# Optimizing Export Strategy of Photovoltaic Modules Under Trade Policy Constraints: A Linear Programming Approach

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Abstract: The This paper develops a linear programming (LP) model to optimize the export strategy of Chinese photovoltaic (PV) manufacturers under dynamic international trade conditions. Given increasing policy complexities-such as tariffs, transportation costs, and carbon adjustment mechanisms-the study simulates cross-border cost structures and identifies optimal production allocation to global markets. The model incorporates key cost factors including unit production cost, destination-specific transportation fees, country-level tariff rates, and carbon border adjustment charges. Using a self-constructed virtual dataset, the model evaluates export allocation to four major markets: the United States, Germany, Japan, and Brazil. Cost structure analysis shows that tariff-related costs are the most influential factor affecting export decisions, followed by carbon adjustment charges. Sensitivity analysis reveals that a reduction in U.S. tariff rates significantly alters the optimal allocation, making the U.S. a viable export destination. Results highlight the importance of flexible planning tools in navigating policy uncertainty. The study provides a decision-support framework for Chinese PV exporters to optimize cross-border logistics and minimize total export costs in a policy-sensitive global environment. This model can be extended to other industries facing similar challenges in global trade optimization.

## 1 INTRODUCTION

Building on this foundation, the present study develops a linear programming (LP) model aimed at minimizing total export costs for PV modules by jointly optimizing production allocation and cross-border distribution. The model integrates critical cost elements such as manufacturing expenses, transportation fees, tariffs, and carbon adjustment levies. This research not only extends the application of LP techniques to policy-sensitive, multi-node global supply chains but also offers Chinese PV exporters a data-driven tool to improve cost efficiency and strategic adaptability in an increasingly uncertain trade environment. In a similar effort to integrate carbon policy into operational models, a carbon-adjusted tariff evaluation framework was developed, highlighting the role of environmental regulations in export decision-making (Zhu et al., 2021).

The global photovoltaic (PV) industry has experienced substantial growth in recent years, driven by the rising demand for sustainable and clean energy solutions. According to the International Energy Agency (IEA), the global installed capacity of solar PV reached 1,047 Gigawatt by the end of 2022 and is projected to exceed 2,400 GW by 2030. As the world's leading producer and exporter of PV modules, China occupies a dominant position in the global solar market. However, this upward trajectory is increasingly threatened by a shifting international trade landscape, characterized by escalating tariffs and tightening regulatory measures.

The global trade environment has grown increasingly volatile. The World Trade Organization (WTO) has reported a surge in protectionist measures and geopolitical tensions, particularly in key sectors such as energy and electronics. Since 2018, the United States has enacted multiple rounds of tariffs on solar imports under trade remedy frameworks such as Section 201 and anti-dumping policies. In response, numerous Chinese manufacturers have relocated production to Southeast Asia in an effort to circumvent these restrictions. Concurrently, the

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European Union (EU) has implemented the Carbon Border Adjustment Mechanism (CBAM) to mitigate “carbon leakage,” which may significantly increase the cost of PV exports from high-emission regions. These developments present new operational constraints for Chinese PV firms, necessitating strategic reconfiguration of production and export plans to maintain global competitiveness under dynamic policy conditions. In response to these challenges, a growing body of research has proposed various modeling approaches to optimize global PV supply chains. A mixed-integer programming model was developed to coordinate production and distribution under tariff-induced cost volatility (Zhang et al., 2020). A dynamic production allocation model was introduced to demonstrate how flexible resource deployment can mitigate the risks associated with tariff uncertainty (Liu and Wang, 2021). The role of regional trade agreements was emphasized in enabling strategic capacity realignment across markets, highlighting the importance of geographic diversification (Gong et al., 2023). It was further argued that operational models should be coupled with policy forecasting mechanisms to support real-time decision-making amid regulatory shocks (Chen and Xu, 2022).

In the context of supply chain resilience, recent studies have investigated structural responses to trade-related disruptions. A resilience-based framework for PV supply chain design was proposed, advocating for multi-country sourcing and distributed manufacturing to mitigate political and policy risks (Sun and Chen, 2022). This framework was expanded by integrating transportation risk and infrastructure capacity into optimization models, showing that alternative routing can substantially reduce vulnerability to bottlenecks (Huang et al., 2023). Empirical evidence was provided that firms optimizing both production and export routing under an integrated cost-minimization framework achieved greater profitability in policy-constrained environments (Wang and Zhao, 2023).

Building on this foundation, the present study develops a linear programming (LP) model aimed at minimizing total export costs for PV modules by jointly optimizing production allocation and cross-border distribution. The model integrates critical cost elements such as manufacturing expenses, transportation fees, tariffs, and carbon adjustment levies. This research not only extends the application of LP techniques to policy-sensitive, multi-node global supply chains but also offers Chinese PV exporters a data-driven tool to improve cost efficiency and strategic adaptability in an increasingly uncertain trade environment.

# 2 METHODOLOGY

In this part, the data resources used in this study, variables involved and specific methods will be introduced.

## 2.1 Data Source and Description

LP is chosen for its ability to efficiently handle continuous decision variables and cost minimization under multiple restrictions. The objective is to minimize the combined costs of production, transportation, tariff, and carbon-related fees. The decision variables represent the number of modules exported to each destination. Constraints include total production capacity and the demand of each country. Due to the sensitivity and limited availability of detailed cost data from real-world enterprises, this study constructs a virtual dataset to simulate representative international export scenarios in the photovoltaic (PV) sector. The simulation reflects typical contemporary policy settings and models the production and policy-induced export costs faced by Chinese PV manufacturers under realistic global trade conditions.

The dataset covers five representative countries: China (serving as the production base), and four major export destinations－Germany, the United States, Japan, and Brazil. These countries were selected based on their strategic relevance, diversity of trade regulations, geographic distribution, and significance in the global PV market. This sample captures typical configurations encountered by export-oriented manufacturers across multiple policy environments.

Cost-related parameters-including production cost, transportation fee, tariff rate, and carbon adjustment charges-are assigned using aggregated estimates from recent industry reports, WTO tariff schedules, and relevant academic literature. Demand quantities in each destination are also preset to reflect market scale. To ensure comparability, all cost elements are standardized on a per-unit basis. The dataset maintains internal consistency while representing plausible trade constraints that affect global solar supply chains.

## 2.2 Indicator Selection and Explanation

To capture the major cost drivers in cross-border PV export, four key indicators are selected in this model: unit production cost, transportation cost, tariff rate, and carbon adjustment charge. These parameters quantify the primary components of total export cost under current trade and environmental policy regimes.

Production cost reflects the baseline manufacturing expense per unit in China and remains constant across destinations.

Transportation cost varies by destination country and reflects route-specific logistics expenses.

Tariff rate represents destination-imposed import duties, applied as a percentage of product value.

Carbon adjustment charge accounts for environmental policy costs such as the EU CBAM and is estimated based on emission intensity and country-specific rules.

These indicators are treated as fixed inputs in the linear programming model and serve as cost coefficients in the objective function. This configuration helps simulate realistic variations in policy and logistics conditions across export destinations. The parameter values used in the simulation are summarized in Table 1.

Table 1: Cost Parameters for PV Export Simulation.

| Country | Production Cost (USD/unit) | Transportation Cost (USD/unit) | Tariff Rate (%) | Carbon Adjustment (USD/unit) |
|---|---|---|---|---|
| China | 100 | - | - | - |
| Germany | - | 25 | 10% | 12 |
| United States | - | 30 | 25% | 10 |
| Japan | - | 20 | 5% | 15 |
| Brazil | - | 35 | 20% | 8 |

## 2.3 Model and Solution Approach

This study uses a linear programming (LP) model to minimize the total cost of exporting photovoltaic modules from China to multiple countries, subject to trade-related constraints. LP is chosen for its ability to efficiently handle continuous decision variables and cost minimization under multiple restrictions.

The objective is to minimize the combined costs of production, transportation, tariff, and carbon-related fees. The decision variables represent the number of modules exported to each destination. Constraints include total production capacity and the demand of each country.

The model is formulated as follows:

$$f(x) = min \sum (C_i + T_i + D_i + E_i) \times X_i \quad (1)$$

Subject to:

$$\sum X_i \leq Total\ Production\ Capacity \quad (2)$$

$$X_i \leq \ Demand\ in\ country \quad (3)$$

Where $X_i$ represents the quantity of modules exported to country $i$ . $C_i$ represents the unit production cost in China. $T_i$ represents the transportation cost to country $i$. $D_i$ represents the tariff per unit imposed by country $i$. $E_i$ represents the carbon adjustment cost per unit in country $i$.

# 3 RESULTS AND DISCUSSION

## 3.1 Model Output and Export Allocation

The linear programming model was successfully solved based on the defined parameters and constraints. The optimal export allocation fully utilizes the total production capacity of 2,500 units, distributing them across three of the four target markets. Specifically, 1000 units are allocated to Germany, 900 units to Japan, and 600 units to Brazil. The United States, despite its high demand of 800 units, receives no allocation. This allocation result is summarized in Table 2.

This outcome reflects the influence of policy-driven costs and demonstrates how the model prioritizes destinations offering the most cost-effective trade conditions. Export allocation, therefore, is shaped not merely by market size but also by trade and environmental policy burdens.

This outcome highlights that the model allocates resources strictly based on cost efficiency, not on perceived market importance. The fact that the United States, a major PV importer, is excluded demonstrates how even large markets can be deprioritized when policy barriers distort cost structures. As shown in Table 2, this reinforces the critical role of modeling tools in revealing non-obvious but rational allocation strategies under complex policy environments. Such prioritization illustrates that trade policy variables can override traditional market metrics, highlighting the need for exporters to monitor geopolitical developments in real-time.

Table 2: Optimal Export Allocation Summary.

| Country | Export Quantity (Units) | Demand (Units) | Allocation Ratio |
|---|---|---|---|
| Germany | 1000 | 1000 | 100% |
| Japan | 900 | 900 | 100% |
| Brazil | 600 | 700 | 85.7% |
| USA | 0 | 800 | 0% |

## 3.2 Cost Structure and Sensitivity Analysis

A detailed examination of the cost structure reveals that tariff-related expenses are the most influential factor affecting export decisions. While all countries incur basic production and transportation costs, variation in policy-induced components-particularly tariffs and carbon adjustment charges-significantly alters each destination's effective unit export cost. Logistics disruptions caused by trade barriers significantly distort the overall cost-effectiveness of cross-border PV delivery routes (Zhao and Zhang, 2023).

Their study emphasizes that route-specific risks and regulatory bottlenecks can undermine cost advantages even in low-tariff environments.

For instance, the effective unit export cost to the United States is approximately USD 165, calculated as:

$$Cost\_US = 100(Production) + 30(Transport) + 25(Tariff) + 10(Carbon) \quad (4)$$

This cost structure comparison is illustrated in Figure 1. In comparison, Germany's total cost is around USD 147, and Japan's is approximately USD 150. Although Japan faces a relatively high carbon adjustment cost (USD 15), its low tariff (5%) offsets the impact. Brazil, despite a high transportation cost (USD 35), remains cost-effective due to moderate tariffs (20%) and the lowest carbon adjustment (USD 8).

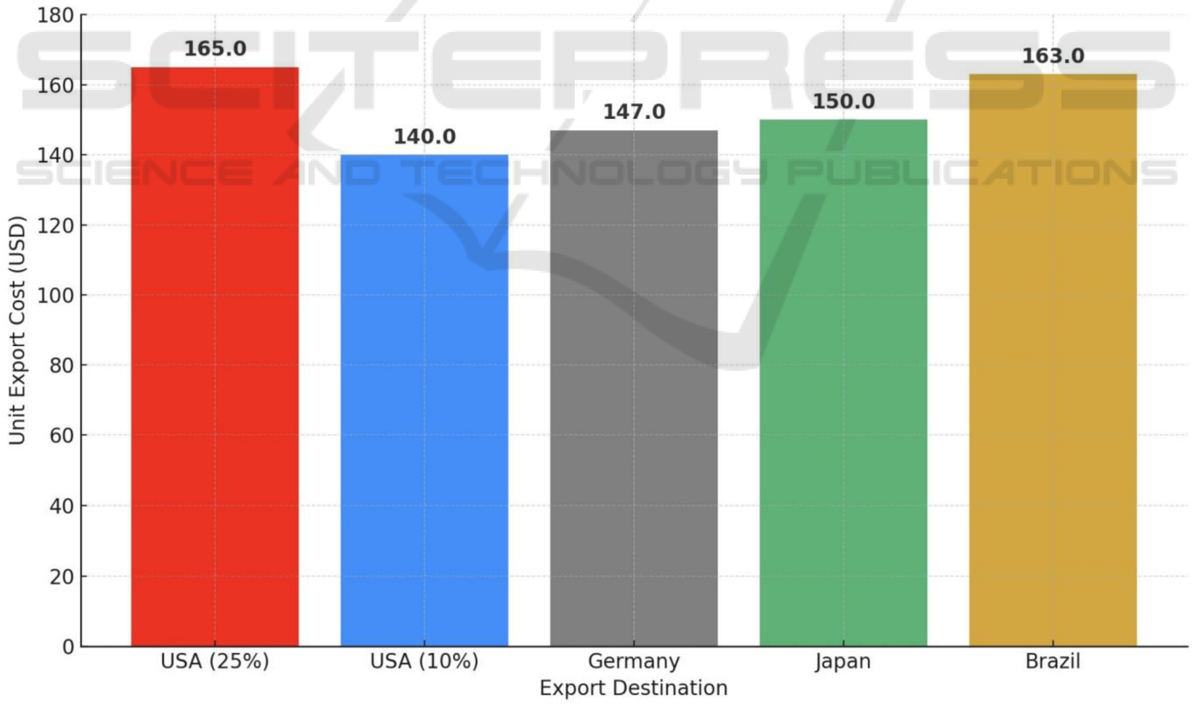


Figure 1: Comparison of Unit Export Costs Across Destinations (Picture credit: Original).

This chart compares the unit export costs to different destinations under baseline and adjusted tariff conditions. The United States becomes cost-competitive only after tariff reduction. To further examine the influence of trade policy, a sensitivity analysis was conducted by lowering the U.S. tariff from 25% to 10%. This adjustment reduces the U.S. unit cost to roughly USD 140, making it more competitive than Brazil. In this scenario, the optimal export allocation shifts: the United States would receive up to 700 units, displacing Brazil. Figure 2 illustrates this shift in export allocation in response to changes in the U.S. tariff rate.

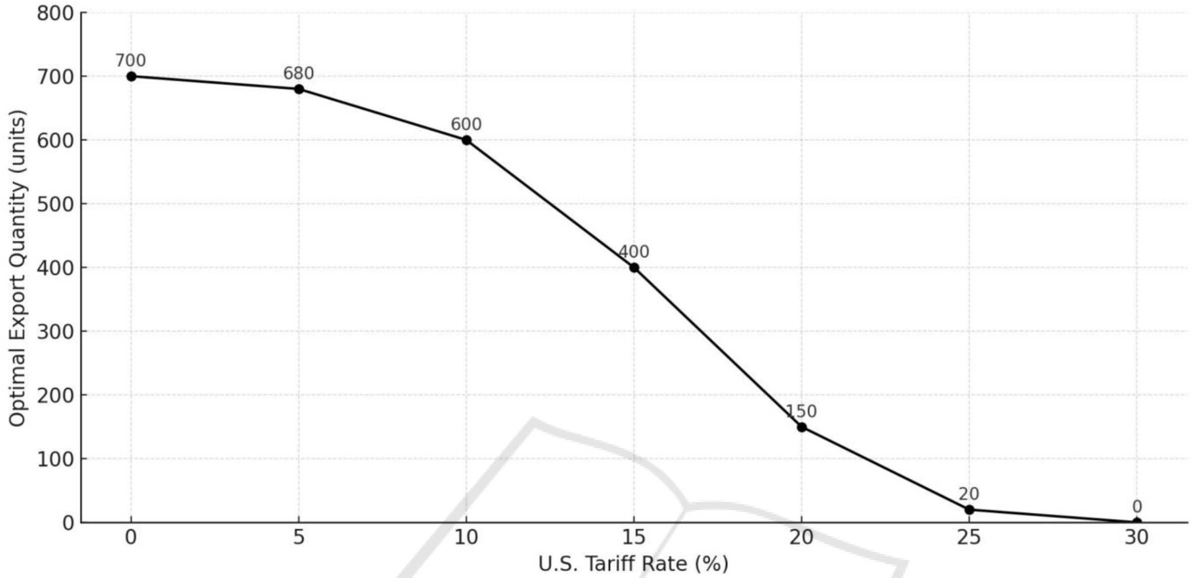


Figure 2: Sensitivity of U.S. Export Allocation to Tariff Rate (Picture credit: Original).

This line graph illustrates how export allocation to the U.S. fluctuates as the tariff rate increases (Figure 2). When tariffs exceed 20%, the U.S. is excluded from the optimal allocation. This finding highlights that even minor tariff changes can lead to significant shifts in export strategy. Sensitivity analysis is therefore crucial for helping firms plan under policy uncertainty and prepare for contingency scenarios.

### 3.3 Strategic Implications and Model Limitations

From a managerial perspective, the model highlights the critical importance of incorporating trade policy environments-not merely demand levels-into global supply chain planning. Germany and Japan emerge as cost-efficient and policy-stable markets, suggesting that exporters should prioritize long-term infrastructure investment and strategic partnerships in these regions.

Moreover, the model functions as a flexible decision-support tool. It allows firms to simulate “what-if” scenarios by adjusting key policy parameters, thereby enabling them to anticipate and adapt to evolving trade conditions. This predictive capability is particularly valuable amid the rapidly shifting regulatory landscape of the renewable energy industry.

Despite offering actionable insights, the current model has certain limitations. First, it assumes fixed unit costs and excludes real-world uncertainties such as currency exchange fluctuations, variable transportation rates, and supply chain disruptions. In addition, it does not account for demand elasticity-namely, how market demand responds to price changes-which can significantly influence actual sales volumes.

Another simplification lies in the assumption of perfect information and static policy environments. In practice, tariffs and carbon regulations may change rapidly, and firms often lack full visibility of future policy shifts. Incorporating stochastic elements or scenario-based modeling could enhance the model’s realism and robustness.

Furthermore, the model focuses solely on cost minimization, overlooking potential trade-offs between cost, revenue, and profit. This narrow focus may limit its applicability for firms pursuing market share expansion or long-term brand positioning. Future models may benefit from integrating multiple objectives that more accurately reflect business priorities.

Future research could expand this model by incorporating multi-period decision frameworks or carbon credit trading mechanisms. Additionally, calibrating the model with empirical trade data would enhance its external validity. Combining qualitative scenario planning with quantitative optimization techniques could further strengthen strategic export planning for firms operating in volatile geopolitical environments. This view aligns with previous research emphasizing the necessity of infrastructure resilience when planning export strategies in politically unstable regions (Zhou and Huang, 2022).

These findings collectively underscore that cost-effective export decisions in the PV industry require data-driven models, sensitivity to policy dynamics, and a long-term strategic outlook on market prioritization.

# 4 CONCLUSION

This research presents a linear programming framework tailored to optimize the global export strategies of Chinese photovoltaic (PV) manufacturers operating under increasingly complex trade environments. By systematically incorporating major cost components－namely production costs, transportation fees, import tariffs, and carbon adjustment levies－the model replicates realistic cross-border decision-making scenarios across multiple destinations.

The analysis demonstrates that tariff policies exert the most profound influence on export competitiveness, followed by carbon-related regulatory costs. Sensitivity testing reveals that even marginal changes in tariff rates can induce substantial shifts in optimal export allocation, highlighting the critical need for adaptive strategy planning under policy uncertainty.

The proposed model offers a scalable and transferable decision-support framework that enables PV exporters to minimize total export costs while maintaining strategic agility. Beyond the solar industry, the methodology holds potential for broader application in sectors navigating policy-sensitive international logistics.

Future enhancements could include the integration of stochastic parameters, dynamic market demand profiles, or multi-objective optimization layers, allowing firms to concurrently balance cost-efficiency, risk exposure, and environmental sustainability.

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