Solar Industry in California: Market Structure and Policy Impacts.

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Abstract

The data on solar installations in California is used to uncover regularities in entry patterns, and sales and price distributions of firms that were engaged in installing solar equipment in California in 2012. A model is developed that is consistent with many of the regularities seen in the data. The model parameters are estimated using simulated method of moments. The calibrated model is used to estimate (i) the impact of government subsidy on welfare and solar penetration levels (ii) the cost reduction that would be necessary to achieve the 2012 solar penetration level in the absence of the subsidy. (JEL: O31, L63)

1 Introduction

Driven by concerns about global warming, governments across the world have adopted a variety of policies to reduce the emission of greenhouse gases. Many such policies have focused on replacing polluting processes and products with less polluting ones, combustion engine cars with electric vehicles in transportation, incandescent bulbs with energy efficient bulbs in lighting, and coal with solar and wind in electricity generation. In evaluating the effect of such government policies, the focus has been on modeling the consumer purchasing process and in quantifying the impact of the policies on consumers' decision to purchase electric cars or solar panels.[1] Very little attention has been paid to the role played by firms in the industry or on the influence of market

[1]Chandra, Gulati and Kandlikar (2010) study the effect of demand side subsidy on adoption of hybrid electric cars, Mian and Sufi (2012) examine the effect of the federal Cash-for-clunkers program on adoption of fuel efficient vehicles. Drury, Miller, Macal, Diane J. Graziano, Ozik and Perry (2012) examine the effect of availability of third party financing, and Bollinger and Gillingham (2012) the impact of peer effects in adoption decision of solar panels in California.

structure in determining the market penetration of these environment friendly products. This paper fills the gap in the literature by developing a model of the solar photovoltaic installation industry in California that is consistent with observations about the market structure, and using the model to quantify the impact of demand side subsidies for solar equipment on welfare and solar penetration in the residential electricity market in California.

The solar photovoltaic industry has grown at a rapid pace during the last decade, aided by consumer subsidies offered by many national and regional governments.[2] Firms that manufacture solar panels have also received government support in their attempts to reduce the cost of making solar panels, for example through research grants and loan guarantees. A number of recent studies, however, have found that the cost of solar panels make up less than forty percent of the price paid for a residential solar system in the U.S, with other items like installation labor costs and markups charged by the contractors adding up to well over sixty percent of the price.[3] This finding has led many government agencies, like the U.S Department of Energy, to place a new emphasis on understanding the factors that determine the price charged by contractors who install solar panels. Existing studies that have looked at the impact of consumer subsidies on welfare and solar penetration levels, for example Burr (2013) and Hughes and Podolefsky (2013), assume a perfectly competitive market for the solar contractors. The assumption of perfect competition is at odds with the data on solar installations in California.[4]

Firms in the solar installation industry are contractors who install solar panels and associated electrical equipment on residences.[5] Taking each county in California to be a separate market, the data on solar contractors in California exhibit many striking regularities in entry and distribu-

[2]The type of subsidy varies across regions. See to Shrimali for a good description of the policies in different countries.

[3]See Friedman, Ardani, Feldman, Citron, Margolis and Zuboy (2013) and Morris, Calhoun, Goodman and Seif (2013).

[4]See Section 2.

[5]Most of these contractors purchase the solar panels from other upstream firms, although a few manufacture the panels themselves.

tion of sales documented in Eaton, Kortum and Kramarz (2011) (henceforth referred to as EKK (2010)). The key elements in the model are heterogenous firms whose efficiencies follow a Pareto distribution as in Melitz (2003), Chaney (2008), and Helpmann, Melitz and Yeaple (2004), and market entry costs as in Arkolakis (2010). The contractors are modeled as selling differentiated varieties of solar equipment and installation services, with the demand for each variety being generated according to a Dixit-Stiglitz aggregator. The aggregate demand for solar equipment within a county is modeled as being generated by a consumer with Cobb Douglass preferences over two goods, electricity generated through solar equipment installed at home and electricity purchased from retail markets.

The parameters in the model are estimated using simulated method of moments. The calibrated model is used to answer two questions that have been central in government policy making in the industry. First, the model is used quantify the impact of the thirty percent subsidy offered by the U.S federal government on welfare and solar penetration levels in California. Second, an often discussed question in the solar industry is the effectiveness of consumer subsidies for solar purchases compared to supply side subsidies aimed at reducing the cost of solar equipment (see Baker and Nemet (2009)). While a welfare comparison between the two type of subsidies is beyond the scope of this paper, the calibrated model delivers the cost reduction necessary to obtain the solar penetration levels that result under a consumer subsidy. To achieve the penetration level for solar in 2012 in California without the federal subsidy, the model estimates that the unit cost would have had to be 35.4% lower than what it actually was in 2012. The next section describes the solar industry in California and documents the empirical regularities that form the motivation for the model in Section 3.

2 Empirical Regularities in California Solar Market

The data used in this paper comes from three sources. The data on solar installations is a subset of the data available from California Solar Center, and is collected from applications submitted for the solar subsidy available under the California Solar Initiative program.[6] The dataset contains information on 27,734 solar installations on residences in California in 2012. For each installation, data is available on the total cost, the capacity, and the county where the residence is located. The capacity is given in watts, the unit of electric power. The data on total installation cost and capacity is used to obtain the price per unit capacity (dollar per watt). The quantity of electricity that can be produced from a unit of capacity depends on the intensity of sunlight in the location, also called insolation. The data on solar insolation in a county is obtained from National Renewable Energy Laboratory.[7] The data on the installed capacity is combined with the data on insolation in the region to calculate the total quantity of electricity that can be produced from each installation over the course of a year. Finally, the annual residential electricity consumption in each county is taken from the California Energy Almanac maintained by the California Energy Commission.[8] These three sources of data together provide a picture of the solar industry in each county, both at the aggregate level in its penetration of the electricity market, and at the firm level with regard to market entry, pricing and sales in each county. The following five observations capture the salient features of the industry.

Figure 1 plots the total consumer expenditure on solar equipment in a county in California against the projected twenty year expenditure on electricity in that county. Solar panels are usually guaranteed to last twenty years, hence the appropriate comparison of the expenditure on solar

[6] More information is available at http://www.californiasolarstatistics.ca.gov.

[7] The National Renewable Energy Laboratory has a program, PVWatts, that provides the electricity that can be produced from each watt of solar panel for every city in California. The value provided by PV Watts for the capital city in each county was taken to calculate the value for the county. The program is available at http://www.nrel.gov/rredc/pvwatts/

[8] The California Energy Almanac is available at http://www.ecdms.energy.ca.gov/.

panels is with the present discounted value of total electricity expenditures over the life time of the solar panel. As the graph shows, not only did the larger (in terms of electricity consumption) counties spend more on solar equipment, the total consumer expenditure on solar equipment showed a tight log-linear relationship with total expenditure on electricity in each county.

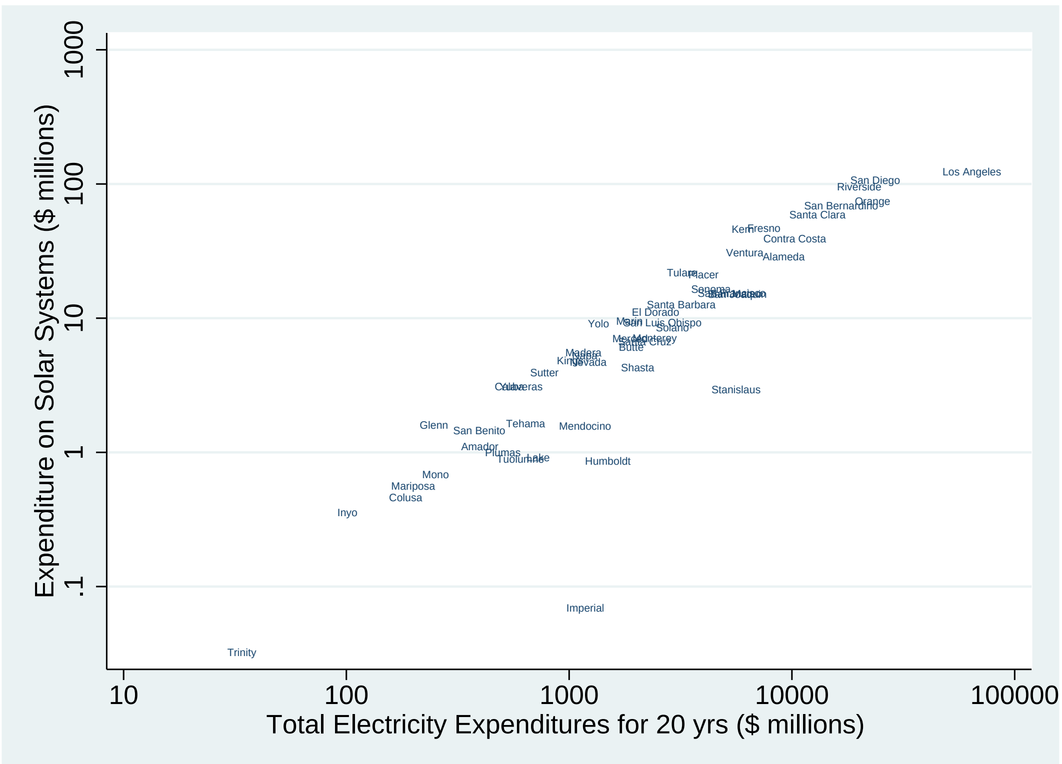


Figure 1: Expenditure on solar systems as a fraction of total discounted expenditure over next 20 yrs.

Notes: The y-axis shows the total sales of solar equipment in a county. The x-axis is the present discounted value of projected expenditures on retail electricity for next twenty years by all households in each county, assuming a discount factor of 4% and constant annual expenditures at the 2012 level.

On the production side, there were 1014 different contractors who operated in California in

2012. Not all contractors entered every county, and the number of contractors entering each county bears a strong log-linear relationship with the market size, as measured by the sales (see Figure 2).

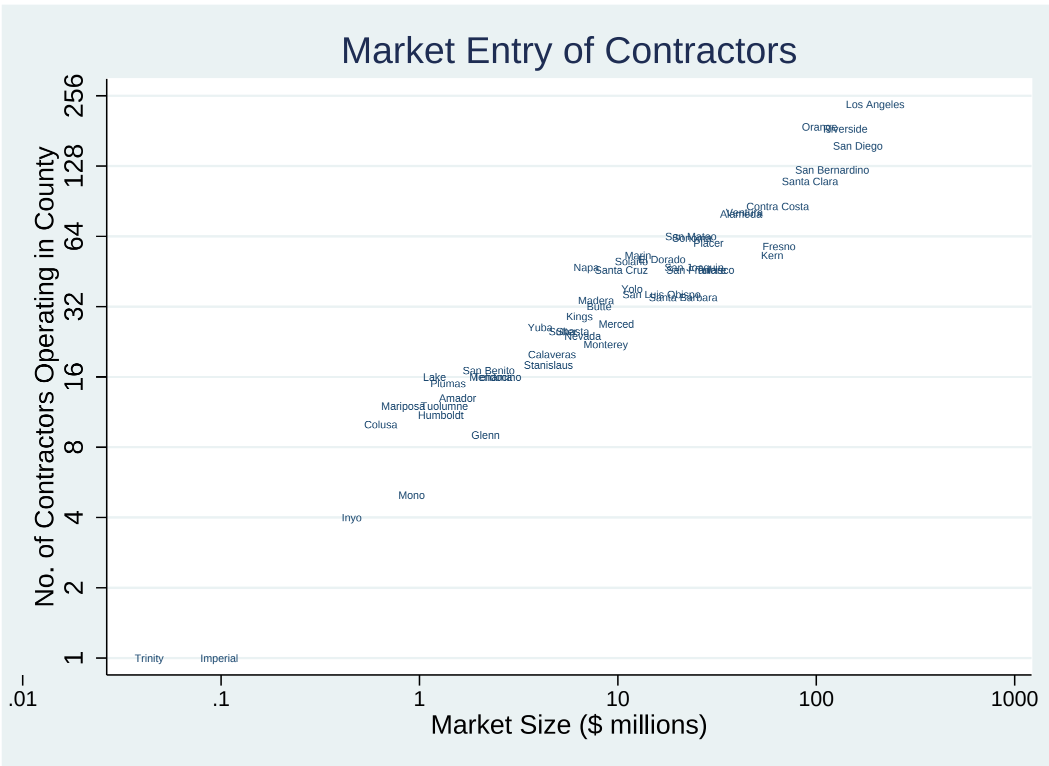


Figure 2: Entry by Market Size.

Notes: Both axes are on log scale. A regression line has a slope of 0.48.

Not only does the number of contractors increase with market size, so does the sales per firm. Figure 3 plots the 50, 75 and 95 percentile sales in each market against the market size. It is clear from the figure that the three percentiles increase with market size.

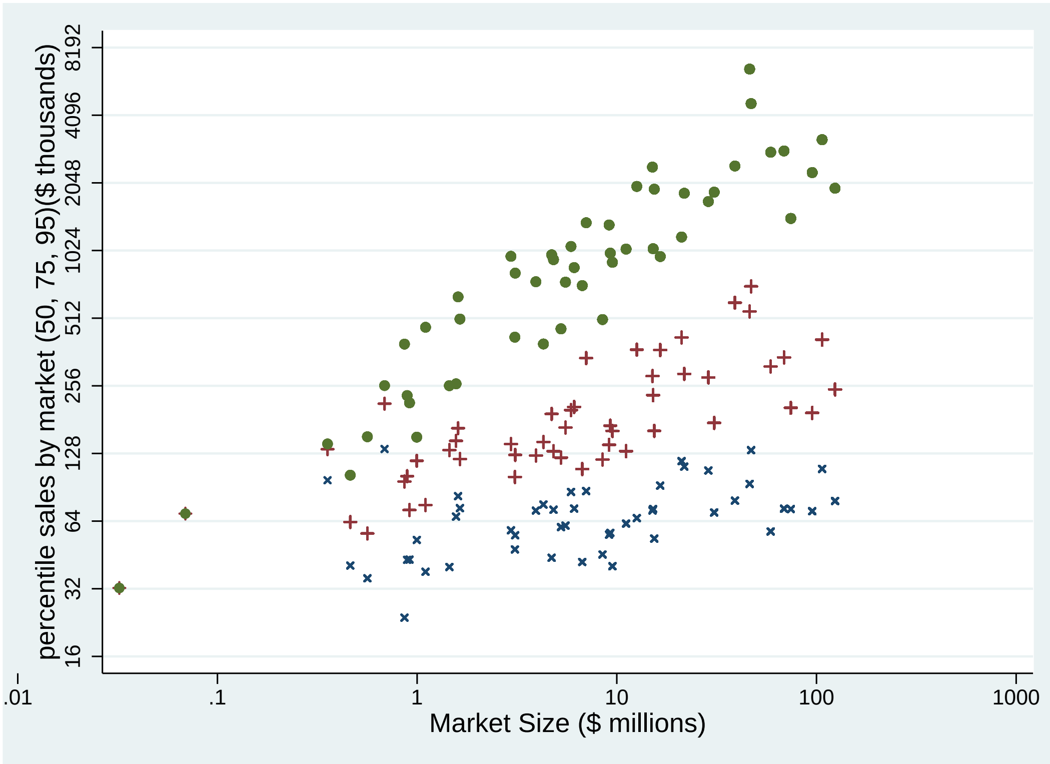


Figure 3: Sales by Market Size.

Notes: The y-axis shows the 50, 75 and 95 percentile sales in each county.

Within each county, the sales distribution of the contractors exhibit a very similar pattern. Figure 4 plots the sales of each contractor, relative to mean sales in the county, against the fraction of firms that sell at least that much in that county. Top four counties (in terms of sales) are shown in the figure. The plots for other counties look very similar. These plots indicate that sales distribution in a county follows a Pareto distribution in the upper tail.[9] The deviation from the Pareto distribution in the lower tail of the distribution is also evident in the graphs, indicating that the number of firms with very small sales is larger than that would be given by the Pareto distribution

[9] See EKK (2010) and Gabaix and Ibragimov (2011) on why data in the figure imply a Pareto distribution for sales.

that characterizes the upper tail.

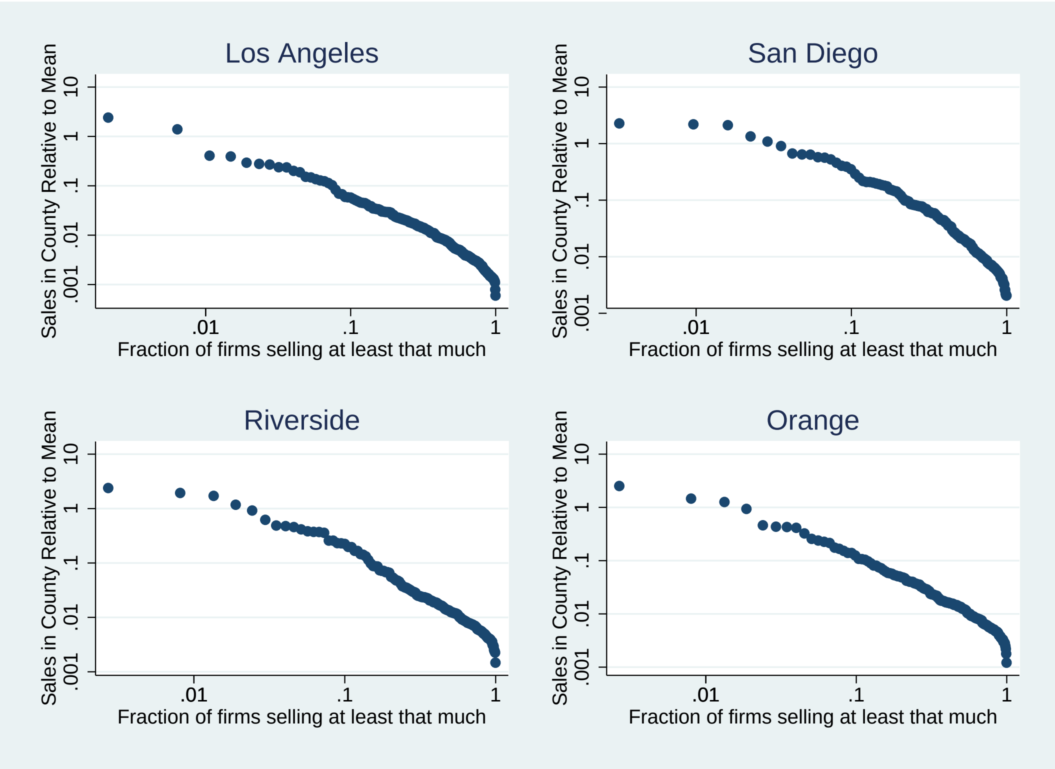


Figure 4: Sales Distribution of Contractors, by county.

Notes: The y-axis is the sales of the firm relative to mean sales in the county. The x-axis is constructed according to the procedure in Gabaix and Ibragimov (2011). The x value for each data point is $\frac{r_{iz}-0.5}{N_i}$, where r_{iz} is the rank of firm z in market i in terms of sales, and N_i is the number of firm that sell in market i.

Finally, Figure 5 shows the distribution of prices charged by contractors in a county. The y-axis in Figure 5 is the ratio of the average price in the county to the price charged by the contractor in the county, and the x-axis is the fraction of contractors for whom the price ratio is at least as much as the corresponding value on the y-axis. Again, the graphs are strikingly similar across counties, and indicate a Pareto in the upper tail of the price ratio distribution and a deviation from the Pareto in the lower end of the distribution.

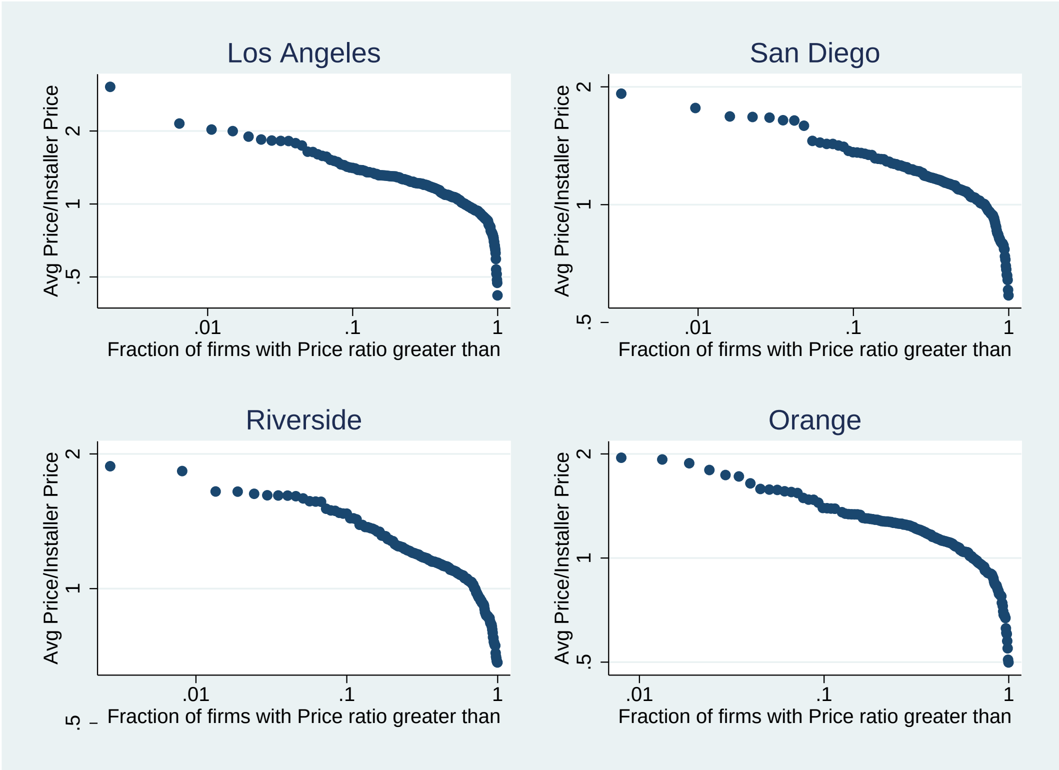


Figure 5: Price Ratio Distributions.

Notes: The y-axis is the ratio of average price in county to the price charged by the contractor. The x axis is constructed in a similar way as in Figure 4.

The next section develops a model that is consistent with the patterns in data described above.

3 The Model

The model is based on Dixit and Stiglitz (1977) model of monopolistic competition. Consumers can obtain electricity either by installing solar equipment in their residences or by purchasing it from utility companies. Since Figure 1 shows that the total expense on solar equipment is a roughly constant fraction of total spending on electricity in each county, the demand side of the market is captured through a representative consumer with Cobb-Douglas utility function, $U(K_i^s, Q_i^e) = \sum_{t=0}^{T-1} \beta^t (h_i K_i^s)^{\alpha} (Q_i^e)^{1-\alpha}$, where β is the discount factor, K_i is the capacity of solar equipment purchased, $h_i K_i$ is the annual electricity that can be produced from K_i units of capacity in market i, and Q_i^e is the total quantity of electricity purchased from utility companies. The *insolation factor* h_i determines the amount of electricity that can be produced from a unit capacity of solar equipment in market i, and depends on the intensity and duration of sunlight in market i.[10] The solar equipment last for T years, hence a purchase of one unit of capacity provides h_i units of electricity to the consumer for the next T years. The consumer faces the market price of $(1-g)P_i^s$ per unit, where g is the percentage subsidy and P_i^s is the producer price in county i. The subsidy for solar equipment is financed through a tax on retail electricity. If electricity is purchased from utilties, the annual purchase of Q_i^e units of electricity involves an expenditure of $(1+\tau)P_i^e Q_i^e$, where τ is the percentage tax. The present discounted value of expenditures on direct electricity purchases for T years is $\sum_{t=0}^{T-1} \frac{1}{(1+r)^t}(1+\tau)P_i^e Q_i^e = R(1+\tau)P_i^e Q_i^e$, where $R = \sum_{t=0}^{T-1} \frac{1}{(1+r)^t}$, and $\frac{1}{1+r}$ is the discount rate. The consumer allocates a total expenditure of M_i between the two choices, where M_i is present discounted value of the annual expenditure on electricity (including expenditure on purchase of solar panels) for T years. Given the Cobb Douglass utility, the consumer allocates a fraction α of the total expenditure to the purchase of solar equipment, i.e.,

$$(1-g)P_i^s K_i^s = \alpha M_i = \frac{\alpha}{1-\alpha} R E_i, \tag{1}$$

where $E_i = (1+\tau)P_i^e Q_i^e$ is the annual expenditure on direct purchase of electricity from utilities, inclusive of taxes. Hence the total revenue to all solar contractors in county i is,

$$X_i = P_i^s K_i^s = \alpha \frac{M_i}{(1-g)} = \frac{\alpha}{1-\alpha} \frac{R E_i}{(1-g)}. \tag{2}$$

The tax τ is set by the government so that the annual payments equal to the tax revenue of $\tau P^e Q^e$ pays of the total government expenditure on subsidy incurred in period zero together with

[10] Sunny places like California will have bigger h_i than less sunny places like Alaska.

interest accrued at the rate r. This implies that the percentage tax set by the government must be equal to, [11]

$$\tau = \frac{\frac{g}{1-g}\frac{\alpha}{1-\alpha}(1+r)}{1 - \frac{g}{1-g}\frac{\alpha}{1-\alpha}(1+r)}. \tag{3}$$

On the production side, each contractor offers a distinct variety of solar equipment and installation service. Contractor z incurs a cost of $\frac{w_i}{z}$ to install a unit in market i, where z is the efficiency.[12] The measure of contractors with efficiency of at least z is given by, $\mu(z) = z^{-\theta}$, $z > 0$ and $\theta > 1$. A market i contains a measure of potential customers. To reach a fraction f of these customers, a contractor must incur a fixed advertising cost,[13]

$$A(f) = a_i \frac{1 - (1-f)^{1-\frac{1}{\lambda}}}{1 - \frac{1}{\lambda}}, \tag{4}$$

where a_i is the market specific component of advertising cost. The parameter $\lambda > 0$ captures the increasing cost of reaching a larger fraction of customers. Each customer in market i has a probability $f_i(z)$ of being reached by contractor z. Customers combine different varieties according to constant elasticity of substitution aggregator with elasticity ρ. This gives the aggregate demand for contractor z in market i as,

$$q_i(z) = f_i(z) X_i \left(\frac{p_i(z)^{-\rho}}{P_i^{1-\rho}} \right) \tag{5}$$

where $p_i(z)$ is the price charged by contractor z and P_i the aggregate price index in market i, derived below. The profit earned by contractor z in market i is then given by,

$$\pi_i(z) = \left(p_i(z) - \frac{w_i(z)}{z} \right) f_i(z) X_i \left(\frac{p_i(z)^{-\rho}}{P_i^{1-\rho}} \right) - A(f_i(z)) \tag{6}$$

[11]For the annual payment $\tau P_i^e Q_i^e$, to pay off an initial amount gP_sK_s with interest at the rate r in T years, it must be that $\tau P_i^e Q_i^e = gP_i^s K_i^s \frac{r(1+r)^T}{(1+r)^T - 1} = gP_i^s K_i^s \frac{1+r}{R}$. But $\tau P_i^e Q_i^e = \frac{\tau}{1+\tau}(1-\alpha)\frac{M}{R}$ and $gP_i^s K_i^s = \frac{g}{1-g}\alpha M$. Together, these give the value of τ obtained above.

[12]This is the total cost incurred by the contractor, and includes the labor cost as well as the cost the solar panels and any associated electrical equipment necessary to set up the solar panels.

[13]Arkolakis (2010) derives the advertising cost function above from assumptions about the decreasing effectiveness of advertisements in reaching customers.

Contractor z maximizes profit by charging the price,

$$p(z) = \frac{\rho}{\rho - 1}\frac{w_i}{z} = \frac{m w_i}{z}. \tag{7}$$

where $m = \dfrac{\rho}{\rho - 1}$ is the Dixit-Stiglitz markup. With this price, the fraction $f_i(z)$ that maximizes profit is,

$$f_i(z) = 1 - \frac{X_i}{a_i \rho}\left(\frac{m}{P_i}\frac{w_i}{z}\right)^{(\rho-1)\lambda} \tag{8}$$

If $f_i(z) < 0$, then it is optimal for contractor z not to enter the market. This implies that there is a cutoff efficiency $\bar{z}_i$ in market i, such that all contractors with efficiency less than $\bar{z}_i$ will decide not to enter the market. The cutoff efficiency is obtained by setting $f_i(z) = 0$ in equation (8),

$$\bar{z}_i = \frac{m w_i}{P_i}\left(\frac{X_i}{a_i \rho}\right)^{\frac{1}{1-\rho}}. \tag{9}$$

The optimal $f_i(z)$ can be written in terms of the cutoff efficiency,

$$f_i(z) = 1 - \left(\frac{\bar{z}_i}{z}\right)^{(\rho-1)\lambda}. \tag{10}$$

Conditional on entering, more efficient firms target larger fractions of the market. Using $f_i(z)$ from equation (10), the price index in market i can be calculated as,

$$P_i = \left(\int_{\bar{z}_i}^{\infty} p_i(z)^{1-\rho} f_i(z)\mu(dz)\right)^{\frac{1}{1-\rho}} = m w_i k_0^{\frac{1}{1-\rho}} \bar{z}_i^{\frac{\theta}{\rho-1}-1}, \tag{11}$$

where

$$k_0 = \frac{1}{1 - \dfrac{\rho - 1}{\theta}} - \frac{1}{1 + \left(\dfrac{\rho - 1}{\theta}\right)(\lambda - 1)} = \frac{1}{1 - \dfrac{1}{\tilde{\theta}}} - \frac{1}{1 + \dfrac{\lambda - 1}{\tilde{\theta}}}. \tag{12}$$

and $\tilde{\theta} = \dfrac{\theta}{\rho - 1}$. Equations (9) and (11) together give P_i and $\bar{z}_i$,

$$P_i = m w_i k_0^{-\frac{1}{\theta}}\left(\frac{X_i}{a_i \rho}\right)^{\left(\frac{1}{\theta} - \frac{1}{\rho-1}\right)} \tag{13}$$

and

$$\bar{z}_i = \left(\frac{1}{k_0}\frac{X_i}{a_i \rho}\right)^{-\frac{1}{\theta}}. \tag{14}$$

Firm sales in market i is,

$$X_i(z) = f_i(z)\left(\frac{p_i(z)}{P_i}\right)^{1-\rho} X_i = \left(1 - \left(\frac{\bar{z}_i}{z}\right)^{(\rho-1)\lambda}\right)\left(\frac{z}{\bar{z}_i}\right)^{\rho-1} a_i\rho. \tag{15}$$

Gross profit of contractor z is $\pi_i(z) = \left(1 - \left(\frac{\bar{z}_i}{z}\right)^{(\rho-1)\lambda}\right)\left(\frac{z}{\bar{z}_i}\right)^{\rho-1} a_i$, which is fraction $\frac{1}{\rho}$ of sales $X_i(z)$, as would be expected for a firm with a constant elasticity demand function. The entry cost for contractor z is,

$$A_i(z) = a_i\frac{1-(1-f_i(z))^{1-\frac{1}{\lambda}}}{1-\frac{1}{\lambda}} = \frac{a_i}{(1-\frac{1}{\lambda})}\left(1 - \left(\frac{\bar{z}_i}{z}\right)^{(\rho-1)(\lambda-1)}\right). \tag{16}$$

The total entry expenses by all firms in market i is,

$$A_i = \int_{\bar{z}_i}^{\infty} A_i(z)\mu(dz) = \frac{\theta-(\rho-1)}{\rho\theta}X_i. \tag{17}$$

Hence the total entry cost as a fraction of total sales is the same across all markets, $\frac{A_i}{X_i} = \frac{\theta-(\rho-1)}{\rho\theta}$, although entry cost as a fraction of sales varies across firms in any given market. Gross profit in market i is given by $\frac{X_i}{\rho}$, and net profit by $\frac{X_i}{m\theta}$. The average price charged by contractors in market i is,

$$\bar{p}_i = \frac{1}{1-\mu(\bar{z})}\int_{\bar{z}_i}^{\infty}\frac{mw_i}{z}\mu(dz) = \frac{\theta}{1+\theta}\frac{mw_i}{\bar{z}_i}. \tag{18}$$

The next section compares the predictions of the model with the empirical regularities documented in section 2.

4 The Model and Empirical Regularities

The model can account for empirical regularities documented in section 2. The measure of firms that enter market corresponds to the actual number of firms in the market. For ease of exposition, define (as in EKK(2010)),

$$u(z) = z^{-\theta} \tag{19}$$

and

$$v_i(z) = \frac{z^{-\theta}}{\bar{z}_i^{-\theta}} = \frac{u(z)}{\bar{u}_i(z)}. \tag{20}$$

where $\bar{u}_i(z) = \bar{z}_i{}^{-\theta}$ can be considered the entry hurdle in market i and $v_i(z)$ as the efficiency of contractor z normalized by the entry hurdle in market i. Since z is distributed Pareto, $v_i(z)$ is distributed uniformly on $[0 \quad 1]$.

4.1 Entry and Average Contractor Sales in a Market

The number of firms that enter market i is,

$$N_i = \bar{z}_i{}^{-\theta} = \frac{X_i}{a_i \rho k_0}. \tag{21}$$

Hence N_i increases with X_i, similar to the relationship seen in Figure 2. The fact that N_i increases systematically with X_i suggests that the cost of advertising a_i increases systematically with market size X_i. The entry cost can be inferred from equation (21),

$$\rho a_i = \frac{1}{k_0}\frac{X_i}{N_i} = \frac{\bar{X}_i}{k_0} \tag{22}$$

using data on average sales in the market, $\bar{X}_i$.

4.2 Sales Distribution in a Market

Using equation (20), equation (15) can be written as,

$$X_i(z) = \left(1 - v_i(z)^{\frac{\lambda}{\tilde{\theta}}}\right) v_i(z)^{-\frac{1}{\tilde{\theta}}} \frac{\bar{X}_i}{k_0}. \tag{23}$$

Since $v_i(z)$ has the same distribution in all markets, the distribution of sales in any market is identical up to the scaling factor $\bar{X}_i$, accounting for the common shapes of the sales distributions seen in Figure 4. If equation (23) did not have the term $\left(1 - v_i(z)^{\frac{\lambda}{\theta}}\right)$, then sales distribution would be Pareto with parameter $\frac{\theta}{\rho-1}$. The term $\left(1 - v_i(z)^{\frac{\lambda}{\theta}}\right)$ gives a downward deviation from the Pareto distribution, especially at the values of $v_i(z)$ close to 1, consistent with the downward deviations seen in Figure 4.

4.3 Price Distribution in a Market

Using equation (7), the ratio of average price in market i to the price charged by contractor z is,

$$\frac{\bar{p}_i}{p_i(z)} = \frac{\theta}{1+\theta}\frac{z}{\bar{z}_i} = \frac{\theta}{1+\theta} v_i(z)^{-\frac{1}{\theta}} \tag{24}$$

Hence $\frac{\bar{p}_i}{p_i(z)}$ is distributed Pareto with parameter θ. Note that while the model accounts for the Pareto distribution at lower values of $\frac{\bar{p}_i}{p_i(z)}$, a limitation is that it does not account for the deviation from Pareto at higher values of $\frac{\bar{p}_i}{p_i(z)}$.

The next section develops a procedure to estimate the model parameters from the data.

5 Estimation

There are three parameters in the model, $\{\theta, \lambda, \rho\}$. The parameters $\{\tilde{\theta}, \lambda\}$, where $\tilde{\theta} = \frac{\theta}{\rho - 1}$, are estimated using the data on contractor sales. The parameter θ is estimated from the data on prices, and ρ is backed out from the estimates of $\tilde{\theta}$ and θ.

The estimates for $\{\tilde{\theta}, \lambda\}$ are obtained using the simulated method of moments approach, as laid out in EKK (2010). Given a value of $(\tilde{\theta}, \lambda)$, a set of artificial contractors who operate according to the model is constructed as follows. Let s denote each artificial contractor, and S the number of such contractors. A set of S realizations of $v(s)$ is taken independently from the uniform distribution $[0 \quad 1]$. A set of entry hurdles into each market $\{\bar{u}_i\}$ is created with the data on N_i, using $\bar{u}_i = N_i$ from equation (20). The largest of these entry hurdles, $\bar{\bar{u}} = Max\ \{\bar{u}\}$, is the minimum u that is consistent with selling in at least one market. For each contractor s that sells in at least one market, $u(s)$ should be a realization from the uniform distribution $[0 \quad \bar{\bar{u}}]$. Hence $\{u(s)\}$ is generated as,

$$u(s) = v(s)\bar{\bar{u}} \tag{25}$$

Contractor s enters market i if $u(s) < \bar{u}_i$. If s enters market i, then sales in market i is calculated as,

$$X_i(s) = \left(1 - v(s)^{\frac{\lambda}{\bar{\tilde{\theta}}}}\right) v(s)^{-\frac{1}{\tilde{\theta}}} \frac{\bar{X}_i}{k_0}. \tag{26}$$

where the value of k_0 is calculated for $(\tilde{\theta}, \lambda)$ using equation (12). Hence for each contractor s, the procedure gives the set of markets that the contractor sells in, and the sales in each market. Using these expressions, one can match moments constructed from the actual contractor data in California. The moments used for matching, as in EKK (2010), are the number of firms that belong to a set of categories connected to the shape of the sales distributions seen in Figure 4. For each market i, the sales of the 50, 75 and 95 percentile firms are calculated from the data. The number of simulated contractors in each of the four categories, $\{0-50, 50-75, 75-95$ and $95-100\}$, percentiles form the set of simulated moments, $\hat{m}(\tilde{\theta}, \lambda)$. Corresponding to these simulated moments are the actual moments, $m = (0.5, 0.25, 0.2, 0.05)$. These moments together give a $(204, 1)$ vector of differences between the actual and simulated data, $y(\tilde{\theta}, \lambda) = m - \hat{m}(\tilde{\theta}, \lambda)$.[14] The estimation procedure is based on the moment condition,

$$E[y(\tilde{\theta}_0, \lambda_0)] = 0$$

where $\{\tilde{\theta}_0, \lambda_0\}$ is the true value of $\{\tilde{\theta}, \lambda\}$. The estimation procedure solves for $(\hat{\tilde{\theta}}, \hat{\lambda})$ that satisfies,

$$(\hat{\tilde{\theta}}, \hat{\lambda}) = arg \min_{(\tilde{\theta}, \lambda)} \{y(\tilde{\theta}, \lambda)' W y(\tilde{\theta}, \lambda)\},$$

where W is a weighting matrix.[15] The optimal Θ is found using the $globalsearch$ routine in Matlab.

[14]There are 4 moments for 51 counties, giving a total of 204 moments.

[15]The weighting matrix used is the generalized inverse of the estimate of the variance-covariance matrix of the moments calculated from the data, obtained according to the bootstrap procedure used in EKK (2010). Random samples of 900 contractors were drawn independently from the set of 1014 contractors, 2000 times. Each time, the

The procedure above gives only the value of $\tilde{\theta}$. To obtain θ and ρ separately, the value of θ is estimated from the data on prices, using the regression suggested in (Gabaix and Ibragimov (2011)). The regression equation is,

$$\ln \frac{\bar{p}_i}{p_i(z)} = -\frac{1}{\theta} \ln r_{iz} + F_i + \epsilon_{iz}, \tag{27}$$

where r_{iz} is the rank of contractor z in county i less 0.5, and F_i is the county fixed effect.[16] Table 1 shows the results.

Table 1: Parameter Estimates

$\tilde{\theta}$	λ	$\frac{1}{\theta}$
1.25	1.00	0.214
(0.02)	(0.02)	(0.002)

The estimates in Table 1 together give, $\theta = 4.67$, $\rho = 4.73$ and $\lambda = 1.00$.

5.1 Model Fit

To gauge the fit of the model with data, the model is simulated for 1014 firms. Using the parameter estimates from Section 5, the set of entry cost parameters $\{a_i\}$ is backed out using equation (22) and the set of variable cost parameters $\{w_i\}$ is backed out using equation (18). The parameter estimates (θ, λ, ρ) and the set of entry and variable cost parameters, $\{a_i\}$ and $\{w_i\}$, are all that is needed to simulate the model. Figure 6 plots the 50 and 95 percentile sales in all markets, obtained in the simulation, against the average sales in that market. In the model, the relationship between the percentile sales and average sales is given by equation (23). As can be seen, the model captures

fraction of firms that fall into each of the four categories above, m^b, were calculated. The variance-covariance matrix was calculated as $\frac{1}{2000}\sum_{b=1}^{2000}(m^b - m)(m^b - m)'$. The matrix is not invertible, because of adding up constraints, and hence the generalized inverse of the variance-covariance matrix is taken as the weighting matrix, W.

[16]The rank is calculated for the ratio $\frac{\bar{p}_i}{p_i(z)}$, and the correction of 0.5 is as suggested in Gabaix and Ibragimov (2011).

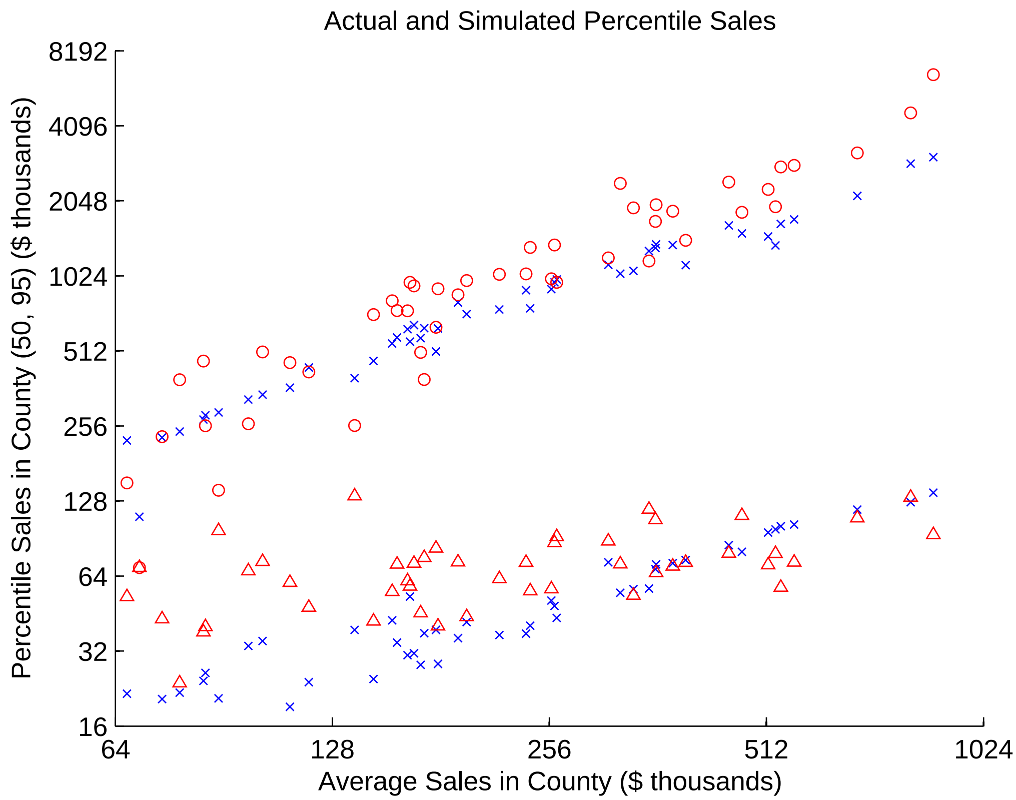


Figure 6: Simulated and Actual Sales Percentiles.

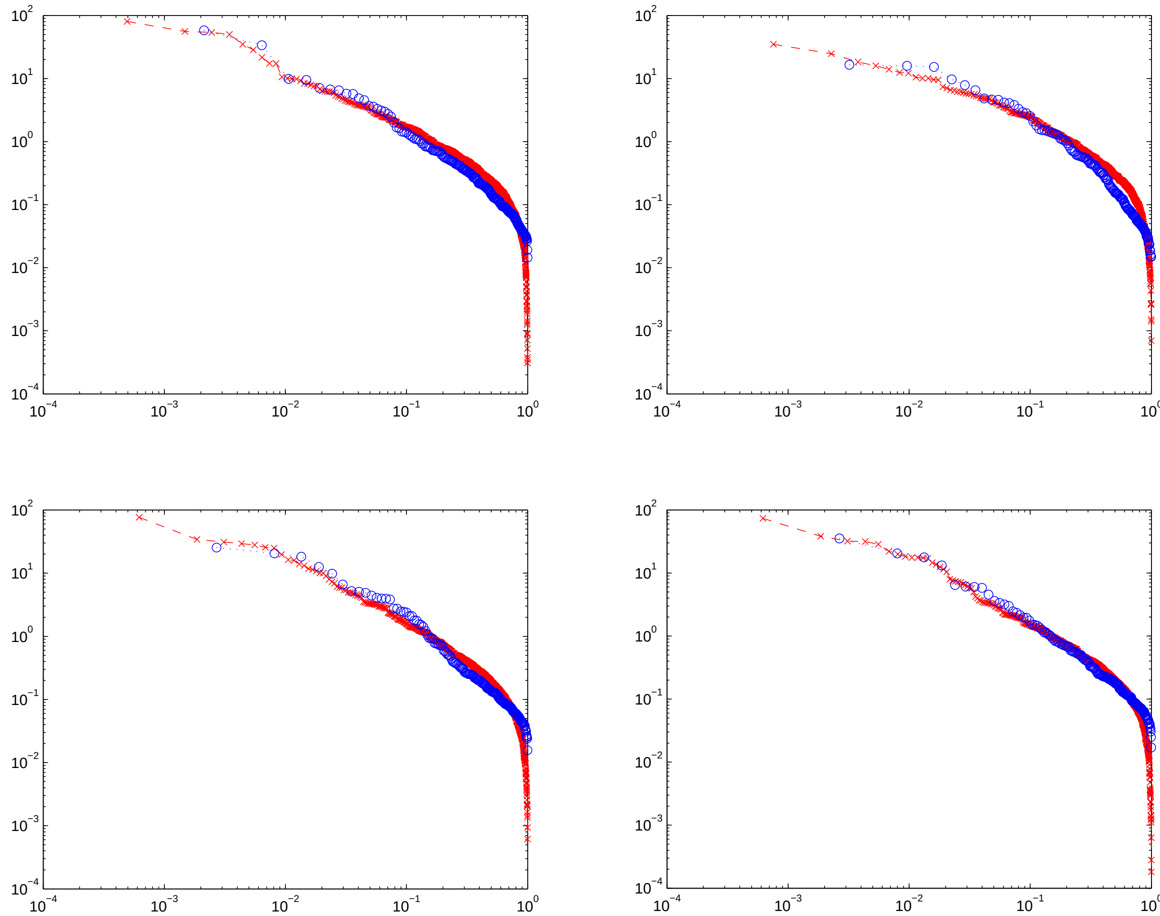
Notes: The triangles and circle show the 50 and 95 percentile sales respectively in a market in the data, and the xs show the corresponding percentile sales predicted by the model.

the trends in each percentile sale with the average sales, as well as the distance between the two percentile sales. Figure 7 shows the actual and fitted sales distributions in the four biggest counties.

5.1.1 Advertising Expenditures

The parameter estimate of $\lambda = 1$ indicates that advertising expenditures are very small for a firm close to cutoff. The estimates are consistent with values found in other papers, Arkolakis (2010)

Figure 7: Sales distribution in a county - Actual and Fitted



Notes: The actual and fitted sales distributions in four counties are shown - Los Angeles, San Diego, Riverside and Orange.

finds a value of 1 and EKK (2010) find a value of 0.92. Although the fraction of revenue spend on advertising varies across firms in a county, the total advertising expenditures in a county is a constant fraction of the sales in that county, which the parameter estimates give to be 4.26 %. In a survey of 15 contractors in the U.S, Ardani, Barbose, Margolis, Wiser, Feldman and Ong (2012) find that the advertising and marketing costs is 5% of revenue in 2010, close to the 4.26% that the parameter estimates indicate.[17]

The next section utilizes the calibrated model to simulate the impact of the federal consumer subsidy on welfare and solar penetration.

6 Solar Penetration : Cost Reduction Equivalent of a Subsidy

A frequently debated policy question in the solar industry is the efficacy of demand side subsides compared to R&D subsides to reduce cost, in increasing the adoption of solar panels. While the relationship between R&D investment and cost of production of solar panels is beyond the scope of this paper, the results here can be used to throw light on the cost reduction necessary to obtain the solar penetration that results from a given demand side subsidy. A measure of solar penetration in county i is the fraction of total electricity consumption in the county that was generated using solar equipment. From the optimal decision of the consumer,

$$\frac{h_i K_i^s}{Q_i^e} = \frac{\alpha}{1-\alpha} \frac{(1+\tau) R P_i^e}{(1-g)\frac{P_i^s}{h_i}}.$$

Hence solar penetration, denoted by SP, is

$$SP = \frac{h_i K_i^s}{h_i K_i^s + Q_i^e} = \frac{\alpha R (1+\tau) P_i^e}{(1-\alpha)(1-g)\dfrac{P_i^s}{h_i} + \alpha R (1+\tau) P_i^e}. \tag{28}$$

[17]Friedman et al. (2013) also conducted a similar survey in 2012, but they do not report advertising and marketing costs separately. They report a number that includes expenses on items like contract negotiations, site visits, document preparation etc, which are not entry costs as captured in the model. The number they report is 7.6%, and the actual marketing and advertising costs is lower than this value.

Equation (28) can be rewritten to get the value of solar system price, P_i^s, needed to achieve penetration level SP,

$$P_i^s = h_i \frac{1-SP}{SP} \frac{\alpha}{1-\alpha} \frac{R(1+\tau)P_i^e}{1-g} \tag{29}$$

Using P_i^s from equation (13), the cost w_i needed to achieve a solar penetration of SP can be calculated. For solar penetration to change from SP to $\hat{SP}$ when subsidy changes from g to $\hat{g}$, the cost of solar equipment has to change by a factor,

$$\frac{\hat{w}_i}{w_i} = \frac{\frac{1-\hat{SP}}{\hat{SP}}}{\frac{1-SP}{SP}} \left(\frac{1+\hat{\tau}}{1+\tau}\right) \left(\frac{1-g}{1-\hat{g}}\right)^{\phi}. \tag{30}$$

where $\phi = 1 - \frac{1}{\theta} + \frac{1}{\rho-1}$ is greater than one. It is intuitive that at higher subsidy level smaller cost reductions are enough to achieve given penetration levels, and equation (30) gives the relationship between these three variable taking account of the impact of efficiency differences among contractors. The higher subsidy also causes the tax on purchase of retail electricity to be high, thus further augmenting the impact of the subsidy on required cost reduction. Figure 8 shows the relationship in equation (30) at two levels of penetration, $SP = 0.003$ and $SP = 0.015$ (i.e 0.3% and 1.5% penetration levels), with the x-axis being $(1-g)$, i.e the fraction of total cost paid by the consumer.

Figure 8 can be used to obtain the reduction in cost that would have resulted in the same solar penetration in 2012 without the federal subsidy of 30% and state equivalent subsidy of 8%, that was available in 2012. The total subsidy amount paid by the state government in 2012 was approximately 8% of the total price paid for all the residential solar installations in the state.[18] Hence the state subsidy is approximated as an 8% subsidy, and the two are combined together as a 38% subsidy. The counterfactual of no federal subsidy is simulated as reduction in the available subsidy from 38% to none. The average solar penetration ratio across the counties in CA was 0.3%. As can be seen from Figure 8, if the subsidy was reduced from of 38% to none, the cost ratio has to reduce to 60% (i.e a reduction of 40%) of its 2012 value to reach the 2012 solar penetration level of 0.3%. If the solar penetration level is to be 1.5%, then cost would have to fall to 20% of

[18] This is obtained by dividing the total incentives paid to residential installations under the California Solar Initiative programs by the total sales of solar equipment that received the subsidy.

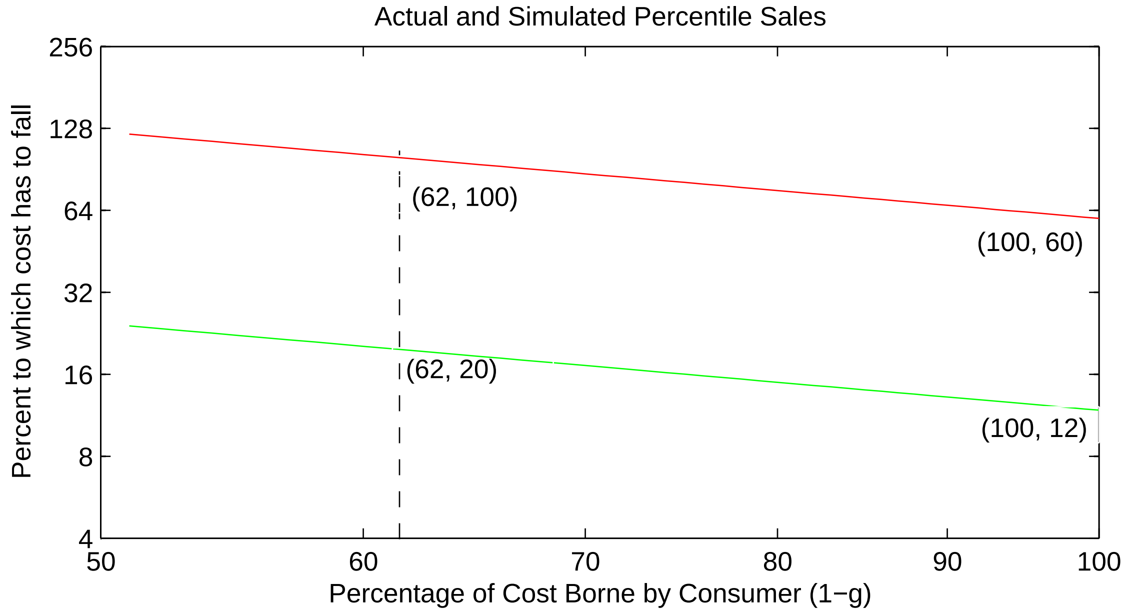


Figure 8: Cost Reduction with Equivalent Effect of Subsidy on Solar Penetration.

Notes: The above graphs shows the cost reduction necessary to achieve 0.3% *and* 01.5% *solar penetration at different levels of the consumer subsidy. Both axes are on log scale. The slope of the graph is given by* $\phi = 1 - \frac{1}{\theta} + \frac{1}{\rho - 1}$.

its 2012 value (i.e a reduction of 80%) with a subsidy of 38%. If the 1.5 % penetration was to be achieved without the federal subsidy, then the cost should fall to 12% (i.e an 88% reduction) of its 2012 value.

7 Welfare Impact of Subsidy

This section derives analytical expressions for changes in welfare that will result under counterfactual scenarios. Let $\hat{x}$ denote the value in the counterfactual scenario of model variable x. The change in consumer surplus under a counterfactual scenario is taken to be the equivalent variation, which is the change in the total electricity expenditure (M_i) required so that the consumer can attain the same level of utility in the baseline scenario as in the counterfactual, with prices that prevail under the counterfactual. The consumer's optimal allocation decision is (see equation 2),

$$K_i^s = \frac{\alpha M_i}{(1-g)P_i^s}, \qquad Q_i^e = \frac{(1-\alpha)M_i}{R(1+\tau)P_i^e}.$$

Using this, the equivalent variation, EV_i between the baseline scenario (P_i^s, P_i^e, g), and the counterfactual scenario $(\hat{P}_i^s, \hat{P}_i^e, \hat{g})$ can be shown to be,[19]

$$EV_i = \left(\left(\frac{(1-g)P_i^s}{(1-\hat{g})\hat{P}_i^s} \right)^{\alpha} \left(\frac{(1+\tau)P_i^e}{(1+\hat{\tau})\hat{P}_i^e} \right)^{1-\alpha} - 1 \right) \frac{RE_i}{1-\alpha}, \tag{31}$$

where τ and $\hat{\tau}$ satisfy equation (3). Hence the consumer surplus under a scenario $(\hat{P}_i^s, \hat{P}_i^e, \hat{g})$ is,

$$CS(\hat{P}_i^s, \hat{P}_i^e, \hat{g}) = CS(P_i^s, P_i^e, g) + \left(\left(\frac{(1-g)P_i^s}{(1-\hat{g})\hat{P}_i^s} \right)^{\alpha} \left(\frac{(1+\tau)P_i^e}{(1+\hat{\tau})\hat{P}_i^e} \right)^{1-\alpha} - 1 \right) \frac{RE_i}{1-\alpha} \tag{32}$$

The producer surplus, which is the total net profits earned by all firms in county i is,

$$PS_i(\hat{g}) = \frac{X_i}{m\theta} = \frac{1}{m\theta} \frac{\alpha}{1-\alpha} \frac{RE_i}{(1-\hat{g})}. \tag{33}$$

The total surplus under a counterfactual scenario is the sum of consumer surplus and producer surplus, as given in equations (32) and (33).

[19] To see this, note that the indirect utility function is,

$$V(P_i^s, P_i^e, g, M_i) = B \left(\frac{1}{(1-g)\frac{P_i^s}{h_i}} \right)^{\alpha} \left(\frac{1}{R(1+\tau)P_i^e} \right)^{1-\alpha} M_i.$$

where $B = \alpha^{\alpha}(1-\alpha)^{1-\alpha} \sum_{t=0}^{T} \beta^t$, and β is the discount factor for utility. The expenditure needed to obtain the same level of utility $V(\hat{P}_i^s, \hat{P}_i^e, \hat{g}, M_i)$ obtained under the counterfactual scenario $(\hat{P}_i^s, \hat{P}_i^e, \hat{g})$ is

$$\hat{M}_i = \frac{1}{B} \left((1-g)\frac{P_i^s}{h_i} \right)^{\alpha} (R(1+\tau)P_i^e)^{1-\alpha} V(\hat{P}_i^s, \hat{P}_i^e, \hat{g}, M_i).$$

The equivalent variation is $EV_i = \hat{M}_i - M_i$. Substituting the expression for V_i, and using $M_i = \frac{RE_i}{1-\alpha}$, gives the expression for equivalent variation in equation (31).

7.1 Welfare Impact of Subsidy

This section uses the model to investigate the welfare impact if the capital subsidy for solar equipment had been absent in 2012 in the California solar market. As discussed earlier, the California state government provided an additional per unit subsidy, which amounted to 8% of the total solar sales that year. Hence, $g = 0.38$ and $\hat{g} = 0.0$ captures the effect of removing both the federal and state subsidy. The tax τ needed to support the $g = 0.38$ subsidy is given by equation (3) to be $\tau = 0.19\%$. The change in consumer surplus, producer surplus and total surplus if the subsidy had been absent can be calculated using equations (31) and (33). The results are shown in Table 2. Total solar sales across all the counties in California would have been lower by $ 366 million. Consumer surplus would have been higher by $77 million and producer surplus would have been lower by $59 million. Thus, in the absence of subsidy total surplus would have been higher by $ 18 million, which is the net welfare loss from the subsidy.

8 Conclusion

There has been numerous government policies that have been enacted in the last few decades to support the growth of renewable energy industries. The availability of firm level data in these industries opens up the possibility of being able to evaluate the impact of these policies using models that take account of market structure and firm heterogeneity. Using a model that accounts for regularities seen in the data on residential solar installations in California, this paper finds that without the federal and state subsidy substantial cost reductions would have been needed to achieve the solar penetration levels achieved in the presence of the subsidy.

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Table 2: IMPACT OF REMOVAL OF FEDERAL AND STATE SUBSIDY

County	Sales		ΔCS	ΔPS	ΔTS
	X_i	$\hat{X}_i$			
Los Angeles	123.88	76.81	17.18	-13.25	3.93
San Diego	106.74	66.18	6.60	-5.09	1.51
Riverside	95.21	59.03	5.75	-4.43	1.32
Orange	74.37	46.11	6.93	-5.34	1.59
San Bernardino	68.79	42.65	4.09	-3.16	0.94
Santa Clara	58.98	36.57	3.51	-2.71	0.80
Fresno	47.06	29.17	2.27	-1.75	0.52
Kern	46.25	28.68	1.93	-1.49	0.44
Contra Costa	39.03	24.20	2.69	-2.07	0.62
Ventura	30.75	19.06	1.83	-1.41	0.42
Alameda	28.74	17.82	2.67	-2.06	0.61
Tulare	21.78	13.50	0.99	-0.76	0.23
Placer	21.11	13.09	1.24	-0.95	0.28
Sonoma	16.51	10.23	1.28	-0.98	0.29
San Francisco	15.41	9.55	1.37	-1.05	0.31
San Mateo	15.21	9.43	1.56	-1.20	0.36
San Joaquin	15.09	9.36	1.51	-1.17	0.35
Santa Barbara	12.60	7.81	0.81	-0.62	0.18
El Dorado	11.13	6.90	0.69	-0.53	0.16
Marin	9.51	5.89	0.59	-0.45	0.13
San Luis Obispo	9.28	5.75	0.63	-0.49	0.14
Yolo	9.15	5.67	0.44	-0.34	0.10
Solano	8.48	5.26	0.89	-0.68	0.20
Monterey	7.11	4.41	0.70	-0.54	0.16
Merced	7.03	4.36	0.56	-0.44	0.13
Santa Cruz	6.72	4.16	0.60	-0.46	0.14
Butte	6.12	3.79	0.61	-0.47	0.14
Madera	5.53	3.43	0.35	-0.27	0.08
Napa	5.26	3.26	0.37	-0.29	0.09
Kings	4.82	2.99	0.32	-0.25	0.07
Nevada	4.72	2.93	0.36	-0.28	0.08
Shasta	4.29	2.66	0.62	-0.48	0.14
Sutter	3.94	2.44	0.24	-0.19	0.06
Calaveras	3.10	1.92	0.17	-0.13	0.04
Yuba	3.09	1.91	0.18	-0.14	0.04
Stanislaus	2.95	1.83	1.58	-1.22	0.36
Tehama	1.64	1.02	0.19	-0.15	0.04
Glenn	1.60	0.99	0.08	-0.06	0.02
Mendocino	1.57	0.97	0.33	-0.25	0.07
San Benito	1.45	0.90	0.11	-0.08	0.02
Amador	1.10	0.68	0.12	-0.09	0.03
Plumas	1.00	0.62	0.15	-0.12	0.03
Lake	0.92	0.57	0.23	-0.18	0.05
Tuolumne	0.89	0.55	0.17	-0.13	0.04
Humboldt	0.86	0.54	0.43	-0.33	0.10
Mono	0.69	0.43	0.08	-0.06	0.02
Mariposa	0.56	0.35	0.06	-0.04	0.01
Colusa	0.46	0.29	0.06	-0.04	0.01
Inyo	0.36	0.22	0.03	-0.03	0.01
Imperial	0.07	0.04	0.35	-0.27	0.08
Trinity	0.03	0.02	0.01	-0.01	0.00
Total	962.94	597.00	76.47	-58.97	17.51