using trade data for six years (2019-2024), gathered from the U.S. International Trade Commission. The network comprises 177 trade relationships that connect 30 different exporting countries to 55 U.S. ports, with a total trade value of $80.225 billion. The analysis indicated substantial concentration risks that threaten U.S. energy security. The findings revealed that Malaysia, Vietnam, and Thailand dominate the supply side of the PV module network, while Los Angeles, New York, and Houston-Galveston collectively manage nearly 50% of all PV module imports. Resilience evaluation via disruption simulation identified significant vulnerabilities, particularly the elimination of Los Angeles alone, resulting in a 24.9% decrease in overall imports. Community detection determined 34 unique communities, which showed considerable imbalances that favor major hubs, hence exposing systemic risks for disruption propagation.

This research has three major contributions: (1) it extends the current network-based methodologies to cover renewable energy supply chains with port-level analysis; (2) it provides a replicable quantitative framework for resilience assessment; and (3) it delivers actionable insights for U.S. energy security policy by highlighting major infrastructure vulnerabilities.

Future research can extend the presented approach by linking port-level trade networks with domestic production capacity, including upstream PV module supply chain stages, and investigating the effects of dynamic and seasonal variations in trade flows.

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