Pass-Through as a Test for Market Power: An Application to Solar Subsidies

Online Appendix

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A Theory and Proofs

A.1 Pass-Through in the Presence of Market Power

We provide the equation for pass-through under monopoly in Equation 2 of the main text. Drawing directly from Weyl and Fabinger (2013), we derive this equation here by considering the monopolist's optimization problem and solving for the pass-through rate ρ, or the rate at which the price, p, changes with marginal cost, mc. The monopolist's revenues are $p(q)q$ with marginal revenue $mr(q) = p(q) + p'(q)q$ and marginal cost $mc(q) = c'(q)$. The monopolist maximizes profits by choosing quantity such that $mr(q) = mc(q) + t$, where t is a per-unit tax on producers. Thus,

$$\begin{aligned} mr'\frac{dq}{dt} = mc'\frac{dq}{dt} + 1 \Rightarrow \frac{dq}{dt} &= \frac{1}{mr' - mc'} \\ \Rightarrow \rho = \frac{dp}{dt} = p'\frac{dq}{dt} &= \frac{p'}{mr' - mc'}. \end{aligned} \tag{A.1}$$

Marginal revenue, $mr = p + p'q$, is made up of two terms, the price p and the negative of the marginal consumer surplus $ms = -p'q$, which is what consumers earn when quantity expands. As such, we can write

$$\rho = \frac{1}{\frac{p' - ms'}{p'} - \frac{mc'}{p'}} = \frac{1}{1 + \frac{\varepsilon_D}{\varepsilon_{ms}}\frac{ms}{p} + \frac{\varepsilon_D}{\varepsilon_S}\frac{mc}{p}}, \tag{A.2}$$

where $\varepsilon_D \equiv -D'p/q$ is the elasticity of demand, $\varepsilon_S \equiv S'p/q$ is elasticity of supply, and the elasticity of the inverse marginal surplus function is $\varepsilon_{ms} = ms/(ms'q)$. We can further simplify the pass-through equation using

$$\frac{ms}{p} = -\frac{p'q}{p} = \frac{1}{\varepsilon_D} \tag{A.3}$$

and Lerner's (1934) rule

$$\frac{p - mc}{p} = \frac{1}{\varepsilon_D} \Rightarrow \frac{mc}{p} = \frac{\varepsilon_D - 1}{\varepsilon_D} \tag{A.4}$$

to yield

$$\rho = \frac{1}{1 + \frac{\varepsilon_D - 1}{\varepsilon_S} + \frac{1}{\varepsilon_{ms}}}. \tag{A.5}$$

As discussed in the main text of the paper, there are two key differences between pass-through under perfect and imperfect competition. First, $\varepsilon_D - 1$ has replaced ε_D. Second, more importantly, there is the new term containing the inverse elasticity of marginal surplus, ε_{ms}, which measures the curvature of (the logarithm of) demand. In other words, pass-through under imperfect competition is not just determined by the elasticity of supply and demand but also the curvature of demand.

As Weyl and Fabinger (2013) discuss more extensively, the inverse elasticity of marginal surplus, ε_{ms}, measures the curvature of the logarithm of demand. Recall $ms = -p'q$ and $D \equiv D(p)$, so $D' = dD/dp = dq/dp$, and thus

$$(logD)' = \frac{D'}{D} = \frac{\frac{dq}{dp}}{q} = \frac{1}{\frac{dp}{dq}q} = \frac{1}{p'q} = -\frac{1}{ms} \tag{A.6}$$

and

$$(logD)'' = \frac{ms'}{ms^2}\frac{1}{p'} = -\frac{1}{\varepsilon_{ms}}\frac{1}{ms}\left(-\frac{1}{p'q}\right) = -\frac{1}{\varepsilon_{ms}}\frac{1}{ms^2}. \tag{A.7}$$

Hence, demand is log-concave when $1/\varepsilon_{ms} > 0$ and log-convex when $1/\varepsilon_{ms} < 0$. Another threshold of interest is that $1/\varepsilon_{ms} > 1$ for concave demand and $1/\varepsilon_{ms} < 1$ for convex demand. This is because the inverse elasticity of marginal surplus is

$$\frac{1}{\varepsilon_{ms}} = \frac{ms'q}{ms} = \frac{(p''q + p')q}{p'q} = 1 + \frac{p''q}{p'} \tag{A.8}$$

and given that $q > 0 > p'$, the second term $p''q/p'$ is positive if $p'' < 0$ and $1/\varepsilon_{ms} > 1$, and vice versa.

One can follow similar steps to derive pass-through for the more general case of symmetric, imperfect competition, which Weyl and Fabinger (2013) show is

$$\rho = \frac{1}{1 + \frac{\theta}{\varepsilon_\theta} + \frac{\varepsilon_D - \theta}{\varepsilon_S} + \frac{\theta}{\varepsilon_{ms}}}, \tag{A.9}$$

where θ is a conduct parameter between zero for perfect competition and one for a pure monopoly. Analogous to the case of the monopoly with constant marginal costs (infinite ε_S), pass-through exceeds unity if and only if ε_{ms} is negative since $1/\varepsilon_\theta = 0$ for many standard models of imperfect competition, such as Cournot.

A.2 Second Order and Stability Conditions

We primarily focus on the threshold for pass-through over-shifting to occur. For completeness, we note that one may also wish to check the range of ε_{ms} values against the second order and stability conditions for the firm's profit maximization problem to ensure consistency with stable symmetric market equilibrium. The second order condition states that the second derivative of the profit function is non-positive. Stability implies that equilibrium is restored when disturbing an initial equilibrium by changing each firm's output by any specified amount δ.

Seade (1985) derives these conditions. In our notation, the second order condition under symmetry can be written as

$$\varepsilon_{ms} < \frac{1}{1-2n}, \tag{A.10}$$

where n is the number of firms in the market. The stability condition that is necessary and sufficient under symmetry can be written as

$$\varepsilon_{ms} < -\frac{1}{n}. \tag{A.11}$$

This implies that a stable equilibrium requires stricter conditions than $\varepsilon_{ms} < 0$ on the range of prices over which over-shifting occurs.

B Data

B.1 Additional Details on Data Preparation

B.1.1 Data for the Pass-Through Regressions

The CSI dataset that we start with is the public "working dataset" file posted on the CSI website on June 24, 2015.[1] We took a few other steps to prepare the data in addition to what we describe in Section 3. First, through the National Renewable Energy Laboratory (NREL), we obtained a non-disclosure agreement with the California Public Utilities Commission to gain access to and transcribe detailed terms from a proprietary dataset of residential third-party solar contracts in California. Obtaining usable price data from these required our manual transcription because they lacked consistency across contract type and company, and they were often hand-written. As such, we stratified the data by quarter and drew a random sample of 200 observations per quarter of all residential TPO projects with a CSI completion date. Not all contracts that we sampled contained enough data to construct a net present cost (NPC), leaving us with 1,346 contracts in total with usable data.

We impose a number of sample selection rules on the full dataset. We drop a small number of observations that are most likely data errors. These include two systems with prices above \$20/watt and seven systems with prices below \$0.50/watt. Next, we limit the data to installations with status listed as "installed" or "pending" because if "cancelled" the recorded contract terms likely do not reflect market conditions. We also drop 13 systems for which the listed incentive amount exceeds the total reported system cost, which is infeasible and thus data entry error.

[1] The CSI data are available online at https://www.californiasolarstatistics.ca.gov/data_downloads/

We keep only residential systems and those who participate in the Expected Performance Based Buydown (EPBB) program, which was the upfront lump-sum rebate option offered by CSI. While residential customers could use a Performance Based Incentive (PBI) instead, more than 99% of residential consumers opted for EPBB. We also drop observations filed under the Multifamily Affordable Solar Housing (MASH) program as decision-making for multi-family housing is fundamentally different from individual households. Another non-representative class of contracts that we drop is those with "GRID Alternatives", a nonprofit that brings together community partners, volunteers, and installers to implement projects for low-income families.

We restrict our dataset to systems up to 10 kilowatts, as larger systems are highly unlikely to have a residential-only purpose. Almost all residential solar electric systems require between 50 square feet and 1,000 square feet, and a general rule that is often applied is that 100 square feet of solar panels will generate 1 kilowatt of electricity (Hois 2016). For systems above 10 kilowatts, there is a high risk of data errors and confusion with small commercial systems, which are outside the scope of the market we are interested in studying.

We reduce dimensionality in the installer fixed effects by grouping together firms with few installations. The smallest firms that together install 5% of solar systems are combined into one category. We apply the same rule for manufacturer and module model fixed effects.

We extend the dataset by merging in demographics at the census tract level using demographics from the American Community Survey. For that purpose, researchers at NREL geocoded the CSI data with latitudes and longitudes from address locations. We merged this with the post-incentive price data as well as the CSI data.

Finally, we end our sample at the end of June 2013. At that time, the CSI program was nearly exhausted. While Southern California Edison (SCE) and San Diego Gas & Electric (SDG&E) territories still provided CSI rebates at the lowest level, Pacific Gas & Electric (PG&E) ran out of CSI funding at the end of April 2013.

B.1.2 Data for the Demand Regressions

The dataset we use for the demand regressions is similar to that for the pass-through regressions, but we modify it in a number of important ways.

First, we need to include *all* TPO installations in order to capture TPO demand, not just those whose contracts we transcribed. Second, as the CSI applied to the three IOUs but not municipal utilities, we need to treat zip codes with partial IOU-coverage carefully. To that end, we obtained information on all California zip codes serviced by one of the three IOUs as well as zip codes covered by California's municipal and other utilities, which were not eligible for the CSI.[2] We then drop

[2]For PG&E, see https://www.pge.com/tariffs/tm2/pdf/ELEC_MAPS_Service_Area_Map.pdfandwww.pge.com/tariffs/RESZIPS.XLS. For SCE, https://www.sce.com/wps/wcm/connect/690b717f-8c57-469b-a87a-ad02decbf9d0/MasterZipCode_DiscBulbs.pdf?MOD=AJPERES. For SDG&E, see https://energydata.sdge.com/. For LADWP, see https://data.lacity.org/A-Livable-and-Sustainable-City/LADWP-Power-use-by-zipcode-GOVSTAT-/a752-uami/data. For other non-IOU zip codes, see https://catalog.data.gov/dataset/u-s-electric-utility-companies-and-rates-look-up-by-zipcode-feb-2011-57a7c.

zip codes that are not serviced by one of the three IOUs or serviced in part by an IOU and in part by a municipal utility.

Finally, we applied a few more detailed sample selection rules. We manually went through all zip codes and dropped 13 zip codes that are not flagged as partially outside IOU territory, but a detailed service area map from the California Energy Commission disagrees.[3] We also drop 133 zip codes with zero population; these are business districts or P.O. boxes.

Third, we aggregate the data to the zip code by year level. When doing so, we are faced with missing variables in the zip code-year combinations where there were no installations. We are also missing demographic data and electrician worker wages data in some cases, as well as TPO prices in zip code-years where there are TPO installations but we do not have contract prices. We interpolate missing data so that we have a balanced panel. We employ the following procedure to fill in zip code by year level prices and control variables. When such variables are missing for a particular observation (most commonly for zip code-year observations with zero installations), we take the county by year average, separately for HO vs. TPO systems. If the county by year aggregate is still missing (highly unlikely, but possible for some variables, such as electricians' wages that are missing for a few sparsely populated counties), we take the population-weighted average over neighboring counties. In the few cases where we are still missing data (all of which are TPO prices in zip code-years where we do not have transcribed contracts in our sample), we use utility-year averages. In this aggregation process, we sum the installations by year for each zip code and contract type. Since we have a limited time series but only partial coverage of the year 2013, we pro-rate the installation rate for 2013 using the end date for each utility (discussed above) and the fraction of systems that were installed in the sample period over the period 2010-2012 (44.34% for SCE, 42.61% for SDG&E, and 26.42% for PG&E).

Table B.1 provides summary statistics of our demand estimation data from 2010 through 2013. Demand rates for HO and TPO are not statistically different. As was the case for the pass-through data, differences for HO and TPO system rebates and post-incentive prices are statistically different but relatively modest in terms of economic magnitudes, and no demographic differences stand out besides HO households having just slightly older heads of household and slightly more household ownership.

B.2 Adjusting the CSI Rebates for ITC and MACRS Subsidies

This section details the method we employed to adjust the CSI rebate to account for its interaction with pre-existing federal incentives, as explained in Section 4.1. Federal incentives available throughout the sample period include the investment tax credit (ITC) for both HO and TPO systems, and the Modified Accelerated Cost Recovery System (MACRS) benefits for TPO systems only. We begin by examining the case of HO systems. Recall that the post-incentive price for HO consumers is the reported total cost minus incentives, such that

[3] http://www.energy.ca.gov/maps/serviceareas/electric_service_areas.html

Table B.1: Descriptive Statistics of Sample for Demand Estimation, 2010-2013.

	Means			Standard Deviations	
	HO	TPO	Difference	HO	TPO
	(1)	(2)	(3)	(4)	(5)
A: Installations					
Demand rate (installations per 1,000 people)	0.495	0.534	-0.039	2.013	2.198
B. System Characteristics					
CSI rebate ($/watt)	$0.42	$0.41	$0.02	$0.35	$0.34
CSI rebate ($)	$2,024	$2,121	-$97**	$1,689	$1,851
Post-incentive price ($/watt)	$3.89	$3.43	$0.46***	$0.89	$0.64
Post-incentive price ($)	$18,432	$18,540	-$108	$4,389	$4,743
System size (watts)	5,065	5,297	-232***	1,259	1,158
C. Demographics					
Weekly electricians' wages ($)	$1,149	$1,149	$0	$210	$210
Bachelor's degree or higher	34.6%	34.2%	0.4%	16.6%	16.6%
Median age of household head	40.9	40.5	0.4***	6.1	6.0
Percent owners of all households	52.1%	52.0%	0.1%**	3.7%	3.5%
Median household income ($)	$76,681	$76,257	$424	$27,043	$26,779
Median house value ($)	$438,084	$432,417	$5,667	$225,690	$223,624
Third highest electricity rate tier ($/kWh)	$0.22	$0.22	$0.00	$0.04	$0.04
Second highest electricity rate tier ($/kWh)	$0.30	$0.30	$0.00	$0.04	$0.04
Highest electricity rate tier ($/kWh)	$0.31	$0.31	$0.00	$0.05	$0.05

Notes: Dataset is a balanced panel with 5,384 observations for both HO and TPO at the zip code-year level. Asterisks denote *p <0.10, **p <0.05, ***p <0.01.

$$p_{HO,i} = TC_{HO,i} - CSI_{HO,i} - ITC_{HO,i}, \tag{B.1}$$

where $p_{HO,i}$ is the post-incentive price for HO consumer i, $TC_{HO,i}$ is the total reported pre-incentive cost in the CSI database, $CSI_{HO,i}$ is the total CSI rebate amount awarded, and $ITC_{HO,i}$ is the implied federal ITC benefit. We do not observe the ITC, so we calculate this assuming that it is fully monetized for all cases. For HO consumers, the CSI rebate is considered a price reduction for tax credit purposes. Thus, the 30% tax credit applies to the after-rebate net price paid by the customer:

$$ITC_{HO,i} = 0.3 * (TC_{HO,i} - CSI_{HO,i}). \tag{B.2}$$

The pass-through of the ITC and CSI incentives cannot be separately identified in our regression model because they are linear functions of each other, however we must account for the way in which they interact. As implied by Equation B.2, a one-dollar increase in the CSI rebate is effectively a 70 cent increase in total subsidies because the CSI mechanically decreases the value of the ITC by 30 cents. We account for this interaction by adjusting the CSI rebate amount that is used in our pass-through regressions. To do that, note that we can re-write Equation B.1 such that

$$p_{HO,i} = 0.7 * (TC_{HO,i} - CSI_{HO,i}). \tag{B.3}$$

However, if we did not adjust our measure of the CSI subsidy, our regression would estimate

$$p_i \sim \alpha + \beta CSI_i + \varepsilon_i, \tag{B.4}$$

where a one-dollar increase in the CSI subsidy would be interpreted as a one-dollar increase in the total subsidy received. As the actual one-dollar increase in the CSI is worth only 70 cents from the consumer's and installer's perspectives, we multiply the CSI subsidies by a correction factor of 0.7, as we want to interpret our pass-through coefficient β as the impact on prices of a full one-dollar subsidy increase.

Adjusting for federal incentives for TPO systems differs somewhat from the HO adjustment for two reasons: the ITC is calculated in a slightly different way, and TPO systems also benefit from MACRS. The post-incentive price that we construct for TPO systems is a net present cost calculation that embeds all incentives (since contract terms are subsidy-inclusive). As such, we do not need to explicitly net out the ITC and MACRS from a gross cost measure (as we do for HO consumers). However, we note that for TPO consumers

$$p_{TPO,i} \equiv NPC_{TPO,i} = U_i + \sum_{y=1}^{t} \frac{payment_{iy}}{(1+d)^t}, \tag{B.5}$$

where $p_{TPO,i}$ is the post-incentive price of system i, or the net present cost of the contract to the customer as described by Equation 7, which embeds the ITC and MACRS. As before, we need to account for these other incentives in our pass-through regressions as they interact with the CSI rebate. First consider the ITC for TPO consumers. The CSI rebate is not a price reduction for tax credit purposes as it is for HO consumers. Instead, the federal ITC received by third parties is based on gross installed cost: $ITC_{TPO,i} = 0.3 * TC_{TPO,i}$. The ITC is thus unaffected by the CSI as the basis for the 30% credit is not reduced by the CSI rebate amount. However, the IRS considers the CSI rebate to be earned income and therefore subject to corporate taxes. Hence, the effective CSI subsidy is $(1-t_c)CSI$, where t_c is the corporate tax rate. Hence, we need to multiply the CSI subsidies by $(1-t_c)$ in the TPO case in order to interpret our pass-through coefficient as the impact of a full dollar increase in the rebate. We do not observe the effective marginal tax rate of each installer in our sample, but following Borenstein (2017), we assume it is 30%—close but somewhat lower than the 35% rate for large companies. Using 35% would scale up our ITC pass-through estimates and make the estimated difference between HO and TPO pass-through even more pronounced.

The second federal subsidy to take into account is MACRS. Over our entire sample period, residential solar PV systems were eligible for 5-year accelerated depreciation as well as an especially high "bonus" depreciation in the first year. For systems placed into service after September 8, 2010 and before January 1, 2012, the first-year bonus depreciation rate was 100%; it was 50% during the other periods in our sample. Under 50% first-year bonus depreciation, the depreciation schedule was (50% bonus + 10% MACRS =) 60%, 16%, 9.6%, 5.76%, 5.76% and 2.88% for years one through six, respectively. Under 100% first-year bonus depreciation, the system was fully depreciated for tax purposes in year one.

Our goal is to calculate a MACRS "adjustment factor" based upon the structure of the MACRS program assuming a one-dollar increase in the CSI rebate. We use Borenstein (2017)'s assumptions. Again, we want to interpret a one-dollar increase in the CSI subsidy as a one-dollar increase in total subsidy received. The reasoning is similar to that for the ITC adjustment in the case of HO: there is a reduction in the present value of the MACRS benefit following a one-dollar increase in CSI because firms were able to depreciate 85% of the system cost *after state rebates*. In other words, the allowable depreciable basis is equal to $0.85 * (TC - CSI)$. The net present value of the reduction in tax savings (depreciation benefits) resulting from a one-dollar increase in the CSI for TPO systems is

$$f_{MACRS} = \sum_{y=1}^{6} \left(\frac{m_y}{(1+r)^y} * t_c * D \right), \tag{B.6}$$

where m_y is the MACRS recovery rate in year y, r is the firm's discount rate, and t_c is the firm's marginal corporate tax rate (which we assume to be 30%, following Borenstein (2017)). D is the allowable depreciable basis, which is equal to 0.85 for solar PV systems.

We calculate real adjustment factors for a range of nominal discount rate assumptions that align with our NPC calculations (2% to 12%). Furthermore, we calculate different sets of adjustment factors based on when the program allowed for 50% and 100% bonus depreciation. We assume that all third parties took advantage of the MACRS program. We thus determine if systems qualified for 50% or 100% bonus deprecation based upon installation date, since eligibility was determined based on the date the system went into service. This date is not included in the CSI database, so we matched the CSI data to the publicly available NEM interconnection dataset. f_{MACRS} ranges from 0.21 to 0.25 depending on the discount rate and the type of bonus depreciation.

Finally, we adjust the CSI rebates for ITC, corporate taxes, and MACRS benefits for our pass-through regressions such that

$$AdjustedCSI_{HO,i} = 0.7 * CSI_{HO,i} \tag{B.7}$$

and

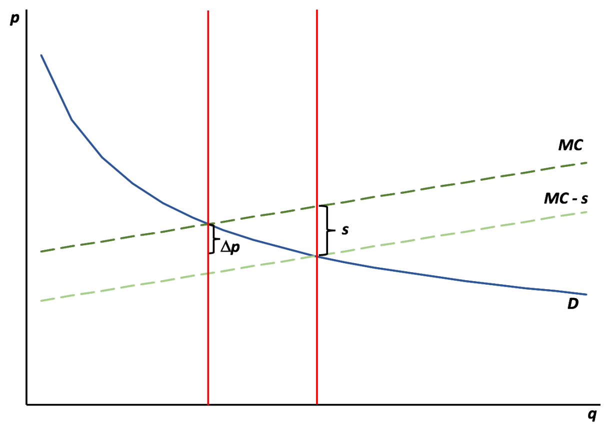
$$AdjustedCSI_{TPO,i} = 0.7 * CSI_{TPO,i} * (1 - f_{MACRS}). \tag{B.8}$$

C Additional Figures and Tables

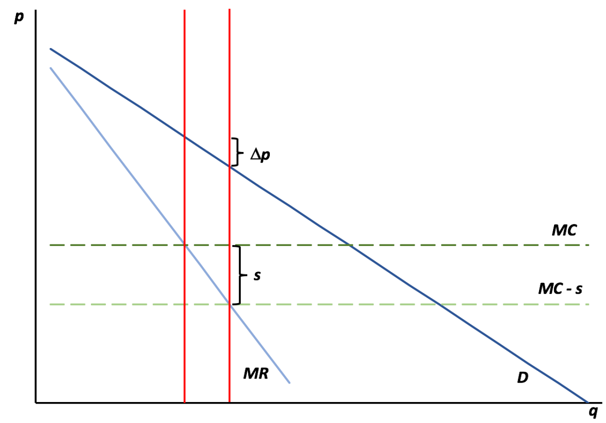
C.1 Additional Theory Figures

In Figure 1 of the main text we show how over-shifting occurs in the presence of market power when demand is log-convex. Figure C.1 demonstrates two related cases where pass-through cannot exceed unity to further illustrate why both sufficiently convex demand and market power are needed to explain over-shifting. Panel A illustrates how pass-through falls between 0 and 100% under perfect competition but with convex demand. Perfectly vertical marginal costs would imply 0% pass-through and flat marginal costs would imply 100% pass-through. Panel B shows how pass-through is exactly 50% for the case of monopoly but with linear demand and constant marginal costs.

Figure C.1: Two Examples of Pass-Through Without Over-Shifting



(a) Pass-Through under Perfect Competition and Constant Elasticity Demand



(b) Pass-Through for a Monopolist with Linear Demand and Constant Marginal Costs

Note: Figure shows the price effect of a subsidy s on the price p under perfect competition when there is constant elasticity demand and when p is set by a monopolist under linear demand. MC refers to marginal cost, D to demand, and MR to marginal revenue. The constant elasticity parameter in panel A is $\epsilon = -0.5$.

C.2 Additional Figures and Tables for the Pass-Through Estimates

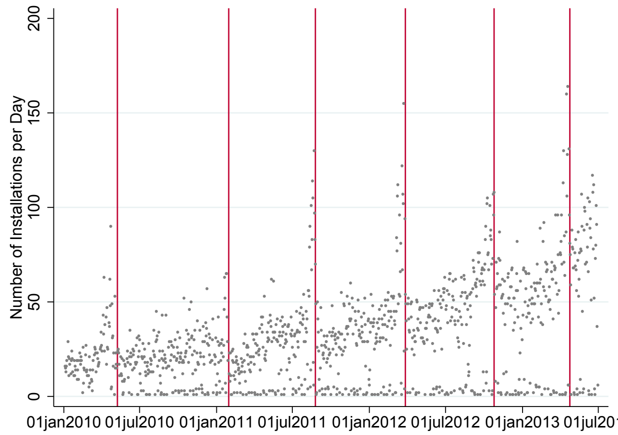
Figure C.2 shows the total daily installations in each of the three IOU territories for our sample period 2010Q1-2013Q2.[4] The figures demonstrate some amount of bunching of applications just before the rebate drop dates. This is consistent with the findings in Hughes and Podolefsky (2015).[5]

This bunching reflects a certain degree of strategic timing behavior on part of consumers and installers. These drop dates could not be perfectly foreseen as they were triggered by reaching a threshold of cumulative installed capacity within each IOU. This date is hard to predict exactly, however the CSI announced on a public website how many CSI megawatts (MW) worth of rebates remained in the current incentive step level. This web-based *CSI Trigger Tracker* allowed users to anticipate when the rebates were going to drop to the next level by comparing "MW Under

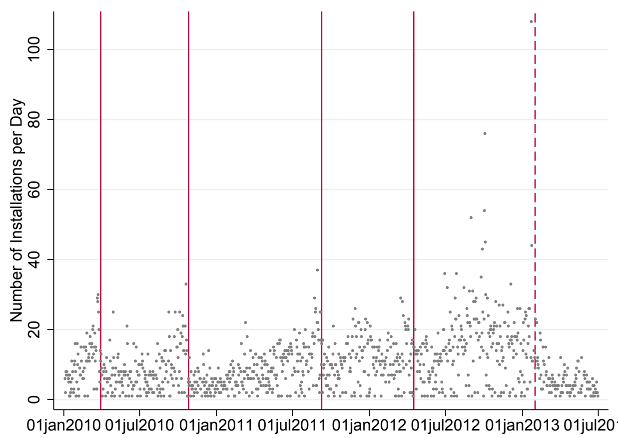
[4]Note that daily "installations" are actually "rebate reservations", since the dates refer to the day when rebate reservations were filed as opposed to when installations were completed.

[5]CSI residential rebates in the SDG&E region were briefly suspended after January 31st, 2013, but it became clear soon afterwards that residential rebates would continue at the same rate per watt as \$5 million from the commercial solar project budget was shifted to residential installations (Center for Sustainable Energy 2014). Around January 31st, however, some consumers may have thought the CSI rebates had run out while in fact they had not. We therefore show this date as a dotted vertical line in Figure C.2, panel B.

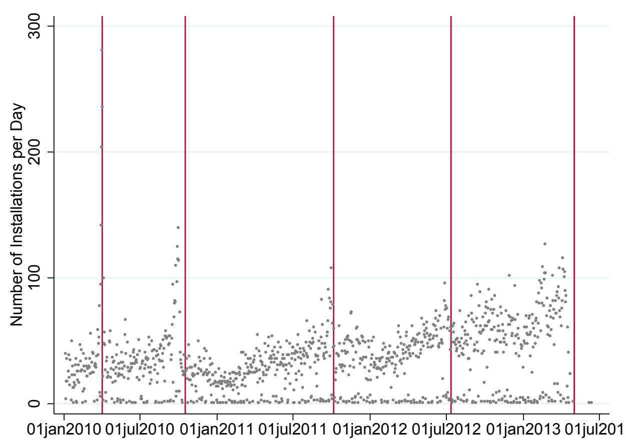
Figure C.2: Total Installations per Day for (a) SCE, (b) SDG&E and (c) PG&E.



(a) Southern California Edison



(b) San Diego Gas and Electric



(c) Pacific Gas and Electric

Note: The dotted vertical line for SDG&E on January 31st, 2013 indicates a temporary rebate suspension but not an actual rebate drop.

Review" with "MW Remaining". The rebate level is determined at the time of the reservation, not the time of project completion, so it was possible to strategically submit reservations as each IOU approached step capacity targets.

Table C.1 shows our baseline specification with increasingly flexible controls and fixed effects. Columns 1-7 gradually add more controls. Throughout all specifications, we find that the difference in pass-through between TPO and HO consumers is large and statistically significant, but we need detailed controls to estimate pass-through more accurately, especially for HO consumers.

Table C.1: Baseline Estimates with Increasingly Flexible Controls

	(1)	(2)	(3)	(4)	(5)
A. Pooled					
Incentive	-0.044	-0.286***	-0.546***	-0.555***	-0.778***
	(0.119)	(0.103)	(0.091)	(0.087)	(0.063)
Incentive *1[system = TPO]	-1.435***	-1.383***	-1.281***	-1.429***	-0.750***
	(0.259)	(0.267)	(0.262)	(0.261)	(0.234)
1[system = TPO]	-0.558***	-0.022	-0.198	-0.196	-0.378*
	(0.216)	(0.217)	(0.229)	(0.222)	(0.203)
Number of obs.	28,108	28,108	28,108	28,108	28,108
p-value: HO pass-through > -1	0.000	0.000	0.000	0.000	0.000
p-value: TPO pass-through < -1	0.024	0.005	0.001	0.000	0.013

B. Separated	HO	TPO	HO	TPO	HO	TPO	HO	TPO	HO	TPO
Incentive	-0.067	-0.923***	-0.309***	-1.070***	-0.567***	-1.186***	-0.578***	-1.202***	-0.787***	-1.333***
	(0.120)	(0.294)	(0.103)	(0.282)	(0.092)	(0.338)	(0.088)	(0.351)	(0.063)	(0.351)
Number of obs.	27,015	1,093	27,015	1,093	27,015	1,093	27,015	1,093	27,015	1,093
p-value: HO pass-through > -1	0.000		0.000		0.000		0.000		0.000	
p-value: TPO pass-through < -1		0.603		0.402		0.291		0.282		0.172
Controls	x	x	x	x	x	x	x	x	x	x
Utility FE	x	x	x	x	x	x	x	x	x	x
Manufacturer FE			x	x	x	x	x	x	x	x
Module FE					x	x	x	x	x	x
County FE							x	x	x	x
Installer FE									x	x
Quadratic contract type time trends	x	x	x	x	x	x	x	x	x	x

Notes: Dependent variable is the post-incentive system price per watt. Data cover systems installed in California for consumers who applied for the CSI rebate during the period 2010-Q2 2013. Controls include census tract level demographics and a dummy if there is more than one inverter. A 7% discount rate is assumed for the net present cost and MACRS calculations. Standard errors clustered by zip code. In Panel A, the p-value labeled "HO pass-through > -1" is the one-sided p-value of $H_0 : \beta_1 \leq -1$ vs. $H_a : \beta_1 > -1$. p-value labeled "TPO pass-through < -1" is the one-sided p-value of $H_0 : \beta_1 + \beta_2 \geq -1$ vs. $H_a : \beta_1 + \beta_2 < -1$. In panel B, all tests are performed on the single coefficient on the incentive variable. Asterisks denote *p <0.10, **p <0.05, ***p <0.01 for $H_0 : \beta = 0$ vs. $H_a : \beta \neq 0$.

C.3 Additional Demand Estimation Results

C.3.1 First Stage

Table C.2 reports the first stage regressions for the solar panel price and its square, along with the Sanderson-Windmeijer multivariate F-test for excluded instruments.

Table C.2: First-Stage Regressions for HO vs. TPO Systems

	(1)	(2)	(3)	(4)
	First-Stage Regression of Price		First-Stage Regression of Price^2	
	HO	TPO	HO	TPO
Incentive	2.026***	-2.779***	19.644***	-21.603***
	(0.394)	(0.317)	(4.001)	(2.498)
Incentive^2	-1.688***	1.973***	-14.875***	15.769***
	(0.384)	(0.334)	(3.961)	(2.600)
Electricians' wages	0.001**	-0.004***	0.011***	-0.021***
	(0.0005)	(0.0004)	(0.004)	(0.004)
Electricians' wages^2	$-2.39 * 10^{-7}$	$1.60 * 10^{-6}$***	$-3.51 * 10^{-6}$*	$9.08 * 10^{-6}$***
	$(2.10 * 10^{-7})$	$(1.90 * 10^{-7})$	$(1.85 * 10^{-6})$	$(1.55 * 10^{-6})$
First stage F-statistic	10.40	18.86	10.16	18.35
p-value	0.000	0.000	0.000	0.000
Controls	x	x	x	x
County FE	x	x	x	x
Year FE	x	x	x	x
Number of observations	5,196	5,196	5,196	5,196

Notes: Observations are at the zip code by year level. Data cover systems installed in California for consumers who applied for the CSI rebate during the period 2010-Q2 2013. Controls includes the same demographics that we use in Table 2, as well as tiered electricity rates. A 7% discount rate is assumed for the net present cost and MACRS calculations. F-statistic is the Sanderson-Windmeijer multivariate F-test of excluded instruments. Standard errors clustered by zip code. Asterisks denote *p <0.10, **p <0.05, ***p <0.01.

C.3.2 Robustness Checks

Table C.3 shows how the demand parameters vary with two important alternative sample selection or variable construction rules. First, we compute the solar installation rate by dividing installations by the number of people who live in houses they own (using information on owner-occupied housing from the census) instead of total population. Renters are unlikely to install solar systems as they do not always capture the full benefits because of limited housing tenure, their apartments or houses are typically less suitable for solar panels, and they need to get property owner approval. Relatedly, homeowners who lease their properties to others may be unlikely to install solar panels when they do not expect to benefit from the electricity bill savings through higher rents. Second, we estimate demand using all zip codes, including those with populations below 100 people.

We conclude that the results when adjusting for homeownership are similar to those in the main specification in Table 6. The parameter values are larger in absolute value, but note that the mean of the dependent variable (the installation rate) is about twice as large since we divide by owner-occupied housing population, not total population. The implied elasticities are also similar. Similarly, dropping small zip codes does not qualitatively affect our results: the estimates are smaller but still indicate substantial convexity. Similarly, including small zip codes does not qualitatively affect our results: the estimates still indicate substantial convexity.

Table C.3: Robustness of Demand Estimates

	(1)	(2)	(3)	(4)
A. Installation Rate Based on Owner-Population				
	OLS		IV	
	HO	TPO	HO	TPO
Price	-0.485***	-0.362**	-0.936	-2.996
	(0.155)	(0.174)	(1.718)	(4.000)
$Price^2$	0.048***	0.053**	0.089	0.429
	(0.015)	(0.022)	(0.191)	(0.514)
Mean of dependent variable	0.870	0.976	0.870	0.976
First stage F-statistic (price)			10.40***	18.86***
First stage F-statistic ($price^2$)			10.16***	18.35***
Number of observations	5,196	5,196	5,196	5,196
B. Including Zip Codes with Less Than 100 Inhabitants				
	OLS		IV	
	HO	TPO	HO	TPO
Price	-0.489	-0.258*	-1.754	-3.166
	(0.311)	(0.140)	(1.873)	(2.420)
$Price^2$	0.048*	0.039**	0.208	0.460
	(0.028)	(0.018)	(0.235)	(0.321)
Mean of dependent variable	0.495	0.534	0.495	0.534
First stage F-statistic (price)			11.03***	21.48***
First stage F-statistic ($price^2$)			10.75***	20.91***
Number of observations	5,384	5,384	5,384	5,384

Notes: Dependent variable is the solar system installation rate, either based on owner-population (panel A) or based on total population (panels B and C). Observations are at the zip code by year level. Data cover systems installed in California for consumers who applied for the CSI rebate during the period 2010-Q2 2013. Controls includes the same demographics that we use in Table 2, as well as tiered electricity rates. A 7% discount rate is assumed for the net present cost and MACRS calculations. IV estimates in columns 3 and 4 instrument for (squared) price using the (squared) CSI rebate and the (squared) county-level electrician/wiring wage rate. F-statistic is the Sanderson-Windmeijer multivariate F-test of excluded instruments (for each of the first-stage regressions). Standard errors clustered by zip code. Asterisks denote *p <0.10, **p <0.05, ***p <0.01.

We also ran IV specifications using only the linear CSI rebate and electrician/wiring wage rate (but not their squares) as instruments. In this case, we have a weak instruments problem for the TPO regression. The coefficient on the squared price indicates convexity, but the TPO point estimates are large and noisy yet still not statistically different from any of the point estimates from alternative specifications.[6]

C.3.3 Calculating Convexity Measures

In order to calculate the convexity parameter ε_{ms} of Equation 2, we need inverse demand and therefore we invert our estimated demand equation. This is straightforward using the quadratic formula and price and squared price parameters estimated in Table 6. We first calibrate the constant by evaluating our estimated demand equations (one for HO and one for TPO) at a fixed price and with all other control variables at their sample means. From this, we obtain a simplified demand expression $q = ap^2 + bp + c$ (with a and b as the estimates from Table 6 and c calibrated as described above). Next, we solve for $p(q)$ using the quadratic formula. We differentiate the resulting expression to obtain $p'(q)$ and $p''(q)$. This allows us to evaluate the criterion given by Equation A.8 along different points at the demand curves, where $1/\varepsilon_{ms} < 0$ indicates over-shifting under the assumptions of the model. The results are discussed in Section 6 of the main paper.

D Additional References

Center for Sustainable Energy. 2014. "CSI Rebates Winding Down for San Diego Homeowners."

Hois, E. 2016. "Selecting the Size of Your Solar PV System." SolarReviews.

[6] For HO, the coefficients on price and squared price equal -0.812 and 0.062, respectively. For TPO, these coefficients are -48.304 and 6.443. None of these coefficients are statistically significant. For TPO, the p-value of the Sanderson-Windmeijer F-statistics for price and squared price are 0.22 and 0.22, respectively.