Trade War and Social Welfare: A Structural Model of US Solar Industry

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Abstract

This paper investigates the welfare effect of anti-dumping policies initiated by the US government against Chinese manufacturers in the solar industry. We estimate a structural econometric model with a differentiated demand system and marginal cost for solar manufacturing that incorporates the vertical structure between upstream solar manufacturers and downstream solar installers. Then we conduct policy simulations and the results show the anti-dumping policy has decreased producer surplus and consumer surplus by around $971 million (in 2015 US dollars) and has increased the greenhouse gas emissions by 4.40 million tons for the period 2010 - 2015. The installation capacity of US solar market would have increased by 24.5% if there had been no anti-dumping policies.

JEL: F14; L10; Q50

Key Words: Anti-dumping Duties; Solar Industry; Structural Model

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1 Introduction

The solar power sector has grown rapidly over the past 10 years. The capacity of photovoltaic (PV) systems has soared 3300%, from 6,660 MW in 2006 to 229,300 MW in 2015 worldwide. Meanwhile, the average solar module price has plummeted by 82.5% from $4/Watt in 2006 to around $0.7/Watt in 2015, a decrease believed to be driven by improvement in technology and economies of scale (Barbose and Darghouth, 2016). While the solar manufacturing sector has been historically dominated by companies located in United States, Japan and Germany, Chinese firms have gradually gained market share since 2010. For the period 2010 - 2015, six Chinese companies have been listed in the top ten cell producers. Several factors explain the market dominance of Chinese firms: cost advantage, generous subsidies from the government, and preferential loans from banks.

In October 2011, several American manufacturers sued Chinese solar manufacturers for violating anti-dumping rules set by World Trade Organization (WTO). Chinese solar manufacturers were accused to sell heavily subsidized solar panels on the US market. In May 2012, the US Department of Commerce announced that anti-dumping duties were set at 31% for Chinese solar manufacturers that chose to participate in the investigation; companies that chose not to participate were subject to a 250% tariff. In retaliation, China imposed tariffs on exports of polysilicon products from United States. Although this trade war affected companies in both countries, Chinese solar companies appeared to be particularly negatively impacted. For example, Suntech Power, a Chinese firm that was once the largest solar manufacturer in the world, became insolvent after the US anti-dumping policy came into effect, and it went bankrupt in February 2014.

The trade war in the solar industry has been widely discussed, but little is know about its total economic cost. In this paper, we fill this gap and estimate the incidence of US anti-dumping policy among different market participants. In particular, we answer four related questions: (1) How much did US and Chinese firms benefit or lose from this policy? (2) How much did US consumers lose? (3) Did US installers benefit or lose from this policy? (4) To what extent has this policy impacted the expansion of the solar market in the US?

We use a structural model to empirically test these predictions and quantify the welfare effect of anti-dumping policies on different market participants. Our data come from the Lawrence Berkeley National Laboratory (LBNL)'s *Tracking the Sun* report series. This dataset provides household-level information on almost all of the solar PV installations in the US market for the period 2010 - 2015. We observe when and where the household installed its residential solar PV system, the size, the price, the brand of the solar panels used, and the name of the installer, among other things. In addition, we observe key characteristics of each product, such as energy conversion efficiency, technology type, and color of the frame. The estimation results are intuitive: on the demand side, the households prefer solar panels with high energy conversion efficiency, panels made of monocrystalline cells and panels with silver frames. On the supply side, we model the vertical structure of the industry and explicitly account for the strategic behaviors of domestic and foreign manufacturers, and domestic installers. The solar manufacturers are assumed to set their prices first and the installers follow. The margin calculated corresponds to pure double-marginalization price-cost margin with linear oligopoly pricing at the manufacturer and retail levels (Berto Villas-Boas, 2007). The estimation results on the supply side suggest that marginal cost increases with manufacturing wage, lending interest rate, energy conversion efficiency and labor cost in installation.

We simulate the estimated demand and supply models for counterfactual scenarios to explore how the anti-dumping duty and manufacturing subsidy rates impact the US solar industry. In one of the counterfactual simulations, we set the anti-dumping duty rates to zero while the US and China's subsidy rates remain unchanged. The simulation result suggests that the anti-dumping duty has decreased producer surplus and consumer surplus by $971 million (in 2015 US dollars) and has increased the greenhouse gas emissions by 4.40 million tons for the period 2010 - 2015. The installation capacity of US solar market would have increased by 24.5% if there had been no anti-dumping policies.

This paper contributes to the literature on trade wars, solar markets and industrial organization. First, this paper improves the empirical understanding of the impacts of trade wars, which have become increasingly common in recent years. Anti-dumping duties are popular instruments of the trade policy which aims at protecting domestic market. Before 1980 anti-dumping tariffs were primarily used by five major developed countries (Australia, Canada, EU, New Zealand and the US), but since 1980, developing countries (i.e. India, Mexico, China) have started to retaliate and have also adopted anti-dumping tariffs. This trend proliferated after the World Trade Organization (WTO) has been established (Vandenbussche and Zanardi, 2008). For example, in the 1980s, the US took anti-dumping action against Japan on the imports of semiconductors. Back then, Japanese firms were very successful in the semiconductor industry and captured a large share in the US market (Irwin, 1996). Also, in the late 1990s, the US steel industry initiated a new round of anti-dumping action aimed at imported steel from Asian countries (Mastel, 1999). India and China have initiated hundreds of anti-dumping investigations since they adopted the anti-dumping law in 1985 and 1997, respectively. Our paper extends the literature on trade wars by studying a fast-growing green industry and focuses on the trade issues between United States and China, which are nowadays the world's two largest economies.

Second, our paper contributes to the growing literature on the solar power market. One stream of this literature has focused on evaluating the factors leading to the adoption of residential solar power. Chernyakhovskiy (2015), Bollinger and Gillingham (2012), Burr (2012), and Gillingham and Tsvetanov (2014) all examine the adoption of residential solar photovoltaic (PV) systems in the United States. They show that the financial incentives, solar-specific mandates, and peer effect as important drivers of solar capacity growth. The uncertainty of the future government subsidy can also affect the household adoption of solar PV when they consider the option value of their investment decision (Bauner and Crago, 2015). A second stream of the literature focuses on the cost reduction of solar prices (Bollinger and Gillingham, 2014; Reichelstein and Sahoo, 2015; Gillingham et al., 2015). They find that learning-by-doing among the installers lowers the solar prices, primarily the non-hardware costs of the solar PV installations. More recent work have shown rising interests on the structural estimation of demand and supply in the solar PV market. Gerarden (2017) finds that consumer subsidies can encourage firms to innovate to reduce their costs over time and he quantifies these impacts by estimating a dynamic structural model of competition among solar panel manufacturers. Dorsey (2017) provides evidence that using online bidding platforms to increase seller's competition and expand buyers choice set can serve as an effective way to increase adoption. Our paper is different in that it uses a structural model of demand and supply with vertical contracting to evaluate the anti-dumping policies in the solar industry.

Third, our paper contributes to the empirical literature on vertical relationships. In the vertical contracting between manufacturers and retailers, the wholesale price data is typically unavailable, which makes the retailers' and manufacturers' marginal cost difficult to measure separately. Berto Villas-Boas (2007) uses a linear pricing model and derives conditions under which data on the retail price and quantities are sufficient to identify the vertical model of upstream manufacturer and downstream retailer oligopoly-pricing behavior. This type of model has been widely used to examine the vertical structure in different industries, such as the contract between smartphone firms and carriers in the smartphone market (Fan and Yang, 2016), the codeshare contract between ticketing and operating carriers in the airline market (Gayle, 2013), and the vertical relationship between manufacturers and retailers in the bottled water market (Bonnet and Dubois, 2010). Our paper is the first to study vertical contracting between upstream manufacturers and downstream installers in the solar sector.

The rest of the paper is organized as follows. Section 2 describes the growth of the US solar market, government incentives and the US-China solar trade war. Section 3 specifies the demand and supply model of solar panels. Section 4 describes the data, identification and estimation detail. Section 5 presents the estimation results. Section 6 uses the model estimates to simulate counterfactual scenarios. Section 7 concludes the paper.

2 The Solar Industry

This section describes the growth of the US solar market, the US and China's subsidy policies on the solar power and the anti-dumping policy initiated by the US against Chinese manufacturers.

2.1 The Solar Market

Solar power has become an important source of renewable energy in the US. According to the Solar Energy Industries Association, the total size of solar PV installation across the US has reached 14.6 gigawatts in 2016. Solar power has overtaken wind, hydro and natural gas to become the largest source of new electricity capacity on US grid in 2016, based on estimates from US Energy Information Administration [1]. The National Solar Jobs Census reports that more people are working in solar now than at oil rigs and in gas fields, and one of every 50 new jobs in the US in 2016 is added by the solar industry [2]. Solar has become one of the fastest-growing sectors of the US economy.

California is the state with the most solar energy in the US and its installed capacity in 2016 was 3.9 gigawatts, which is enough to provide electricity to millions of homes. California benefits from high insolation, but has also enacted policies to support solar, such as the Renewable Portfolio Standard which requires that 33% of California's electricity come from renewable resources by 2020. New Jersey is second in the country in terms of solar usage. It has 1.5 gigawatts capacity of solar power installed. Though not the sunniest place in United States, the Garden State's solar market has benefited by one of the most favorable net metering standards, allowing customers of any size array to use net metering. The rest of the top 10 states in solar installation capacity are Arizona, Massachusetts, New York, Nevada, Texas, Pennsylvania, Minnesota and Colorado.

[1]Source: https://arstechnica.com/science/2016/12/solar-is-top-source-of-new-capacity-on-the-us-grid-in-2016/
[2]Source: National Solar Jobs Census 2016, The Solar Foundation, available at:SolarJobsCensus.org

2.2 Government Incentives

The growth of the US solar sector has been helped with various subsidy programs offered by the federal and state governments.

The federal government's main push for solar energy began in the early 2000s as a part of the energy strategy for the 21st century launched by the Bush administration. The Energy Policy Act of 2005 created a 30% investment tax credit (ITC) for solar PV installations, with a $2,000 limit for residential installations. Subsequently the Energy Improvement and Extension Act of 2008 removed the $2,000 limit and the American Recovery and Reinvestment Act of 2009 temporarily converted the 30% tax to a cash grant (Bollinger and Gillingham, 2014). The federal subsidy is believed to be an important factor leading to the recent growth of the solar sector. In 2006, when the 30% tax credit was introduced, the annual installation of residential solar PV system in the US was 2,573 units. Nine years later, the annual installation has grown hundredfold, to about 246,554 units (see Figure 2). Cumulative installation of solar PV system has reached to nearly 700,000 units with 4.36 gigawatts capacity in total by the end of 2015.

The financial subsidy for residential solar PV installations at the state level varies considerably from place to place and the incentive generally falls into four categories: 1) cash rebate, a one-time rebate provided on a $/kW basis at the time the system is installed; 2) state tax credit, an additional tax credits offered by some states; 3) Solar Renewable Energy Certificates (SREC), credits that the homeowner can obtain by selling the solar electricity to the grid; 4)Performance-based Incentives (PBI), per kilowatt-hour credits that are paid based on the actual total energy produced by the solar system during a certain period of time.[3].

In addition to subsidizing consumers in the solar PV installations, the US government also subsidizes its solar manufacturers to promote the development of its solar sector. There are generally three types of subsidies offered to the US solar manufacturers: 1) Advanced Energy

[3]See energysage.com for more details: `https://www.energysage.com/solar/cost-benefit/solar-incentives-and-rebates/`

Manufacturing Tax Credit. Solar manufacturers who build factories or upgrade equipment are eligible for these tax credits which equal to 30% of the investment cost in their manufacturing facilities; 2) Business and Property Tax Credit. Some states provide heavy subsidies in the this form to attract investment from solar manufacturers and expand local employment; 3) Subsidized Land. State may provide subsidized land and infrastructure improvement to attract business to their areas.

Chinese solar firms has also got various subsidies from their government. China has been one of the world's largest manufacturers of solar panels since 2008 and became the largest producer of photovoltaic power in 2015 when it surpassed Germany. In 2017, China became the first country to exceed 100 gigawatts of cumulative installed PV capacity. The extremely rapid development of its solar industry coincides with the government support. China first launched the solar strategy in 2001 when formulating its Tenth Five-Year Plan (2001 - 2005). Back then, there was no domestic solar industry in China and the global solar market was tiny. Later on, China implemented a series of policies to encourage the development of renewable energy and its solar subsidies initially focused on the manufacturing side, offering tax breaks, subsidized land, cash grants and preferential lending (Ball et al., 2017).

2.3 Anti-dumping Policies

In the context of international trade, dumping occurs when manufacturers export products to another country at a price below the price charged in its home market or below its cost of production (definition in the GATT/WTO). In October 2011, a coalition of solar manufacturers, led by SolarWorld, a German company with considerable manufacturing in the United States, filed an anti-dumping petition against solar products from China. They claimed that Chinese solar manufacturers collected heavy subsidies from their government and dumped the solar cells and panels into the American market. In November 2011, US Department of Commerce initiated anti-dumping and countervailing duties [4] investigations of imports of solar cells from China. The merchandise covered by these investigations consisted of "crystalline silicon photovoltaic cells, and modules, laminates, and panels, consisting of crystalline silicon photovoltaic cells, whether or not partially or fully assembled into other products, including, but not limited to, modules, laminates, panels and building integrated materials."[5]

In October 2012, the Department of Commerce issued its affirmative final determination and concluded that Chinese solar producers were benefiting from unfair government subsidies and were selling solar cells in United States by dumping margins ranging from 18.32% to 249.96%. The rates of anti-dumping duties faced by Chinese solar makers fell into four categories: 1) 31.73%, received by Suntech Power, one of the largest solar manufacturers; 2) 18.32%, received by Trina Solar; 3) 25.96%, received by fifty-nine other exporters; 4) 249.96%, received by all remaining Chinese exporters. In the countervailing duties investigation, Suntech Power and Trina Solar received countervailing rates of 14.78% and 15.97%, respectively, while all other Chinese producers received a rate of 15.24%.

However, this ruling only applied to panels made from Chinese solar cells. A few Chinese companies were able to evade the duties by assembling panels from cells produced elsewhere, for example in Taiwan Region, even though the production materials (such as ingots and wafers) for those cells came from China.

To close this loophole, in January 2014, SolarWorld filed new anti-dumping and anti-subsidy cases against China and Taiwan Region with the US Department of Commerce and the US International Trade Commission. In December 2014, the Department of Commerce announced the investigation result and imposed steep tariffs on imports from China and Taiwan Region. Trina Solar and Renesola/Jinko received anti-dumping duty rates of 26.71% and 78.42%, respectively

[4] Countervailing duties, also known as anti-subsidy duties, are trade import duties imposed under World Trade Organization (WTO) rules to neutralize the negative effects of subsidies.

[5] See the detail in the fact sheet released by the International Trade Administration of the US Department of Commerce: `http://enforcement.trade.gov/download/factsheets/factsheet_prc-solar-cells-ad-cvd-init.pdf`

and forty-three other exporters qualified for a separate rate of 52.13%. All remaining Chinese producers received an anti-dumping rate of 165.04%. In the countervailing duties investigation, Trina Solar and Suntech Power received countervailing rate of 49.79%and 27.64%, respectively. All other producers in China have been assigned a countervailing rate of 38.72%.

In July 2012, in retaliation to the US policies, the Ministry of Commerce of the People's Republic of China began the anti-dumping and countervailing investigation on the solar-grade polysilicon exports from United States. In January 2014, the Ministry of Commerce announced the final investigation result and imposed tariffs on imported US polysilicon products. On average, the US polysilicon manufacturers received anti-dumping and countervailing duty rates of 57% and 2.1%, respectively. [6]

3 Econometric Model

We now outline a model of the solar industry where demand and supply are represented. The demand side is modeled within a discrete choice framework. Specifically, we use a mixed logit demand model, where for simplicity we ignore the timing of the purchase decision. The supply side captures the vertical structure, in which the upstream manufacturers determine the wholesale prices for the solar panels and the downstream installers determine the retail price while providing installation service for the consumers.

3.1 Consumer Demand for Solar Panels

The main purpose of the demand model is to capture the behavioral responses to solar panel prices. A consumer can choose the solar installer as well as different types of solar panel to install. We assume that a consumer's choice is a solar panel/installer combination, indexed by j. Since there are many solar installers in my sample, to simplify the empirical process, we classify the

[6]See the fact sheet released by the Ministry of Commerce of the People's Republic of China: http://www.mofcom.gov.cn/article/b/e/201401/20140100466573.shtml

installers into ten groups, in which the first nine groups represent the top nine installers who have significant market share across the sample and the tenth group represents the rest of the installers (see Table 5).

We use a mixed logit model to analyze consumer purchase decision. The mixed logit model obviates the three limitations of standard logit by allowing for random taste variation, unrestricted substitution patterns, and correlation in unobserved factors over time (Train, 2009). The conditional indirect utility of consumer i in MSA w from purchasing and installing j during year t is given by

$$U_{ijwt} = X_j \beta_i + \alpha p_{jwt} + \lambda_{mr} + \eta_t + \zeta_{jt} + \epsilon_{ijt} \tag{1}$$

where X_j is a vector of observed nonprice product characteristics (energy conversion efficiency, a zero-one indicator that takes one if the panel is made of polycrystalline cells, a zero-one indicator that takes one if the solar panel(module) has a black frame); β_i is a vector of consumer-specific marginal utilities (assumed random) associated with the different nonprice product characteristics in X_{jt}; p_{jwt} is the consumer purchase price for product j, which is calculated by subtracting government subsidies from total installed price and divide by the size of the solar PV system; α represents marginal disutility of price (assumed fixed across consumers); λ_{mr} is the solar manufacturer and installer fixed effect, where m represents the solar manufacturer and r represents the solar installer; η_t is the year fixed effect; ζ_{jt} is the product characteristics unobserved by the econometrician but observed by the consumers and firms; error ϵ_{ijt} is i.i.d and follows the type I extreme value distribution.

The consumer taste parameter for nonprice product characteristics is modeled as

$$\beta_i = \beta + \Sigma v_i \tag{2}$$

where v_i is a random draw from a multivariate standard normal distribution (i.e., $v_i \sim$

$N(0, \mathbf{1})$), Σ is a diagonal scaling matrix. This specification allows the individual taste parameter for nonprice characteristics varies across consumers. The predicted market share of product j is given by

$$s_{jwt}(X_{jt}, p_{jwt}; \alpha, \beta, \Sigma) = \int \frac{exp(\delta_{jwt} + \mu_{ijwt})}{1 + \sum_{l=1}^{J} exp(\delta_{lwt} + \mu_{ilwt})} dF(\nu) \tag{3}$$

where $\delta_{jwt} = X_{jt}\beta + \alpha p_{jwt} + \lambda_{mr} + \eta_t + \zeta_{jt}$ is the mean utility across consumers obtaining from purchasing and installing product j; μ_{ilwt} is a consumer-specific deviation from the mean utility level which associates with the consumer tastes for different product characteristics. $F(\cdot)$ is the standard normal distribution function.

The trans-log version of the predicted market share of solar panel/installer pair j in MSA w during year t is

$$\ln s_{jwt} - \ln s_{0wt} = X_j\beta_i + \alpha p_{jwt} + \lambda_{mr} + \eta_t + \zeta_{jt} \tag{4}$$

where s_{jwt} is the market share of the inside goods and s_{0wt} is the market share of the outside goods. The market share for the outside goods is usually defined as one minus the shares of inside goods. We select 42 solar panel models which have significant sales in United States as the inside goods. These 42 popular models are manufactured by eight publicly listed solar companies, including five Chinese manufacturers (Trina Solar, Suntech Power, Canadian Solar, Renesola and Yingli Green Energy), two US manufacturers (SunPower and REC Solar), and one South Korean manufacturer (Hanwha Q CELLS). The names of the brands and the models are listed in Table 3.

To include the no-purchase option into the choice set of the outside goods, we need to define the market size on each MSA-year level accordingly. Assume the number of single family homes in MSA w is M_w, then the observed market share of product j is given by $s_{jwt} = \frac{q_{jwt}}{M_w \times V}$, where q_{jwt} is the actual demand for product j and V is the percentage of buildings which are solar-viable in that MSA area. The parameter V reflects the fact that not all buildings are suitable for installing solar PV systems.

The demand model has two potential limitations. First, we assume that the model is static and the consumers are not forward looking. In the case of solar panel whose price falls over time, a forward-looking consumer may anticipate the price reduction and delay her purchase decision. Therefore, the static demand specification may underestimate the true price elasticity (Aguirregabiria and Nevo, 2013). Second, the specification of static model also assumes that the consumers are off the market after their initial purchase and installation of solar modules. This will again underestimate the price elasticity by phasing out the change in the distribution of consumers (Gowrisankaran and Rysman, 2012). However, as argued by Gerarden (2017), there is a feature of the solar market that ameliorates the first concern brought by the static model specification: continued price reductions in the solar market were not fully anticipated, even by the government and industry practitioners, hence the consumers may not anticipate the decline of solar prices.

3.2 Supply Side

In this section, we derive a supply equation that approximates the solar manufacturer' optimizing behavior in the vertical contracting with the solar installer. The structural econometric model is inspired by Fan and Yang (2016) and Gayle (2013), and the price-cost margins are derived in the spirit of Berto Villas-Boas (2007).

The supply side of the model can be described as a three-stage game. In the first stage, the solar manufacturer chooses its products. In the second stage, it sets the upstream price charged to the solar installers given the demand shock. In the third stage, the solar installers choose the final price charged to the consumers.

To solve for this subgame perfect Nash equilibrium it is standard to use backward induction, i.e., by solving the final subgame first. In the final stage of the model, the solar installer chooses total installed price p_{jt} after observing the set of products available (denoted by F_{rt}), the price paid to the solar manufacturers for getting the solar panels (denoted by p^m_{jt}), and the given demand. The total installed price p_{jt} is a package price charged to the consumer, which includes the solar module(panel) price and the price on the installation. Suppose the marginal cost for the solar installer to complete an installation of product j is c^r_{jt} per consumer. Then the installer r's profit for each unit of a product sold is $p_{jt} - p^m_{jt} - c^r_{jt}$.

The derivation for the price-cost margin follows the procedure in Berto Villas-Boas (2007). Each installer r's profit function in period t is given by

$$\max \pi_{rt} = \sum_{j \in F_{rt}} \left[p_{jt} - p^m_{jt} - c^r_{jt}\right] M s_{jt}(p) \tag{5}$$

where M is the market size. Then the first order condition is given by

$$p_t - p^m_t - c^r_t = -(T_r * \Delta_{rt})^{-1} s_t(p) \tag{6}$$

where T_r is the installer's ownership matrix with the general element $T_r(k, j)$ equal to one when both products k and j are sold by the same installer and zero otherwise; Δ_{rt} is the installer's response matrix, with element $(k, j) = \frac{\partial s_{jt}}{\partial p_{kt}}$.

In the second stage, the solar manufacturer sets the upstream price that it charges the installer given the observed demand. The solar manufacturer m's profit-maximizing problem is therefore

$$\max \pi_{mt} = \sum_{j \in F_{mt}} \left[p^m_{jt} - c^m_{jt}\right] M s_{jt}(p) \tag{7}$$

where c^m_{jt} is the marginal cost of the solar manufacturer that produces the product j. The first order condition is given by

$$p^m_t - c^m_t = -(T_m * \Delta_{mt})^{-1} s_t(p) \tag{8}$$

where T_m is the ownership matrix for the solar manufacturer, analogously defined as the matrix T_r above. Δ_{mt} is the solar maker's response matrix, with element $(k, j) = \frac{\partial s_{jt}}{\partial p^m_{kt}}$, which represents the first order differentiation of the market share of all products with respect to all upstream prices.

Combining equations (6) and (8) yields the solar manufacturer and installer's joint marginal cost mc_t,

$$mc_t = c_t^m + c_t^r = p_t + (T_r * \Delta_{rt})^{-1} s_t(p) + (T_m * \Delta_{mt})^{-1} s_t(p) \tag{9}$$

Specifically, we assume the solar manufacturer's marginal cost depends on a vector of variables X_t and the solar installer's marginal cost depends on a vector of variables Y_t. Then the joint marginal cost is

$$mc_t = \gamma_1 X_t + \gamma_2 Y_t + \kappa + \varepsilon_t \tag{10}$$

where X_t includes wage rate in manufacturing, lending interest rate and the panel's energy conversion efficiency; Y_t includes the wage rate in roofing; κ is installer-year fixed effect. In our specification, we assume the manufacturer's marginal cost is determined by the labor cost, capital cost and the panel's key product attributes (i.e., energy conversion efficiency), and the installer's marginal cost is determined by the labor cost in installation. The fixed effect captures the time effect and installer-level heterogeneity.

Combining equations (9) and (10) yields

$$p_t + (T_r * \Delta_{rt})^{-1} s_t(p) + (T_m * \Delta_{mt})^{-1} s_t(p) = \gamma_1 X_t + \gamma_2 Y_t + \kappa + \varepsilon_t \tag{11}$$

which we bring to the data for estimation.

4 Data and Identification

4.1 Data and Descriptive Statistics

For this study, we have compiled a new dataset on US solar market between 2010 and 2015 from various sources. The main dataset comes from Lawrence Berkeley National Laboratory (LBNL)'s *Tracking the Sun* report series, which provide the information on prices and quantities of solar PV installation. LBNL collects project-level data on residential and commercial solar PV installations. The original sources of the data are from state agencies and utility companies that manage solar PV incentive programs and solar energy credit registration systems. The dataset is accessible publicly and can be downloaded from the National Renewable Energy Laboratory's Open PV Project data portal. This data file includes residential and commercial solar PV systems, excluding utility-scale projects. As of the end of 2015, the data file includes over 0.8 million observations of the solar PV installations and has a rich set of observables. For each solar PV system recorded by this data file, we can observe various information about this installation, including installation date, system size, total installed price, sales tax cost, rebate or grant, zip code or city, insolation rate, reported annaul PV generation, installer name, module manufacturer name, module model, module technology, module efficiency, etc.

The other sources of data used in this paper are: (1) US Census Bureau, which provides MSA-level demographic variables on the education, median income and age across the US; (2) US Energy Information Administration, which provides the state-level electricity prices information; (3) US Bureau of Labor Statistics, which provides hourly wage in manufacturing across different counties and hourly wage rate in roofing in the US; (4) World Bank, which provides information on the lending interest rates across different countries; (5) Google Project Sunroof, which estimates the technical solar potential of all buildings in a region based on sunlight, installation size and space, and reports the percentage of buildings that are solar-viable in the region.

The sample used in this paper is confined to the residential PV installation, which has a total number of 645,269 installations nationwide and nearly half of them happening in the state of California. Among different solar makers, Chinese companies (including Suntech Power, Trina Solar, ET Solar and Yingli Green Energy, etc) accounted for 25% of the market share in 2011 and accounted for 14% of the market share in 2015 (see Table 1). More than 1,000 models of solar panels produced by over 150 firms are observed in the dataset (see Table 2). The inside goods we select consist of 42 models produced by eight solar manufacturers (see Section 2.1 for more details), and the MSA markets selected in my sample accounts for nearly 31% of the total markets in the US.

Table 4 reports the summary statistics for the key variables in our paper. The average of the total installed price for one solar PV system is \$5.12/W, with a standard deviation of \$1.65/W. The average government subsidy received by the consumers is \$0.82/W, which is nearly 16% of the total cost for a solar PV system. The average energy conversion efficiency for solar panels is 0.17 with a standard deviation of 0.02. Nearly 46% of the solar modules are made of polycrystalline panels, and 20% of the solar modules have black frames. The average electricity price on the state level is 16.11 cents/kWh with a standard deviation of 3.01 cents/kWh. Across the MSA markets in our sample, on average, 30.23% people have a bachelor's degree or higher, and the average of the median income and median age are \$78,280 and 38.78 years old, respectively. The average number of single family homes on the MSA level is 868,000, and on average, for each MSA, nearly 72% of the buildings are solar-viable. The average manufacturing wage and lending interest rate are \$18.84/hour and 4.67%, respectively. The average wage rate in roofing across different states in the US is \$23.82/hour.

4.2 Identification

In the demand side estimation, the purchase price p_{jwt} is expected to be correlated with unobserved product characteristics, leading to an endogeneity problem. The other product characteristics are however assumed to be exogenous. The coefficient on the price is identified using variation from instrumental variables (Berry, 1994). There are three candidates for the instruments that are plausibly uncorrelated with unobserved product characteristics: government subsidies, the so-called BLP instruments, and the Hausman instrument.

Government Subsidies. Li (2016) uses government subsidies as instrumental variables for vehicle price to identify the demand parameter in the US electric vehicle market, as they are uncorrelated with demand shocks. Government subsidies offered to the households for solar

PV installations vary by state, year and panel model. A larger subsidy indicates lower purchase price faced by the consumer. The government subsidies can be regarded as cost-shifters, as they only affect the consumer demand for the solar panels through the purchase prices, and they are uncorrelated with unobserved product characteristics.

BLP Instruments. A natural instrument for the price is to use a cost side instrument, however, the cost variable is often not available (Berry et al., 1995). The BLP instruments provide an alternative approach for variation in prices in differentiated product settings that is based on a first order approximation of the equilibrium pricing function (Gandhi and Houde, 2016). They are one series of differentiation in attribute space and are constructed by adding up the values of (i) characteristics of other products made by the same manufacturer, and (ii) the characteristics of products made by other manufacturers. They are uncorrelated with the demand shock given the assumption that the other product characteristics arrive as part of an exogenous development process (Li, 2016). We construct BLP instruments based on all three product characteristics, namely energy conversion efficiency, technology type and frame color, and denote them by $BLP\_efficiency$, $BLP\_technology$ and BLP_black, respectively.

Hausman Instrument. A particular type of proxy for cost-shifter is Hausman instrument (Hausman, 1996): the prices of product j in other market M' can be used a a proxy for marginal cost of good j in market M. In our paper, the Hausman instrument is the average installed price for the same type of solar panel sold in other MSAs in the same year, denoted by $Hausman_{jwt}$. The identifying assumption for the Hausman instrument is that demand for a given type of solar panel in MSA A is independent from the demand for the same type in MSA B. The advantage of Hausman instrument stems from the fact that all the instruments are contained in the price data. However, the underlying assumption associated with Hausman instrument is sometimes too restrictive. Successful applications of Hausman instrument rely on the validity of two assumptions: (i) the unobserved shocks to product costs affect all geographic markets, and (ii) there are only geography-specific unobservable demand shocks and not nationwide demand shocks (Megerdichian, 2010). The first assumption captures the relevance of the instrument, and the second assumption validates the exogeneity of the Hausman instrument. If there is a general shock throughout the nation, then the prices in areas other than C would be correlated with the error term in the demand function for area C, and so the Hausman instrument would not satisfy the exclusion restriction. Criticisms of the Hausman instrument mainly focus on its exogeneity assumption (Bresnahan and Gordon (1997), Nevo (2000) and Nevo (2001)). For a nationally-branded differentiated product, including solar panels, national advertising campaigns can affect both demand and price, thus rendering Hausman instrument invalid.

In order to select the appropriate instrumental variables from the three candidate sets described above, we use the two-stage least square (2SLS) method to estimate a standard logit model which is more restrictive than the mixed logit model. Table 6 reports the results for the first-stage regression, in which price is regressed on different instruments. Models 1 - 3 use each set of the instruments (subsidy, BLP instruments and Hausman instrument), models 4 - 6 employ pairs of them, and model 7 applies all three of them. The F-tests of the joint significance of the instruments in models 1 - 7 all yield values greater than 10. Model 1 has the largest (F-statistic = 383) and Model 3 the smallest (F-statistic = 12.49). The results suggest that the instruments do have explanatory power of variations in price. Then we move forward to the second-stage estimates, in which Berry-type market shares (i.e., $\ln s_{jwt} - \ln s_{0wt}$) are regressed on the instrumented price. The results in Table 7 suggest that, BLP instruments lead to significant price coefficient (Model 2, 4, 5 and 7), while subsidy and Hausman IVs result in smaller and insignificant price coefficient (Model 1, 3 and 6). This may be explained by the following reasons: state subsidies and nation-wide demand shock (such as national advertising campaigns) vary across years, thus they don't have much variation left once year-fixed effect has been controlled. Overall, the BLP instruments perform well and are generally accepted in the literature. We will use BLP instruments as instrumental variables in my model, and will also do two robustness checks, each of which adds one more instrument (subsidy or Hausman IV) to our main specification.

5 Estimation Result

The demand and supply model are estimated separately. Following Grigolon et al. (2018), we have addressed multiple computation issues that have come to the attention of recent literature. First, we use a tight convergence level of 1e-12 in the inner loop of the contraction mapping. Second, we use the most advanced optimization algorithm in Knitro, and set the tolerance level at 1e-6. Third, we use a set of 100 starting values to find the global minimum and verify the solution by checking the first and second order condition.

5.1 Demand Parameters

Table 8 reports the estimation results for the demand side in our main specification. The upper panel of demand side estimation reports the mean marginal utility for each product characteristics (α and β), and the panel immediately below this upper panel reports the variation in taste for nonprice characteristics (Σ). The price coefficient is negative and statistically significant at the 5% level. The coefficient on efficiency is positive and statistically significant at 1% level, suggesting that consumers on average favor panels with higher energy conversion efficiency. Energy conversion efficiency quantifies a solar panel's ability to convert sunlight into electricity. High efficiency indicates the panel can convert solar energy at a low cost. The coefficient on technology is negative and statistically significant at the 1% level, suggesting that consumers tend to choose panels made of monocrystalline cells. Compared with polycrystalline panels, monocrystalline solar panels generally have higher efficiency rates, and they are also more space-efficient and have a longer lifespan. The coefficient on black is negative and statistically significant at the 1% level, suggesting that consumers prefers solar panels with silver frames rather than those with black frames. The taste variation parameters on technology and black are both statistically significant at the 1% level, suggesting that consumers are heterogeneous, with respect to their tastes, for the nonprice characteristics of the solar panels.

The demand parameter in Table 8 yields a mean own-price elasticity of demand of -2.871, which is higher than the estimates (-1.76) in Gillingham and Tsvetanov (2014). This may be due to the fact that the choice sets defined in my model are panel/installer combinations which provide more flexibility for the consumers' choices. Table 12 reports the price elasticity of demand for the most popular models within each brand: Sunpower's SPR-327, REC Solar's REC260, Trina Solar's TSM-250PA, Canadian Solar's CS6P-250P, Suntech Power's STP185S, Hanwha Q CELLS's Q.PRO, Yingli Green's YL250P, and Renesola's JC250M. The own-price elasticity of demand for models produced by Suntech Power is the highest(-3.231) and the own-price elasticity for models produced by Hanwha Q CELLS is the lowest(-2.004).

Table 9 and 10 present the results of the robustness checks for the demand side estimation, in which the former uses the BLP instruments and government subsidies as IVs and the latter uses the BLP instruments and Hausman instruments as IVs. In Table 9, the estimated price coefficient is -0.486 and is statistically significant at the 1% level. The estimated coefficients on the nonprice characteristics have the same sign as those in our main specification and all of them are statistically significant except for the efficiency. For the taste variation parameters, all of them are statistically significant at the 1% level. In Table 10, the estimated price coefficient is -0.898 and is statistically significant at the 5% level. The estimated coefficients on nonprice characteristics are all statistically significant at conventional levels of significance and their signs are consistent with those in my main specification. The taste variation parameters are all statistically significant at conventional levels of significance.

5.2 Supply Parameters

Table 11 reports the firms' markups and marginal cost. With vertical relationships between the upstream and downstream firms, the average markup for the solar manufacturer and the solar installer is \$1.521/W and \$1.514/W, respectively. The average margin for the solar manufacturer and the solar installer is 29.70% and 29.56%, respectively. Considering the government subsidy accounts for around 30% of the total installed price for each residential solar PV installation, the price charged by the solar manufacturers and installers seems reasonable. The joint marginal cost amounts to \$2.128/W on average.

Table 8 also reports the estimation result on the supply side in our main specification. The coefficients on manufacturing wage and interest rate are both positive and statistically significant at the 1% level, suggesting that joint marginal cost increases with labor cost in manufacturing and capital cost, which are proxied by hourly compensation cost in manufacturing and lending interest rate, respectively. The significantly positive coefficients on energy conversion efficiency and installing wage suggest that, joint marginal cost increases with the product's energy conversion efficiency and the labor cost in installation, in which the latter is proxied by the hourly wage rate for the roofing. Table 9 and 10 provide robustness checks for the supply side estimation. The coefficients on the cost variables have the same signs as those in our main specification and are all statistically significant at conventional levels of significance.

6 Policy Analysis of Trade Restrictions

In this section, we use the estimated structural model to study the market outcome of trade-related policies. As shown earlier, subsidy policy on the solar manufacturing and anti-dumping policy are the two important factors that may have influenced the development of the solar industry. Moreover, countries may respond in subsidy rates when facing dumping from foreign companies by increasing the subsidy rates for their domestic firms. We conduct two counterfactual simulations based on different anti-dumping duty and subsidy rates : In simulation I, we set the anti-dumping duty rates to zero while the US and China's subsidy rates remain unchanged; In simulation II, we set the anti-dumping duty rates to zero, while setting China's subsidy rates to be equal to that of US.

In each counterfactual scenario, we compute the simulated equilibrium price and demand,

and then compare the outcome with the simulated outcome in the baseline scenario. The baseline scenario refers to the situation when there is an anti-dumping policy. For example, in counterfactual simulation I, on average, the prices for Chinese solar products will decrease by around 10% and the prices for US solar products will not change much, when we set the anti-dumping duty rates to zero.

Following Small and Rosen (1981), we use the compensating variation to calculate the change in consumer surplus in any counterfactual scenario, given by

$$\Delta CS = -\frac{1}{\alpha}\left[\ln\left(\sum_{j=1}^{J}\exp(W_j^1)\right) - \ln\left(\sum_{j=1}^{J}\exp(W_j^0)\right)\right] \tag{12}$$

where α is the consumer marginal disutility of price, W_j^0 and W_j^1 are the expected maximum utility for the consumers in baseline and simulated scenario, respectively.

Before proceeding further, we discuss three important components in performing the welfare calculation. First, the anti-dumping and countervailing duty rates imposed on Chinese solar products. As shown in Table 13, different Chinese manufacturers may face different anti-dumping and countervailing duty rates, and these duty rates that have been implemented since 2014 are higher than that in 2012. Chinese solar manufacturer Renesola was not subject to the anti-dumping and countervailing duty rates in 2012. This was because the anti-dumping policy which came out in 2012 only applied to China-made cells and modules assembled with such cells, but it didn't apply to the firms (such as Renesola) whose solar products were assembled from cells manufactured elsewhere. To close the loophole that let the Chinese solar manufacturers sidestep the duties, the US Department of Commerce amended its ruling in 2014 and set steeper tariff since then.

Second, the proportion of module price and non-module cost in a typical residential solar panel installation in the US. The anti-dumping and countervailing duty rates are imposed on the solar panels (modules), however, in our dataset, the price for the solar panel is not observable and only the total installed price is available. To resolve this problem, we obtain the price for solar module from total installed price. The total installed price includes module price and non-module cost, with the latter involving labor, overhead and marketing costs (Bollinger and Gillingham, 2014). Table 14 reports the breakdown of total installed price. In 2010, the module price accounted for nearly 30% of the total cost, and in 2015 this ratio decreased to around 20%. Based on the proportion of module price in the total installed price as listed in Table 14, we can approximate the panel (module) price from the total installed price.

Lastly, the environmental benefits that arise from solar PV installation. There are two categories of avoided pollution from installing solar PV systems: carbon dioxide emission and local air pollutants. The amount of pollution that can be avoided is dependent on the type of electric power generation displaced by solar PV systems 25 years from now on. Following Gillingham and Tsvetanov (2014)'s approach, we set 25 years as the time limit for estimating environmental benefit and employ damage estimates of air pollutants from natural gas fired generation. These are based on the fact that most manufacturers provide a 25-year warranty on their solar panels and natural gas accounts for a significantly large fraction of the electricity generation in the US. Other parameters involved include the average carbon dioxide emission rate across the US, the total external costs from natural gas-fired generation in the US, and social cost of carbon. The average carbon dioxide emission rate across all regions and hours of the day is estimated to be 1.21 pounds of CO2 per kilowatt hour, i.e., 0.000605 tCO2/kWh. (Zivin et al., 2014). The total external cost from natural gas-fired generation is estimated to be 0.021/kWh (Muller et al., 2011). For the social cost of carbon, we apply the result $37/tCO2 from IAWG (2013) which is widely used by the US government.

Based on the parameters estimated by the main specification of our structural model, we calculate the simulated results for the two counterfactual scenarios and report them below. We also conduct simulations based on alternative models using two other sets of IVs (i.e., BLP instruments and government subsidies, BLP instruments and Hausman instrument), and the results are similar and available upon request.

6.1 Simulation I: Removing Anti-dumping Duties

In this section, we evaluate the effect of removing the anti-dumping duties while keeping the US and China's subsidy rates on their solar manufacturing unchanged. As shown by the two-country model, removing the anti-dumping policy will drive down the price of imported Chinese products and stimulate their sales.

Table 16 presents the change in demand for solar panels in the simulated scenario I, when the anti-dumping duty rates levied on imported Chinese solar products are set to be zero but US and China's subsidy rates remain unchanged. Simulating the purchase price, the percentage increase in product sales from Chinese solar manufacturers (Canadian Solar, Renesola, Suntech Power, Trina Solar and Yingli Green Energy) would range from 15.5% to 62.6% for the period 2010 - 2015, while the percentage decrease in sales from US solar manufacturers (REC Solar and SunPower) would range from -0.02% to -0.4%. The overall sales of solar panels for the MSA markets in our sample would increase by 61,727 kW, or 24.5% compared with the baseline scenario when the anti-dumping policy is in place. Since the MSA markets selected in our sample account for 31% of the total markets in the US, the simulated sales across the US would increase by 199,121 kW.

The anti-dumping policy initiated by the US changes the competition among Chinese and US solar manufacturers. Removing the anti-dumping duties would decrease the imported Chinese solar panel prices and may make more consumers switch to US solar products. The simulation results in Table 17 show the social welfare change incurred for different market participants and the environmental benefit implied if the anti-dumping policy had been removed. Over the period 2010 - 2015, for MSA markets in our sample, the net gain for US consumers, US manufacturers, Chinese manufacturers and US installers would be 90.70, -0.25, 106.63 and 103.72 million dollars, respectively. If I scale the results to all MSA markets across the US, the net gain for US consumers, US manufacturers, Chinese manufacturers and US installers would be 292.57, -0.80, 343.98 and

334.58 million dollars, respectively.

The anti-dumping duties seem to have a relatively small effect on the domestic manufacturers' profits. This can be explained by the fact that the substitution effect between US and Chinese solar products is quite small. If the anti-dumping policy is in place, the consumers may switch to solar products produced by other countries, for example, the European and Japanese solar products. These products may have captured many of the lost Chinese sales.

Without anti-dumping duties, the US solar market would expand by 24.5%, and the increase in solar PV installations would result in greater environmental benefit in terms of reducing greenhouse gas emissions and local air pollutants. The simulation results in Table 17 suggest that, the greenhouse gas emission would be reduced by 1.36 million tons and the economic cost of air pollution resulted from natural gas-fired generation would be reduced by 22.60 million dollars, together amounting to total environmental benefit of 46.69 million dollars. If we scale the results to all MSA markets across the US, the reduced greenhouse gas emission would reach 4.40 million tons and the total environmental benefit would be worth 150.60 million dollars.

6.2 Simulation II: Reducing Subsidy Rates

In this section, we examine the market outcome when the anti-dumping duty rates are set to zero and China matches its subsidy rates on solar manufacturing with that of United States. Subsidy policy provides an alternative tool to anti-dumping issues. A country which has been sued for dumping can respond by reducing subsidy rates on domestic firms as a settlement with the dumping allegation, thus avoiding anti-dumping duties.

Table 18 presents the change in demand for solar panels in the simulated scenario II. Assume the countervailing duty rates (see Table 13) calculated by the US Department of Commerce are reasonable, and we use the averages (28.31%) as a proxy for China's average subsidy rates on its domestic solar manufacturers. As described in Section 2.3, the average subsidy rates of United States on its domestic solar manufacturers is 2.1%. If China's subsidy rates were set to be equal to that of US, then the average price of imported Chinese solar products would be presumably higher.

Simulating the consumer purchase price, we find that the percentage increase in sales from Chinese manufacturers (Canadian Solar, Renesola, Suntech Power, Trina Solar, Yingli Green Energy) would range from 6.3% to 36.2%. The percentage decrease in sales from US manufacturers (REC Solar and SunPower) would range from -0.2% to -0.01%. The overall sales of solar panels for the MSA markets in our sample would increase by 30,712 kW, or 12.2% compared with the baseline scenario when the anti-dumping policy is in place. Since the MSA markets selected in our sample account for 31% of the total markets in the US, the simulated sales across the US would increase by 99,071 kW.

The relative decrease in subsidy rates from China will change the competition among Chinese and US solar manufacturers. The resulted price increase in the imported Chinese solar products may make more consumers switch to US products. The simulation results in Table 19 show the social welfare change incurred for different market participants and the environmental benefit implied in this counterfactual simulation. Over the period 2010 - 2015, for MSA markets in my sample, the welfare change for US consumers, US manufacturers, Chinese manufacturers and US installer would be 45.71, -0.11, 52.09 and 50.77 million dollars, respectively. If we scale the results to all MSA markets across the US, the net gain/loss for US consumers, US manufacturers, Chinese manufacturers and US installers would be 147.45, -0.34, 168.03 and 163.78 million dollars, respectively.

Generous government subsidy is believed to be the key factor that has enabled Chinese solar manufacturers to rapidly gain market shares in the US. If China were to respond by reducing its subsidy rates offered to solar manufacturers and setting it equal to the rate offered in the US, the solar market in United States would expand by 12.2%. This result can be separated into two parts: first, China would avoid the anti-dumping policy by matching the subsidy rates, thus the US market would achieve a 24.5% growth in the installed solar capacity, compared with the baseline scenario (as shown in Simulation I); second, reducing subsidy rates on Chinese firms would drive up the price of Chinese solar products, thus slowing down the expansion of US solar market by 12.3% (24.5% - 12.2%).

The environmental benefit from reducing greenhouse gas emissions and local air pollutants also seems quite significant. The simulation results in Table 19 suggest that, the greenhouse gas emissions would be reduced by 0.68 million tons and the economic cost of air pollution resulted from natural gas-fired generation would be reduced by 11.24 million dollars, together amounting to total environmental benefit of 23.23 million dollars. If we scale the results to all MSA markets across the US, the reduced greenhouse gas emissions would reach 2.19 million tons and the total environmental benefit would be worth 74.93 million dollars.

7 Conclusion

In this paper, we have examined how the trade war between China and the US affects the social welfare in the fast-growing solar industry with vertical structure between upstream and downstream firms. The solar sector is an important market to study, because as one of the main sources of renewable energy it has the potential to become a dominant energy source.

This paper estimates a structural econometric model of consumer demand for solar panels and marginal cost on solar manufacturing which incorporates the vertical structure between upstream solar manufacturers and downstream solar installers. Based on the estimated model, we conduct two counterfactual simulations regarding different hypothetical changes on anti-dumping duties and subsidy rates. The results of our simulations show that the installation capacity in the US solar market would expand by 24.5% if there were no anti-dumping policies and welfare change for US consumer, US manufacturers, Chinese manufacturers and US installers would reach 292.57, -0.80, 343.98 and 334.58 million dollars (in 2015 US dollars), respectively. Compared with the big losses in Chinese solar manufacturers, the US manufacturers have only gained small profits from the anti-dumping policy.

We conclude by highlighting a few caveats of our paper. First, further work needs to be done to model demand. Our paper assumes that the demand system is static, however, there still exists a possibility that a wait-or-buy decision may be involved when the consumers choose to install a solar PV system. Thus future research would benefit from making the demand side dynamic. Also, once the households have the solar system installed, they are no longer in the market, so the demand system needs to be modified to account for this feature. Second, our paper has not discussed the effect of anti-dumping policies on US employment and manufactures. It would be very interesting to consider what happens to US employment, as well as to US manufactures when a trade war has been initiated. Has this trade war resulted in more job creation in the US solar manufacturing industry? Have the solar firms invested more in their manufacturing capacity? Has the employment in the solar installer industry changed as a result of the anti-dumping policy? Answering these and other questions will help guide future research and inform trade policy, as well as energy and environmental policies.

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Installed_price.jpg

Figure 1: Price decline of residential solar PV

Source: Lawrence Berkeley National Laboratory.

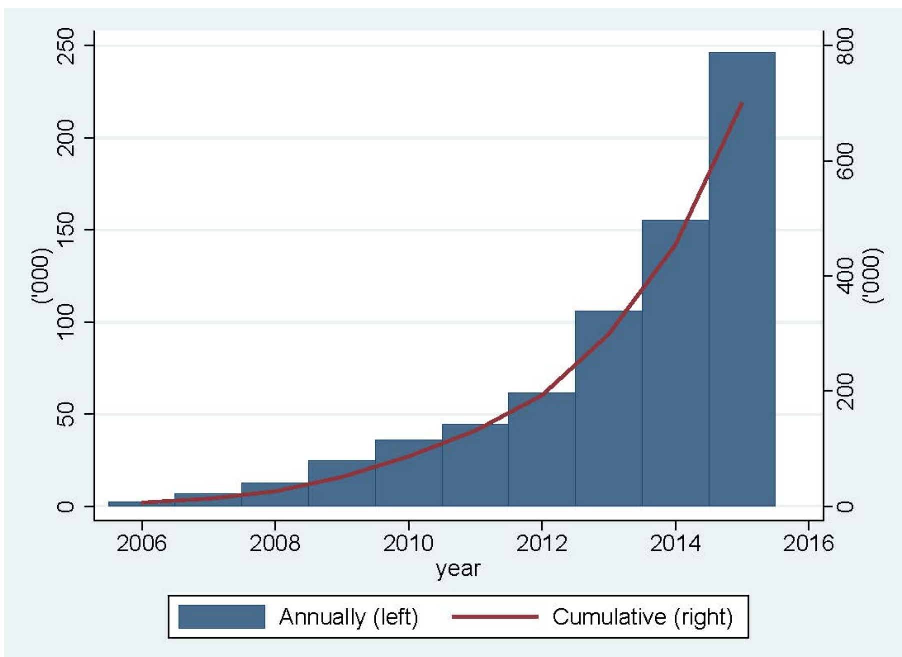

Figure 2: Number of installations of residential solar systems over time

Source: Lawrence Berkeley National Laboratory.

Table 1: Top 15 manufacturers by market share

Rank	2011	Market Share	2015	Market Share
1	SunPower	17.18%	REC Solar	16.68%
2	Suntech*	13.31%	SunPower	12.90%
3	Kyocera Solar	10.83%	Kyocera Solar	12.66%
4	Sharp	10.20%	Trina Solar*	11.67%
5	Trina Solar*	7.11%	SolarWorld	10.44%
6	Schuco USA	6.19%	Canadian Solar*	7.85%
7	Canadian Solar*	4.62%	LG Electronics	7.41%
8	SolarWorld	4.17%	Hanwha Q CELLS	6.97%
9	REC Solar	4.03%	Hyundai	3.75%
10	BP Solar	3.95%	SunEdison	1.91%
11	Panasonic Group	2.28%	AU Optronics	1.49%
12	ET Solar*	2.01%	Suniva	1.32%
13	Schott Solar	1.42%	Renesola*	0.98%
14	Yingli Green Energy*	1.26%	Axitec	0.47%
15	Centrosolar	1.22%	ET Solar*	0.35%

Notes: This table represents the top 15 manufacturers in US solar market by market share in 2011 and 2015, respectively. The firms with asterisk are Chinese solar makers.

Table 2: Descriptive statistics across years

Panel A	2010	2011	2012	2013	2014	2015
MSA	42	49	45	51	41	42
solar makers	4	6	6	7	7	8
solar panels	10	17	26	35	33	34
installation	1,087	1,612	4,214	6,469	12,821	17,340
Panel B						
MSA	153	150	148	149	137	129
solar makers	109	138	145	161	150	158
solar panels	490	685	831	1,194	1,209	1,343
installation	33,584	41,958	58,598	102,828	151,455	239,490

Notes: This table represents the descriptive statistics for the key variables, including the number of MSAs, the number of different solar makers, the number of different types of solar panels and the number of solar PV installations. Panel A shows the statistics summary for the inside goods and Panel B shows the statistics summary for the whole dataset.

Table 3: List of models for the solar panels

Brand	Model	Brand	Model
Suntech Power	STP180S-24/Ab-1	**SunPower**	SPR-215-WHT
	STP185S-24/Ab-1		SPR-225-BLK
	STP190S-24/Ad		SPR-230-WHT
	STP250-20/Wd		SPR-230NE-BLK-D
Trina Solar	TSM-240PA05		SPR-240E-WHT-D
	TSM-250PA05		SPR-245NE-WHT-D
	TSM-250PD05.08		SPR-320E-WHT-D
	TSM-255PA05		SPR-327NE-WHT-D
	TSM-255PD05.08		SPR-E20-327
	TSM-260PA05		SPR-X20-250-BLK
	TSM-260PD05.08		SPR-X21-335
Yingli Green Energy	YL235P-29b		SPR-X21-335-BLK
	YL250P-29b		SPR-X21-345
Renesola	JC250M-24/Bb	**Canadian Solar**	CS6P-230P
Hanwha Q CELLS	Q.PRO BFR G4 265		CS6P-235PX
REC Solar	REC240PE (BLK)		CS6P-250M
	REC245PE (BLK)		CS6P-250P
	REC250PE (BLK)		CS6P-255M
	REC255PE(BLK)		CS6P-255P
	REC260PE		CS6P-260P
	REC260PE(BLK)		
	REC275TP		

Notes: This table lists all the models of the solar panels in the inside goods.

Table 4: Summary statistics for key variables

Variable	Description	Max	Min	Mean	SD
A. Basic Characteristics					
InstalledPrice	Total installed price (2015$/Watt)	35.96	1.10	5.12	1.65
Subsidy	Government subsidies (2015$/Watt)	4.69	0	0.82	0.77
Price	Consumer purchase price [a] (2015$/Watt)	34.96	1.10	4.30	1.50
Efficiency	Energy conversion efficiency	0.21	0.14	0.17	0.02
Technology	=1, if polycrystalline; =0 if monocrystalline	1	0	0.46	0.50
Black	=1, if solar panel frame is black	1	0	0.20	0.40
B. Geo. and Demo. Var					
Electricity Price	Average electricity price (cents/kWh)	20.93	10.97	16.11	3.01
Education	Percent of people with a bachelor degree (%)	48.70	13.00	30.23	6.45
Income	Median income ($1000) on the MSA level	130.52	50.32	78.28	15.61
Age	Median age (years old)	49.90	28.70	38.78	3.72
Homes	# of single family homes (1,000)	4,631	20	868	1,196
Solar Potential	Percent of buildings that are solar-viable (%)	92	28	72	13
C. Cost Variable					
Manufacturing Wage	Wage rate (2015$/hour) in manufacturing	37.04	1.74	18.84	16.24
Installing Wage	Wage rate (2015$/hour) in roofing	35.67	15.75	23.82	4.63
Interest Rate	Lending interest rate (%)	6.56	3.25	4.67	1.37

Notes: the prices are in 2015 US dollars

[a] Consumer Purchase Price = Total Installed Price - Government Subsidies

Table 5: List of solar installers

Number	Name	Number	Name
1	SolarCity	6	Sunpower
2	Vivint	7	REC Solar
3	Verengo	8	PetersenDean
4	Sungevity	9	RGS/Real Goods
5	Sunrun	10	All others

Notes: This table lists the ten groups of solar installers in US market. The first nine groups are the nine biggest solar installers as marked by number 1 - 9 and the tenth group is all other solar installers in my data sample.

Table 6: Results for the first-stage regression

VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Subsidy	-0.827***			-0.785***		-0.847***	-0.806***
	(0.0581)			(0.0625)		(0.0578)	(0.0621)
$BLP\_efficiency$		0.0742		0.107	0.0726		0.106
		(0.0769)		(0.0734)	(0.0765)		(0.0728)
$BLP\_technology$		0.0404***		-0.00674	0.0407***		-0.00753
		(0.0149)		(0.0147)	(0.0149)		(0.0146)
BLP_black		-0.0424*		0.00516	-0.0388		0.0107
		(0.0253)		(0.0245)	(0.0252)		(0.0243)
Hausman			0.257***		0.276***	0.313***	0.323***
			(0.0634)		(0.0625)	(0.0597)	(0.0596)
Control Variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer-Installer FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,647	1,647	1,647	1,647	1,647	1,647	1,647
F-statistic	383	18.07	12.49	54.33	18.57	116.76	50.12
R-squared	0.339	0.279	0.262	0.344	0.288	0.350	0.356

Note: The variable Subsidy represents the government subsidies received by the consumer for installing a solar PV system; the variables $BLP\_efficiency$, $BLP\_technology$ and BLP_black are the BLP instruments based on the product characteristics; the variable Hausman represents the Hausman instrument. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 7: Results for the second-stage regression

VARIABLES	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Price	-0.0726	-1.167***	0.274	-0.240***	-0.825***	-0.0390	-0.196**
	(0.0852)	(0.212)	(0.300)	(0.0829)	(0.158)	(0.0802)	(0.0776)
Efficiency	28.64***	32.02***	27.57***	29.16***	30.97***	28.53***	29.02***
	(6.833)	(9.209)	(7.269)	(6.861)	(7.992)	(6.844)	(6.839)
Technology	1.445***	1.922***	1.294***	1.518***	1.773***	1.430***	1.499***
	(0.212)	(0.296)	(0.257)	(0.213)	(0.254)	(0.212)	(0.212)
Black	-0.235**	-0.126	-0.269**	-0.218**	-0.160	-0.238**	-0.223**
	(0.106)	(0.144)	(0.116)	(0.107)	(0.125)	(0.107)	(0.106)
Electricity Price	0.0638***	0.106***	0.0505**	0.0703***	0.0929***	0.0625***	0.0686***
	(0.0178)	(0.0249)	(0.0218)	(0.0178)	(0.0213)	(0.0178)	(0.0178)
Education	7.308***	9.041***	6.759***	7.573***	8.499***	7.254***	7.504***
	(0.928)	(1.281)	(1.080)	(0.932)	(1.102)	(0.929)	(0.928)
Income	-0.0502***	-0.0462***	-0.0515***	-0.0496***	-0.0475***	-0.0504***	-0.0498***
	(0.00349)	(0.00474)	(0.00383)	(0.00350)	(0.00410)	(0.00349)	(0.00349)
ln (Age)	3.328***	3.282***	3.343***	3.321***	3.296***	3.330***	3.323***
	(0.421)	(0.566)	(0.445)	(0.423)	(0.492)	(0.422)	(0.421)
Constant	-27.01***	-24.22***	-27.89***	-26.58***	-25.09***	-27.10***	-26.69***
	(1.874)	(2.562)	(2.109)	(1.881)	(2.212)	(1.876)	(1.874)
Manufacturer-Installer FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,647	1,647	1,647	1,647	1,647	1,647	1,647
R-squared	0.313	-	0.235	0.308	0.063	0.311	0.312

Table 8: Estimation result for main specification

	Variables	Estimates	Standard Errors
Demand side parameters			
Means, (α, β)	Constant	-26.213***	(1.858)
	Price	-0.669**	(0.276)
	Efficiency	99.998***	(13.402)
	Technology	-14.039***	(1.611)
	Black	-19.532***	(4.379)
Taste variation, (Σ)	Constant	0.857	(0.706)
	Efficiency	-0.078	(5.036)
	Technology	8.961***	(0.645)
	Black	-13.124***	(2.296)
Cost side parameters			
	Constant	-7.520***	(1.324)
	Manufacturing Wage	0.055***	(0.016)
	Interest Rate	0.624***	(0.192)
	Efficiency	18.437***	(3.064)
	Installing Wage	0.059***	(0.007)

Note: This table reports the result for the demand and supply estimation based on the mixed logit specifications, in which I use BLP instruments as IVs. The sample is from year 2010 to 2015. On the demand side, Price is the after-subsidy average installed price for solar module (in \$/W); Efficiency represents the energy conversion efficiency; Technology represents the type of solar photovoltaic technology, which is a dummy variable and equals to one if its made of polycrystalline solar cells; Black is dummy variable, which equals to one if the solar module has a black frame; Manufacturing Wage refers to the average hourly compensation cost in the manufacturing in the solar brands origin country; Interest Rate refers to the one-year lending interest rate in the solar brands origin country; Efficiency represents the energy conversion efficiency; Installing Wage refers to the MSA-level wage rate (\$/hour) for the roofing; Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 9: Result for robustness check I

	Variables	Estimates	Standard Errors
Demand side parameters			
Means, (α, β)	Constant	-17.602***	(1.590)
	Price	-0.486***	(0.296)
	Efficiency	15.759	(13.515)
	Technology	-7.678***	(1.145)
	Black	-12.440***	(3.128)
Taste variation, (Σ)	Constant	0.7527***	(0.2562)
	Efficiency	-29.024***	(3.435)
	Technology	-8.118***	(0.542)
	Black	10.416***	(1.677)
Cost side parameters			
	Constant	-8.327***	(1.334)
	Manufacturing Wage	0.054***	(0.016)
	Interest Rate	0.599***	(0.193)
	Efficiency	16.600***	(3.087)
	Installing Wage	0.061***	(0.007)

Note: This table reports estimation result for the demand and supply models by using BLP instruments and government subsidies as instrumental variables. The sample is from year 2010 to 2015. On the demand side, Price is the after-subsidy average installed price for solar module (in $/W); Efficiency represents the energy conversion efficiency; Technology represents the type of solar photovoltaic technology, which is a dummy variable and equals to one if its made of polycrystalline solar cells; Black is dummy variable, which equals to one if the solar module has a black frame; Manufacturing Wage refers to the average hourly compensation cost in the manufacturing in the solar brands origin country; Interest Rate refers to the one-year lending interest rate in the solar brands origin country; Efficiency represents the energy conversion efficiency; Installing Wage refers to the MSA-level wage rate ($/hour) for the roofing; Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 10: Result for robustness check II

	Variables	Estimates	Standard Errors
Demand side parameters			
Means, (α, β)	Constant	-26.479***	(2.427)
	Price	-0.898**	(0.228)
	Efficiency	65.980***	(11.545)
	Technology	-3.834***	(1.448)
	Black	-5.580**	(1.445)
Taste variation, (Σ)	Constant	-5.240***	(0.553)
	Efficiency	9.708**	(4.729)
	Technology	-6.062***	(1.122)
	Black	-6.296***	(1.125)
Cost side parameters			
	Constant	-6.198***	(1.326)
	Manufacturing Wage	0.050***	(0.016)
	Interest Rate	0.564***	(0.192)
	Efficiency	17.422***	(3.068)
	Installing Wage	0.060***	(0.007)

Note: This table reports estimation result for the demand and supply models by using BLP instruments and Hausman instrument as instrumental variables. The sample is from year 2010 to 2015. On the demand side, Price is the after-subsidy average installed price for solar module (in \$/W); Efficiency represents the energy conversion efficiency; Technology represents the type of solar photovoltaic technology, which is a dummy variable and equals to one if its made of polycrystalline solar cells; Black is dummy variable, which equals to one if the solar module has a black frame; Manufacturing Wage refers to the average hourly compensation cost in the manufacturing in the solar brands origin country; Interest Rate refers to the one-year lending interest rate in the solar brands origin country; Efficiency represents the energy conversion efficiency; Installing Wage refers to the MSA-level wage rate (\$/hour) for the roofing; Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 11: Price elasticity, marginal costs, and markups

Variable	Mean	Std.Dev	10%	Median	90%
Price ($/W)	5.122	1.653	3.419	4.964	7.097
Own-price elasticity	-2.871	1.003	-	-	-
Markup for solar manufacturer ($/W)	1.521	0.077	1.494	1.496	1.565
Markup for solar installer ($/W)	1.514	0.063	1.494	1.496	1.531
Joint marginal cost ($/W)	2.128	1.667	0.344	1.951	4.095

Note: This table reports means, standard deviations, as well as the 10th, 50th, and 90th percentiles of price, own-price elasticity, markup for the solar manufacturer and solar installer, and joint marginal cost.

Table 12: Demand elasticities with respect to price

	SPR-327	REC260	TSM-250PA	CS6P-250P	STP185S	Q.PRO	YL250P	JC250M
SPR-327	-2.819							
REC260		-2.676						
TSM-250PA			-2.423					
CS6P-250P				-2.598				
STP185S					-3.231			
Q.PRO						-2.004		
YL250P							-2.913	
JC250M								-2.438

Note: The full name for these eight solar models are SPR-327NE-WHT-D, REC260PE, TSM-250PA05, CS6P-250P, STP185S-24/Ab-1, Q.PRO BFR G4 265, YL250P-29b and JC250M-24/Bb, repectively.

Table 13: Anti-dumping and countervailing duties (%)

	Anti-dumping		Countervailing	
	2012	2014	2012	2014
Suntech	31.73	52.13	14.78	27.64
Trina Solar	18.32	26.71	15.97	49.79
Canadian Solar	25.96	52.13	15.24	38.72
Yingli Green	25.96	52.13	15.24	38.72
Renesola	-	78.42	-	38.72

Note: This table reports the anti-dumping and countervailing duties rates imposed on the imported solar panels produced by Chinese manufacturers. Different Chinese manufacturers may face different level of duties. The duty rates were first set by US Department of Commerce in 2012, and then revised in 2014.

Table 14: Breakdown of total installed price over 2010 - 2015

Year	Total Price	Module Price	Non-Module Costs	Module Price/Total Price
2010	7.1	1.9	5.2	26.83%
2011	6.3	1.3	5.0	20.78%
2012	5.3	0.9	4.5	16.03%
2013	4.6	0.8	3.8	17.74%
2014	4.3	0.8	3.5	18.29%
2015	4.1	0.8	3.3	19.24%

Note: This table reports the trend of solar prices from 2010 to 2015. Total Price is the total installed price ($/W), which is decomposed into module price and non-module cost. The data for this table comes from Lawrence Berkeley National Laboratory.

Table 15: Assumptions of parameters in estimating environmental benefit

Parameter	Value	Sources
Number of years	25	Gillingham and Tsvetanov (2014)
Discount rate	3%	Muller et al. (2011)
Full Sunlight hours	4 hours/day	
CO2 emission rate	1.2 lbs/kWh	Zivin et al. (2014)
External cost	$ 0.021/kWh	Gillingham and Tsvetanov (2014), Muller et al. (2011)
Social cost of carbon	$37/tCO2	Inter-Agency Working Group (2013)

Note: Full sunlight hours represents the total amount of full sunlight hours per day. CO2 emission rate represents the average greenhouse gas emission from electricity generation across all regions and hours of day in the US. External cost represents the total external cost of air pollutants produced by natural gas-fired generation.

Table 16: Demand response in simulation I

Origin Country	Manufacturer	Baseline (kW)	Simulated (kW)	Demand Change	Percent
China	Canadian Solar	50,425	81,974	31,548	62.6%
	Renesola	482	596	114.006	23.6%
	Suntech Power	6,303	7,279	976	15.5%
	Trina Solar	51,812	75,766	23,953	46.2%
	Yingli Green Energy	10,512	15,772	5,260	50.0%
USA	SunPower	106,138	106,118	-20	-0.02%
	REC Solar	25,430	25,325	-105	-0.4%
South Korea	Hanwha Q CELLS	1037	1038	1	0.1%
Subtotal		252,141	313,868	61,727	24.5%
All markets		813,358	1,012,479	199,121	24.5%

Note: This table reports the demand change for the counterfactual simulation scenario I, when anti-dumping duty rates are set to zero and subsidy rates remain unchanged. The column Baseline represents the simulated demand for solar panels when the anti-dumping policy is in place.

Table 17: Welfare effect for simulation I

Items	MSA markets in our sample	All MSA markets
A. Welfare (2015$ Million)		
Δ CS	90.70	292.57
Δ US Manufacturers	-0.25	-0.80
Δ China Manufacturers	106.63	343.98
Δ Installers	103.72	334.58
B. Environmental Benefit		
ΔReduced CO2 Emission (tons)	1,363,096	4,397,083
ΔReduced External Cost ($ Million)	22.60	72.90
ΔTotal Environmental Benefit ($ Million)	46.69	150.60

Note: This table reports the welfare changes for US consumer, US manufacturers, US installers and Chinese manufacturers in simulated scenario I, when anti-dumping duty rates are set to zero.

Table 18: Demand response in simulation II

Origin Country	Manufacturer	Baseline (kW)	Simulated (kW)	Demand Change	Percent
China	Canadian Solar	50,425	68,682	18,257	36.2%
	Renesola	482	513	30	6.3%
	Suntech Power	6,303	6,805	502	8%
	Trina Solar	51,812	60,942	9,130	17.6%
	Yingli Green Energy	10,512	13,361	2,848	27.1%
USA	SunPower	106,138	106,127	-10	-0.01%
	REC Solar	25,430	25,384	-46	-0.2%
South Korea	Hanwha Q CELLS	1,037	1,038	1	0.1%
Subtotal		252,141	282,853	30,712	12.2%
All markets		813,358	912,429	99,071	12.2%

Note: This table reports the demand change for the counterfactual simulation scenario II, when the anti-dumping duty rates are set to zero and China's subsidy rates are set to be equal to that of US. The column Baseline represents the simulated demand for solar panels when the anti-dumping policy is in place.

Table 19: Welfare effect for simulation II

Items	MSA markets in our sample	All MSA markets
A. Welfare (2015$ Million)		
Δ CS	45.71	147.45
Δ US Manufacturers	-0.11	-0.34
Δ China Manufacturers	52.09	168.03
Δ Installers	50.77	163.78
B. Environmental Benefit		
ΔReduced CO2 Emission	678,198	2,187,735
ΔReduced External Cost	11.24	36.27
ΔTotal Environmental Benefit	23.23	74.93

Note: This table reports the welfare changes for US consumer, US manufacturers, US installers and Chinese manufacturers in simulated scenario II, when China's subsidy rates are set to be equal to that of US.