Mixing Tariffs and Subsidies for Industrial Policy Objectives in Oligopolistic Markets*

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Abstract

Tariffs and subsidies are frequently deployed to support and scale up production by domestic firms, but they are typically evaluated in isolation or as alternatives. What if the policymaker could optimally *mix* the two instruments? We study this question, theoretically and empirically, in the Indian solar industry. Using a model of oligopolistic competition between domestic and foreign firms, we derive three key results. First, a subsidy-only policy is never optimal for any given domestic expansion target; introducing a small tariff dominates using subsidies alone. Second, for small expansion targets, a tariff-only policy maximizes welfare. Third, for large expansion targets, the optimal policy involves a mix of tariffs and subsidies. To test these theoretical results, we estimate a structural model of the Indian solar industry using data from the upstream solar panel industry and the downstream solar power plant industry. We use this structural model to simulate the optimal policy for a range of expansion targets and confirm our theoretical predictions: for small expansion targets, the optimal policy is a tariff, but for larger expansion targets, the optimal policy is a mix of tariffs and subsidies.
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1 Introduction

A new wave of industrial policy and protectionist interventions, centered around tariffs and subsidies, shows governments are leaning on both tools to boost domestic manufacturing.[1] In the United States, for example, the Inflation Reduction Act (IRA) provides production and investment subsidies for clean energy industries while the U.S. government simultaneously maintains tariffs on imported solar cells, wafers, lithium-ion EV batteries, and wind turbine components from China and other countries.[2] Similarly, India has implemented both production-linked incentives and import duties in its solar sector. Although a large literature studies the welfare impacts of tariffs and subsidies independently — or compares them as alternative policy options — there is relatively little work examining how policymakers might *simultaneously* use the two instruments, particularly in oligopolistic markets.

In this paper, we investigate this idea of optimally mixing tariffs and subsidies to achieve a given expansion in domestic production of a good. Our approach is atypical in the literature; rather than deriving the optimal level of domestic production, we take the policymaker's expansion target as exogenous — perhaps driven by strategic or security concerns, political constraints, or economic externalities — and ask which policy, or combination of policies, best meets that target. We can remain agnostic about the specific rationale for intervention because any benefits tied to the size of the domestic sector are held constant by design across the policies we compare. To characterize this optimal policy mix, we proceed both theoretically and empirically. First, we outline a theoretical model of oligopolistic competition between domestic and foreign firms. Under mild assumptions on the demand and cost primitives, we derive results that characterize the optimal policy for a given expansion target. Then, we develop and estimate a structural model of the Indian solar industry, which has been subject to both production subsidies and import tariffs, and use it to evaluate the empirical validity of our theoretical results.

[1] See Amiti, Redding, and Weinstein (2019), Fajgelbaum et al. (2020), Juhász et al. (2022), and Shih (2023).

[2] See Associated Press (2024), Reuters (2025), and U.S. Environmental Protection Agency (2025) for more details.

Our theoretical model features a standard Cournot-Nash framework with a twist: the policymaker must choose policies subject to a domestic industry expansion constraint. Under this constraint, the policymaker chooses levels of tariffs and subsidies that maximize *domestic* welfare, which consists of domestic profits, domestic consumer surplus, and tariff revenue minus subsidy payments. This setup yields three key results.[3]

First, we show that a subsidy-only policy is never optimal for any given expansion target; adding a small tariff dominates using subsidies alone. This is because at a subsidy-only policy, the policymaker can introduce a small tariff to generate tariff revenue while simultaneously lowering subsidy payments as subsidies and tariffs are substitutes for the purposes of expanding the domestic industry. This hurts downstream firms and consumers but in oligopolistic markets, some of the incidence of the tariff falls on foreign firms, so net welfare is higher.

Second, we show that for small enough expansion targets, a tariff-only policy is optimal. This follows from the first result. Substituting subsidies with modest levels of tariffs increases welfare. Therefore, when expansion targets are small enough to require only minimal policy intervention, tariffs fully replace any subsidies.

Finally, we show that for large expansion targets, the optimal policy involves a mix of tariffs and subsidies. Achieving a large target with tariffs alone requires prohibitively high rates that all but eliminate imports and tariff revenue. At this point, introducing a subsidy while slightly reducing the tariff — in a manner that keeps domestic output fixed at its target — becomes welfare-improving. The key insight is that the revenue gained from an expanded import tax base (as more foreign goods enter) outweighs the revenue lost from the small reduction in the tariff rate, making the mixed policy dominant.

While these theoretical results identify the key mechanisms at play, they leave several quantitative questions unanswered. At what expansion target does a mixed policy become optimal, and is this threshold economically meaningful? More importantly,

[3]Our static model abstracts from several considerations including learning-by-doing, potential foreign policy responses, and environmental externalities. We discuss how these factors might affect our results in Remarks 1-3.

are the welfare gains from mixing instruments substantial enough to justify the added complexity? To answer these questions, we develop and estimate a structural model of India's solar sector that incorporates rich firm-level heterogeneity in costs and allows us to provide empirical evidence on the optimal policy mix in a real-world setting.

The solar sector in India includes an upstream industry that produces solar panels (or modules) and a downstream industry that develops utility-scale solar power plants. The downstream industry in India has experienced explosive growth over the past decade, going from a few hundred megawatts of installed utility-scale capacity in 2010 to over 35 gigawatts (GW) of installed capacity by the end of 2020 (CAGR 70%). This rapid growth created substantial demand for solar panels, the primary component in solar power plants. Yet, domestic producers in the upstream industry failed to grow in tandem with the downstream industry. Instead, during this period, the upstream industry was dominated by foreign producers, especially Chinese firms: in the early 2010s, roughly 90% of the solar panels installed in Indian projects came from China.

To support domestic producers of solar panels, in recent years, the Indian government has introduced two major policy interventions. First, starting in August 2018, the government implemented a safeguard duty of 25% on solar cells and modules imported from China and Malaysia. From April 2022 onwards, this was converted into a basic customs duty of 40% on all imports of solar cells and modules. Second, in November 2020, the government rolled out a production-linked incentive (PLI) scheme, allocating approximately \$3 billion to incentivize domestic solar PV module production.[4] This program offers incentives that are explicitly linked to the level of output and sales, and is thus a form of production subsidy.

To trace the impact of these policies, we compile comprehensive data on both the upstream and downstream markets of the utility-scale solar sector in India. First, we gather firm-level data on solar power plant projects to identify which upstream manufacturer

[4]The subsidy to the solar sector under the PLI scheme is part of a broader push to provide production-linked subsidies to a wide variety of manufacturing industries. As of 2022, subsidies totaling over \$26 billion have been announced.

supplied panels to which utility-scale solar project. These data show that a small number of foreign producers dominate the upstream market: the top ten firms control 60% of market share, seven of which are Chinese, while only two are Indian.

Second, we obtain transaction-level data on imports of solar panels to India. We use these data to construct a price series for panels from China and Malaysia. Our analysis of these prices shows incomplete tariff pass-through – foreign suppliers reduce their ex-tariff prices when facing import duties. While not definitive proof, this is consistent with our model of oligopolistic competition.

Finally, we collect detailed data on the downstream market. In this market, power distribution companies organize multi-unit English auctions where solar plant developers bid to secure long-term power purchase agreements. For all solar auctions conducted until the end of 2020, we obtain data on all price and quantity bids, and the corresponding outcome for each of these bids. We use these data to show that bids are sensitive to the price of solar panels — thus interventions upstream would trickle down to the downstream market and the eventual price of electricity generated by the solar plants. This underscores the necessity of jointly modeling upstream and downstream markets to fully understand the welfare implications of policies targeting the upstream industry.

Next, we briefly describe the structural model we develop and estimate. Similar to the theoretical model, we model the upstream industry as a Cournot oligopoly, treating solar panels as homogeneous goods. However, we allow for rich firm-level heterogeneity in the cost structure of foreign and domestic producers. We estimate the various parameters governing these cost functions using temporal data on firm-level market shares in the upstream market. For the downstream market, we simplify the analysis of an English multi-unit auction by assuming a descending-bid auction, and estimate the distribution of private costs of developing solar power plants as a function of the price of solar panels. Finally, we use a demand model to link demand for solar panels to the price of solar panels, intermediated by the price of electricity (winning bid) generated by solar plants. We estimate this demand elasticity by instrumenting the price of solar panels using the spot price of polysilicon, a key input in the production of solar panels.

Using the estimated model, we characterize the optimal policy for expansion targets ranging from 1% to 15% of baseline domestic production under three policy regimes — tariff-only, subsidy-only, or a mix of tariffs and subsidies. We find that for small expansion targets ($< 8\%$), the optimal policy is a tariff-only policy. For these expansion targets, the optimal subsidy rate is zero. However, for larger expansion targets, the optimal policy simultaneously uses both tariffs and subsidies, thus confirming our theoretical predictions.

Our paper contributes to three bodies of research: strategic trade policy, empirical analyses of industrial policy interventions, and the broader literature on the welfare impact of protectionism. We outline each of these connections below and clarify our contributions.

First, we contribute to the extensive theoretical literature on strategic trade policy by showing how policymakers can optimally deploy both tariffs and subsidies in oligopolistic markets to achieve specific domestic expansion objectives. Classic analyses of such interventions often study them in isolation or present them as alternatives under various assumptions about market structure, competition, and information (Brander, 1995; Brander & Spencer, 1981, 1985; Creane & Miyagiwa, 2008; Eaton & Grossman, 1986; Etro, 2011; Miller & Pazgal, 2005). In contrast, we show how to *mix* these two instruments — i.e., use them simultaneously — to meet a policy mandate of scaling up domestic production. While some earlier papers like Dixit (1984) and Cheng (1988) do consider multiple instruments, they focus on unconstrained welfare maximization. Our approach differs fundamentally by deriving results from a constrained optimization problem where the policymaker has a mandate to expand domestic production by a specific target. Although the underlying economic forces — profit shifting and reduction in domestic distortions — remain the same, to the best of our knowledge, our results on optimal industrial policy using these two instruments are new to the literature.

Second, we speak to an empirical literature that evaluates industrial policy interventions using structural models (Baldwin & Krugman, 1988a, 1988b; Bartelme et al., 2024; Lashkaripour & Lugovskyy, 2023; Liu, 2019).[5] Our work is closest to studies like Barwick, Kalouptsidi, and Zahur (2023), Kalouptsidi (2018), and Miravete and Moral (2024), which develop structural models of a single oligopolistic sector to quantify the effects of government interventions. Barwick, Kalouptsidi, and Zahur (2023), in particular, examines how combining multiple types of subsidies in Chinese shipbuilding can become excessively distortionary. We instead focus on utility-scale solar in India and study tariffs and production subsidies, which, consistent with our theoretical predictions, can sometimes be jointly optimal. Similar to our work, Bollinger et al. (2024) and Houde and Wang (2023) also examine government interventions under market power in the solar industry. Bollinger et al. (2024) compares tariffs on imported panels to consumer subsidies in the U.S. market (not simultaneously), while Houde and Wang (2023) focuses on tariff pass-through in the U.S. residential segment. In contrast, we concentrate on the utility-scale segment in India and the joint use of import tariffs and production subsidies to achieve industrial policy objectives.

Finally, we contribute to research on the welfare consequences of protectionism (Amiti & Khandelwal, 2013; Amiti & Konings, 2007; Amiti, Redding, & Weinstein, 2019; Cavallo et al., 2021; Fajgelbaum et al., 2020; Flaaen, Hortaçsu, & Tintelnot, 2020; Goldberg et al., 2010; Irwin, 2007, 2014, 2019; Topalova & Khandelwal, 2011). We provide new evidence on incomplete pass-through of tariffs in a renewable industry (solar modules) dominated by few large foreign suppliers. Our finding — that foreign producers bear a fraction of the tariff burden — is consistent with models of oligopolistic competition. Further, using our structural model, we quantify the overall welfare effects of various tariff-subsidy combinations and their impact on key stakeholders in India's utility-scale solar sector: foreign and domestic producers of solar panels, project developers, and power distribution companies.

[5] There is also a large and growing literature using natural experiments to study the effects of industrial policy interventions. See Blonigen (2016), Harris, Keay, and Lewis (2015), Irwin (2000a, 2000b), Juhász (2018), and Lane (2024).

2 Benchmark Model

Before introducing the empirical setting and the corresponding structural model, we present a theoretical model of an oligopolistic market that is subject to import tariffs and production subsidies aimed at expanding domestic output. We use this model to prove our main results: a subsidy-only policy is never optimal, a tariff-only policy is optimal for small expansion targets, and for large expansion targets, the optimal policy involves a mix of tariffs and subsidies. Later, we confirm and quantify these results using a structural model of the Indian solar panel industry.

A key feature of our framework is that we take the policymaker's domestic expansion target as given. This approach reflects the reality of industrial policy implementation, where policymakers frequently announce explicit production or capacity targets that may be driven by political, strategic, or security considerations rather than textbook economic optimization. For instance, the US CHIPS Act explicitly targets producing "roughly 20 percent of the world's leading-edge logic chips by the end of the decade" (Raimondo, 2024), while India's PLI scheme for solar PV modules aims to "build 65 GW of capacity" (Ministry of Commerce and Industry, 2025).

Such targets may not align with what some economic models would identify as welfare-maximizing levels of domestic production. Our analysis does not question the wisdom of these targets. Instead, we ask a different question: given that a policymaker has committed to achieving a specific expansion target, what is the optimal mix of policy instruments to achieve it? One reason why we can circumvent the question of *why* expansion is desirable is that any policy combination we evaluate — whether using tariffs, subsidies, or both — achieves the exact same level of domestic production by design. Consequently, any benefits tied to the scale of the domestic sector, such as external economies of scale, are held constant across our comparisons. This allows our welfare analysis to isolate the relative efficiency of the policy instruments themselves, independent of the underlying rationale for the intervention.

2.1 Model Setup

Consider a domestic market for solar panels with n_f foreign firms, indexed by f, and n_d domestic firms, indexed by d. The inverse demand curve is given by $P(Q)$, where Q is the total quantity of solar panels sold in the market. Foreign firms face an ad valorem tariff $0 \leq \tau < 1$ on their imports, and domestic firms receive a production subsidy $0 < s \leq 1$. Note that while our constraint $\tau < 1$ may appear to limit tariffs to less than 100%, this notation actually allows for arbitrarily high tariff rates in conventional policy terms.[6] Thus, a firm i of type $k \in f, d$ faces the following optimization problem:

$$\max_{q_{ik}} \pi_{ik}(q_{ik}) = (1 - \tau_k)P(Q)q_{ik} - (1 - s_k)c_k q_{ik} \tag{1}$$

where c_k is the constant marginal cost of firm i of type k and q_{ik} is the quantity of solar panels produced by it.[7] All firms compete in a Cournot fashion and choose their quantities simultaneously.

2.2 The Policymaker's Constrained Optimization Problem

The domestic policymaker seeks to increase domestic production by an exogenous target χ relative to the baseline level of domestic production under no intervention. Formally, the policymaker solves:

$$\max_{\tau,s} W(\tau,s) \quad \text{subject to} \quad \sum_{i=1}^{n_d} q_{id}(\tau,s) - \sum_{i=1}^{n_d} q_{id}(0,0) = \chi, \quad 0 \leq \tau < 1, \quad 0 \leq s < 1. \tag{2}$$

where $W(\tau,s)$ is the domestic welfare function under tariff τ and subsidy s, and $q_{id}(\tau,s)$ is the quantity of solar panels produced by domestic firm i under the given level of intervention. We define domestic welfare as the sum of domestic profits, $\Pi_d(\tau,s)$, consumer

[6] Our tariff parameter, τ, represents the fraction of the final consumer price per unit quantity collected as revenue. This differs from the tariff rates often cited in public policy discussions, which we denote as t, that are typically calculated as a percentage of the producer price per unit quantity. The two are linked by the formula $\tau = t/(1+t)$. This relationship arises from equating the government's revenue per unit under both definitions: $\tau P = t \cdot P_{\text{producer}} = t(1-\tau)P$. Consequently, our formulation where $\tau \in [0,1)$ can represent any non-negative tariff t. For example, a 100% tariff ($t = 1$) corresponds to $\tau = 0.5$, while a 300% tariff ($t = 3$) corresponds to $\tau = 0.75$ As $t \to \infty$, $\tau \to 1$.

[7] Note that $s_k = 0$ for all foreign firms and $\tau_k = 0$ for all domestic firms.

surplus, $CS(\tau, s)$, and tariff revenue, $R(\tau, s)$, minus subsidy payments $S(\tau, s)$ scaled by the cost of public funds $\mu \geq 1$:

$$W(\tau, s) = \Pi_d(\tau, s) + CS(\tau, s) + R(\tau, s) - \mu S(\tau, s)$$

Before presenting our main results, we impose a restriction on the expansion target χ chosen by the policymaker.

Definition 1 (Reasonable Expansion Target). *An expansion target χ is* reasonable *if*

1. *it can be achieved with a subsidy-only policy ($\tau = 0$) with a subsidy rate $s < 1$,*
2. *it can be achieved with a tariff-only policy ($s = 0$) with a tariff rate $\tau < 1$, and*
3. *foreign firms continue to earn non-negative profits.*

The first condition ensures that the expansion target can be achieved using subsidies alone while ensuring that the *effective* (post-subsidy) marginal cost of the domestic firm remains positive. The second condition ensures that the expansion target can be achieved with tariffs alone while ensuring that post-tariff revenues of foreign firms are non-negative. The third condition prevents exit of foreign firms by ensuring that the market price does not fall below the marginal cost of foreign firms.

Assumption 1. *The expansion target χ is* reasonable.

Additionally, as in Hahn (1962), we impose the following condition on the demand curve.

Assumption 2. *Marginal revenue of firm i is decreasing in the output of firm $j \neq i$ for all i, j. That is,*

$$\frac{\partial^2 \left(P(Q) \cdot q_i\right)}{\partial q_i \partial q_j} = P'(Q) + q_i \cdot P''(Q) < 0$$

This assumption ensures that best response functions are downward sloping, i.e., the best response of firm i to the output of firm j is decreasing in the output of firm j, which is a standard assumption in Cournot models.

While the above two assumptions are sufficient to prove all of the propositions below for the case where there is a single foreign firm, for extending propositions 1 and 2 to markets with multiple foreign firms, we require a stronger assumption on the curvature of the demand curve.

Assumption 2*. *For markets with more than one foreign firm ($n_f > 1$), we require that*

$$P'(Q) + n_f \cdot q_f \cdot P''(Q) < 0$$

where q_f denotes the output of a single foreign firm.

2.3 Main Results

Under these assumptions, we characterize the optimal policies in the following propositions. Complete proofs are in Appendix A.

Proposition 1. *A subsidy-only policy is never optimal.*

See Appendix A.5.1 for details of the proof. Here, we sketch the intuition behind it. Starting from a subsidy-only policy, consider introducing a small tariff while reducing the subsidy rate to keep domestic output constant. While this substitution triggers several welfare changes, most are simply transfers between domestic agents; for instance, the higher price on domestic goods transfers surplus from consumers to producers. The overall effect on welfare hinges on the relative magnitudes of the change in tariff revenue and consumer surplus through foreign output. A marginal tariff generates revenue equal to the full price (P) for each imported unit. The corresponding loss in consumer surplus, however, is determined by the price increase, which, due to imperfect pass-through in an oligopoly, is less than the full price ($\frac{\mathrm{d}P}{\mathrm{d}\tau} < P$). Because the revenue gain exceeds the consumer surplus loss, this policy substitution is always welfare-improving.

Note that the finding that positive tariffs can be welfare-improving is well-established, arising in both neoclassical models with upward-sloping supply curves (Feenstra, 2016) and in strategic trade policy models with oligopolistic firms (Brander & Spencer, 1981, 1985). Our analysis, however, examines a constrained optimization problem where policymakers can deploy multiple instruments to achieve a given domestic expansion target. Specifically, when the objective is to achieve a given expansion target using any combination of tariffs and subsidies, we show that a subsidy-only policy is never optimal. However, as we show below, a tariff-only policy may be optimal in some cases.

Proposition 2. *There exists an expansion target $\overline{\chi} > 0$, such that a tariff-only policy is optimal for all $\chi \in (0, \overline{\chi})$.*

This proposition follows directly from our first result. Consider a tariff-only policy for an expansion target χ that approaches 0. In the limit, the required tariff rate also approaches 0, which is akin to a subsidy-only policy. Following the above proposition, a subsidy-only policy is never optimal, and one can increase welfare by introducing a small tariff. Thus, by continuity of the welfare function, there's some region around $\chi = 0$ where a tariff-only policy is optimal. This yields a key insight of our paper: even though the policymaker has multiple instruments at their disposal, for a non-trivial set of expansion targets $\chi \in (0, \overline{\chi})$, the optimal policy is to rely exclusively on tariffs. See Appendix A.5.2 for additional details.

Having established that tariffs alone are optimal for small expansion targets, we now examine whether mixing instruments ever becomes optimal. The following proposition summarizes our final theoretical insight.

Proposition 3. *Consider $\mu \to 1$. There exists an expansion target $\underline{\chi} > 0$ such that for any reasonable expansion target $\chi > \underline{\chi}$, the optimal policy combines a positive tariff and a positive subsidy ($s > 0$ and $\tau > 0$).*

This proposition implies that when subsidies are not too costly ($\mu \to 1$), the optimal policy for large expansion targets involves mixing tariffs and subsidies. To see why, consider a tariff-only policy sufficient to achieve a very large expansion target. Such a target requires a very high tariff rate, which severely restricts imports and makes foreign sales negligible.

Now, consider replacing a small portion of this tariff with a subsidy, while holding domestic output constant. When μ is close to 1, the subsidy payment is a near-perfect transfer from the government to domestic firms. Similarly, because foreign output is minimal, any resulting price decrease is primarily a transfer from domestic firms to consumers. With these effects being fiscally neutral transfers, the net welfare impact hinges on what happens to tariff revenue.

Reducing a very high tariff has two opposing effects on revenue: a lower tax rate and a larger tax base (i.e., more imports). When the initial tariff is so high that the tax base is nearly zero, the effect of a lower rate is negligible. The dominant effect is the expansion of the tax base, which increases total tariff revenue. Since this substitution increases tariff revenue while other welfare effects are neutral, the optimal policy is to mix tariffs and subsidies, provided that subsidies are not too fiscally costly. See Appendix A.5.3 for additional details.

Remark 1 (Static model)**.** We abstract from dynamic considerations such as learning-by-doing, which may be important in an industry like solar panel manufacturing, where production costs likely fall with own and industry's cumulative output. In a dynamic setting, firms would have a private incentive to increase current production to lower their future costs. A production subsidy directly amplifies this private incentive, making it a more potent instrument for expanding output than in a static context. This increased effectiveness of subsidies implies that the switch from a tariff-only to a mixed policy would occur at a lower expansion target in a dynamic model than our static analysis predicts. While dynamics would alter the precise switching point, the core logic would persist: as the expansion target grows, a tariff-only policy becomes so distortionary that it is optimal to mix in its substitute instrument, the subsidy, to achieve a given expansion target at a lower welfare cost. This preserves the insight that the optimal policy mix depends on the scale of the expansion.

Remark 2 (Foreign retaliation)**.** Our analysis assumes the domestic country does not export the good in question to the home countries of the foreign firms. This assumption, which holds in our empirical setting for the Indian solar panel market, implies that classic tit-for-tat tariff retaliation is not a primary concern. Instead, the relevant strategic response is a retaliatory subsidy by the foreign government to its own firms. We explore this in Appendix B, where we endogenize this foreign subsidy response and computationally solve for the Nash equilibrium in policy instruments. Even in this strategic setting, our central finding holds: a tariff-only policy is optimal for small expansion targets (χ), while a mixed policy of tariffs and subsidies is optimal for large targets.

Remark 3 (Environmental externalities)**.** The above model abstracts from carbon benefits of additional solar deployment. If the planner values emissions reductions from *total* industry size (domestic + foreign), tariffs become less attractive because they contract total output; subsidies expand both domestic production and, via lower prices, demand for foreign panels. Appendix D incorporates the value of avoided CO_2 damages and shows that introducing these benefits lowers the χ threshold at which subsidies enter the optimal mix. Indeed, if the environmental benefits are large enough, they can overturn Proposition 2, making it optimal to include a subsidy even for the smallest expansion targets.

To translate our theoretical results into empirically relevant insights, we now estimate a structural model of the Indian solar panel industry. This empirical approach serves three purposes. First, it allows us to verify our theoretical predictions using real-world data. Second, it demonstrates the magnitude of the welfare gains from using the optimal instrument mix rather than relying on a single policy tool, providing policymakers with concrete evidence on when the added complexity of mixing instruments is justified. Third, and more importantly, it enables us to pin down the threshold at which the optimal policy shifts from being tariff-only to a mix of tariffs and subsidies. Quantifying this threshold is critical for policy design: if the switch occurs at a negligible expansion target, a simple rule of thumb would be to always combine instruments. Conversely, if the threshold is substantial, the model would support a tariff-only approach for a non-trivial range of policy objectives.

3 Setting & Data

In this section, we describe our empirical setting – the utility-scale solar sector in India. We begin by highlighting the key features of the upstream and downstream industries within this sector, and outline the various industrial policy interventions that have been deployed to support the domestic production of solar panels. We conclude this section by providing details about the data we use to estimate our model.

3.1 The Downstream Industry: Solar Power Plants

The downstream industry comprises utility-scale solar power plants, which generate electricity from solar energy. The term *utility-scale* is used to indicate the power generation capacity of each solar plant, typically greater than 1 megawatts (MW), and the intended end-use — solar power generated through these plants is fed into the electricity transmission grid operated by various state-run power distribution companies (DISCOMs). These DISCOMs then distribute this electricity to agricultural, industrial, and residential consumers.[8]

To incentivize large upfront investments in the construction of these plants, DISCOMs sign long-term power purchase agreements (PPA), usually 25 years, which guarantee long-run revenues for the developers of these solar plants. These power purchase agreements can be bilaterally negotiated or, in most cases, awarded through an auction process. In these auctions, participants bid on the rate at which they would sell electricity for the duration of the PPA. The PPAs are then awarded to developers with the lowest bids.

Since 2010, state agencies in India have experimented with multiple auction formats to award these power purchase agreements. In the early years, they relied on sealed

[8]Our analysis focuses exclusively on utility-scale solar power plants. Although rooftop and off-grid solar installations have grown in recent years, during our study period (2010–2021), these segments remained relatively small, each constituting only a minor fraction of the total installed solar capacity. Therefore, we exclude them from our analysis.

bid auctions. They have also experimented with auctions where the price of electricity is nominally fixed, and firms instead bid on capital subsidy they require from the government to build these solar plants. However, in recent years, the most frequently used auction format has been a multi-unit English auction. We describe this auction game in detail below.

Suppose the auctioneer wants to incentivize development of a solar plant of total capacity Q (say, 1 GW). As such, it will broadcast a call for applications, formally known as a Request for Selection (RFS). Interested developers submit an initial bid containing a quantity bid (say, 200 MW) and a price bid (say, INR 4/kWh). In this example, the bidder is proposing to erect a solar plant of capacity 200 MW and sell the electricity generated by it at a rate of INR 4 per kilowatt-hour. Based on some basic financial and techno-commercial criteria[9], as well as the initial bids, a subset of respondents are invited to participate in an English auction.[10]

This English auction is conducted online. Starting at the initial sealed bid, bidders are allowed to adjust their price bids downwards while holding quantity bids fixed. At all times, the bids (but not the identities) of all other participants are visible to everyone. The auction ends when no player adjusts their bids for a pre-specified duration of time (say, 8 minutes). Capacity allocations are made in the order of increasing price bids, starting with the lowest bid, until the initial target Q is met. All winners sign a PPA with the auctioneer at their final price bid in the auction.

In Figure 1a, we plot the cumulative installed capacity of solar power plants in India over the past decade or so. In 2010, the total installed solar photovoltaic (PV) capacity in India was under 200 megawatts (MW). By 2021, the total installed capacity was over 35 gigawatts (GW) with another 52 GW in pipeline.

[9]This is to ensure that the bidder would be able to build and operate a plant of the proposed size.

[10]In our data, we do not observe the initial price bid nor do we see the full set of initial respondents. For each auction, we only observe the set of participants invited to the second-stage of the auction process and their final price and quantity bids. As such, in our model and estimation, we disregard the first-stage selection process.

3.2 The Upstream Industry: Solar Panels

The upstream industry produces solar panels. A solar panel, also known as solar module, is a collection of solar photovoltaic (PV) cells that convert sunlight to electricity. These panels are marketed in terms of watts (W) per piece and serve as the primary input for the downstream solar power plants. For instance, a 100 MW solar plant would require 400,000 pieces of 250 W solar panels. At a conservative price of $100 a piece in 2016, that equals an investment of over $40 million in solar panels alone.

Despite the large demand generated for these panels by the downstream industry, domestic solar panel manufacturing has failed to take off. Globally and in India, solar panels from China dominate this industry. In the first half of the past decade, the market share of Chinese solar panels in the utility-scale solar sector in India was close to 90%. While there has been an uptick in domestic manufacturing in recent years, Chinese solar panels still command a majority share of the market. Industry experts point to several reasons behind China's relative dominance in the industry, including the availability of cheap credit, free land, manufacturing subsidies by the Chinese government, and the presence of an "ecosystem" that makes it easier to procure raw materials such as cells, wafers, and polysilicon.

In recent years, the Indian government has introduced two major policies to support the domestic production of solar panels.[11] These include: (1) tariffs on imported solar panels, and (2) production subsidies for domestic producers of solar panels.

The Indian government first introduced safeguard tariffs in August 2018 against panels from China and Malaysia. The initial import duty was set at 25% for one year, and then reduced by 5 percentage points every six months until July 2020. These safeguard tariffs remained at 15% until April 2022, when the government imposed a basic customs

[11] In the past, the Indian government has also tried to support the domestic panel manufacturing industry through two other channels — Domestic Content Requirement (DCR) auctions and Modified Special Incentive Package (MSIP) Scheme. The former is a class of auctions where the winners must procure their solar panels from domestic manufacturers, while the latter is a set of investment incentives to support manufacturing industries. The impact of these policies on domestic solar panel production is unclear and not investigated in this paper. Conversations with industry experts suggest that take-up of the MSIP scheme, announced in 2012, has been very low.

duty against all imports of solar cells and panels. This basic customs duty is set at 40% for solar panels and 25% for solar cells. We show the impact of the initial safeguard tariffs in Figure 2. Tariffs affected the composition of imports into the country. The value of imports from Malaysia essentially dropped to zero and there was a small dip in the imports from China; while imports from the rest of the world picked up. However, imports from China continued to make up a large share of total imports into India.

In 2020, the Indian government also announced plans to subsidize manufacturing in the domestic solar panel industry. As part of a broader push to boost manufacturing, the government has pledged $28 billion under Production Linked Incentive (PLI) Schemes across 13 sectors. Of this, approximately $3 billion (or ₹24,000 crore) has been earmarked to incentivize production in the solar PV panel industry under the National Programme on High Efficiency Solar PV Modules. This program was rolled out in two phases – Tranche I with ₹4,500 crore approved in 2021, and Tranche II with ₹19,500 crore approved in 2022. The scheme is explicitly designed to "build up solar PV manufacturing capacity of high efficiency modules" and "reduce import dependence".[12] Importantly, the program operates as a production subsidy rather than a traditional upfront grant; companies do not receive the full subsidy in advance. Instead, they earn the incentive on an annual basis in proportion to their actual output and sales of solar panels. Given this explicit link between subsidy and output, we view the PLI scheme as a production subsidy for domestic firms.

From the outlays in Tranche 1 of the scheme, we approximate the subsidy amount to be ₹5.15 per watt, paid out over 5 years.[13] Using the Bloomberg New Energy Finance (BNEF) Solar Spot Price Index in early 2020 ($\approx$ ₹14/watt) as a benchmark (see Figure 1b), this corresponds to a subsidy to price ratio of 7.3% per year.

[12] MNRE. (n.d.). Production Linked Incentive (PLI) Scheme: National Programme on High Efficiency Solar PV Modules. https://mnre.gov.in/en/production-linked-incentive-pli/

[13] Tranche 1 supported setting up of 8,737 MW capacity of manufacturing units.

3.3 Data

We rely on three primary sources of data for our estimation. These include data on (1) solar plants (or projects), (2) imports of solar panels, and (3) government-run auctions.

Solar Projects Database. The projects database, compiled by a market research firm, Bridge to India, includes solar project-level data on the status of all solar projects in India. Importantly, the database provides the commissioning date of each project and the identity of the upstream supplier of solar panels for each downstream project. This granularity enables us to work with firm-level market shares rather than simply distinguishing between domestic and foreign suppliers. In Figure 3a, we show the market shares of the top 10 solar panel suppliers between 2012 and 2020. These top 10 suppliers hold 60% of the market, and notably, seven are Chinese firms while only two are Indian.

To create a smooth time series for firm-level market shares, we use data on 1,970 projects totaling 45 GW of solar capacity, each with a known panel supplier. Industry experts suggest solar panels typically arrive during the last three months of the 12-18 month plant construction timeline. Leveraging this industry insight, we evenly distribute each project's capacity over the three months before commissioning. Aggregating across projects by supplier generates a smooth monthly sales series for each manufacturer. We then aggregate these monthly series quarterly and present foreign versus domestic market shares in Figure 3b. The combined market share of domestic firms is stable at around 10% before the import duty starts, and gradually increases afterwards.[14]

Import Data. The *imports* database records transaction-level data between 2014 and 2020 on imports of products categorized under HS code 8541.[15] We manually clean text fields describing the product being imported to construct a monthly price per watt series for

[14]Our data ends in January 2021. As such, we cannot observe the full impact of the import duty on domestic market share.

[15]HS Code 8541 is defined as "Diodes, transistors and similar semiconductor devices; photosensitive semiconductor devices, incl. photovoltaic cells whether or not assembled in modules or made up into panels (excluding photovoltaic generators); light emitting diodes; mounted piezoelectric crystals; parts thereof".

imported panels. This involved identifying the peak-wattage of each product being imported (e.g. 250 W) and the number of panels being imported, and then dividing total value of the shipment by the total imported watts. As a robustness check, in Figure 1b, we plot our constructed measure of imported panel prices against the spot prices recorded in the Bloomberg New Energy Finance (BNEF) Solar Spot Price Index. We find that our constructed measure tracks the BNEF index quite closely, with a correlation coefficient of 0.96.

In Appendix C.2, we use these data to run pass-through regressions that test a key prediction of our theoretical model: tariffs are not fully passed through to market prices, and foreign firms receive lower net prices after tariffs are introduced. Our analysis employs several distinct specifications: first, we compare price changes for imports from China and Malaysia (subject to tariffs) with other countries; in separate regressions, we control for global and China-specific technological changes using spot prices from Bloomberg New Energy Finance. Across all specifications and multiple time horizons, we find consistent evidence of incomplete passthrough, confirming that foreign firms bear part of the tariff burden.

While this finding is consistent with our oligopolistic competition framework, we recognize that incomplete passthrough can also arise in perfectly competitive markets and therefore treat these results as suggestive rather than definitive evidence of market power. Still, when combined with the significant market concentration documented above — where we show that a few Chinese firms dominate the upstream solar panel industry — these passthrough results present a compelling case for the presence of foreign market power.

Auction Data. Our final dataset contains auction-level data on the universe of solar auctions held in India. This was also provided to us by Bridge to India, which aggregates these data from various official and private sources. In these data, we observe each auction's characteristics, particularly the total capacity being auctioned and the various dates associated with the auction, such as announcement date, bid submission date, and results date. Each auction is also linked to detailed bid-level data, including the price and quantity bids of all bidders and the associated outcome of their bid. We restrict the auctions dataset to those that were held as multi-unit English auctions.[16] This left us with 52 auctions with 312 total bids, of which 48% were successful in winning a power purchase agreement. Overall, these auctions resulted in the allocation of 24.6 GW of solar capacity.[17] In Table 1, we provide preliminary evidence on the impact of the price of solar panels on price bids placed by developers in solar auctions. We find that a 1% increase in the price of solar panels is associated with a 0.8% increase in the price bid.

Importantly, a large share of the total variation in bids is explained by only the price of solar panels. This relationship between solar panel prices and auction bid prices underscores the crucial role of upstream costs in shaping downstream market outcomes. Given that winning bids determine the electricity tariffs that consumers ultimately pay, policies targeting the upstream solar panel industry – such as import tariffs and production subsidies – can have significant spillover effects on electricity prices.

Therefore, to fully assess the impact of industrial policy interventions in the solar sector, it is essential to account for their effects not just on domestic panel production and market share but also on the outcomes of solar auctions and the cost of electricity generation. In the following sections, we develop a structural model that explicitly incorporates these linkages, allowing us to quantify the equilibrium effects of policy changes on both the upstream and downstream segments of the market.

4 Model

In this section, we present a model of the utility-scale solar sector which consists of two industries: the upstream industry which manufactures solar panels, and the downstream

[16] Some auctions involved simultaneous bids on multiple tenders which were not disaggregated by our data provider. As such, we observe the same bidder submitting multiple bids for the same RFS. We exclude these auctions too.

[17] Our initial set of filters yielded 60 auctions with 375 total bids, but the availability of price data from panel imports further restricted this sample to 52 auctions.

industry which produces solar power. We first detail each industry's structure separately and then describe how they interact.

The objective of this model is to allow us to evaluate how different industrial policy interventions in the upstream industry affect equilibrium outcomes in the entire utility-scale sector. In particular, the model allows us to trace out the impact of tariffs and subsidies for solar panels on the profits of domestic firms and the welfare of the ultimate buyer of solar power.

4.1 Upstream supply of solar panels

In the upstream industry, firms manufacture solar panels (or modules). There are two types of firms in this industry: domestic firms and foreign firms. Each firm is indexed by j, and $\mathcal{J}_t = \bigcup_k \mathcal{J}_{kt}$ denotes the set of all active firms in period t, where $k \in \{domestic, foreign\}$ is the type of firm j. Firms are subject to an ad valorem tariff τ_{kt}, and a production subsidy s_{kt}. We treat s_{kt} as the proportion of production cost borne by the government.[18] Only foreign firms are subject to the tariffs, i.e. $\tau_{dt} = 0$ and only domestic firms receive the subsidy, i.e. $s_{ft} = 0$.

Solar panels are homogeneous goods that are sold at a single price in each period t. This market price of solar panels, p_t, is determined by the inverse demand function for solar panels, $P(Q_t^{supply})$, where $Q_t^{supply} = \sum_{j \in \mathcal{J}_t} q_{jt}$ is the total quantity of solar panels supplied in the market.

Firms differ in their production costs as well as their eligibility for tariffs or a subsidy; both affect firm production decisions. Let $c_{jt}(q)$ be the total cost of production of firm j in period t when it produces q units of solar panels. Firm $j \in \mathcal{J}_t$ chooses quantity q to maximize variable profits

$$\max_q \ \pi_{jt}^u(q) = (1 - \tau_{kt}) \cdot p_t \cdot q - (1 - s_{kt})\, c_{jt}(q) \tag{3}$$

[18] In other words, this is an ad valorem subsidy on cost of production, which is equivalent to a subsidy per unit of production when marginal cost is constant.

which gives rise to the optimal quantity q^*_{jt} and profits $\pi^u_{jt}(q^*_{jt})$. The superscript u denotes upstream industry to distinguish it from the downstream industry which we describe in Section 4.2.

Finally, all active firms also pay a fixed cost of accessing the domestic market, denoted by λ_{jt}. Therefore, the *net payoff* of an upstream firm j is

$$V_{jt}(q^*_{jt}) = \pi^u_{jt}(q^*_{jt}) - \lambda_{jt} \tag{4}$$

In equilibrium, only firms with positive net payoff, $V_{jt}(q^*_{jt}) \geq 0$, are active in period t in the upstream industry.

This concludes our description of the upstream industry that is subject to industrial policy interventions. Compared to the simple model presented in Section 2, we now allow for firm-level heterogeneity in the cost of production, and a fixed cost of accessing the domestic market. Thus, changes in subsidies and tariffs would not only change output but could also change the number and composition of both foreign and domestic firms in the upstream industry.

4.2 Downstream supply of solar power plants

In the downstream industry, firms build solar power plants. These power plants generate electricity which is sold to power distribution companies. The cost of solar panels makes up a large share of the total cost of building a solar power plant; as such, the price of solar panels is a potentially important determinant of the price of solar power. Since we expect policy interventions in the upstream industry to change the equilibrium price of solar panels, the purpose of this part of the model is to understand how changes in the price of solar panels translate into changes in the price of solar power.

One could estimate this elasticity by modeling the reduced-form relationship between the price of solar power and the price of solar panels, as we did in Section 3.3. However, this approach precludes us from computing the impact of policy interventions on firm profits in the downstream industry. Here, we introduce a simple model that allows us to recover the cost function of solar plant developers, and also estimate the elasticity of the price of solar power with respect to the price of solar panels.

The output of the downstream industry is measured in terms of *solar power generation capacity*, which is developed through auctions. We denote a specific auction by h. In auction h, the auctioneer auctions off total capacity A_h. The participants in these auctions are solar plant developers, indexed by $i \in \mathcal{N}_h$, where $\mathcal{N}_h$ is the set of all participants in auction h. Participant i enters the auction with a pre-committed capacity bid $a_{ih} \leq A_h$; this is the capacity of the solar plant that would be developed by the participant if it wins.[19] Depending on the relative magnitudes of the capacity bids and the total capacity being auctioned, there may be multiple winners in a given auction. Therefore, these auctions are multi-unit auctions.

The winner(s) in auction h, denoted by $\mathcal{N}_h^W \subseteq \mathcal{N}_h$, sign a contract with the auctioneer for L years. This contract is a power purchase agreement which specifies the price per unit of power, usually expressed in kilowatt-hour (kWh), that each winning developer would receive from the offtaker for its bid capacity a_{ih} for the next L years. If this price is b, the net present value of the stream of revenues per unit capacity is $r(b)$. We compute this net present value as follows

$$r(b) = \sum_{l=0}^{L-1} \beta^l \times b \times c.u.f. \times 24 \times 365$$

where β is the discount factor and $c.u.f.$ is the capacity utilization factor, which adjusts for the fact that a solar plant does not generate electricity at all hours of a day.

For developer i, the constant marginal cost of developing solar power plant capacity is $e_{ih}(p)$, where p is the price of solar panels at the time of the auction. Let $\pi_{ih}^d(b, p)$ be the *profits per unit capacity*, conditional on winning, at purchase price b and panel price

[19] We do not model how participants choose their capacity bid, or how they decide whether to enter a given auction. For the purposes of this model, these are exogenous. However, when we compute counterfactuals, we describe how we pick these quantities.

p, where

$$\pi^d_{ih}(b, p) = r(b) - e_{ih}(p) \tag{5}$$

Thus, all else equal, a higher price of solar panels reduces the profits of solar plant developers.

Next, we describe how winners and winning solar power prices are determined. In modeling the auction format, we make one simplification: we assume that the auction is organized as a descending-bid ("button press") auction. This abstracts away from the dynamic structure of an English auction which is difficult to capture in a model.

In this auction, the auctioneer starts off at a sufficiently high bid such that $\pi^d_{ih}(\hat{b}, p) > 0$ for all participants, and keeps lowering it. At each bid $\hat{b}$, all auction participants with $\pi^d_{ih}(\hat{b}, p) = 0$ drop out. The auctioneer stops at bid b^* when the total capacity bid by all remaining participants equals A_h.[20] The price b^* is the *uniform price* of the auction, and all winners receive this price.[21]

Since these solar plant developers are domestic firms, their profits factor into our estimates of total welfare under alternative industrial policy interventions. These profits are given by

$$\pi^d_h(b^*, p) = \sum_{i \in \mathcal{N}^W_h} \pi^d_{ih}(b^*, p) \cdot a_{ih} \tag{6}$$

Next, we outline how the size of the auction, A_h, is determined.

[20]In certain cases, the remaining quantity might be greater than A_h but lowering the bid further would result in another participant dropping out so that the remaining total capacity bid is less than A_h. Here, the auctioneer awards only part of the capacity bid to one of the participants to ensure that total capacity awarded is exactly equal to the open capacity A_h. This assumption does not affect our estimation strategy. When computing counterfactuals, we assume that the winner with the highest unit cost receives part of the capacity bid in cases where the total capacity bid by all winners is greater than A_h.

[21]This is a consequence of the assumption of descending-bid auction. In the solar auctions conducted in India, participants receive the price they bid in the online English auction. However, due to our simplication of the auction format, we do not generate variation in the prices received by winners.

4.3 Downstream demand for solar power

The power generated by solar power plants is sold to power distribution companies. Depending on the price of solar power, these power distribution companies may demand more or less solar power. This price of solar power b, determined by the auction process described above, is in itself a function of the price of solar panels p. Thus, we can write the demand for solar power as

$$\begin{aligned} Q_t^{demand} &= \widetilde{D}(b(p)) \\ &= D(p) \end{aligned} \tag{7}$$

where quantity Q_t^{demand} is expressed in the same units as plant capacity and the quantity of solar panels. In the above equation, $\widetilde{D}(b)$ is the demand function which gives rise to the procurement auctions in the downstream industry, while $D(p)$ is the reduced-form demand function which generates demand for solar panels.

4.4 Equilibrium

This is a full-information, simultaneous-move static game. Each period t is an independent market, and the equilibrium of each market is a price p^* of solar panels such that the quantity of solar panels supplied in the upstream industry equals the quantity of solar panels demanded in the downstream industry, which in turn equals the quantity of solar power supplied in the downstream industry. At this equilibrium price, the auctioneer conducts one auction with total capacity $A = \widetilde{D}(b(p^*))$, which yields $b(p^*)$ as the equilibrium price of solar power. Finally, at this price, firms in the upstream industry are in a static Cournot-Nash equilibrium with respect to their production decisions.

5 Structural Estimation

5.1 Demand for solar panels

We estimate the reduced-form demand for solar panels $D(p)$, described in equation (7), using a log-linear specification as follows

$$\ln Q_t = \delta_0 + \delta_p \cdot \ln p_t + \varepsilon_t \tag{8}$$

where Q_t is the total quantity of solar panels consumed in quarter t, and p_t is the price of solar panels in that quarter. We use data from 25 quarters, from 2014 Q1 to 2020 Q1. To address concerns about endogeneity of the price of solar panel, we instrument it using the spot price of polysilicon, which is a key raw material used in the production of solar photovoltaic cells which make up solar panels.

To measure total consumption Q_t, we rely on two approaches. First, we rely on our *imports* data to construct total quantity of solar panels (measured in megawatts) imported into India each quarter. Second, we use the *projects* data to infer the total quantity of solar panels used in utility-scale solar projects each quarter. To do so, we take the total installed capacity of each solar power plant, and assign it equally to each of the three months prior to its date of commissioning.[22] Summing up over all installed solar power plants yields quarterly consumption of solar panels.

We present the estimated demand parameters in Table 2. Column (1) presents results from the first-stage regression, which confirms that price of polysilicon is a strong and relevant instrument for the price of solar panels. Columns (2) and (3) present results from the second-stage regression. The estimated demand elasticity is -2.0 when we use the imports data, and -1.5 when we use the projects data. Our preferred estimate is the one derived from the projects data as it also captures demand fulfilled by domestic producers. We use this estimate in the estimation of the cost function of upstream solar

[22] This is a reasonable assumption. Solar power plants take 12 to 18 months to construct, and solar panels are one of the last items to be installed.

panel producers, as well as in our counterfactual analysis.

5.2 Cost of production of solar panels

In this section, we estimate parameters governing the production costs of upstream solar panel producers and their fixed cost of accessing the domestic market in India. Since policy interventions will apply differently to different firms based on their *type* (i.e. domestic or foreign), we focus on estimating these parameters flexibly by firm type.

We begin by describing our functional form assumptions, and then delve into our estimation routine. We assume that the marginal cost of producing q units of solar panels in period t by firm j of type k is given by

$$\begin{aligned} mc_{jt}(q) &= c_{jt} \cdot q^{\gamma_{q,k}} \\ &= \exp\left\{\gamma_{0,k} + \gamma_{t,k} \cdot t + \nu_{jt}\right\} \cdot q^{\gamma_{q,k}} \end{aligned} \tag{9}$$

where $\nu_{jt} \sim \mathcal{N}\left(0, \sigma^2_{\gamma,k}\right)$ is a firm- and period-specific idiosyncratic shock to marginal cost. The type-specific intercept $\gamma_{0,k}$ denotes the initial stock of technological know-how of the two types of firms in this industry at $t = 0$. The parameter, $\gamma_{t,k}$, gives the rate at which marginal costs change over time. This is a period with rapid advancements in solar technology, so this parameter captures the rate of technological progress of the two types of firms.[23] Finally, the parameter $\gamma_{q,k}$ controls how marginal costs change with quantity produced. It is informative about the type-specific returns to scale and/or type-specific latent capacity constraints.

In addition to production costs, firms are also subject to a fixed cost of accessing the domestic market, denoted by λ_{jt}, where

$$\lambda_{jt} \sim \exp\left(\frac{1}{\lambda_k}\right) \tag{10}$$

[23]We assume that the rate of cost declines is exogenous. A common motivation for industrial policy interventions is external economies of scale where the marginal cost of production declines with the size of the domestic industry (Bartelme et al., 2024). In our counterfactual analysis, we consider different policy combinations that achieve the same domestic industry size. Therefore, the cost reduction benefits from economies of scale should be the same across all policy combinations, and we abstract away from dynamic considerations.

This fixed cost is crucial for matching the number of active firms in a given period.

Next, we outline our estimation routine. Let $\gamma_k = \{\gamma_{0,k}, \gamma_{t,k}, \gamma_{q,k}, \sigma_{\gamma,k}, \lambda_k\}$. As an overview, for each guess of parameters $\gamma = \{\gamma_{domestic}, \gamma_{foreign}\}$, we solve for the model-implied equilibrium in the upstream market and generate a simulated dataset with equilibrium quantities. Then, we construct moments from this simulated dataset and search for parameters that minimize the (variance-weighted) distance between these moments and their empirical counterparts.[24]

Specifically, for each period (i.e. quarter), we take a set of *potential* firms and draw their production cost shocks and fixed cost shocks. The set of potential firms is chosen as follows: take all firms which ever show up as suppliers in the projects database between 2014 Q1 and 2020 Q1, and then drop those which were founded after the period of interest. Next, we determine the set of *active* firms i.e. the subset of potential firms which choose to operate in a given period. Here, we rely on an iterative algorithm that searches for the largest subset of potential firms which can operate with non-negative net payoff in the market. We begin with all potential firms and solve for the profit-maximizing level of output (which may be zero for some). Next, we compute the net payoff by differencing out the fixed cost of market access. If all firms have non-negative net payoff, then we stop. Else, we drop the firm with the lowest net payoff and repeat the process with the remaining firms. This procedure yields the equilibrium for one period and for one draw of cost shocks. For each observed quarter, we repeat this 30 times with a different draw of cost shocks for each potential firm.

So, given a guess $\widehat{\gamma}$, we solve the upstream equilibrium in $25 \times 30 = 750$ periods. This yields a simulated dataset with 750 quarters of data. We then compute the following moments from this simulated dataset: (1) average number of firms of each type in a period, (2) average total output by firms of each type in a period, and (3) the interquartile range of output by firms of each type in a period. We compute the first two moments separately for the pre-tariff period (2014 Q1 to 2018 Q2) and the post-tariff period (2018

[24]Our estimation relies on simulation-based estimators (McFadden, 1989; Pakes, 1986; Pakes & Pollard, 1989).

Q3 to 2020 Q1). This gives us 5 moments for each type of firm, which help us identify the 5 type-specific parameters $\boldsymbol{\gamma}_k$. We match these 5 moments with their empirical counterparts, as shown in Table 3.[25]

The estimated parameters are given in Table 4. Our estimates of the intercept γ_0 and technological progress γ_t suggest lower baseline costs for foreign firms but more rapid decline in marginal costs of domestic firms. Marginal costs are increasing with output for both types of firms, but the marginal cost curve is more convex for domestic firms, suggesting costs rise more sharply with output for domestic firms. The estimated variance of production costs is also higher for domestic firms, suggesting greater heterogeneity in production costs for domestic firms. Finally, the mean of the distribution of fixed costs of market access is higher for foreign firms, suggesting that domestic firms face lower barriers to accessing the domestic market.[26]

Identification. We provide brief intuition for the identification of the parameters in Table 4. The intercept of the cost function, $\gamma_{0,k}$, is identified by the overall level of output produced by each type of firm, while the time trend in marginal cost, $\gamma_{t,k}$, is informed by how total output changes over time. The variation in the level of tariffs across periods and their differential impact on foreign and domestic firms provide additional identifying power. The fixed cost of market access, λ_k, is pinned down primarily by the average number of active firms of each type. The exponent on quantity, $\gamma_{q,k}$, is identified by the upper tail of the output distribution — particularly the 90th percentile — because a higher exponent implies that marginal cost rises more sharply with quantity, thereby limiting very high production levels. Finally, the variance of production cost shocks, $\sigma_{\gamma,k}$, is determined by the dispersion of firm output, captured by the interdecile range, since greater shock variance leads to a wider spread of realized outputs.

[25] When minimizing the distance between simulated and empirical moments, we weigh each moment by the inverse of its variance. For the first two moments, we compute the variance by bootstrapping quarters 100 times. For the third moment, we take the variance across the 25 quarters in our sample.

[26] The values are reported in millions of rupees. Note that this parameter describes the distribution of fixed costs of market access, and not necessarily the average fixed cost for *active* firms, which would be lower.

5.3 Cost of developing solar power plants

We estimate the per unit cost of developing solar power plants, $e_{ih}(p)$, using auction-level bid data. In this data, for each auction, we observe the full set of participants in the online auction, their final bids, as well as their status (i.e. whether they won or lost the auction).

As discussed in Section 4.2, we abstract away from the actual English auction by assuming that the auction is organized as a descending-bid auction. Under this simplification, participants drop out when the prevailing bid b is such that their profits per unit capacity $\pi^d_{ih}(b, p)$ are equal to zero. Specifically, for the set of participants who lose the auction, we have

$$\pi^d_{ih}(b_{ih}, p) = 0 \quad \forall i \in \mathcal{N}^L_h = \mathcal{N}_h \setminus \mathcal{N}^W_h \tag{11}$$

where b_{ih} is the final bid observed in the data, and p is the price of solar panels at the time of auction h.

The direct consequence of (11) is that, for losers in each auction, the cost of developing a solar power plant must equal the net present value of the stream of revenues from one unit of capacity at the final bid b_{ih}. That is,

$$e_{ih} = r(b_{ih}) \quad \forall i \in \mathcal{N}^L_h = \mathcal{N}_h \setminus \mathcal{N}^W_h \tag{12}$$

The (log) cost of developing one unit of solar power plant capacity is given by

$$\log e_{ih} = \eta_0 + \eta_p \cdot \log p_{t(h)} + \eta_{ih} \tag{13}$$

where $p_{t(h)}$ is the price of solar panels at the time of the auction, and $\eta_{ih} \sim \mathcal{N}\left(0, \sigma^2_\eta\right)$ is a firm- and auction-specific idiosyncratic shock. Combining (12) and (13), we have

$$\log r(b_{ih}) = \eta_0 + \eta_p \cdot \log p_{t(h)} + \eta_{ih} \quad \forall i \in \mathcal{N}^L_h = \mathcal{N}_h \setminus \mathcal{N}^W_h \tag{14}$$

This looks like a regression equation but we cannot estimate (14) directly using OLS since the set of losers in an auction do not constitute a random sample. In particular, firms with a higher draw of the cost shock η_{ih} are more likely to end up in the set of losing firms.

We deal with this selection issue by exploiting the *relative rank* of each bid within an auction as follows. Let $\boldsymbol{\eta} = \{\eta_0, \eta_1, \sigma_\eta\}$. For a guess $\widehat{\boldsymbol{\eta}}$, we can recover $\widehat{\eta}_{ih}(\widehat{\boldsymbol{\eta}}) = r(b_{ih}) - \widehat{\eta}_0 - \widehat{\eta}_p \cdot p_{t(h)}$. If b_{ih} is the i^{th} lowest bid in auction k, then $\widehat{\eta}_{ih}(\widehat{\boldsymbol{\eta}})$ must be the i^{th} lowest draw out of $|\mathcal{N}_h|$ draws from $\mathcal{N}\left(0, \widehat{\sigma}_\eta^2\right)$. Using the density function for the i^{th} order statistic given $\widehat{\sigma}_\eta^2$, we can compute the probability that $\widehat{\eta}_{ih}$ is the i^{th} lowest draw. Doing this across all losing bids and all auctions, we can construct a likelihood of the data, $\mathcal{L}(\widehat{\boldsymbol{\eta}})$. We estimate $\boldsymbol{\eta}$ by maximizing this likelihood, and present the estimated parameters in Table 5.

5.4 Demand for solar power plants

To compute welfare statistics under different policy interventions, we also need to estimate the demand for solar power plants $\widetilde{D}(b)$ as a function of the price of solar power b. As discussed in Section 4.3, we have

$$\widetilde{D}(b(p)) = D(p)$$

where $D(p)$ is the reduced-form relationship between the price of solar panels and the demand for solar panels, estimated in Section 5.1. Let $\widetilde{D}(p)$ be an isoelastic function with price elasticity of demand δ_b. Then, the above equation can be used to derive the following relationship between elasticities

$$\delta_p = \delta_b \cdot \delta_a \tag{15}$$

where $\delta_p = \frac{\partial \ln D(p)}{\partial \ln p}$ is the price elasticity of demand for solar panels, $\delta_b = \frac{\partial \ln \widetilde{D}(b)}{\partial \ln b}$ is the price elasticity of demand for solar power, and δ_a is the elasticity of the winning auction bid with respect to the price of solar panels. Since we already have an estimate for δ_p, if we were to estimate δ_a, we can back out δ_b using the above relationship.

We estimate δ_a by simulating auction game play 100,000 times under a baseline price and baseline auction size. This baseline price and auction size are computed by solving the upstream industry equilibrium at no tariff or subsidy. We set the number of auction participants to 5, which is the median number of participants in our dataset.[27] Each auction play yields a winning bid, and we take mean over simulations to compute the average winning bid. Then, we increase the baseline panel price and simulate auction play another 100,000 times. Finally, we take the ratio of the percentage change in the average winning bid to the percentage change in the baseline panel price to recover δ_a.

Using the procedure described above, we estimate δ_a to be 1.03; that is, a 1% increase in the price of solar panels leads to a 1.03% increase in the winning bid. We use this to back out δ_b to be -1.49. This means, a 1% increase in the price of solar power (winning bid) leads to a -1.49% change in the demand for solar power (auction capacity).

6 Counterfactuals: Optimal Policy Mix

In this section, we use our estimated model to solve for the optimal policy for different values of domestic output expansion targets. In particular, we compute optimal policies under three different scenarios. In the first scenario, we allow the policymaker to use only import tariffs ("tariff-only"). That is, the subsidy rate is set to zero and the domestic expansion target is achieved only through the use of tariffs. In the second scenario, we allow the policymaker to use only production subsidies ("subsidy-only"); here, import tariffs are set to zero. Finally, in the third scenario, we allow the policymaker to use both instruments ("both"), again subject to the constraint that the domestic expansion target is achieved. Here, the policymaker may choose to set either instrument to zero, or use non-zero levels of both instruments. As multiple combinations of tariffs and subsidies achieve the same expansion target, the policymaker selects the combination that maximizes welfare.

[27] Each participant bids the same share of total auction capacity (q_{ik}/Q_k), where the share is assumed to be the average capacity share computed using observed bids in the data.

Before proceeding to results, we briefly describe how we solve for the equilibrium in the upstream and downstream segments of the utility-scale solar sector for different values of import tariffs and production subsidies. We first solve for the equilibrium in the upstream solar panel industry, given the estimated upstream cost parameters and demand parameters, presented in Tables 2 and 4. Here, we set the time period t to be such that the market is in 2019. All firms established by 2019 are included in the set of potential firms, and we arrive at the equilibrium set of active firms using the procedure described in Section 5.2. This yields an equilibrium price and quantity of solar panels. We use these to simulate auction play 20,000 times in the downstream industry and compute solar plant developers' average profits and the average winning bid. Finally, using our estimates of the price elasticity of demand for solar power, δ_b, we compute the change in consumer surplus relative to the baseline under the assumption of an isoelastic demand curve.

Once we have solved for the equilibrium of the utility-scale solar sector, we compute total domestic welfare. Its key components are (1) government revenues (or expenditures), (2) total profits of domestic upstream producers, (3) total profits of downstream solar plant developers, and (4) consumer surplus associated with solar power consumption.[28] For tariffs, government revenues are $\tau_f \cdot p \cdot q_{if}$ summed over all active foreign firms. For subsidies, government expenditures are $\mu \cdot (1 - z_d) \cdot p \cdot q_{id}$ summed over all active domestic firms, where $z_d = 1 - s_d$ is the proportion of production cost borne by domestic firms, and μ is the cost of public funds. We set $\mu = 1$ for all results in this section, i.e., the cost of 1 rupee of production subsidy is 1 rupee.[29] Total profits of domestic upstream producers are net of the fixed cost of accessing the domestic market. The profits of downstream solar plant developers are given in (6). Recall that these are net present values of power purchase agreements spread over 25 years. Finally, the change

[28]Our baseline welfare calculation does not incorporate environmental externalities associated with solar power deployment. In Appendix Appendix D, we extend our analysis to include the positive environmental benefits of solar power and show how this affects the optimal policy mix.

[29]Increasing μ does not change our qualitative results; tariffs continue to be optimal for small expansion targets, and for large enough expansion targets, a combination of tariffs and subsidies is optimal.

in consumer surplus relative to the baseline is given by

$$\Delta CS(\tau,s) = -\left(\frac{b\left(\tau,s\right)A\left(\tau,s\right) - b\left(0,0\right)A\left(0,0\right)}{1+\delta_b}\right)$$

where $b\left(\tau,s\right)$ and $A\left(\tau,s\right)$ are the average winning bids and the corresponding solar capacity auctioned under a given counterfactual with tariff τ and subsidy s, $b\left(0,0\right)$ and $A\left(0,0\right)$ are the baseline average winning bids and the baseline level of solar capacity auctioned, and δ_b is the price elasticity of demand for solar power.

Now, we present the results of our counterfactual analysis.

We consider expansion targets ranging from 1% to 15% of the baseline output of domestic solar panel producers. For each expansion target, we compute the optimal policy under the three regimes: tariff-only, subsidy-only, and both. We show the optimal policy under each of the three regimes in Figure 4a, and the corresponding change in welfare in Figure 4b.

Tariff-only and subsidy-only policies. When using tariffs or subsidies alone, the optimal policy is strictly increasing in the expansion target — a larger expansion target requires a higher tariff-only or subsidy-only rate. For instance, to increase the size of the domestic industry by 6%, the policymaker can either impose a tariff of 19% or subsidize production costs by 9%. On the other hand, to expand the domestic industry by 15%, the required tariff rate is 40% and the required subsidy rate is 21%. Achieving this expansion target of 15% using tariffs alone results in a welfare gain of about 20 million USD, while achieving the same expansion target using subsidies alone results in a welfare gain of about 14 million USD (assuming cost of public funds, μ, is equal to 1).

In our empirical setting, which features substantial market power, we expect a moderate level of either tariffs or subsidies to be welfare improving due to profit shifting and reduction in domestic distortions caused by market power. However, this is not necessarily true for very high levels of either instrument. Thus, since larger expansion targets require more aggressive policy rates, the welfare function may be decreasing in the expansion target for some range of expansion targets. This pattern is evident for a tariff-only policy in Figure 4b. To go from an expansion target of 12% to 15% under a tariff-only policy requires raising the tariff from 33% to 40%. This increases tariff revenue and domestic profits in the upstream sector, but this increase is not enough to compensate for the resulting losses in consumer surplus and downstream solar plant developers' profits, leading to a net decline in welfare. We provide a breakdown of the different components of welfare in Figure 5. For a subsidy-only policy, while welfare is increasing for the given range of expansion targets and $\mu = 1$, an analogous fall in welfare would arise for sufficiently large expansion targets or when μ is sufficiently high.

These observations give us some intuition for why mixing tariffs and subsidies can be preferable for larger expansion targets. Because both instruments help domestic producers expand, using them in tandem allows each to be set at a lower level than would be required under a tariff-only or subsidy-only regime. In doing so, the policymaker avoids the most distortionary portions of each policy instrument, thereby delivering higher overall welfare.

Mixing tariffs and subsidies. Now, we allow the policymaker to freely choose the mix of tariffs and subsidies to achieve a given expansion target. The policymaker picks the combination that gives the highest welfare while meeting the expansion constraint. The optimal mix may involve a boundary solution such that the required tariff or subsidy is zero under the mixed policy. As such, the welfare under the mixed policy is (weakly) greater than the welfare under the tariff-only or subsidy-only policy.

We find that for expansion targets below 8%, the optimal policy is a tariff-only policy. That is, the policymaker chooses to set the subsidy rate to zero and use only tariffs to achieve the expansion target. This is consistent with Proposition 2. For these expansion targets, the required tariff rate is low. Thus, a marginal increase in tariff increases government revenue more than it hurts downstream solar plant developers and consumers. As such, replacing subsidies with tariffs is welfare improving.

However, for expansion targets above 8%, the optimal policy is a mixed policy where the policymaker uses non-zero levels of both tariffs and subsidies. For example, a 15% target is optimally achieved with a 25% tariff combined with an 11% subsidy. The welfare under this mixed policy is substantially higher than the welfare under the tariff-only or subsidy-only policies which achieve the same 15% expansion target. We take this finding as providing empirical support for Proposition 3, which predicts that mixing tariffs and subsidies is optimal for large enough expansion targets. Finally, note that for the range of expansion targets considered, the optimal policy is never a subsidy-only policy, which lends empirical support to Proposition 1.

7 Conclusion

This paper studies how best to expand domestic industry in an oligopolistic setting using two policy levers: tariffs and subsidies -—- either one at a time or in combination. Using a theoretical model of oligopolistic competition between domestic and foreign firms, we establish three key results. First, a subsidy-only policy is never optimal when the goal is to expand domestic output by a given target; one should always use some positive tariff. Second, if the given expansion target is relatively small, a tariff-only policy is optimal. Third, for large expansion targets, the optimal policy involves a mix of tariffs and subsidies.

We test these results using a structural model of India's solar industry estimated using microdata from upstream solar panel manufacturers and downstream solar power plant developers. We model the upstream industry as a Cournot oligopoly with domestic and foreign producers of solar panels, and then link it to the downstream industry where solar power plant developers compete in auctions to win long-term power purchase agreements (PPAs) from power distribution companies. Using the estimated model, we simulate counterfactuals to characterize the optimal policy for a range of expansion targets. Our empirical results are in line with the theoretical predictions — for small expansion targets ($< 8\%$), the optimal policy is a tariff, and for larger expansion targets, the optimal policy is a mix of tariffs and subsidies.

These findings help rationalize why many countries rely on both tariffs and subsidies to expand domestic industries. Of course, policymakers usually have a broader set of tools at their disposal, and understanding how best to combine them, especially in the presence of market power, remains an important research question. It would be valuable to extend the analysis to other policy instruments—such as import quotas, domestic-content requirements, or mandated joint ventures—and to settings where domestic firms compete more actively in export markets. Investigating the interplay of these additional factors would shed further light on the most effective ways to achieve domestic industrial expansion goals in oligopolistic markets.

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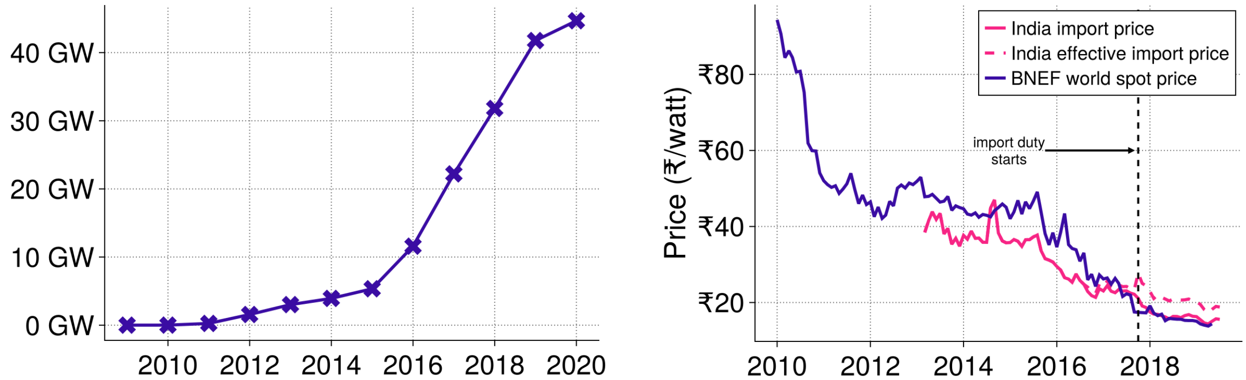
Figure 1: *Indian solar capacity and global solar panel prices*

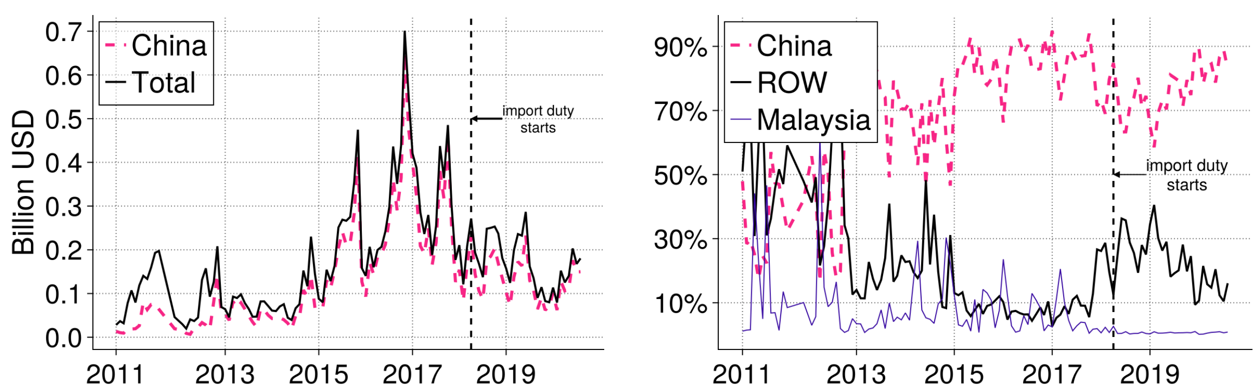
(a) *Cumulative installed solar capacity* **(b)** *Solar panel price per watt*



Notes. In the left panel, we plot the sum total of the capacities of all commissioned solar plants upto a given year as recorded in the projects database of our data provider, Bridge to India. In the right panel, we show the monthly average spot prices of multi crystalline silicon panels, expressed in price per watt. These values are obtained from the Bloomberg New Energy Finance (BNEF) Solar Spot Price Index.

Figure 2: *Impact of safeguard duties against China and Malaysia*

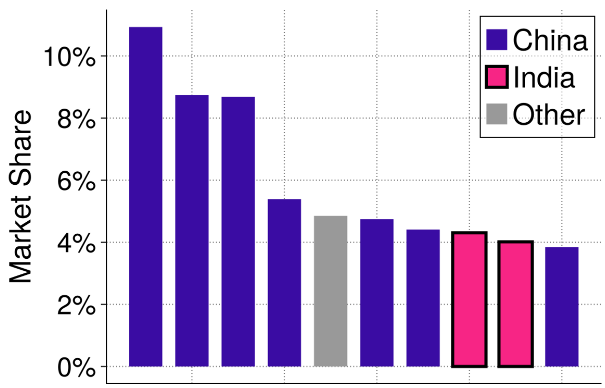
(a) *Import value (billion USD)* **(b)** *Share of total imports*



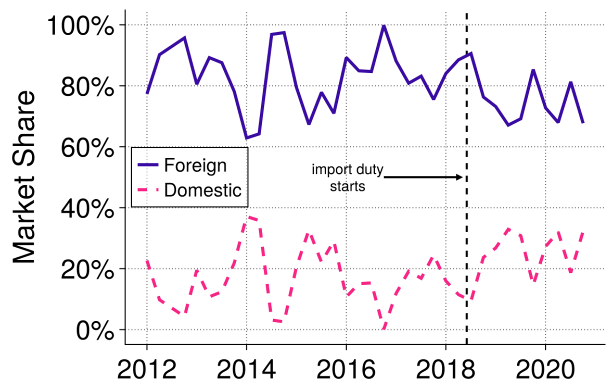
Notes. This figure plots monthly imports of products categorized under HS code 854140 into India as recorded under UN Comtrade Database. In the right panel, share of imports are calculated using value of imports recorded in US dollars; ROW refers to value of all imports excluding China and Malaysia.

Figure 3: *Market shares in the upstream industry*

(a) *Top 10 suppliers (2012-2020)*

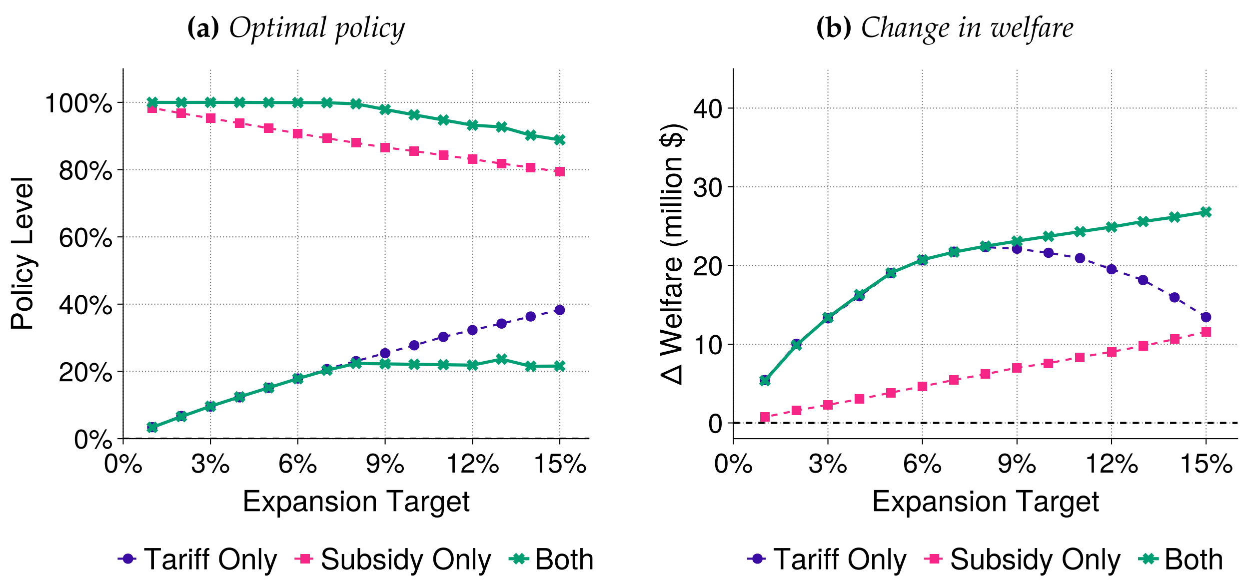


(b) *Market shares by supplier country*



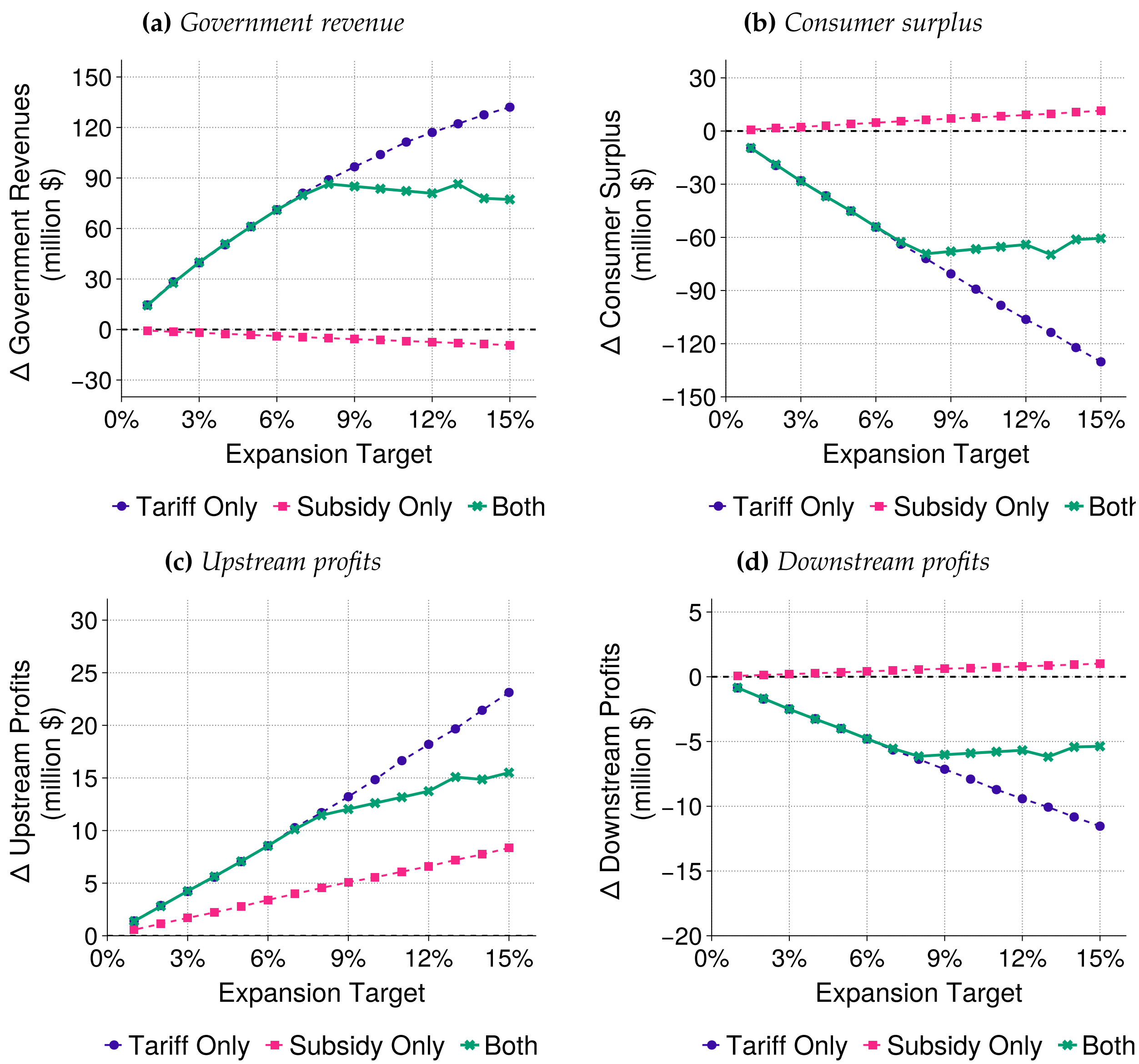
Notes. The left panel display the market shares of the top 10 suppliers of solar panels to utility-scale solar projects in India between 2012 and 2020. The combined market share of these top 10 suppliers is 60%. Out of the top 10, 7 are Chinese firms while only 2 are Indian firms. The right panel uses data on project-level panel suppliers to plot market shares of foreign and domestic panel manufacturers. For each project, the total project capacity is evenly split over the three months prior to its commissioning and assigned to its supplier. Aggregating over all projects yields a smooth monthly series on sales by each panel manufacturer. The above figure plots quarterly market shares derived from this smooth monthly series.

Figure 4: *Optimal policy and change in welfare at different expansion targets*



Notes. In the left panel, we show the optimal policy for a given expansion target for total domestic output relative to its level under no policy intervention. There are three policy regimes: (1) tariff-only, (2) subsidy-only, and (3) a combination of tariffs and subsidies, referred to as "both" above. For each policy regime and for each expansion target ranging from 1% to 15%, we plot the optimal level of import tariff τ on foreign firms and optimal level of $z = 1 - s$, i.e., the proportion of production cost borne by domestic firms. A lower z corresponds to a higher subsidy. For the policy regime where we mix the two instruments under "both", we show two curves with the same color and marker; these correspond to the level of τ and z under the mixed policy. In the right panel, we show the change in welfare relative to baseline under the three regimes at each expansion target. Welfare consists of consumer surplus, government revenue, and profits of domestic upstream and downstream firms.

Figure 5: *Components of welfare at different expansion targets*



Notes: This figure plots the change in welfare components under the three regimes for expansion targets ranging from 1% to 15%. Panel (a) plots the change in government revenue under the three regimes. Panel (b) plots the change in consumer surplus under the three regimes. Panel (c) plots the change in profits of domestic firms in the upstream solar panel industry under the three regimes. Panel (d) plots the change in profits of downstream solar plant developers under the three regimes.

Table 1: *Effect of panel prices on auction bids*

	(log) Bid	(log) Maximum winning bid	(log) Weighted winning bid
	(1)	(2)	(3)
(log) Price of solar panels	0.83***	0.76***	0.76***
	(0.15)	(0.10)	(0.10)
N	312	52	52
R^2	0.59	0.52	0.52

Notes. This table contains the results from regressing auction bids on solar panel prices, inclusive of import tariffs. For column (1), standard errors are clustered at the auction-level and given in parentheses. For columns (2) and (3), regressions are at auction-level and standard errors are reported in parentheses.

Table 2: *Demand for solar panels*

	(log) price of panels	(log) quantity of panels	
		Imports	Projects
	(1)	(2)	(3)
(Intercept)	-2.56	12.95	11.90
	(0.27)	(1.81)	(1.84)
(log) price of polysilicon	0.87		
	(0.04)		
(log) price of panels		-2.00	-1.51
		(0.57)	(0.56)
F statistic	395.42	12.33	7.21
R^2	0.76	0.45	0.42
N	25	25	25

Notes: This table presents estimated parameters of the log-linear reduced-form relationship between the price of solar panels and the demand for solar panels. The data are at the quarterly-level and span from 2014 Q1 to 2020 Q1. We instrument the price of solar panels using the price of polysilicon, which is an important raw material used in the production of solar photovoltaic cells. We present estimates from the first-stage in column (1). In columns (2) and (3), we present the estimated elasticity of demand using instrumented price of solar panels. Column (2) uses quarterly imports of solar panels into India as the dependent variable, while column (3) uses the (smooth) quarterly solar panel consumption derived from the database of utility-scale solar projects in India. We report standard errors in parentheses.

Table 3: *Upstream Model Fit: Targeted Moments*

	Domestic		Foreign	
	Data	Model	Data	Model
	(1)	(2)	(3)	(4)
N firms	6.9	6.9	15.2	15.2
(Pre-Tariff) Total output	230.4	221.5	1210.0	1154.7
(Post-Tariff) Total output	473.2	444.6	1447.5	1470.1
90^{th} percentile of output	84.2	82.4	171.6	172.0
Interdecile range of output	80.2	72.5	160.9	154.8

Notes: This table presents the moments targeted in the estimation of the upstream model. We target three sets of moments: (1) number of firms, (2) total output in a quarter, and (3) interquartile range of output in a quarter. All three moments are computed separately by type of firm (domestic and foreign). For the first two sets of moment, we split the sample into pre-tariff (2014 Q1 to 2018 Q2) and post-tariff (2018 Q3 to 2020 Q1) periods. When computing data moments, we calculate these statistics at the quarter-level and then take the average across quarters. When computing simulated moments, we solve for the equilibrium in each quarter 30 times with different draws of production and entry cost shocks, and then take the average across all simulations and all quarters.

Table 4: *Upstream cost parameters*

	Domestic	Foreign
	(1)	(2)
Intercept, γ_0	0.84	-0.51
	[0.09, 1.37]	[-1.56, -0.13]
Time, γ_t	-0.40	-0.25
	[-0.65, -0.15]	[-0.47, 0.00]
Quantity, γ_q	1.84	1.49
	[1.73, 2.01]	[1.36, 1.58]
Standard deviation of cost shocks, σ_γ	2.52	1.88
	[2.23, 3.01]	[1.69, 2.00]
Mean of fixed costs, λ	352.93	716.67
	[194.40, 579.42]	[522.41, 977.15]

Notes: This table presents the estimated parameters of the upstream industry where firms supply solar panels. The parameter γ_0 gives the mean level of (log) marginal costs at $t = 0$ and $q = 0$; γ_t captures the rate at which marginal costs change over time for the two types of firms in our data; γ_0 gives the mean level of marginal costs at $t = 0$ and $q = 0$; γ_q controls how marginal costs change with output level; σ_γ is the standard deviation of the idiosyncratic cost shock for the two types of firms in our data. The parameter λ governs the fixed cost of accessing the domestic market for the two types of firms in our data. The data are at the quarterly-level and span from 2014 Q1 to 2020 Q1. We report the 95% confidence interval in parentheses, estimated via 50 bootstrap draws.

Table 5: *Downstream cost parameters*

	Estimate
	(1)
constant, η_0	0.27
	[-0.29, 0.74]
(log) price of solar panels, η_p	1.15
	[1.00, 1.32]
std. dev. of cost shocks, σ_η	0.20
	[0.16, 0.27]

Notes: This table presents estimated parameters which govern the per unit cost of developing solar power plant capacity. Price of solar panels is inclusive of import tariffs, if any, in the month of the auction. We report the 95% confidence interval in square brackets, estimated via 300 bootstraps where we sample auctions with replacement.

Appendix

A Benchmark Model Appendix

This appendix provides detailed derivations and proofs for the propositions presented in the main text. We begin by stating the first-order conditions of the firm's problem and then establish a series of lemmas regarding the effects of policy instruments. Finally, we use these results to prove each proposition.

A.1 General Setup

The profit maximization problems for a domestic firm (d) and a foreign firm (f) are given by:

$$\max_{q_d} \pi_d = P(Q)q_d - (1-s)c_d q_d$$

$$\max_{q_f} \pi_f = (1-\tau)P(Q)q_f - c_f q_f$$

where $Q = Q_d + Q_f = n_d q_d + n_f q_f$ is the total market quantity, Q_d is the total domestic output, and Q_f is the total foreign output. The inverse demand curve is given by $P(Q)$ and we assume it is strictly downward sloping, i.e., $P'(Q) < 0$. The first-order conditions (FOCs) for this Cournot game are:

$$P(Q) + q_d \cdot P'(Q) - (1-s) \cdot c_d = 0 \tag{16}$$

$$(1-\tau)\left[P(Q) + q_f \cdot P'(Q)\right] - c_f = 0 \tag{17}$$

The policymaker's problem is to maximize domestic welfare subject to an expansion target for domestic production:

$$\begin{aligned} \max_{\tau,s} \quad & W(\tau,s) = CS(\tau,s) + \Pi_d(\tau,s) + R(\tau,s) - \mu S(\tau,s) \\ \text{s.t.} \quad & Q_d(\tau,s) - Q_d(0,0) = \chi \\ & 0 \leq \tau < 1, \quad 0 \leq s < 1 \end{aligned}$$

where CS is the consumer surplus, Π_d is the domestic firm's profit, R is the tariff revenue, S is the subsidy payment, and $\mu \geq 1$ is the cost of public funds. The constraint $Q_d(\tau, s) = Q_d(0, 0) + \chi$ implicitly defines the subsidy s as a function of the tariff policy τ for a given expansion target χ for total domestic output. We denote this function as $s(\tau; \chi)$. The policymaker's problem can then be rewritten as a single-variable optimization problem:

$$\max_{\tau} \quad W(\tau, s(\tau; \chi))$$
$$\text{s.t.} \quad 0 \leq \tau < 1 \quad \text{and} \quad 0 \leq s(\tau; \chi) < 1 \tag{18}$$

A.2 Preliminary Results

We now establish three lemmas that are needed for the main proofs.

Lemma 1 (Domestic Output Response to Policy)**.** *An increase in the subsidy rate or the tariff rate increases the equilibrium output of a domestic firm. That is,*

$$\frac{\partial q_d}{\partial s} > 0 \quad \textit{and} \quad \frac{\partial q_d}{\partial \tau} > 0.$$

Proof. We begin by defining two variables as follows:

$$\phi_d \equiv -\frac{P'(Q) + q_d \cdot P''(Q)}{P'(Q)} < 0 \tag{19}$$
$$\phi_f \equiv -\frac{P'(Q) + q_f \cdot P''(Q)}{P'(Q)} < 0 \tag{20}$$

which are both negative given Assumption 2. Totally differentiating the FOC in (16) with respect to τ and s yields:

$$-\phi_d \frac{\partial Q}{\partial \tau} + \frac{\partial q_d}{\partial \tau} = 0 \tag{21}$$
$$-\phi_d \frac{\partial Q}{\partial s} + \frac{\partial q_d}{\partial s} = -\frac{c_d}{P'(Q)} \tag{22}$$

Similarly, totally differentiating the FOC in (17) with respect to τ and s gives us:

$$\frac{\partial q_f}{\partial \tau} = \phi_f \frac{\partial Q}{\partial \tau} + \frac{1}{(1-\tau)^2} \cdot \frac{c_f}{P'(Q)} \tag{23}$$
$$\frac{\partial q_f}{\partial s} = \phi_f \frac{\partial Q}{\partial s} \tag{24}$$

Using $Q = n_d q_d + n_f q_f$, we have

$$\frac{\partial Q}{\partial \tau} = n_d \frac{\partial q_d}{\partial \tau} + n_f \phi_f \frac{\partial Q}{\partial \tau} + \frac{n_f}{(1-\tau)^2} \cdot \frac{c_f}{P'(Q)} \Rightarrow \frac{\partial Q}{\partial \tau} = \frac{n_d}{1 - n_f \phi_f} \frac{\partial q_d}{\partial \tau} + \frac{n_f}{(1 - n_f \phi_f) \cdot (1-\tau)^2} \cdot \frac{c_f}{P'(Q)}$$

$$\frac{\partial Q}{\partial s} = n_d \frac{\partial q_d}{\partial s} + n_f \phi_f \frac{\partial Q}{\partial s} \Rightarrow \frac{\partial Q}{\partial s} = \frac{n_d}{1 - n_f \phi_f} \frac{\partial q_d}{\partial s}$$

Plugging these into (21) and (22) gives us:

$$\frac{\partial q_d}{\partial \tau} = \frac{1}{1 - n_f \phi_f - n_d \phi_d} \cdot \left(\frac{n_f \phi_d}{(1-\tau)^2} \cdot \frac{c_f}{P'(Q)} \right)$$

$$\frac{\partial q_d}{\partial s} = -\left(\frac{1 - n_f \phi_f}{1 - n_f \phi_f - n_d \phi_d} \right) \cdot \frac{c_d}{P'(Q)}$$

Since $\phi_d < 0$, $\phi_f < 0$, and $P'(Q) < 0$, we have $\frac{\partial q_d}{\partial \tau} > 0$ and $\frac{\partial q_d}{\partial s} > 0$.

□

Lemma 2 (Policy Substitutability)**.** *Tariffs and subsidies are substitutes in achieving the expansion target. Specifically:*

$$\frac{\mathrm{d}s(\tau; \chi)}{\mathrm{d}\tau} < 0 \tag{25}$$

Moreover, both instruments increase with the expansion target:

$$\frac{\partial s}{\partial \chi} > 0, \quad \frac{\partial \tau}{\partial \chi} > 0 \tag{26}$$

Proof. The expansion constraint is $Q_d(\tau, s(\tau; \chi)) = Q_d(0, 0) + \chi$. Differentiating this constraint with respect to τ yields:

$$\frac{\partial Q_d}{\partial \tau} + \frac{\partial Q_d}{\partial s} \frac{\mathrm{d}s}{\mathrm{d}\tau} = 0 \quad \Longrightarrow \quad \frac{\mathrm{d}s}{\mathrm{d}\tau} = -\frac{\partial Q_d / \partial \tau}{\partial Q_d / \partial s}$$

From Lemma 1, we know that $\partial Q_d / \partial \tau > 0$ and $\partial Q_d / \partial s > 0$. Therefore, $ds/d\tau < 0$.

For the second part, fixing τ (or s) in the expansion constraint:

$$\frac{\partial s}{\partial \chi} = \frac{1}{\frac{\partial Q_d}{\partial s}} > 0, \quad \frac{\partial \tau}{\partial \chi} = \frac{1}{\frac{\partial Q_d}{\partial \tau}} > 0 \tag{27}$$

where the inequalities follow from Lemma 1. Therefore a larger expansion target requires a larger subsidy or a larger tariff (holding the other policy constant). □

Before moving on, we also use these results to ensure that we only consider expansion targets which satisfy Assumption 1. First, note that $s(0;0) = 0$ and since $\frac{\mathrm{d}s}{\mathrm{d}\chi} > 0$, there is some $\chi^s_{max} > 0$ such that $s(0;\chi) \to 1$ as $\chi \to \chi^s_{max}$. Similarly, $\tau(0;0) = 0$ and since $\frac{\mathrm{d}\tau}{\mathrm{d}\chi} > 0$, there is some $\chi^\tau_{max} > 0$ such that $\tau(0;\chi) \to 1$ as $\chi \to \chi^\tau_{max}$.

Thus, to satisfy Assumption 1, we only consider expansion targets which satisfy

$$\chi \in \Big[0, \min\left(\chi^\tau_{max}, \chi^s_{max}\right)\Big) \tag{28}$$

Lemma 3 (Foreign Output Response to Tariffs)**.** *For a given expansion target χ, a higher tariff reduces foreign output. That is,*

$$\frac{\mathrm{d}Q_f(\tau, s(\tau;\chi))}{\mathrm{d}\tau} < 0.$$

Proof. As $Q_f = n_f q_f$, the above holds if $\frac{\mathrm{d}q_f}{\mathrm{d}\tau} < 0$. When the expansion constraint binds, $dQ_d = 0$, so $dQ = dQ_f$. Using equation (23), we have

$$\frac{\mathrm{d}q_f}{\mathrm{d}\tau} = \frac{1}{1 - n_f\phi_f} \cdot \frac{1}{(1-\tau)^2} \cdot \frac{c_f}{P'(Q)} < 0 \tag{29}$$

since $\phi_f < 0$ and $P'(Q) < 0$. □

A.3 Components of Welfare

We now characterize how the various components of welfare respond to policy changes.

Subsidy Payments. Subsidy payments are $S = s \cdot c_d \cdot Q_d$. Since Q_d is fixed by the constraint:

$$\frac{\mathrm{d}S}{\mathrm{d}\tau} = \frac{\mathrm{d}s(\tau;\chi)}{\mathrm{d}\tau} \cdot c_d \cdot Q_d < 0 \tag{30}$$

using Lemma 2.

Consumer Surplus. Consumer surplus is given by $CS = \int_0^Q P(q)dq - P(Q) \cdot Q$. Note that, given the expansion constraint,

$$\frac{\mathrm{d}Q}{\mathrm{d}\tau} = \frac{\mathrm{d}Q_d}{\mathrm{d}\tau} + \frac{\mathrm{d}Q_f}{\mathrm{d}\tau} = 0 + \frac{\mathrm{d}Q_f}{\mathrm{d}\tau} = \frac{\mathrm{d}Q_f}{\mathrm{d}\tau}$$

Now,

$$\frac{\mathrm{d}CS}{\mathrm{d}\tau} = -\frac{\mathrm{d}P}{\mathrm{d}\tau} \cdot Q = -P'(Q) \cdot \frac{\mathrm{d}Q}{\mathrm{d}\tau} \cdot Q = -P'(Q) \cdot \frac{\mathrm{d}Q_f}{\mathrm{d}\tau} \cdot Q < 0 \tag{31}$$

which follows from Lemma 3 and the fact that $P'(Q) < 0$.

Domestic Profits. Domestic profits are given by

$$\Pi_d(\tau, s(\tau;\chi)) = (P(Q(\tau, s(\tau;\chi))) - (1 - s(\tau;\chi)) \cdot c_d) \cdot Q_d(\tau, s(\tau;\chi))$$

and the corresponding derivative is given by

$$\begin{aligned}\frac{\mathrm{d}\Pi_d(\tau, s(\tau;\chi))}{\mathrm{d}\tau} &= \left(\frac{\mathrm{d}P(Q(\tau, s(\tau;\chi)))}{\mathrm{d}\tau} + \frac{\mathrm{d}s(\tau;\chi)}{\mathrm{d}\tau} \cdot c_d\right) \cdot Q_d(\tau, s(\tau;\chi)) \\ &= \frac{\mathrm{d}P(Q(\tau, s(\tau;\chi)))}{\mathrm{d}\tau} Q_d(\tau, s(\tau;\chi)) + \frac{\mathrm{d}S(\tau, s(\tau;\chi))}{\mathrm{d}\tau}\end{aligned} \tag{32}$$

where we again use the fact that $\frac{\mathrm{d}Q_d(\tau,s(\tau;\chi))}{\mathrm{d}\tau} = 0$. In the above expression, increasing the tariff has two effects on domestic profits. On the one hand, it increases the market price of the good, which increases profits. On the other hand, it decreases subsidy payments from the government (since $\frac{\mathrm{d}S(\tau,s(\tau;\chi))}{\mathrm{d}\tau} < 0$), which reduces profits. Note that the first term is just a transfer from consumers to domestic firms. To see this, note that we can write equation (31) as

$$\frac{\mathrm{d}CS}{\mathrm{d}\tau} = -\frac{\mathrm{d}P}{\mathrm{d}\tau} \cdot \left(Q_d(\tau, s(\tau;\chi)) + Q_f(\tau, s(\tau;\chi))\right)$$

Tariff Revenue. Tariff revenue is given by

$$R(\tau, s(\tau;\chi)) = \tau \cdot P \cdot Q_f$$

and the corresponding derivative is given by

$$\frac{\mathrm{d}R(\tau, s(\tau;\chi))}{\mathrm{d}\tau} = P \cdot Q_f + \tau \cdot \left(\frac{\mathrm{d}P}{\mathrm{d}\tau} \cdot Q_f + P \cdot \frac{\mathrm{d}Q_f}{\mathrm{d}\tau}\right) \tag{33}$$

Here, the first term captures the impact of a change in tariff policy on tariff revenue holding the tax “base” fixed, while the second term captures the impact on tariff revenue as a result of a change in foreign sales induced by higher tariffs.

Welfare. The derivative of welfare with respect to tariff policy τ is given by

$$\frac{\mathrm{d}W(\tau,s(\tau;\chi))}{\mathrm{d}\tau} = \frac{\mathrm{d}CS(\tau,s(\tau;\chi))}{\mathrm{d}\tau} + \frac{\mathrm{d}\Pi_d(\tau,s(\tau;\chi))}{\mathrm{d}\tau} + \frac{\mathrm{d}R(\tau,s(\tau;\chi))}{\mathrm{d}\tau} - \mu \cdot \frac{\mathrm{d}S(\tau,s(\tau;\chi))}{\mathrm{d}\tau}$$

Some terms cancel out when we plug in equations (30), (31), (32), and (33). For example, change in consumer surplus due to higher price of *domestic* goods is exactly offset by the same term in domestic profits. The other term in the derivative of domestic profits is the change in subsidy payments, which also cancels out. Thus, we have

$$\frac{\mathrm{d}W(\tau,s(\tau;\chi))}{\mathrm{d}\tau} = -\frac{\mathrm{d}P}{\mathrm{d}\tau} \cdot Q_f - (\mu - 1) \cdot \frac{\mathrm{d}S}{\mathrm{d}\tau} + P \cdot Q_f + \tau \cdot \left(\frac{\mathrm{d}P}{\mathrm{d}\tau} \cdot Q_f + P \cdot \frac{\mathrm{d}Q_f}{\mathrm{d}\tau}\right) \tag{34}$$

A.4 Optimal Policy

For a non-zero expansion target χ which satisfies (28), we can reformulate the problem in (18) as

$$\begin{aligned} \max_{\tau} \quad & W(\tau,s(\tau;\chi)) & \\ \text{subject to} \quad & \tau \geq 0, & \text{(tariff constraint)} \\ & s(\tau;\chi) \geq 0 & \text{(subsidy constraint)} \end{aligned}$$

The associated Lagrangian is given by

$$\mathcal{L}(\tau,\lambda_\tau,\lambda_s) = W(\tau,s(\tau;\chi)) + \lambda_\tau \tau + \lambda_s s(\tau;\chi) \tag{35}$$

with multipliers $\lambda_\tau, \lambda_s \geq 0$.

At the optimal policy, the following first-order condition must hold:

$$\frac{\mathrm{d}\mathcal{L}(\tau,\lambda_\tau,\lambda_s)}{\mathrm{d}\tau} = \frac{\mathrm{d}W}{\mathrm{d}\tau} + \lambda_\tau + \lambda_s \frac{\mathrm{d}s}{\mathrm{d}\tau} = 0 \tag{36}$$

A.5 Proof of Propositions

A.5.1 Proof of Proposition 1

Proof. From equation (36), if the optimal policy is a subsidy-only policy, we have $\tau = 0$ and $s > 0$, which implies that $\lambda_\tau \geq 0$ and $\lambda_s = 0$. Then, we have

$$\left.\frac{\mathrm{d}W}{\mathrm{d}\tau}\right|_{\tau=0} + \lambda_\tau = 0 \Rightarrow \left.\frac{\mathrm{d}W}{\mathrm{d}\tau}\right|_{\tau=0} \leq 0 \tag{37}$$

Thus, to show that a subsidy-only policy is never optimal, we evaluate $dW/d\tau$ at $\tau = 0$ and show that it is strictly positive. At $\tau = 0$, equation (34) becomes:

$$\left.\frac{\mathrm{d}W}{\mathrm{d}\tau}\right|_{\tau=0} = P \cdot Q_f - Q_f \cdot \frac{\mathrm{d}P}{\mathrm{d}\tau} - (\mu - 1) \cdot \frac{\mathrm{d}S}{\mathrm{d}\tau}$$

The term $-(\mu-1)dS/d\tau$ is non-negative since $\mu \geq 1$ and $dS/d\tau < 0$. Thus, we only need to show that $PQ_f - Q_f(dP/d\tau) > 0$, which simplifies to showing that $P > dP/d\tau$, where the term $dP/d\tau$ is the passthrough of the tariff to market prices given by $P'(Q) \cdot dQ/d\tau$. Note that

$$\left.\frac{\mathrm{d}Q}{\mathrm{d}\tau}\right|_{\tau=0} = \left.\frac{\mathrm{d}Q_f}{\mathrm{d}\tau}\right|_{\tau=0} = \frac{n_f}{(1 - n_f\phi_f) \cdot P'(Q)} \cdot c_f$$

from (A.2).

Now,

$$\begin{aligned} P - P'(Q) \cdot \left.\frac{\mathrm{d}Q}{\mathrm{d}\tau}\right|_{\tau=0} &= P - \frac{n_f}{1 - n_f\phi_f} \cdot c_f \\ &= P - \frac{n_f \cdot P'(Q)}{(n_f + 1) \cdot P'(Q) + n_f \cdot q_f \cdot P''(Q)} \cdot c_f \end{aligned}$$

where the second equality uses the definition of ϕ_f given in (20).

Since $P \geq c_f$ by Assumption 1 (foreign firms remain active), it suffices to show that

$$\frac{n_f \cdot P'(Q)}{(n_f + 1) \cdot P'(Q) + n_f \cdot q_f \cdot P''(Q)} < 1$$

For $n_f = 1$, this reduces to

$$\frac{P'(Q)}{2P'(Q) + q_f \cdot P''(Q)} = \frac{P'(Q)}{P'(Q) + (P'(Q) + q_f \cdot P''(Q))} < 1$$

which holds since $P'(Q) + q_f \cdot P''(Q) < 0$ by Assumption 2.

For $n_f > 1$, we can rewrite the condition as

$$\frac{n_f \cdot P'(Q)}{n_f P'(Q) + (P'(Q) + n_f \cdot q_f \cdot P''(Q))} < 1$$

which holds since $P'(Q) + n_f \cdot q_f \cdot P''(Q) < 0$ by Assumption 2*.

Therefore, $\left.\frac{\mathrm{d}W}{\mathrm{d}\tau}\right|_{\tau=0} > 0$, which violates condition (37). Thus, a subsidy-only policy is never optimal. □

A.5.2 Proof of Proposition 2

Proof. Let $\tau_{only}(\chi)$ denote the tariff rate that satisfies the domestic expansion target when no subsidy is used. If the optimal policy is a tariff-only policy, from equation (36), we have $\lambda_\tau = 0$ and $\lambda_s > 0$. Then, we have

$$\left.\frac{\mathrm{d}W}{\mathrm{d}\tau}\right|_{\tau=\tau_{only}} \geq 0 \tag{38}$$

since $ds/d\tau < 0$ from Lemma 2.

Now, we need to show that the above holds for small enough $\chi > 0$.

From Lemma 2, we know that $\frac{d\tau}{d\chi} > 0$. Thus, for any $\chi > 0$, we have $\tau_{only}(\chi) > 0$. Moreover, by continuity,

$$\lim_{\chi \to 0} \tau_{only}(\chi) = 0.$$

From the proof of Proposition 1, we know that at $\tau = 0$, the derivative of welfare with respect to τ is strictly positive. By continuity, there exists a neighborhood around

$\tau = 0$ in which the derivative $dW/d\tau$ remains positive. Moreover, since domestic output is strict increasing in τ (Lemma 1), an increase in τ above 0 corresponds to an increase in χ above 0. Thus, there exists an upper bound $\overline{\chi} > 0$ such that for all $\chi \in (0, \overline{\chi})$, the derivative $dW/d\tau$ remains positive under a tariff-only policy. This satisfies the condition in (38) and so a tariff-only policy is optimal for all $\chi < \overline{\chi}$.

□

A.5.3 Proof of Proposition 3

Proof. We consider a tariff-only policy ($s = 0$) and show that $dW/d\tau < 0$ for a large enough expansion target χ.

Let's examine the derivative of welfare with respect to τ from (34) at a tariff-only policy. From Lemmas 2 and 3, we know that $d\tau/d\chi > 0$ and $dQ_f/d\tau < 0$. Thus, for a large enough χ, the required tariff τ is large enough that total foreign output approaches zero, $Q_f \to 0$. Consequently, in the derivative of the welfare function, we can ignore terms which are multiplied by Q_f. We are left with

$$\left.\frac{\mathrm{d}W}{\mathrm{d}\tau}\right|_{s=0} = -(\mu - 1) \cdot \frac{\mathrm{d}S}{\mathrm{d}\tau} + \tau \cdot P \cdot \frac{\mathrm{d}Q_f}{\mathrm{d}\tau}$$

As $\mu \to 1$, the first term in the above expression approaches zero and we are left with $\tau \cdot P \cdot \frac{\mathrm{d}Q_f}{\mathrm{d}\tau}$ which is negative, as shown in Lemma 3. Thus, for a large enough χ, the derivative of welfare with respect to τ is negative at a tariff-only policy, which violates (38) implying that a mixed policy of tariffs and subsidies is optimal. □

B Benchmark Model Simulation

For the simulation, we consider a duopoly, i.e., $n_f = n_d = 1$. The inverse demand curve is given by,

$$P(Q) = a - bQ.$$

We set $a = 100$ and $b = 1.95$. Marginal cost of production for both the domestic and foreign firms is set to \$400, and the cost of public funds is set to 1.

We compute optimal policies under three different scenarios. In the first scenario, we allow the policymaker to use only import tariffs ("tariff-only"). That is, the subsidy rate is set to zero and the domestic expansion target is achieved only through the use of tariffs. In the second scenario, we allow the policymaker to use only production subsidies ("subsidy-only"); here, import tariffs are set to zero. Finally, in the third scenario, we allow the policymaker to use both instruments ("both"), again subject to the constraint that the domestic expansion target is achieved. Here, the policymaker may choose to set either instrument to zero, or use non-zero levels of both instruments. As multiple combinations of tariffs and subsidies achieve the same expansion target, the policymaker selects the combination that maximizes welfare.

We consider expansion targets ranging to 1% to 40%. The results are in Figure D.1. We find that for expansion targets less than 15% the optimal policy is to use only import tariffs (Proposition 2). For larger expansion targets, the policymaker uses a combination of tariffs and subsidies (Proposition 3). Finally, it is never optimal to use subsidies alone (Proposition 1).

B.1 Retaliation

In this section, we consider the case where the foreign country retaliates against the industrial policy of the domestic country. As firms are competing in the domestic market, retaliation takes the form of subsidies provided by the foreign country to its firms.

The problem solved by firm i of type k is given by,

$$\max_{q_{ik}} \pi_{ik}(q_{ik}) = (1-\tau_k)P(Q)q_{ik} - (1-s_k^{k'})c_k q_{ik}$$

where $s_k^{k'}$ is the subsidy provided by country $k' \in \{f, d\}$ to firm of type k. Countries only provide subsidies to firms in their own country, i.e., $s_k^{k'} = 0$ for $k' \neq k$.

We assume that when retaliating, the foreign country chooses the subsidy rate to maximize its own welfare, which consists of profits of foreign firms net of the cost of the subsidy. We solve for the Nash equilibrium of the game, where the domestic country chooses its optimal policy $\{\tau_k, s_k^d\}$ to meet the expansion target, and the foreign country chooses its optimal subsidy rate $\{s_k^f\}$ to maximize welfare.

The results are in Figure D.2. Our theoretical results continue to hold. When the expansion target is small (less than 10%), the optimal policy is to use only import tariffs. When the expansion target is larger, the optimal policy is a combination of tariffs and subsidies.

C Passthrough of tariffs to prices

C.1 Net price for foreign firms

Before we present our regression results, we briefly mention the expected effect of a small tariff on the pre-import price of foreign firms using the benchmark model developed earlier.

Let $\widetilde{P}(\tau) = (1-\tau)P(\tau)$ be the net price received by foreign firms.

Starting from a no-tariff or subsidy-only equilibrium, adding a small tariff τ has the following effect on the net price:

$$\begin{aligned}\frac{\mathrm{d}\widetilde{P}(\tau)}{\mathrm{d}\tau} &= (1-\tau)\,\frac{\mathrm{d}P(\tau)}{\mathrm{d}\tau} - P(\tau) \\ &< \frac{\mathrm{d}P(\tau)}{\mathrm{d}\tau} - P(\tau) \quad \text{for } 0 < \tau < 1\end{aligned}$$

which is a combination of two effects: the market price is higher because of some passthrough of the tariff to the market price, but also foreign firms keep a lower share of the market price because of the tariff. In particular, for a one unit increase in tariff τ, foreign firms pay $\$P$ to the government in the form of tariff revenue, but not all of these P dollars are passed through to the market price under the assumptions of our oligopoly model. As such, $\frac{\mathrm{d}P(\tau)}{\mathrm{d}\tau} < P(\tau)$, and the net price received by foreign firms goes down when a small tariff is added.

C.2 Regression analysis

We now test for incomplete tariff passthrough, a key prediction of our oligopoly model. As noted in the main text, this condition can also arise in perfectly competitive markets with upward-sloping export supply curves. Therefore, this empirical test is not intended to be definitive evidence of market power, but rather to verify that the data are consistent with the oligopoly framework that we employ based on the market structure detailed in

Section 3.3.

Before proceeding, we note that the above condition is equivalent to

$$\frac{\mathrm{d}\widetilde{P}(\tau)}{\mathrm{d}\,(1-\tau)} = -\frac{\mathrm{d}\widetilde{P}(\tau)}{\mathrm{d}\tau} > 0$$

This is a useful transformation since τ may be zero for many observations in our data but $(1-\tau)$ is never zero.

We expect

$$\frac{\mathrm{d}\log\widetilde{P}(\tau)}{\mathrm{d}\log(1-\tau)} = \frac{1}{P(\tau)}\frac{\mathrm{d}\widetilde{P}(\tau)}{\mathrm{d}\,(1-\tau)} > 0$$

To empirically test this prediction, we use the log-log specification to estimate the elasticity of the net foreign price with respect to changes in tariffs:

$$\Delta\log\left(\widetilde{P}_t\right) = \beta_0 + \beta_1 \cdot \Delta\log(1-\tau_t) + \beta_2 \cdot \Delta\log(X_t) + \varepsilon_t \tag{39}$$

where $\widetilde{P}_t$ is the price received by foreign firms, τ_t is the tariff rate on imports, and X_t are control variables used in some of the specifications below.

We estimate the model using monthly data from 2016 to 2020 and present the results across multiple time horizons (3, 6, 9, and 12 months). Specifically, we use three distinct specifications to ensure robustness:

1. **Comparison with Non-Tariff Countries**: We first compare prices of solar panels imported from China and Malaysia (subject to tariffs) to those imported from everywhere else. Only imports from China and Malaysia are subject to tariffs during this period. These results are in Table D.1.
2. **Controlling for World Spot Prices**: To account for technological change that may be behind changes in the imported price, we include the Bloomberg New Energy Finance (BNEF) world spot price as a control variable. This is a proxy for the world price of solar panels. Here, we restrict the sample to only Chinese and Malaysian imports. We present these results in Table D.2.

3. **Controlling for Chinese Spot Prices**: Similarly, we use the BNEF spot price specifically for Chinese solar panels to account for technological dynamics in this sector specific to China, again limiting the analysis to imports from China and Malaysia. We present these results in Table D.3.

The positive and statistically significant coefficients on $\Delta \log(1-\tau)$ across all specifications indicate that tariffs are not fully passed through to market prices. This finding is consistent with the predictions of our oligopoly model. We acknowledge that this result alone does not distinguish between a market with oligopolistic firms and a perfectly competitive one with an upward-sloping export supply curve. Our choice to model this market as an oligopoly is primarily motivated by the high degree of observed market concentration (see Section 3.3), and these passthrough results serve as an important consistency check for that framework.

D Incorporating Value of Avoided CO_2 Damages

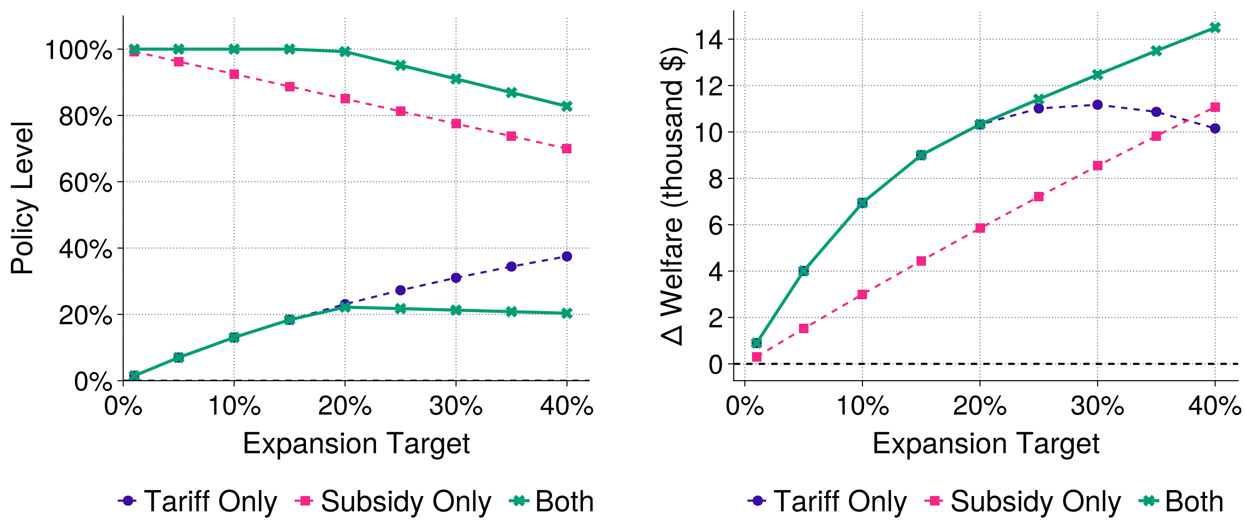
In this section, we extend our analysis to incorporate benefits from avoided environmental damages due to additional solar deployment. If the planner values emissions reductions from *total* industry size (domestic + foreign), tariffs become less attractive because they contract total output; subsidies expand both domestic production and, via lower prices, demand for foreign panels. This could reduce the threshold at which mixed policy becomes optimal.

To quantify this effect, we modify our welfare calculation to include environmental benefits valued at \$60,000 per MW of solar panel capacity installed.[30] The results, shown in Figure D.3, show that incorporating environmental externalities lowers the threshold expansion target at which mixed policy become optimal.

[30] Our valuation is derived from Sexton et al. (2021), who find that the environmental benefits of solar capacity are highly varied across the United States. They report a national mean for avoided CO_2 damages of approximately \$170 per year for a typical 4kW rooftop solar array. Linearly scaling this mean value to a 1 MW capacity yields an annual benefit of approximately \$42,500 per MW ($170 \times (1000/4)$). However, the authors stress that benefits are not uniform; annual avoided damages from CO_2 alone range from \$29 to \$432 per 4kW system depending on the location. This implies a range of \$7,250 to \$108,000 per MW per year. Considering this substantial heterogeneity and the fact that the authors use a 2016 social cost of carbon value (\$41 per ton), we adopt the conservative value of \$60,000 per MW per year as the value of avoided CO_2 damages per MW of solar panel capacity installed.

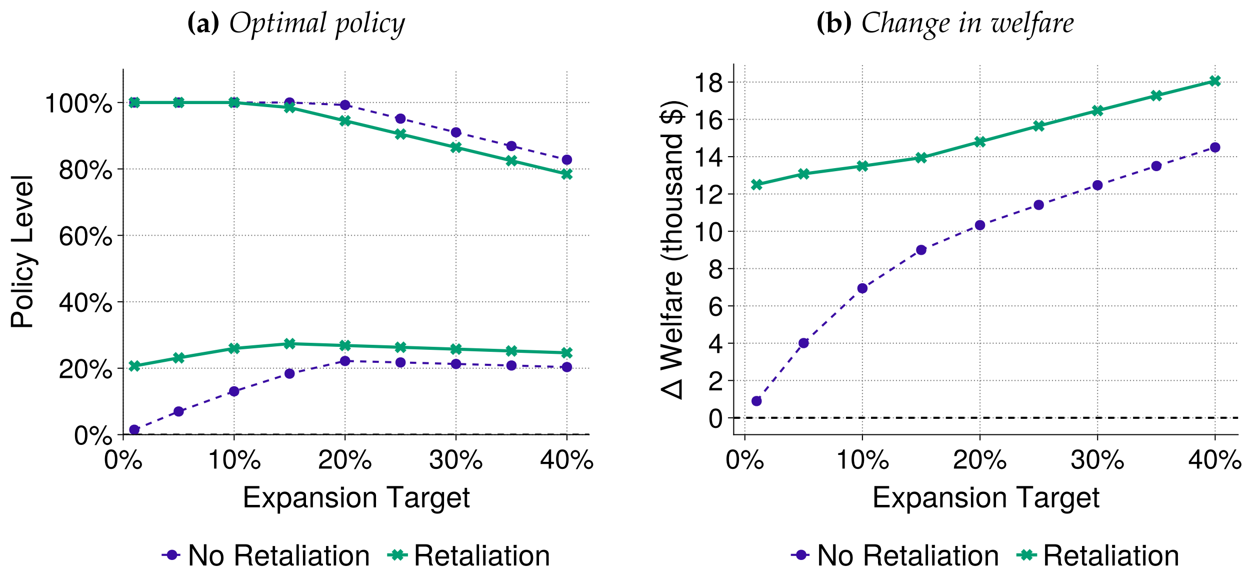
Figure D.1: *Optimal policy and change in welfare at different expansion targets*

(a) *Optimal policy* **(b)** *Change in welfare*



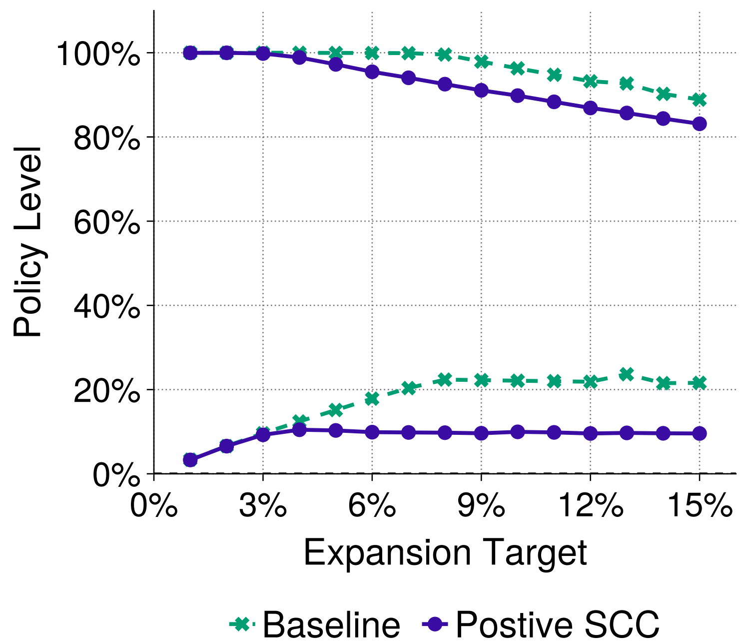
Notes. In the left panel, we show the optimal policy for a given expansion target for total domestic output relative to its level under no policy intervention. There are three policy regimes: (1) tariff-only, (2) subsidy-only, and (3) a combination of tariffs and subsidies, referred to as "both" above. For each policy regime and for each expansion target ranging from 1% to 40%, we plot the optimal level of import tariff τ on foreign firms and optimal level of $z = 1 - s$, i.e., the proportion of production cost borne by domestic firms. A lower z corresponds to a higher subsidy. For the policy regime where we mix the two instruments under "both", we show two curves with the same color and marker; these correspond to the level of τ and z under the mixed policy. In the right panel, we show the change in welfare relative to baseline under the three regimes at each expansion target. Welfare consists of consumer surplus, government revenue, and profits of domestic firms.

Figure D.2: *Optimal policy and change in welfare under retaliation*



Notes. In the left panel, we show the optimal policy for a given expansion target for total domestic output relative to its level under no policy intervention. We plot the optimal policy under retaliation by foreign country and under no retaliation. For each expansion target ranging from 1% to 40%, we plot the optimal level of import tariff τ on foreign firms and optimal level of $z = 1 - s$, i.e., the proportion of production cost borne by domestic firms. A lower z corresponds to a higher subsidy. In the right panel, we show the change in welfare relative to baseline under retaliation and no retaliation at each expansion target. Welfare consists of consumer surplus, government revenue, and profits of domestic firms.

Figure D.3: *Social cost of carbon*



Notes. This figure shows the optimal policy for different expansion targets when accounting for the positive environmental externality of solar power, valued at $30,000 per MW of solar panel capacity installed. Baseline refers to the case without the environmental externality. Positive SCC refers to the case where the externality is priced in at $30,000 per MW of solar panel capacity installed.

Table D.1: *Comparing China and Malaysia with other countries*

	$\Delta \log(\textit{Price Received by Foreign Firm})$			
	lag = 3 months	lag = 6 months	lag = 9 months	lag = 12 months
	(1)	(2)	(3)	(4)
$\Delta \ln(1-\tau)$	0.292*	0.376**	0.436***	0.378**
	(0.155)	(0.159)	(0.159)	(0.151)
Observations	105	105	105	105
R^2	0.033	0.051	0.068	0.057

Notes. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Standard errors are in parentheses. Columns correspond to changes calculated over intervals of 3, 6, 9, and 12 months. Data includes monthly panel prices from 2016–2020.*

Table D.2: *Using World Spot Price of Solar Modules as a Control*

	$\Delta \log(\textit{Price Received by Foreign Firm})$			
	lag = 3 months	lag = 6 months	lag = 9 months	lag = 12 months
	(1)	(2)	(3)	(4)
$\Delta \ln(1-\tau)$	0.213*	0.298**	0.296**	0.160
	(0.109)	(0.139)	(0.132)	(0.134)
Δ ln World spot price	0.145*	0.096	0.155	0.246**
	(0.073)	(0.106)	(0.108)	(0.103)
Observations	51	51	51	51
R^2	0.176	0.138	0.201	0.193

Notes. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Standard errors are in parentheses. Columns correspond to changes calculated over intervals of 3, 6, 9, and 12 months. Data includes monthly panel prices from 2016–2020.*

Table D.3: *Using Chinese Spot Price of Solar Modules as a Control*

	$\Delta \log(\textit{Price Received by Foreign Firm})$			
	lag = 3 months	lag = 6 months	lag = 9 months	lag = 12 months
	(1)	(2)	(3)	(4)
$\Delta \ln(1-\tau)$	0.238**	0.299	0.483***	0.274*
	(0.112)	(0.179)	(0.169)	(0.151)
$\Delta \ln$ China spot price	0.138	0.155	0.022	0.233
	(0.146)	(0.230)	(0.243)	(0.235)
Observations	31	29	26	23
R^2	0.236	0.237	0.524	0.476

Notes. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Standard errors are in parentheses. Columns correspond to changes calculated over intervals of 3, 6, 9, and 12 months. Data includes monthly module prices from 2016–2020.*

D.1 Alternative specification

The standard specification for testing passthrough of tariffs to prices, e.g. in Amiti, Redding, and Weinstein (2019), involves regressing price changes on changes in $(1+\tau)$. That's because we define net price differently in our model. In usual settings, the consumer price is $P = (1+\tau)\widetilde{P}$, while in our model, the price received by foreign firms is $\widetilde{P} = (1-\tau)P$.

In Tables D.4 to D.6 we re-run the above regressions but with the alternative specification that regresses price changes on changes in $(1+\tau)$.

These findings from the alternative specification are qualitatively similar to our main findings, except that the sign of the relevant coefficient is reversed.

Table D.4: *Comparing China and Malaysia with other countries*

	$\Delta \log(\textit{Price Received by Foreign Firm})$			
	lag = 3 months	lag = 6 months	lag = 9 months	lag = 12 months
	(1)	(2)	(3)	(4)
$\Delta \ln(1+\tau)$	-0.373*	-0.481**	-0.564***	-0.492**
	(0.203)	(0.208)	(0.209)	(0.198)
Observations	105	105	105	105
R^2	0.032	0.050	0.066	0.057

Notes. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Standard errors are in parentheses. Columns correspond to changes calculated over intervals of 3, 6, 9, and 12 months. Data includes monthly module prices from 2016–2020.*

Table D.5: *Using World Spot Price of Solar Modules as a Control*

	$\Delta \log(\textit{Price Received by Foreign Firm})$			
	lag = 3 months	lag = 6 months	lag = 9 months	lag = 12 months
	(1)	(2)	(3)	(4)
$\Delta \ln(1+\tau)$	-0.268*	-0.375**	-0.375**	-0.206
	(0.143)	(0.182)	(0.174)	(0.175)
$\Delta \ln$ World spot price	0.146*	0.100	0.159	0.247**
	(0.073)	(0.106)	(0.108)	(0.103)
Observations	51	51	51	51
R^2	0.172	0.132	0.196	0.192

Notes. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Standard errors are in parentheses. Columns correspond to changes calculated over intervals of 3, 6, 9, and 12 months. Data includes monthly module prices from 2016–2020.*

Table D.6: *Using Chinese Spot Price of Solar Modules as a Control*

	$\Delta \log(\textit{Price Received by Foreign Firm})$			
	lag = 3 months	lag = 6 months	lag = 9 months	lag = 12 months
	(1)	(2)	(3)	(4)
$\Delta \ln(1+\tau)$	-0.301**	-0.376	-0.648***	-0.375*
	(0.147)	(0.237)	(0.225)	(0.200)
$\Delta \ln$ China spot price	0.142	0.165	0.011	0.223
	(0.147)	(0.232)	(0.245)	(0.234)
Observations	31	29	26	23
R^2	0.228	0.230	0.525	0.481

Notes. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. *Standard errors are in parentheses. Columns correspond to changes calculated over intervals of 3, 6, 9, and 12 months. Data includes monthly module prices from 2016–2020.*