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Getting Green with Solar Subsidies: Evidence from the California Solar Initiative

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Abstract

1 Introduction

Many state and local governments have become involved in efforts to reduce local air pollution and emissions of greenhouse gases. Electric utilities have also adopted policies to promote residential energy efficiency and renewable energy production. For both groups, a common approach is the use of subsidies for \green technologies." In this paper, we study a popular program that awards rebates for residential photovoltaic (PV) solar electricity installations in California. Currently, over 130 programs in 27 states and the District of Columbia award rebates for residential PV systems.[1] If the effects of these programs are large, residential solar subsidies may play an important role in efforts to reduce carbon emissions. However, while a number of green technology subsidy programs have received attention in the empirical literature, the extent to which solar subsidies create new adopters, lower emissions, raise or lower welfare is still largely unknown. Given that these policies are costly to ratepayers, governments or both, the extent to which they achieve their desired environmental goals is an important policy question.

We study the California Solar Initiative (CSI), a large subsidy program which targets residential and commercial consumers of PV and related solar technologies. We focus on the Expected Performance Based Buydown (EPBB) program which awards rebates, in dollars per Watt, based on expected PV system generation capacity. Using installation data from 2007 to 2012, we estimate the effect of upfront rebates on adoptions. Three investor owned utilities (IOUs) participate in this program: Pacific Gas and Electric (PG&E), Southern California Edison (SCE) and San Diego Gas and Electric (SDG&E). Program rebates are substantial and amount to between 5 and 25 percent of system cost. One feature of the CSI is that rebate rates decline over time depending on each utility's total installed capacity. This creates variation in rebates across utilities over time that we exploit in our empirical analysis. Because rebate levels depend on the history of past installations and unobserved factors that affect adoption may be correlated over time, our estimation strategy controls for utility-specific time-varying factors related to PV adoption.

Overall, we find that CSI rebates have a large effect on residential PV adoption. Across a number of specifications we find that a $0.10 per Watt or 7 percent increase in the mean rebate rate on average increases the number of installations per day between 11 and 15 percent. In our preferred specification, increasing average rebates from $5,600 to $6,070 would increase installations

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[1] For a current count of residential solar rebate programs see http://www.dsireusa.org/solar/.

by 13 percent. Furthermore, while consumers do appear to anticipate changes in the rebate rate by increasing adoptions in the weeks immediately prior to a rebate change, the overall effect we estimate does not depend solely on this short-run behavior. The estimated effect of the rebate does not change substantially across the geographic areas we study or across IOUs. We also provide evidence that the level effect of rebates on adoptions is greater later in the sample despite smaller rebates.

To investigate the overall impacts of the CSI we use our estimates to predict the number of installations, solar electricity capacity and emissions reductions created by the program. Of the approximately 99,000 installations that occurred over this period, we find that 57,000 or 58 percent of installations were due to rebates. This suggests that the CSI had a substantial effect on adoptions. The estimated increase in solar generation capacity, approximately 260 MW, is small at less than 1 percent of typical electricity load in the state.[2] We predict the additional solar generation under the CSI lowers CO_2 emissions by 2.98 to 3.15 million metric tons (MMT) and cuts emissions of nitrogen oxides (NOx) by 1,100 to 1,900 tons over 20 years.

Back of the envelope calculations suggest the CSI results in large benefits to consumers and installers. Total rebates paid from 2007 to 2012 are $437 million. Private surplus, defined as the sum of producer and consumer surplus, increases by approximately $268 million including $98 million in rents to inframarginal installations that would have occurred absent rebates. These effects may explain the popularity of the program. However, overall the program appears costly. Social surplus, which we define as private surplus net of subsidy payments, decreases under the CSI by approximately $169 million.[3,4] Comparing this cost to estimated carbon emission reductions implies average abatement costs between $46 and $69 per metric ton (MT) CO_2, substantially more than recent estimates for the social cost of carbon. For NOx, we find average abatements costs are very high, between $91,000 and $142,000 per MT.

Understanding the relationship between PV subsidies and adoptions is important for several reasons. Upfront rebates of the type awarded under the CSI are widely used. Many utilities, states

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[2] Daytime loads in California typically range between 25,000 and 30,000 MW but can peak as high as 60,000 MW.

[3] Our calculations assume price taking firms and linear demand. This allows us to estimate welfare effects of the CSI using only subsidy levels and the change in the number of installations due to CSI rebates.

[4] The change in private surplus in this context is equivalent to the deadweight loss of the subsidy where private marginal costs exceed private marginal benefits.

and local governments have programs similar to California's.[5] In addition to upfront rebates, tax rebates and production based subsidies may provide similar incentives. The US federal government has awarded a tax rebate of up to 30 percent for qualified solar installations since 2005. Internationally, several nations including Germany and Spain, offer production based subsidies. Recent work by Burr (2012) suggests consumers may respond similarly to these different incentives. Understanding how consumers respond to incentives highlights the costs and benefits of promoting PV adoption and may help policy makers design more effective policies. Finally, understanding the effects of solar subsidies provides insight into similar programs for other green energy technologies.

This paper is part of a small but growing literature to understand the impact of subsidies for solar PV. Bollinger and Gillingham (2012) explore the role of CSI rebates in their study of peer effects in PV adoption. They use 33 zip codes along the PG&E and SCE boundary to show of have adopted without rebates.

Several authors have investigated the effects of a variety of demand side incentives for hybrid plans are more likely to invest in green technologies, this appears to be the result of underlying environmental preferences in these areas rather than the plans themselves. These results highlight the spatial aspects of demand for energy efficient building technologies which may parallel trends in solar adoption.

The remainder of this paper is organized as follows. Section 2 describes the California Solar Initiative and market for residential PV systems in California. Section 3 describes our data and Section 4 presents our empirical strategy. Sections 5 and 6 summarize our main empirical results and calculations for the overall effects of the CSI. Finally, Section 7 concludes.

2 Policy background

The California Public Utilities Commission (CPUC) created the California Solar Initiative (CSI) at the start of 2007 to manage the state PV rebate program and to help meet the solar goals set by the California greenhouse gas law, AB32. The CSI is a $2 billion program targeting both commercial and residential customers and includes incentives aimed at low income households in single and multi-family residences. The CSI is funded by a ratepayer surcharge assessed by utilities.[7] This surcharge contributes an average of $217 million annually to the CSI.[8] Three IOUs participate in the initiative | Pacific Gas and Electric (PG&E), Southern California Edison (SCE) and San Diego Gas and Electric (SDG&E). Rebates are available for solar PV technologies as well as solar hot water heaters. In addition, the CSI offers grants for research, development and deployment of solar technologies. We focus on incentives for residential solar PV installations which represents approximately $500 million of the overall program budget.[9] For these customers the CSI program offers two options, an upfront rebate based on predicted system electricity production, and a monthly payment based on actual production. Because relatively few customers select the monthly option, we focus on the upfront payment called the Expected Performance Based Buydown

Under the EPBB system, rebate rates begin at $2.50 per Watt and decrease based on each IOU's total installed solar capacity. The schedule, reproduced in Table 1, was set at the program outset and allocates the statewide solar capacity to utility-specific quantities within each rebate "step." For example, for statewide PV capacity greater than 50 MW and less than 70 MW, CSI rebates are awarded at step 2 or $2.50 per Watt. However, determining whether a particular residential installation in an IOU qualifies for the step 2 incentive requires that the program administrator allocate the total capacity within the step to the different utilities and their residential and commercial customers. Table 1 shows that PG&E residential installations that occur when the utility's total residential PV capacity is less than 10.1 MW receive $2.50 per Watt. Similarly for SCE and SDG&E, the relevant thresholds are 10.6 and 2.4 MW. The remaining capacity within the step is allocated to commercial installations under each of the participating IOUs. Looking ahead to the empirical exercises, we exploit the fact that rebate levels change at different times for each IOU depending on that utility's installed residential capacity.

Overall, CSI statistics suggest that the program had a large effect. As of February 2013, CSI reports 1,432 MW of capacity installed or pending under the program consisting of nearly 142,000 projects. Approximately 546 MW are listed as residential with the remaining 886 MW classified as commercial. Since 2007, over $1.5 billion in incentives have been awarded including over $400 million for residential installations.

other time-varying factors using time fixed-effects.[12]

3 Data

Our analysis exploits installation data from the California Solar Initiative (CSI). CSI reports installation date, rebate amount, utility and zip code as well as installation characteristics for all cation. Looking across IOUs, average system prices range from approximately $35,900 to $37,400 and rebate levels range from $3,600 to $5,300. Average CSI ratings are fairly consistent at between 4.46 to 4.77 kW. The data also suggest large subsidies are awarded for a few very large residential installations. Across the three IOUs, maximum rebates range from $106,000 to $138,000 for systems costing between $397,000 and over $1 million.

In several empirical specifications below we focus on a subsample defined by a 20-mile corridor analysis. Average system costs per Watt decrease over the period from approximately $10 per Watt to $6 per Watt. Average daily installations increase from nearly zero, initially, to almost 50 per day in 2012 for PG&E and SCE. Daily installations are substantially lower for SDG&E, peaking at approximately 15 per day.[18] Given that prices have steadily decreased over time while installation rates have risen, one may wonder about the impact of CSI rebates on adoptions.

Figures 4(a), 4(b) and 4(c) provide evidence that consumers do respond to changes in rebate levels. The number of installations per day is plotted for each utility from 2007 through 2012. For exposition we plot only weekdays, though a surprising number of installations are recorded on weekends.[19] The vertical lines denote dates when the rebate rate was lowered. In general, we see large increases in the number of installations in the weeks leading up to a drop in the rebate rate. The periods between rebate changes also show a general upward trend consistent with greater numbers of installations over time. Looking forward to the empirical exercises, the overall increase in installation rates combined with decreasing rebate levels suggests that controlling for changes in time-varying factors that affect PV adoption will be important in identifying the effect of rebates on installations.

Finally, our empirical approach below proposes using the boundary between the PG&E and SCE territories to help create exogenous variation in CSI rebate rates. We focus on PG&E and SCE because SDG&E represents a substantially smaller share of adoptions. We use GIS data obtained from Ventyx to locate the boundary and to identify zip codes that lie within a 20-mile corridor around the boundary. Figure 3 shows the PG&E and SCE service territories as well as the region around the territory boundary. These two IOUs serve regions that cover the vast majority of the state stretching from southern California to near the Oregon border. The boundary between PG&E and SCE, drawn in black, begins in Santa Barbara and stretches nearly 900 miles north to the Nevada border. Zip codes whose centroids fall within the 20-mile corridor are shaded in gray. Because less populous zip codes tend to be larger in size, the 20-mile corridor excludes some rural regions of the boundary as some zips code centroids do not fall within 10 miles of either side of the territory boundary.[20]

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[18] This difference may largely be due to the relative sizes of these utilities. While SCE and PG&E serve 14 and 15 million electricity consumers respectively, SDG&E serves only 1.4 million. In per capita terms, 2012 installations are significantly higher in SDG&E than in either SCE or PG&E.

[19] Our estimates for the effect of rebates on adoption in Section 5 include installations on weekdays and weekends. Parameter estimates are similar to those reported when weekends are excluded.

[20] These zip codes are left unshaded in Figure 3.

4 Empirical strategy

Because rebate levels are determined by prior installations and because unobserved factors that affect adoptions within each utility territory may be correlated over time, our identification strategy seeks to isolate exogenous variation in rebate rates while holding constant unobserved factors that affect PV adoption.[21] Our approach is twofold. First, we use time effects to account for mean and utility specific time varying unobservables that may affect PV adoption. Second, we exploit the geographic discontinuity created by the boundary between the PG&E and SCE service territories. This boundary was created in the early 1900's when the area between the two utilities was largely rural, such that the location is plausibly orthogonal to factors affecting PV adoption today. We focus on a narrow 20 mile corridor around this territory boundary. This approach is similar to Ito (forthcoming) who investigates consumer responses to marginal and average electricity prices using the territory boundary between SCE and SDG&E in Southern California. Because changes in the rebate rate are determined by total installed PV capacity in either IOU's territory, installations in the boundary region should minimally affect the rebate rate. Further, by looking in a small neighborhood around the boundary we hope to hold constant unobserved factors affecting adoption. A key identifying assumption is that unobservables that affect adoption for households in the boundary region are not correlated with unobservables at the utility level more broadly.

To get a sense for the similarity of households within each region, Table 3 summarizes zip code mean demographic and housing characteristics for all zip codes within the PG&E and SCE territories as well as within 40-mile and 20-mile wide corridors at the territory boundary. These observable characteristics are reasonably good predictors of PV installations.[22] We present means weighted by population within each zip code. Beginning with the full sample, we see that percent white, household income, percent family occupied, and number of rooms are all significantly different between PG&E and SCE territories.[23] When the sample is limited to the 40-mile corri-

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[21] For example, environmental preferen328(apresen)28(e334(ut)en)28(e33cm[]0 d 0 J 0.398 en)29(tal)-351(prefereyren38neren3244285g

dor around the boundary, the differences in observable characteristics between utilities in general decrease. Income and number of rooms are no longer statistically significantly different. Finally, moving to the preferred 20-mile corridor sample, we see that the differences decrease further. In no case are the differences in means between utilities significant at the 5 percent level and only in the cases of percent white and percent family occupied are they significant at the 10 percent level. This suggests that focusing on a small neighborhood around the utility boundary does result in observations with similar observable characteristics.[24] Furthermore, to the extent that unobservables that affect solar installations are correlated with these observable factors, these results suggest that the 20-mile corridor sample may also have the property of holding these factors constant across utilities.[25]

Since PV installations even at the zip code level are relatively rare events, we sum installations on each side of the boundary to produce daily installation totals for each IOU.[26] We model the number of installations per day as:

$$I_{u;t} = {}_0 + {}_1 rebate_{u;t} + {}_u + {}_t + {}_{u;t} \qquad (1)$$

Where $I_{u;t}$ is a count variable for the daily installation rate for utility u at time t. We focus on the effect of changes in the rebate on adoption rather than estimating demand directly from consumer system prices for two reasons. First, prices reported to the CSI may be unreliable because of incentives for third-party installers to over-report costs.[27] Second rebate levels, rather than consumer prices net of rebates, may be more salient for policy makers.[28] Since the rebate rate determines the net cost to the consumer of adopting solar, in our preferred specification $rebate_{u;t}$ enters in levels. We model unobserved factors that affect PV installations at the utility level as

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[24] As discussed below, our dependent variable aggregates installations across zip codes by utility within the boundary area. Therefore, including observable characteristics directly or using zip code fixed effects is not possible.

[25] While these results also suggest a more narrow corridor may be desirable, we do not observe the precise installation location. Therefore, the fineness of the discontinuity is limited by the width of each zip code, which can be several miles.

[26] As a robustness check, Appendix Table 1 presents results using zip code daily level data. These results are quite similar to those presented below using utility daily level data.

[27] Installers may receive a federal tax credit under the Investment Tax Credit program based the fair-market value of leased systems. This may lead to misreporting of prices as alledged by the US Treasury. http://www.renewableenergyworld.com/rea/news/article/2012/10/treasury-dept-fingers-solarcity-in-exploration-of-the-dark-underbelly-of-solar-leasing.

[28] Of course, the effect of rebates on consumer prices requires an understanding of subsidy pass-through, which may vary from market to market. Here by focusing on the equilibrium effect of rebates, we implicitly lump pass-through into an overall effect of changing rebate levels on adoption.

mean effects u

increase of $0.10 in the rebate rate corresponds to a 14.4 percent increase in the daily installation rate.[32] To get a sense for the size of the incentive change, a $0.10 increase in the rebate rate equals an increase in the total rebate awarded from $6,193 to $6,728 for the mean installation in this sample rated at 5.35 kW. Comparing across estimation strategies, the *OLS* and *Poisson* models produce mean effects of similar magnitudes. An increase in the rebate of $0.10 per Watt is associated with mean effects of 11.8 percent and 14.3 percent in the more flexible specification and 1.6 percent and 1.7 percent when assuming common time-effects.

The differences in estimates across columns 1-3 and 4-6 of Table 4 suggest that controlling

rate.

in rebate. We see that dropping weeks immediately before and after each rebate change results in somewhat larger estimates of the effect of the rebates of approximately 14.6 percent and 15.0 percent for a $0.10 change in the rebate level. Excluding observations 8 weeks and 12 weeks before and after each change suggests slightly smaller estimates of 10.9 percent and 11.6 percent. These results seem consistent with the type of anticipatory behavior we observed in Figures 4(a) and 4(b). Overall, the relationship between rebates and adoptions seems fairly robust to the short-run effects around rebate changes.

One may worry that our use of utility daily level data may ask more of our identification strategy than is necessary. In particular, aggregation ignores potential spatial variation in solar preferences, an indicator variable for each two-year period. Table 6 shows the results of this exercise. The point estimates vary from 1.826 early in the sample to 0.835 in the period from 2011 through 2012. The similarity of our estimates across the different samples suggests that the our results may generalize more broadly to all of PG&E and SCE.

To investigate the overall impact of the CSI we would like to use data on all installations from each of the three participating IOUs. Column 5 shows the estimated relationship between rebates and installation rates using data from all zip codes and all three utilities. We see that the point estimate is somewhat smaller at 1.223 suggesting that a $0.10 increase in the mean rebate level implies a 13.0 percent increase in daily installations. Comparing with the 20-mile sample, here a $0.10 increase in the rebate rate equals an increase in the total rebate awarded from $5,600 to $6,070 for the mean installation in this sample rated at 4.60 kW. However, since the percentage effects are quite similar to those in the various PG&E and SCE samples, we use the estimates from all three IOUs in our calculations of the overall program impacts.

the large number of rebate changes, adoptions shifted forward in time to take advantage of higher rebates are in a sense borrowed from a later time period and would have still occurred under the program, albeit several weeks later. Therefore, we ignore these effects when calculating the overall impacts of the CSI. To predict the total number of installations under the CSI program we use the parameter estimates from the sample including all three IOUs, *i.e.* column 5 of Table 7. We then compare the predicted number of installations with a counterfactual prediction assuming no rebates. In each case, we generate the predicted number of installations (*i.e.* $\hat{f}_{u;t} = exp(X_{u;t} \quad))$ assuming either the actual CSI rebate or zero rebate then sum over all utilities and all prior periods to calculate the total number of installations to date. Figure 5 shows the results of this exercise where cumulative installations are plotted over time using actual installations, predicted installations under the CSI rebate levels and predicted installations without rebates. Predicted installations follow the actual CSI installations quite closely, beginning with zero in 2007 and growing to approximately 99,000 total installations by October 2012. The counterfactual case assuming no rebates illustrates the large effect of the CSI on installations. Here, the overall growth in installations is much more modest, reaching a maximum of approximately 41,000 installations by October 2012. This suggests that the effect of CSI was quite large, resulting in over 57,000 additional installations or approximately 58 percent of total installations.

These results suggest substantial increases in private surplus due to a greater number of adoptions and subsidy payments for installations that would have occurred without rebates. For inframarginal installations, the CSI generates pure rents that given the size of the rebates awarded may be substantial. However, estimating the welfare effects of the CSI is difficult without knowing the nature of competition in the installation market and the underlying marginal cost and demand curves. To learn something about costs and benefits from the CSI we make the following assumptions. We define private surplus as the sum of consumer and producer surplus. Social surplus is defined as private surplus net of subsidy payments. We estimate the change in private surplus under the CSI by assuming the predicted number of installations with and without rebates fall on the same demand curve.[36] We assume linear demand between these points. In addition, we assume that installers are price takers and marginal costs are linear. While these assumptions are admittedly restrictive, to a first approximation, they allow us to estimate the changes in private and

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[36] Recall that predicted installations are based on our empirical model using a full set of utility by time effects. Here we assume these effects capture changing preferences for solar, peer effects, marketing, mean electricity prices and other potential demand shifters.

social surplus under the CSI using only subsidy levels and changes in the number of installations due to rebates. This approach seems reasonable given the limitations of our data, however, several qualifications are warranted. First, the true surplus changes depend on the shapes of demand and marginal costs, which are unlikely to be linear. Second, if there is market power in the installation market, CSI subsidies may act to reduce deadweight loss from market power. In this case, our calculations would overstate the social cost of the CSI.[37]

we remain agnostic to the incidence of the subsidy and instead focus on the overall changes in social and private surplus.[40]

A final issue relates to the possibility that the financing of CSI rebates creates additional distorimately 61 percent of installations during this period. Total subsidy payments are approximately \$392 million and lead to an increase in private surplus of approximately \$235 million including \$78 million in rents for inframarginal installations. The total decrease in social surplus is approximately \$157 million.

One of the main justifications for incentivizing solar is that additional PV capacity lowers emissions associated with electricity generation. We use the predictions above to estimate reductions in CO_2 and NOx emissions due to the CSI. To do this we assume that none of the additional installations under the CSI would have occurred otherwise at some point in the future. That is to say, the rebates create new adopters and don't simply result in the temporal shifting of future adoptions to the present. This assumption is conservative in the sense that it creates the largest possible benefit for the CSI. For simplicity, we assume PV systems have a 20-year system life and ignore discounting.[43] We assume a PV capacity factor of 0.18 and use two scenarios for the emissions of electricity generation displaced by solar installations.[44] In the first scenario we use average CO_2 and NOx emissions rates for electricity generation. In the second scenario, we note that the solar generation profile is more likely to coincide with periods of peak electricity demand (Borenstein, 2008). We also use two sources for average and marginal emissions rates. Graff Zivin, Kotchen, and Mansur (2013) derive emission rates for the Western interconnection (WECC) using the US EPA's continuous emissions monitoring data for fossil-fuel electricity generating plants. To approximate the peak period, we average the Graff Zivin, Kotchen, and Mansur (2013) estimates over the period from 10am to 4pm.[45] Second, because WECC as a whole may be dirtier than California, we use California average emissions rates from eGRID (2009). We approximate peak emissions using annual \non-baseload" emissions rates.

Results of these calculations are summarized at the bottom of Table 9. Total solar capacity increases by approximately 260 MW. At the average emissions rate, total emissions savings are approximately 2.98 MMT CO_2 using the WECC rate and 2.45 MMT CO_2 using the California

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[43] The assumption of zero discounting is conservative given that it weighs equally system costs, incentives and benefits that accrue over many years of operation and treats equally carbon emissions reductions today and at the

average. Assuming solar displaces primarily peak generation, the estimated CO_2 emissions savings range from 3.15 MMT to 3.70 MMT. As before, the righthand side of Table 9 summarizes results when installations in SDG&E are excluded. In this case, estimated emissions reductions are between 2.26 and 3.41 MMT CO_2. To get a sense for the size of these emissions reductions, the 260 MW of solar electricity capacity times the assumed capacity factor translates into approximately 50 MW in effective capacity. The emissions rates we use here closely represent natural gas generators in California. Since gas fired plants in California range in size from several MW to several hundred MW, with median size of about 20 MW, these emissions reductions are comparable to removing a small to mid-sized gas plant. Arguably, these savings are modest but still non-trivial.

In terms of costs, a common measure of cost-effectiveness is program cost, here subsidy payments, per unit of abatement. Table 9 shows that average program costs range from \$139 per MT to \$147 per MT CO_2 assuming WECC emissions and \$118 per MT to \$178 per MT CO_2 using California values. However, this calculation ignores the benefits of rebates to consumers and installers. Instead we use average abatement cost, defined as the total change in social surplus divided by the total change in CO_2 emissions, as our measure of the economic cost of carbon reductions under the CSI. Average abatement costs in Table 9 range from approximately \$54 per MT to \$57 per MT (WECC) and \$46 per MT to \$69 per MT (California). In comparison, the Interagency Working Group on Social Cost of Carbon, United States Government (2013) estimates the social cost of CO_2 under a variety of assumptions. Their mean values for 2010 range from \$11 to \$52 per MT depending on the social discount rate. This suggests that the costs of CO_2 abatement under the CSI may exceed the benefits of lower emissions.[46]

For NOx, the total estimated emissions savings over 20 years range from 1,195 to 1,866 MT for all three IOUs depending on our assumption about the emissions rate of generation displaced by solar. When installations in SDG&E are excluded, emissions savings range from 1,100 to 1,718 MT. Across the scenarios, average abatement costs range from \$91,000 and \$142,000 per ton of NOx. These costs are quite high. During the California electricity crisis, permit prices under Southern California's NOx trading program peaked at \$62,500 per ton. After the crisis, permit prices ranged between \$2,000 and \$3,000 per ton (Fowlie, Holland, and Mansur, 2012). This suggests NOx abatement

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[46] Interestingly, even if the displaced electricity had the emissions rates of peak ERCOT or Eastern interconnection estimates (Graff Zivin, Kotchen, and Mansur, 2013), average abatement costs would still be approximately \$49 and \$37 per MT, respectively.

costs under the CSI are substantially higher than abatement costs for other technologies. Similarly, abatement costs exceed NOx damages, around $200 per ton, according to recent estimates by Muller and Mendelsohn (2009).[47] Of course, these high abatement costs in part reflect the relatively clean electricity displaced by solar installations in California. Residential PV would have a larger effect on NOx emissions in places like the US Midwest where peak NOx emissions rates can be 5 to 10 times larger. Holding constant electricity generation and using an emissions rate 10 times larger than our California peak estimate still suggests costs on the order of $10,000 per ton.[48]

Some qualification of the results above is warranted. First, the calculations above can be thought of as a near-term analysis that holds fixed factors such as load, generation and the configuration of the electricity grid. Second, additional solar generation capacity may create other benefits such as reduced grid congestion, improvements in air quality and lower marginal generation costs. Here we abstract from these other potential benefits and instead focus on CO_2 and NOx costs to allow the reader to compare the CSI with other programs to reduce emissions.[49] Third, we ignore the possibility of peer effects such as those documented by Bollinger and Gillingham (2012) which may amplify or diminish the effect of rebates. Fourth and perhaps most important, some proponents of solar subsidies argue that incentives are justified due to learning economies. Our counterfactual above assumes learning is negligible and therefore would underestimate the overall effect of the CSI on adoptions if learning effects are large.

While estimating the effect of learning is beyond the scope of this paper, we provide the following evidence that our assumption of little learning is justified. First, learning implies a reduction in marginal costs as the industry streamlines production and installation processes. In terms of materials, over 50 percent of the final installed cost of a system is due to modules and other components for which prices have fallen considerably over the past decade.[50] However, the market for these components is global, and learning likely depends primarily on total experience. California PV adoptions, particularly installations attributable to the CSI program, account for only a small percentage of the global PV market. As of 2012, approximately 100 GW of PV capacity had been

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[47] We use the median across California counties as reported in Appendix B of Muller and Mendelsohn (2009).

[48] This calculation is optimistic as these locations may also have less solar generation potential than California.

[49] For a more thorough discussion of these issues we refer the reader to Borenstein (2008) and Baker et al. (2013).

[50] The Solar Energy Industries Association reports a 60 percent decrease in average solar panel prices between 2011 and 2012, http://www.seia.org/research-resources/solar-industry-data

installed worldwide,[51] of which about 0.5 GW had been installed in our study area with only 0.3 GW attributable to the CSI. Given that the CSI accounted for less than half a percent of the worldwide PV market, any learning effects of the CSI on lowering component costs are likely small. Moreover, recent studies by Nemet (2006) and Papineau (2006) find little evidence for learning in module costs.

Learning could also bring down labor and overhead costs associated with installation which account for approximately 25 percent of installed system cost.[52] Baker et al. (2013) summarize recent estimates of learning-by-doing in the PV market and find learning rates of approximately 20 percent. This implies that a doubling of cumulative installed capacity, a proxy for experience, results in a 20 percent decrease in costs. Given our finding that the CSI roughly doubled adoptions during our study period, a 20 percent learning rate implies a 20 percent decrease in labor and overhead costs through learning. Since these costs contribute roughly 25 percent to final system prices, this translates to a 5 percent decrease in system price due to learning. In short, the incremental effect installations would have occurred during this period.

To understand the overall impacts of the program we estimate changes in emissions and private surplus under the CSI in a series of back of the envelope calculations. We find that benefits to consumers and installers appear large. Of the approximately \$437 million in rebates paid during this period, private surplus gains to installers and adopters are approximately \$268 million. Because subsidies for green technologies are often motivated by energy or environmental goals, we estimate the overall increase in PV capacity and reduction in CO_2 emissions under the program. We find that solar capacity increases by approximately 260 MW relative to a counterfactual assuming no rebates. Emissions of CO_2 are between 2.98 million MT and 3.15 million MT lower due to the program. Similarly, we predict NOx emissions over 20 years fall between 1,100 and 1,900 MT. However, these emissions reductions are costly. Comparing the estimated change in social surplus to emissions reductions suggests average abatement costs between \$46 per MT to \$69 per MT CO_2 and \$91,000 and \$142,000 per MT of NOx.

In terms of program design, a key feature of the CSI is the declining schedule of rebates over time. This appears to have been motivated by the expectation that PV system prices would fall, potentially leading to a larger market for solar systems later in program. Our results in Table 6 provide some evidence consistent with this idea, namely that changes in rebates later in the sample appear to have a larger effect on average daily installation rates in levels. Whether this is the effect of lower prices, third party installers, federal tax credits, stronger environmental preferences or more familiarity with solar technology remains an open question. Nevertheless, this design feature may have reduced the overall cost of the program by allowing CSI to pay lower rebates later in the program.

To explore this issue we compare total rebate payments under the CSI with a constant rebate designed to produce the same total number of installations. Using our three period model, the rebate required to achieve the same total number of installations is approximately \$0.71 per Watt. At this level, the overall expenditure on rebates would have been \$329 million compared with \$437 under the actual program. In hindsight, the CSI may have achieved similar results with a constant rebate for over \$100 million less. That said, the declining rebate schedule did have the advantage of reducing year-to-year variation in rebate payments, which may have simplified planning and administration. Because fewer installations took place during the early (late) years when rebate rates were high (low), annual rebates awarded ranged between $60 and $100 million compared with $2 to $175 in our constant rebate case. Of course, another potential advantage of the CSI declining rebate schedule over constant rebates is that more adoptions were encouraged early in the program. This featureepsup(p)-28(rte)de56(early)-415(instlleris)-401thor ii(tial)-405(p)-28eriop of

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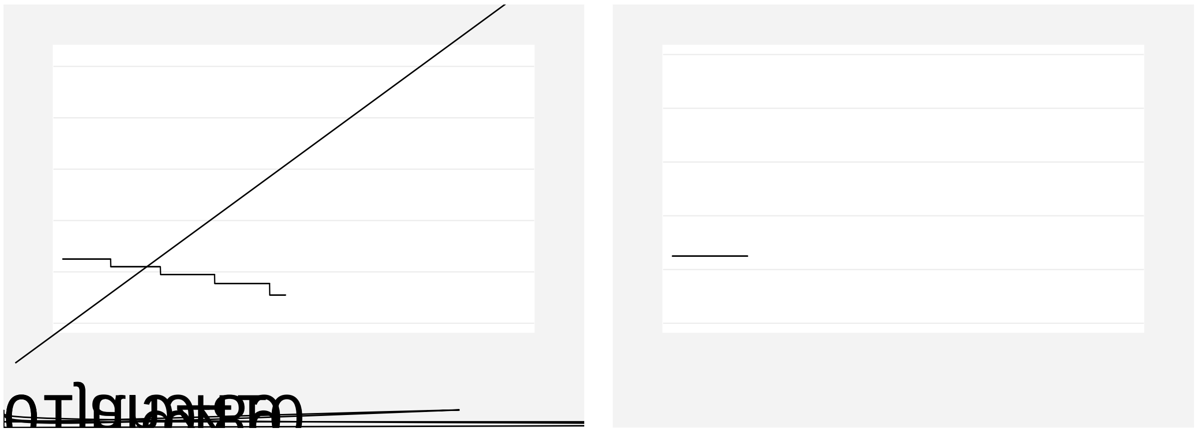
8 Figures

Figure 1: Total CSI residential PV installations and population density by zip code.

Figure 2: Average rebates, system prices and installations for Pacific Gas and Electric (PG&E), Southern California Edison (SCE) and San Diego Gas and Electric (SDG&E).



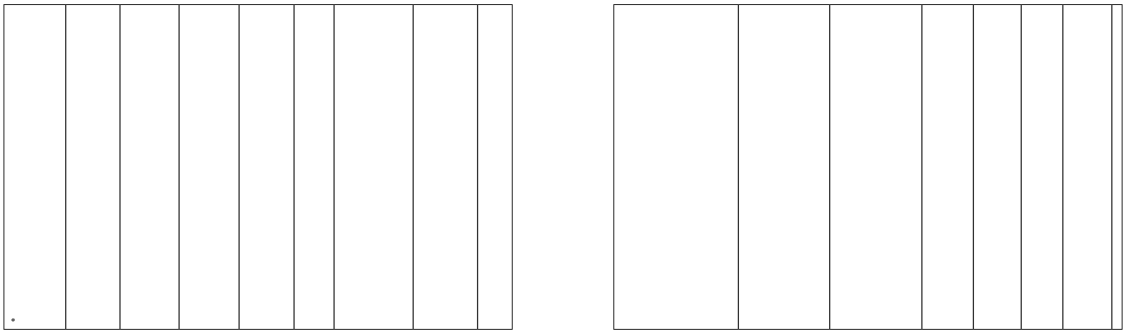
(a) PG&E

(b) SCE

(c) SDG&E

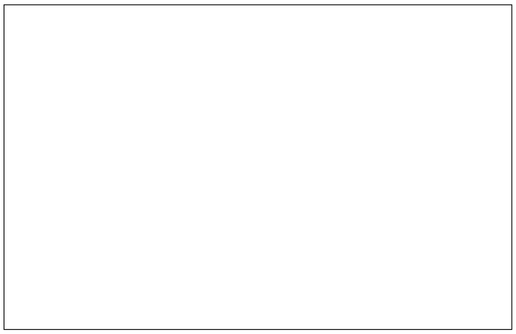
Figure 3: Map of PG&E, SCE and SDG&E territories and the PG&E-SCE boundary region. Zip codes included in the 20-mile buffer sample are darkly shaded in the righthand figure.

Figure 4: Total installations per day for Pacific Gas and Electric (PG&E), Southern California Edison (SCE) and San Diego Gas and Electric (SDG&E).



(a) PG&E

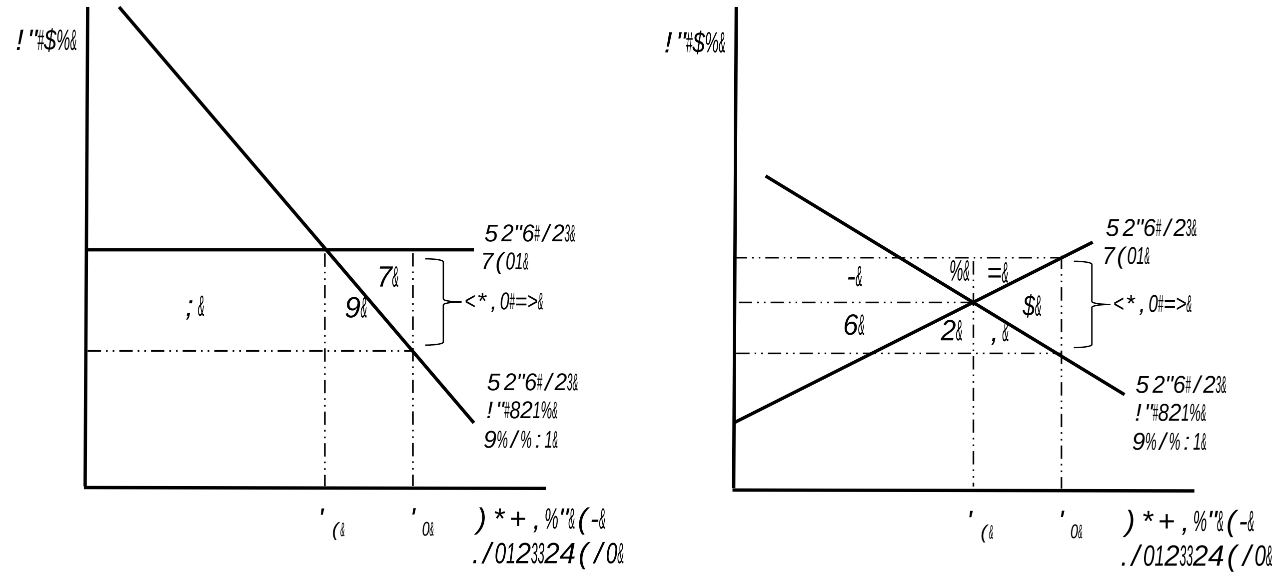
(b) SCE



(c) SDG&E

Figure 5: Predicted total PV installations and counterfactual installations assuming no CSI

Figure 6: Welfare effects of CSI program rebates in terms of changes in private and social surplus.



9 Tables

Table 1: CSI rebate rate schedule for EPBB program by utility.

Table 2: Summary statistics for the full sample and the 20-mile corridor.

	Mean	**Std. Dev.**	**Max.**	**Min.**
		Full Sample		
PG&E				
total rebate ($)	4,002	4,950	137,895	53
rebate rate ($/W)	1.21	0.82	2.50	0.20
total system cost ($)	36,474	24,925	1,028,017	0
CSI rating (kW)	4.46	2.82	71.55	0.27
installation rate (num./day)	23.40	24.57	280.00	0.00
total installations	49,866			
SCE				
total rebate ($)	5,291	5,069	137,216	252
rebate rate ($/W)	1.72	0.72	2.50	0.25
total system cost ($)	37,377	21,109	483,784	0
CSI rating (kW)	4.77	2.67	54.88	0.72
installation rate (num./day)	16.39	21.11	186.00	0.00
total installations	34,925			
SDG&E				
total rebate ($)	3,612	4,382	106,240	201
rebate rate ($/W)	1.28	0.89	2.50	0.20
total system cost ($)	35,864	20,256	396,560	1,400
CSI rating (kW)	4.72	2.74	48.29	0.80
installation rate (num./day)	6.07	7.92	83.00	0.00
total installations	12,939			
		20-mile corridor		
PG&E				
total rebate ($)	4,572	4,925	40,710	349
rebate rate ($/W)	1.21	0.82	2.50	0.20
total system cost ($)	42,990	23,211	191,787	4,898
CSI rating (kW)	5.68	2.94	28.51	1.02
installation rate (num./day)	0.56	1.03	8.00	0.00
total installations	1,192			
SCE				
total rebate ($)	6,175	5,537	63,954	383
rebate rate ($/W)	1.72	0.72	2.50	0.25
total system cost ($)	39,224	21,844	226,781	3,000
CSI rating (kW)	5.19	2.79	34.14	0.97
installation rate (num./day)	0.85	1.40	11.00	0.00
total installations	1,804			

Table 3: Observable household characteristics by geographic region.

Table 4: Effect of California Solar Initiative (CSI) rebate rates on the daily PV installation rate near the PG&E and SCE boundary.

	(1) OLS	(2) Poisson	(3) Neg. Binomial	(4) OLS	(5) Poisson	(6) Neg. Binomial
Rebate rate ($/W)	0.116	0.170***	0.211	0.829	1.337**	1.346**
	(0.1520)	(0.0540)	(0.1740)	(0.4210)	(0.6060)	(0.6550)
Confidence interval (95%) % change in install rate	[-1.817,2.049]	[0.065,0.275]	[-0.131,0.552]	[-4.518,6.176]	[0.149,2.525]	[0.061,2.630]

Table 5: Robustness to excluding periods near rebate step changes for installations in the 20 mile region near the PG&E and SCE boundary.

			C D		
	(1)	(2)	(3)	(4)	(5)
	B	**2 .**	**4 .**	**8 .**	**12 .**
Rebate rate ($/W)	1.346**	1.361**	1.401**	1.034***	1.095**
	(0.6550)	(0.6270)	(0.6320)	(0.3160)	(0.4280)
Confidence interval (95%)	[0.061,2.630]	[0.133,2.589]	[0.163,2.640]	[0.415,1.652]	[0.257,1.933]
% change in install rate	14.4%	14.6%	15.0%	10.9%	11.6%
Year Effects	No	No	No	No	No
Quarter Effects	Yes	Yes	Yes	Yes	Yes
Utility Effects	No	No	No	No	No
Year*Utility Effects	Yes	Yes	Yes	Yes	Yes
Observations	4262	3865	3459	2647	1835

Notes: Dependent variables are the total daily PV installation rates in number per day by utility for zipcodes within 20 mile buffer. Base model includes all observations. "2 week," "4 week," "8 week," and "12 week" models drop observations within 2, 4, 8, and 12 weeks of each change in rebate level. Percentage change in installation rate calculated for a $0.10 increase in the rebate rate at the mean values of independent variables. Standard errors clustered at the utility level. ***, ** and * denote significance at the 1 percent, 5 percent and 10 percent levels.

Table 6: Effect of California Solar Initiative (CSI) rebate rates on the daily PV installation rate

Table 7: Robustness of main results across different geographic samples.

	(1)	(2)	(3)	(4)	(5)
	All PG&E and SCE Zip Codes	40 mi.	20 mi.	Split Zip Codes	All IOUs

Table 8: Effect of rebates on average daily installation rates by utility.

Rebate rate ($/W)	1.417*** (0.0530)	1.118*** (0.0790)	1.150*** (0.0370)
Confidence interval (95%)	[1.314,1.521]	[0.964,1.272]	[1.077,1.223]
% change in install rate	15.2%	11.8%	12.2%
Year Effects	No	No	No
Quarter Effects	Yes	Yes	Yes
Utility Effects	No	No	No
Year*Utility Effects	Yes	Yes	Yes
Observations	6393	6393	6393

Notes: Dependent variables are the total daily PV installation rates in number per day by utility for all zipcodes within PG&E, SCE and SDG&E territories. Percentage change in installation rate calculated for a $0.10 increase in the rebate rate. Standard errors clustered at the utility level. ***, ** and * denote significance at the 1 percent, 5 percent and 10 percent levels.

Table 9: Installations, capacity, carbon emissions and social surplus under the California Solar Initiative.

Appendix

As a robustness check on our main specification, we repeat our analysis using zip code daily installation data in place of our utility level aggregate data. These results are shown in Appendix Table 1. Column 1 uses only quarter and utility by year time effects. Because solar preferences may depend on local demographic factors, column 2 adds zip code level demographics. Column 3 adds observable characteristics of the local housing stock. Finally, column 4 replaces zip code controls with mean effects. Across all four specifications the estimated relationship between CSI rebates and PV installations is quite similar to our main results. A $0.10 per Watt increase in the rebate rate is associated with a 13.0 to 13.3 percent increase in the average daily adoption rate. In

Appendix tables

Table 1: Effect of California Solar Initiative (CSI) rebate rates on the daily zip code-level PV installation rate near the PG&E and SCE boundary.