

Valuing Solar Subsidies

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Sustainable and "green" goods often require up-front investment

- EVs
- Solar panels

Benefits are a "flow" over time

Focus on Solar Net metering incentive

- During sunny periods, "spin the meter backwards"
 - Offsets consumption after sunset, lowering total amount billed.
 - Depending on "true-up period", can bank net-negative months
 - Utility acts like a *battery*, banking during day, offsetting at night.

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- Effect on bill
 - Under **increasing block-tier pricing**, net metering allows consumer to sell power to the utility at the retail rate the consumer faces
 - If each kWh reduces bill by higher tier rates that are above wholesale rates, then net metering is a **flow (monthly) subsidy**

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- Solar households pay far less, even when depending on grid electricity.
 - Fixed costs are often included in per-kWh retail prices, thus there could be a cost-shift to non-solar households.

Solar Net Metering provides a flow benefit to solar adopters

- May be rationalized by reduction in externalities
 - Probably not: Sexton et al. (2021)
- Learn-by-doing:
 - Only partly: Bollinger and Gillingham (2019)
- Long-run innovation incentives:
 - Some, but second-best approach Gerarden: (2017)
- Nevertheless, it continues

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NPV of flow payoff depends on household discount rate

Household **heterogeneity** in rate → different NPV for adoption

Discount rate may explain differences in solar adoption across wealth and income

- Bednar, Reames, and Keoleian (2017) show lower-wealth households tend to spend *more* on electricity per sq ft
 - Borenstein and Davis (2016) top quintile of income received 60% of all federal tax benefits
 - Sunter, Castellanos, and Kammen (2019)
 - O'Shaughnessy et al (2020) on income inequity in solar adoption
 - O'Shaughnessy (2022) and Borenstein (2022) in *Nature Energy*

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Policy lever: put the subsidy up front

- Increase efficiency with up-front subsidies
- If discount rates vary systematically → less disparity in solar uptake.
- Many states working on new versions of net metering
- Any proposed reform requires understanding effect of flow vs. up-front subsidies by wealth or income

Discount rates in energy investments: Energy-Efficiency Gap

- Large literature finding implicit discount rates between 10% and 30+%
- Hausman (1979); Busse, Knittel, and Zettelmeyer (2013); Bollinger (2015); see Train (1985) for early summary

Discount rates in solar panel adoption

- de Groote and Verboven (2019) find 15% implicit discount rates
 - Identified using dynamic model of installation shares in Belgium with time variation in per-kWh-produced subsidy, panel costs
 - Abstracts away from household variation in cost, potential generation.

Discount rates over wealth

- Lawrence (1991) - 12-20% using PSID
- Houde and Myers (2021) find heterogeneity in valuation of flow energy costs relative to up-front costs
 - Uses zip-level aggregate purchases and wealth; county-year level variation in energy costs

This paper

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Estimating discount rates requires variation that changes expected discounted future utilities without affecting current period utility (Magnac and Thesmar (2002))

- Household variation in flow incentives (payoff) comes from:
 - Variation in electricity rates over *location*
 - Variation in electricity rates over *time*
 - Variation in consumption levels over *household*
 - **Variation in potential generation over household**

Empirical Setting

- California under NEM 1.0 (2014-2016)
 - Post-expiration of CSI subsidies

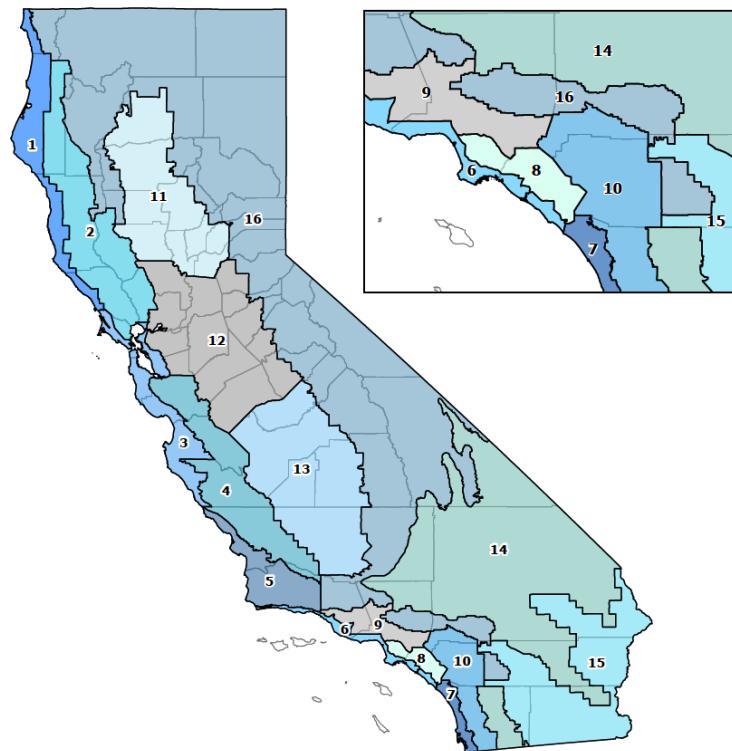
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Roadmap

1. Sources of identifying variation & data
2. Model
 - Optimal sizing
 - Adoption
 - Quasi-unobserved heterogeneity in consumption
3. Estimation
4. Results

Sources of Identifying Variation

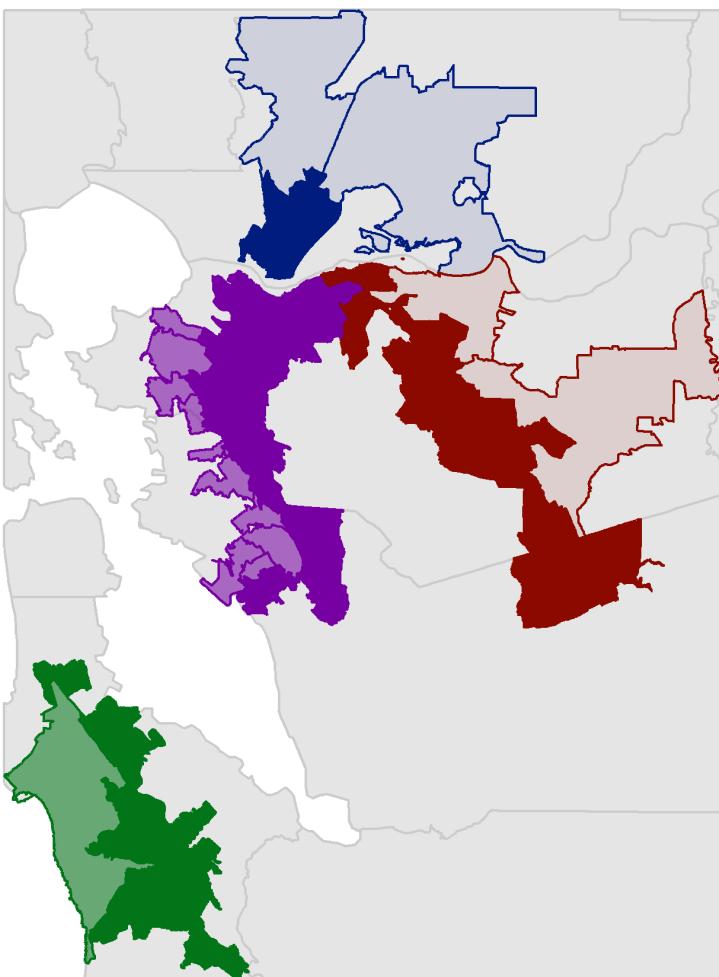


Climate zones allow different thresholds for block pricing steps.

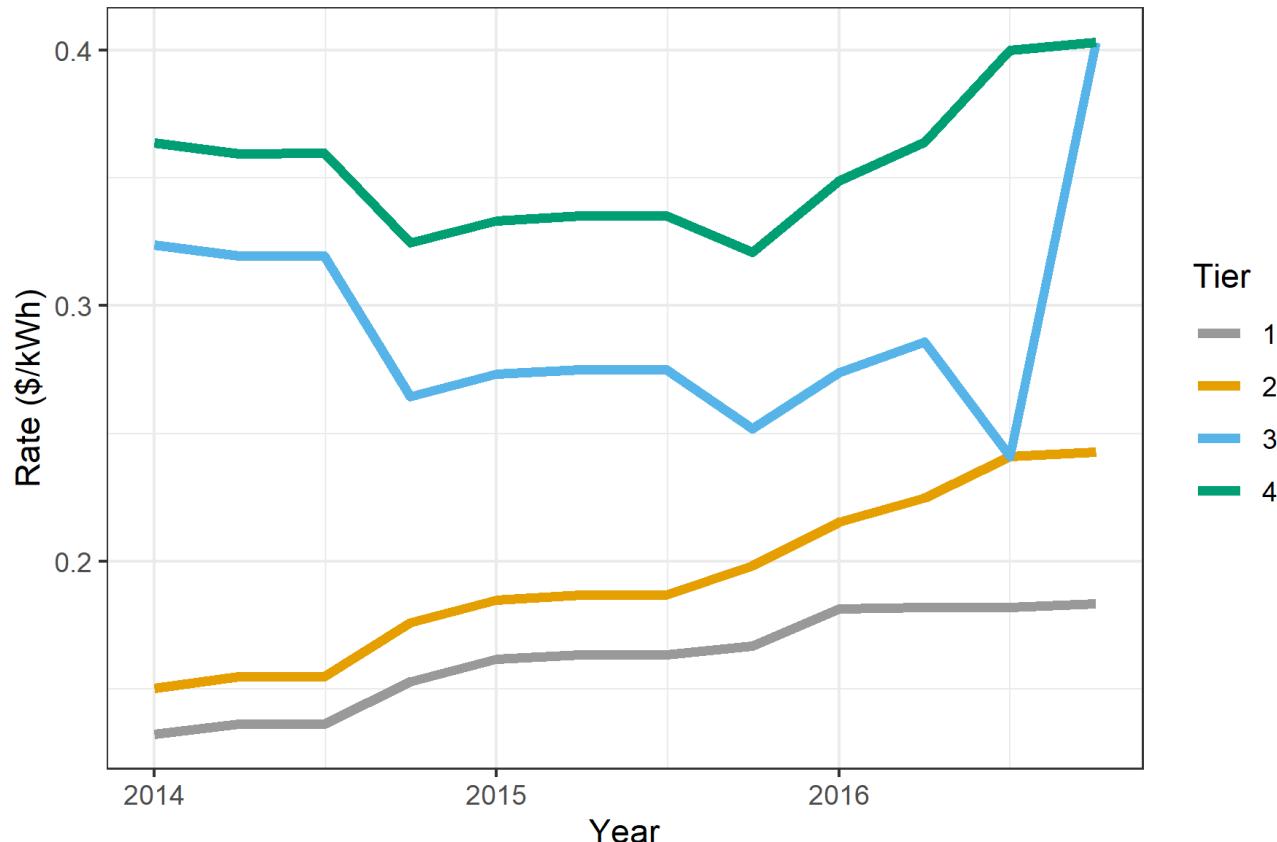
- Two identical households with identical consumption on each side will face different marginal prices, different average prices, different payoff from solar.
- Rates (at each of 4 tiers) change over time.

Identifying Variation

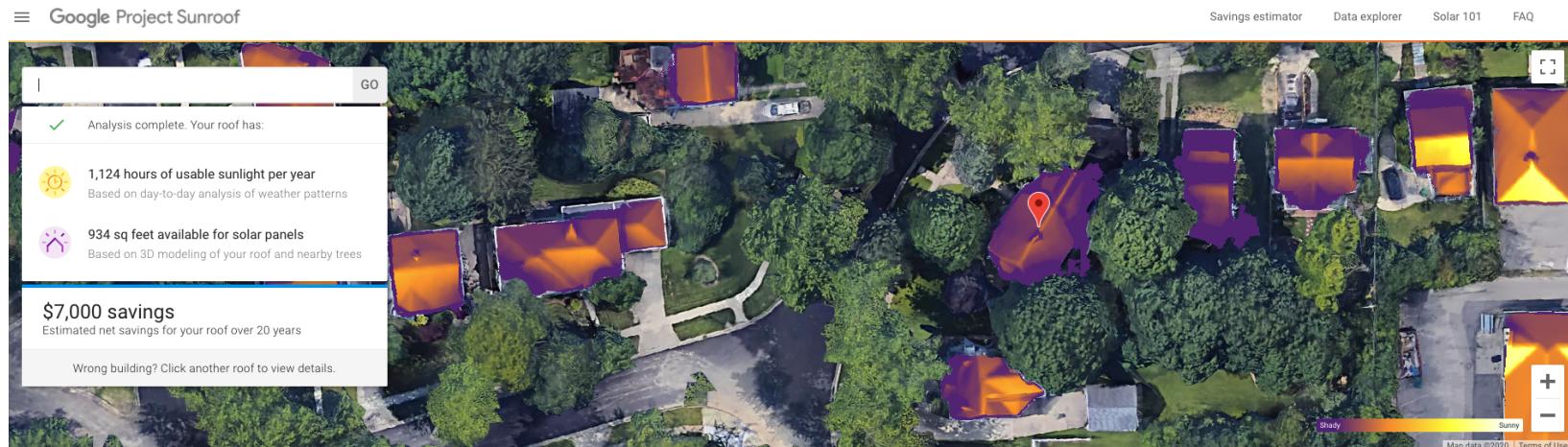
Rate zone boundaries from Bollinger, Gillingham, Kirkpatrick, and Sexton (2017)



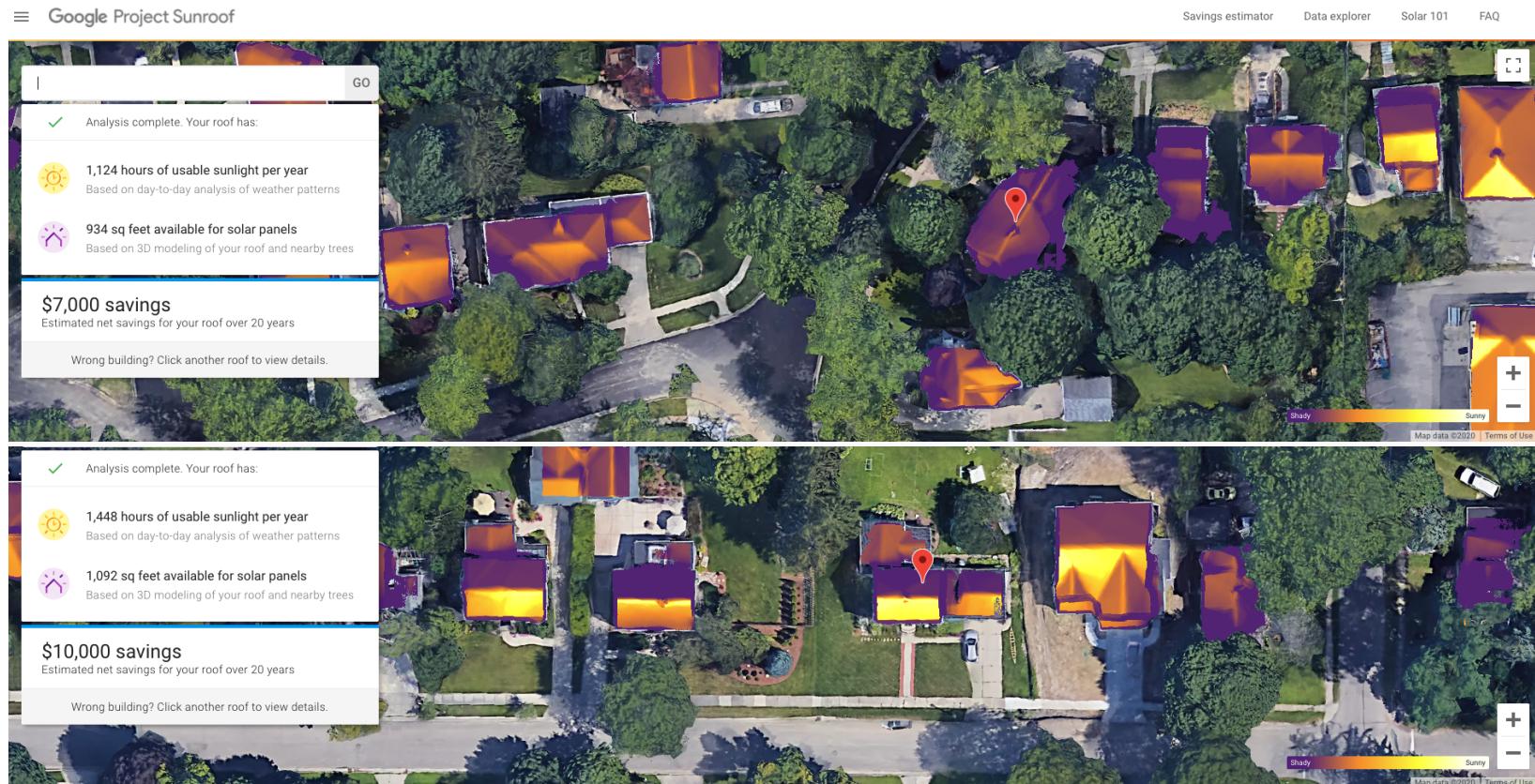
Rates: California has 4 (later 3) tiers of pricing during study window.



Variation in cost per kWh of solar generation using Google Project Sunroof

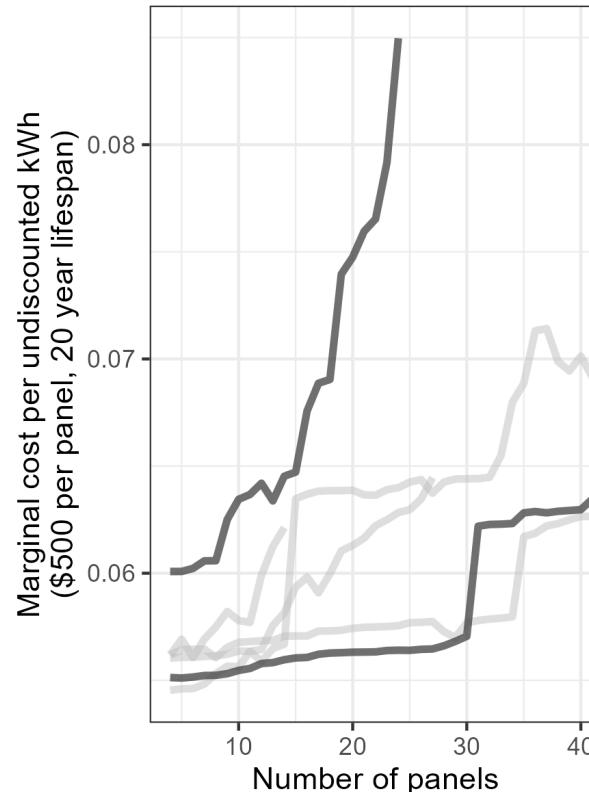
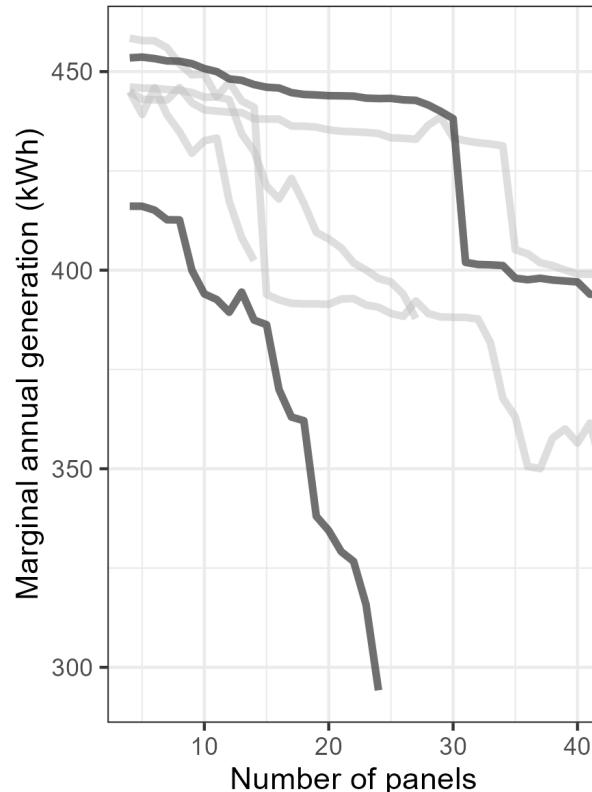


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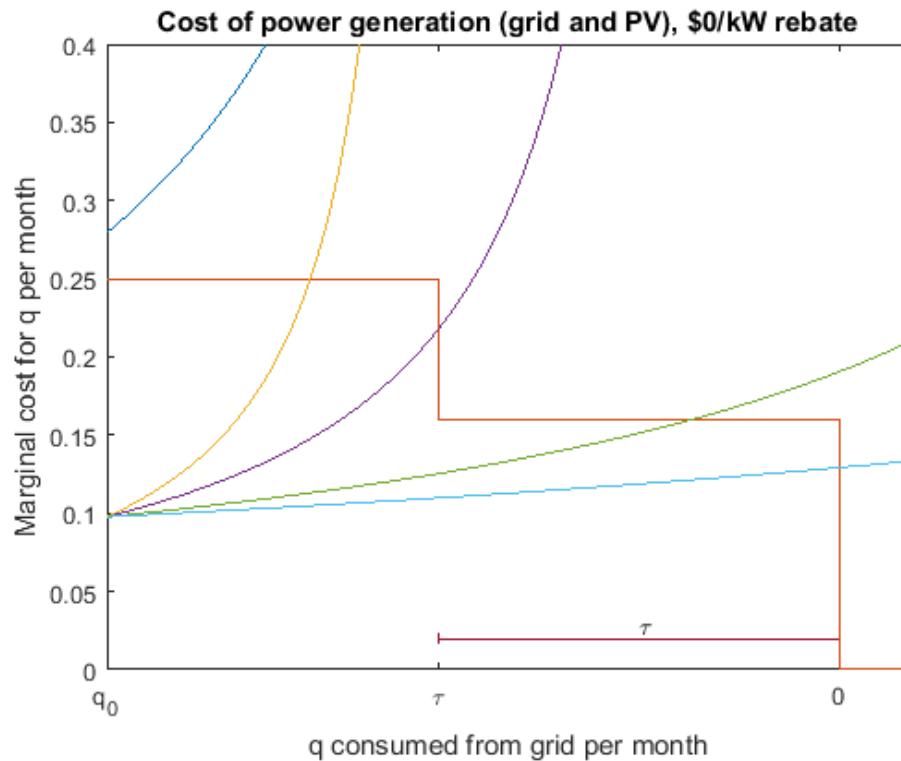
Google Sunroof roof irradiance

- Marginal generation of each 250w panel (weakly decreasing-ish)
- Converting generation to marginal cost requires fixing discount rate
- Roof irradiance affects optimal size and flow payoff



Optimal Sizing Model

Optimal sizing

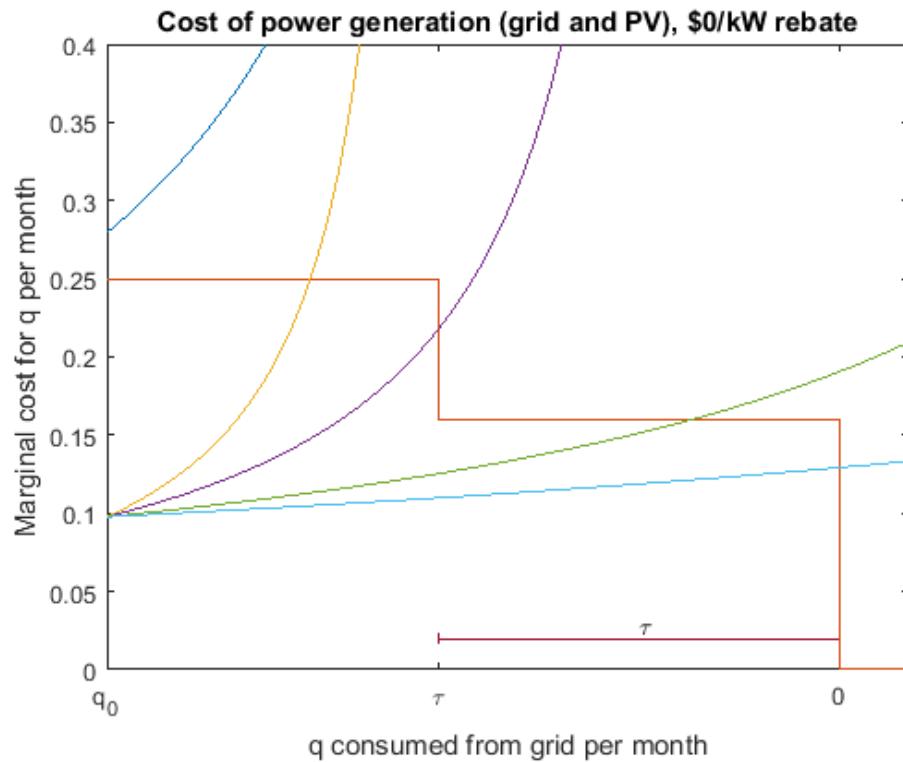


1. Dark blue is a shady roof
2. Yellow-orange is a sunny roof with few high-irradiance segments
3. Purple is a sunny roof with moderate high-irradiance segments
4. Green is a sunny roof with many high-irradiance segments
5. Light blue is a sunny roof on a flat, south-oriented roof.

Example is two-tier pricing with step at τ .

Increasing q^0 slides steps to right.

Optimal sizing



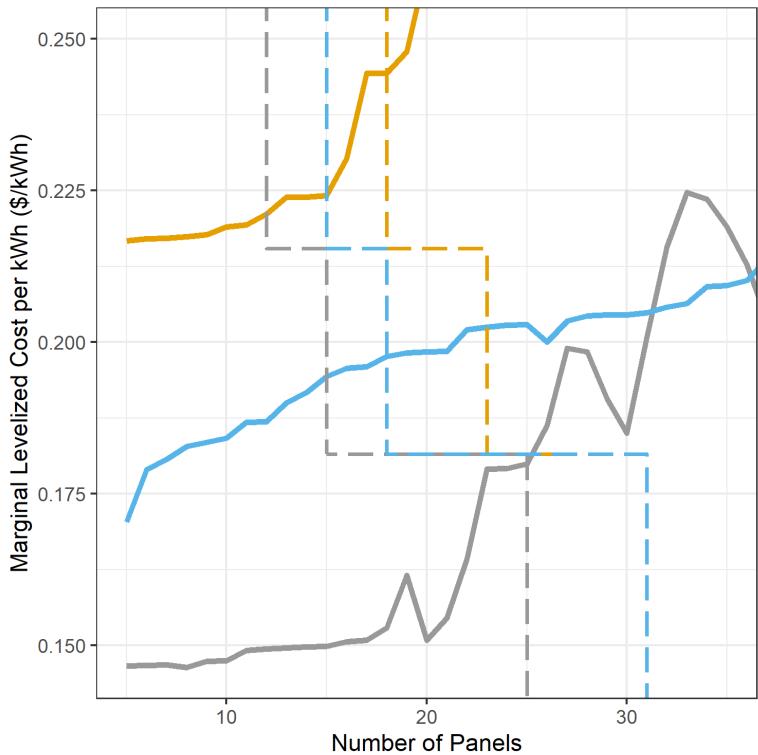
Given consumption, rate structure, and Google Sunroof profile, find capacity K^* to install.

1. Calculate marginal cost per kwh of solar generation
 - Starts low
 - Increases based on roof
 - Reflects cost of panels
2. Calculate marginal cost per kWh from the grid
 - Based on annual consumption q^0
 - Decreases as solar generation increases
3. Optimal is when

$$MC_{grid} = MC_{solar}$$
 - May be "lumpy" due to steps

K^* is optimal size; q^* is optimal generation; $q^* \bar{p}$ is annual value of generation

Optimal sizing in data



- Location of steps from q^0
- Height of steps from p_t
- Width of steps from climate zone

Data & Model Inputs

Sample of households

- 279k+ owner-occupied households in California 2014-2016 (CoreLogic)
 - Square footage, stories, year built (CoreLogic)
 - Lat-lon (rooftop) from geocoding address
 - **Wealth** (from InfoUSA)
 - Income (from InfoUSA)
 - Lines of credit (from InfoUSA, not used)
 - Owner or Renter (from InfoUSA)
 - Age (from InfoUSA)
 - Race (from InfoUSA)
 - Presence of children (from InfoUSA)
 - Length of residence (from InfoUSA)
 - Voter registration (CA Sec. of State)
- In PGE territory zip codes where
 - All households are in one electricity rate
 - *Border* another zip code where all households are in a different rate

Electricity consumption (PGE)

- Household-level electricity annual consumption (kWh) & rates 2014-2016 with zipcode (PGE)

Solar adopters (LBNL Tracking the Sun)

- 9k+ Solar Adopters
 - **Address**, cost, size, date
 - Lease or purchase
 - Match Interconnection ID to PGE

Google Project Sunroof

- Roof profiles
- Location (lat-lon)

PGE Consumption Data

For **Non-adopters**: we observe complete distribution of consumption at zip level

- Calculate quintiles of consumption in each zip $b \in \{1, 2, 3, 4, 5\}$ (1=lowest)
 - After removing matched solar adopters
 - See consumption bins

For **Adopters**: we observe consumption, q^0 exactly.

- We can match to consumption bin b .

Unobserved Consumption (non-adopters)

For non-adopters, conditional on:

- b_z (consumption level for bin b in zip z)
- Roof profile
- Rates and climate zone

We can calculate:

- K^*
- q^*
- $TC(K^*)$ (inclusive of 30% FTC)
- \bar{p} (average value of offset electricity)
- $q^* \bar{p}$ (flow benefits of adopting solar)

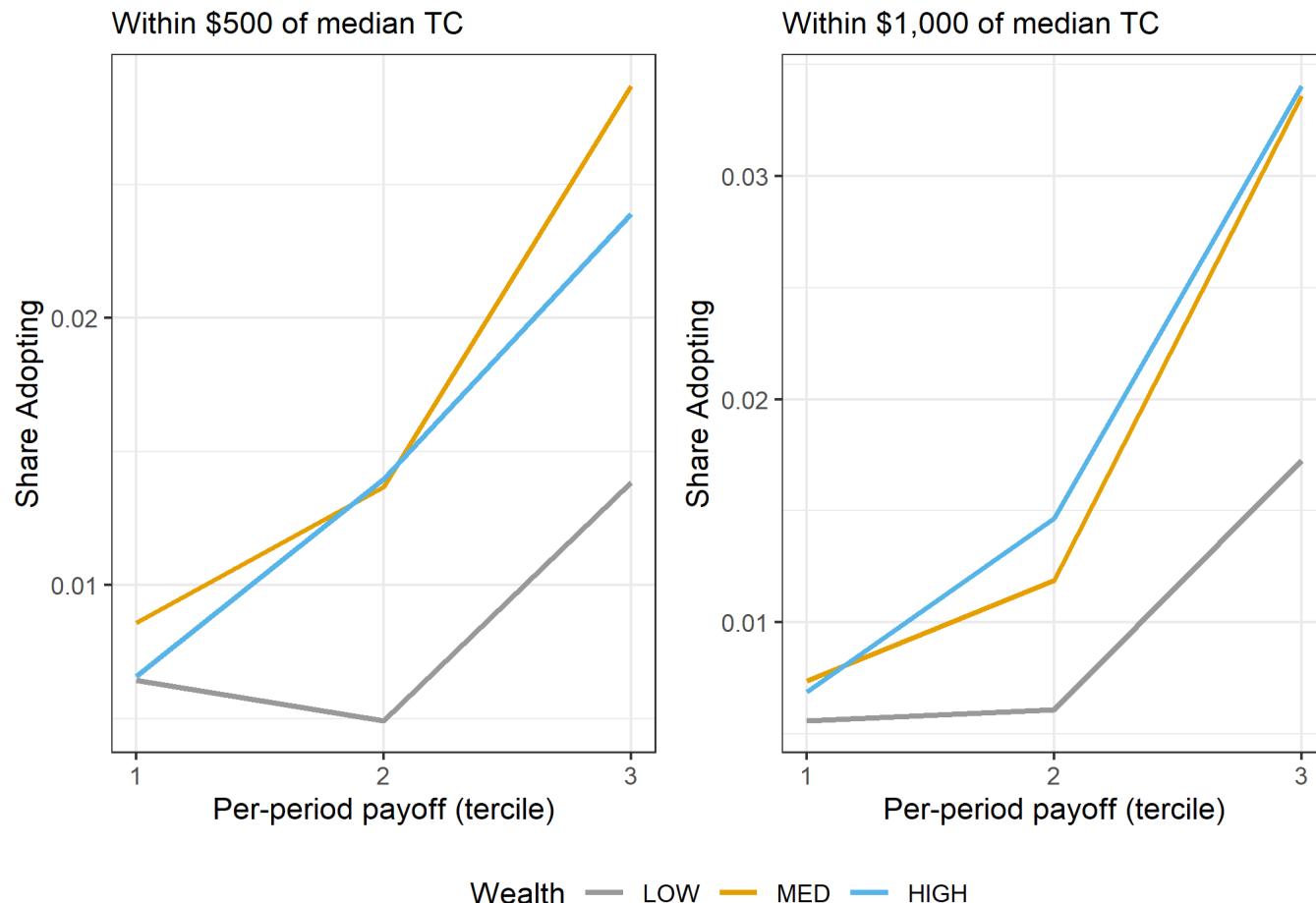
Observed Consumption (adopters)

For adopters, we observe q^0

- Place in bin b_z
- Calculate same as non-adopters

Model Inputs

Model-free evidence of response to flow payoff of optimal-sized installation ($q^* \bar{p}$)



Dynamics: Expectations about future

Panel generation declines by $\lambda = .8\%$ per year (LBNL)

Electricity rate increase over time estimated AR(1) w/ PGE rate data

- Elec. rates increase $\zeta_{bz} \in [.026, .056]$ per year
- ζ_{bz} is estimated using average price (Ito 2014)
 - Average price is a function of consumption b , which varies by zipcode z
 - Future $q^* \bar{p}$ is equal to $q^* \bar{p}(1 + \zeta_{bz})$

Total panel cost declines over time estimated AR(1) w/ LBNL data

- Annual price decline factor: $\eta = .988$
- Fixed cost variation by zipcode z (but common η)

Model

Overview

Modeling demand as consumers make dynamic decisions about whether to adopt.

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Consumers consider:

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- Up-front cost

Dynamics

- Value of waiting depends on state variables
- Differs by rooftop irradiance

Tradeoff between flow and up-front cost differs by:

- Lease vs. own
- Initial household consumption

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Tradeoff between flow and up-front cost differs by:

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Once we account for these, estimate discount rates as a function of household characteristics, primarily wealth.

Utility of adopting:

$$v_1 = \delta_1 + \sigma\epsilon_1$$

$$\delta_1 = \underbrace{\int_{q_0 - q^*}^{q_0} \sum_{t=1}^T \frac{1}{(1+\delta)^{t-1}} p_t(x) dx}_{\text{Discounted value of offset electricity}} - VC(K^*) - FC + X\beta$$

Discounted value of offset electricity

$$\delta_1 = \overbrace{\theta q^* \bar{p}}^{} - VC(K^*) - FC + X\beta$$

$$\text{where } \theta = \sum_{t=1}^T ((1+\zeta)(1-\lambda)\rho)^{(t-1)}$$

- $p_t(x)$ is price (step function)
- T is lifetime of panels (25yr)
- $VC(K^*)$ is the variable cost of adopting
- FC is the fixed cost of adopting
- $\epsilon \sim \text{Type 1 Extreme Value}$

- $X\beta$ includes
 - Age, race, children, voter reg
 - Square footage of home
 - Wealth bins: low/med/high
 - Quarter x Wealth x Lease FE
 - Boundary zone FE

Normalize outside option:

$$\delta_0 = 0 + \sigma\epsilon_0$$

Using Hotz and Miller (1993) Conditional Choice Probability (CCP) leads to:

$$\begin{aligned}\delta_1 - \delta_0 = & (1 - \rho(1 + \zeta))\theta q^* \bar{p} - (1 - \rho\eta)VC(K^*) - (1 - \rho)FC + \\ & (1 - \rho)X\beta + \sigma\rho(\log(Pr'_1) - .5772)\end{aligned}$$

This produces the familiar logit form for the probability of adopting, and the likelihood function.

Heterogeneity in discount rate by wealth

$$\rho_i = \alpha_0 + \alpha_1 \mathbf{1}(\text{wealth}_i = \text{med}) + \alpha_2 \mathbf{1}(\text{wealth}_i = \text{high})$$

ρ is a function of observables (wealth) to allow for heterogeneity in discount rate by wealth.

Three main issues

- Pr_1' is household-specific
 - Cannot subsume into intercept as different roof profiles will have different adoption probabilities
- A large number of adopters lease their systems
- q^0 (initial consumption) is not observed for non-adopters
 - Do observe zipcode distribution (quintiles)

Flexible logit for Pr'_1 (Arcidiacono and Miller, 2011)

- Estimate a logit with X 's, flexibly interacted, including a time trend and boundary zone FE
- Predict Pr'_1 by advancing
 - Rate by ζ^b
 - VC by η
 - Time +1

Lease vs. Own

- We observe which installations are leased, but not the terms
- We assume leaser/purchaser is a permanent, unobserved state (type)
- Write model conditional on type
 - Owner: same as before
 - Leaser: incorporate payment to lessor
 - Computationally, easiest to write as a change in up-front cost, possible when ρ_i is known or estimated

Lease model

- Lease price: $p^{ppa} = \frac{TC(K^*)(1+\kappa^{TC})}{\theta^I} \frac{1}{q^*}$
 - θ^I is identical to θ , but with installers discount rate $\sim 4\%$
 - κ^{TC} is markup on the cost of capital
- Leasing can then be written as a multiplicative factor on cost that varies with ρ :

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$$\delta_1^l - \delta_0^l = (1 - \rho(1 + \zeta))\theta q^* \bar{p} - \frac{\theta^{ppa}}{\theta^I} (1 + \kappa^{TC}) ((1 - \rho\eta)VC(K^*) + (1 - \rho)FC) + (1 - \rho)X\beta + \sigma\rho(\log(Pr'_1) - .5772)$$

Where: $\frac{\theta^{ppa}}{\theta^I} = \frac{\sum_{t=1}^T ((1 + \zeta^{ppa})(1 - \lambda)\rho)^{(t-1)}}{\sum_{t=1}^T ((1 + \zeta^{ppa})(1 - \lambda)\rho^I)^{(t-1)}}$

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The term in blue is unity for purchasers, simplifying computation.

Lease model continued

- A per-kWh markup κ^p can be accommodated:

$$\begin{aligned}\delta_1^l - \delta_0^l = & (1 - \rho(1 + \zeta)) (\theta q^* \bar{p} - \theta^{ppa} q^* \kappa^p) - \\ & \frac{\theta^{ppa}}{\theta^I} (1 + \kappa^{TC}) ((1 - \rho\eta) VC(K^*) + (1 - \rho) FC) + \\ & (1 - \rho) X\beta + \sigma\rho(\log(Pr'_1) - .5772)\end{aligned}$$

Unobserved states: consumption and lease/purchase type

- Conditional on consumption b and type e (and given parameter vector), we can calculate $\Pr(\text{adopt})$ and the conditional likelihood L_{ibe} .
- Unobserved heterogeneity in b and e
 - Integrate likelihood over 10 unobserved states: 5 bins b and 2 types e
- **But** must constrain s.t. w_{ibe} sums over b within zip z to $\frac{N_{zip}}{5}$
 - Enforcing the constraint makes w_{ibe} depend on w_{jbe}
 - Rules out Arcidiacono and Miller (2011) method for unobserved consumption.

Integrating L over b, e .

- Draw (once) $R = 1,000$ random allocations of consumption b : $b^{(r)}$
- For each evaluation of the likelihood function:
 1. Evaluate at the parameters to get conditional likelihood L_{ibe}
 2. Calculate weights for type e conditional on b : $w_{ie|b} = \frac{L_{ieb}}{L_{ieb} + L_{ie'b}}$ following Arcidiacono and Miller (2011).
 3. For each allocation, sum the $w_{ie|b}$ -weighted L_{ibe} for $b = b^{(r)}$ into $L_{ib^{(r)}}$
 4. Calculate probability of observing each allocation conditional on L as

$$w_z^{(r)} = \frac{\prod_{i \in z} L_{ib^{(r)}}}{\sum_r \prod_{i \in z} L_{ib^{(r)}}}$$

5. Calculate the log-likelihood LL_i by $LL_i = \log \left(\sum_{(r)} w_z^{(r)} L_{ib^{(r)}} \right)$
6. Sum $LL = \sum_i LL_i$

Results

Main findings

Q1: To what degree do households discount the flow...?

Avg. Discount Rate	θ	$\theta_{4\%}$	ratio
13.67%	42.64	95.22	2.23

^a $\theta_{4\%}$ is value to government entity discounting at 4%

θ converts $q^* \bar{p}$, the per-period flow payoff, into a present value.

13.7% implies $\theta = 42.64$, or 2.2x the NPV at a government discount rate of 4%.

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Adopter	Average TC	Average $q^* \bar{p}$	$\bar{\theta}$	$\bar{\theta} q^* \bar{p}$	$\bar{\theta}_{4\%} q^* \bar{p}$
All	\$9,957.93	\$217.38	42.64	\$9,268.21	\$20,702.55
Adopters Only	\$13,658.51	\$329.55	42.71	\$14,074.74	\$29,831.90

The average present value of average flow $q^* \bar{p}$ is \$9,268. The same flow discounted at a government discount rate of 4% is \$20,703.

Main findings

Q2: Do discount rates vary systematically...?

Wealth	Annual Discount Rate	$\bar{\theta}$	ratio
High	10.5%	50.6	1.8
Med	10.3%	51.6	1.9
Low	19.8%	27.6	1.0

Counterfactuals

Reduce up-front costs by 1%

Wealth	Rate	1% Decrease in Up-Front Variable Cost		
		Counterfactual Installations	Counterfactual Purchases	Counterfactual Leases
HIGH	10.5%	1.024	1.026	1.020
MED	10.3%	1.020	1.023	1.016
LOW	19.8%	1.009	1.014	1.006
All	–	1.018	1.022	1.013

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All	–	1.018	1.022	1.013

Wealth	Rate	1% Decrease in Up-Front Variable Cost				
		Households	Observed Adopt	Share Obs. Adopt	Counterfactual Adopt	Share Counterfactual Adopt
HIGH	10.5%	50298	2009	3.99%	2058	4.09%
MED	10.3%	67631	3272	4.84%	3336	4.93%
LOW	19.8%	65738	1963	2.99%	1981	3.01%
All	–	183667	7244	3.94%	7375	4.02%

Proposed NEM Rate of \$.0625/kWh

- From CPUC-comissioned Avoided Cost Calculator
- \$.0625/kWh is average avoided cost for normalized load shape of solar

Wealth	Rate	NEM Proposed \$.0625/kWh Rate		
		Counterfactual Installations	Counterfactual Purchases	Counterfactual Leases
HIGH	10.5%	0.221	0.226	0.208
MED	10.3%	0.251	0.249	0.253
LOW	19.8%	0.570	0.569	0.572
All	—	0.327	0.306	0.352

^a Avg. offset price in sample: \$0.17/kWh. Avg. offset price for adopters: \$0.20/kWh.

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LOW	19.8%	65738	1963	2.99%	1120	1.70%
All	—	183667	7244	3.94%	2371	1.29%

Proposed NEM Rate, but equivalent up-front subsidy

- Proposed NEM Rate of \$.0625 reduces flow payoff
- Subsidize by up-front value of net change in flow
- Budget-neutral to gov't assuming 4% government discount rate

Wealth	Rate	NEM \$.0625, Difference as Up-front Subsidy		
		Counterfactual Installations	Counterfactual Purchases	Counterfactual Leases
HIGH	10.5%	2.752	3.714	0.570
MED	10.3%	1.991	3.301	0.638
LOW	19.8%	1.595	2.757	0.788
All	—	2.104	3.344	0.676

^a Avg. equivalent subsidy: \$5 () .

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		Households	Observed Adopt	Share Obs. Adopt	Counterfactual Adopt	Share Counterfactual Adopt
HIGH	10.5%	50298	2009	3.99%	5530	10.99%
MED	10.3%	67631	3272	4.84%	6516	9.63%
LOW	19.8%	65738	1963	2.99%	3130	4.76%
All	–	183667	7244	3.94%	15239	8.30%

Household discount rates exceed government borrowing rate

- Efficiency gains from up-front payments
- Important for redesigning NEM
- Applies to many flow subsidies for up-front investments

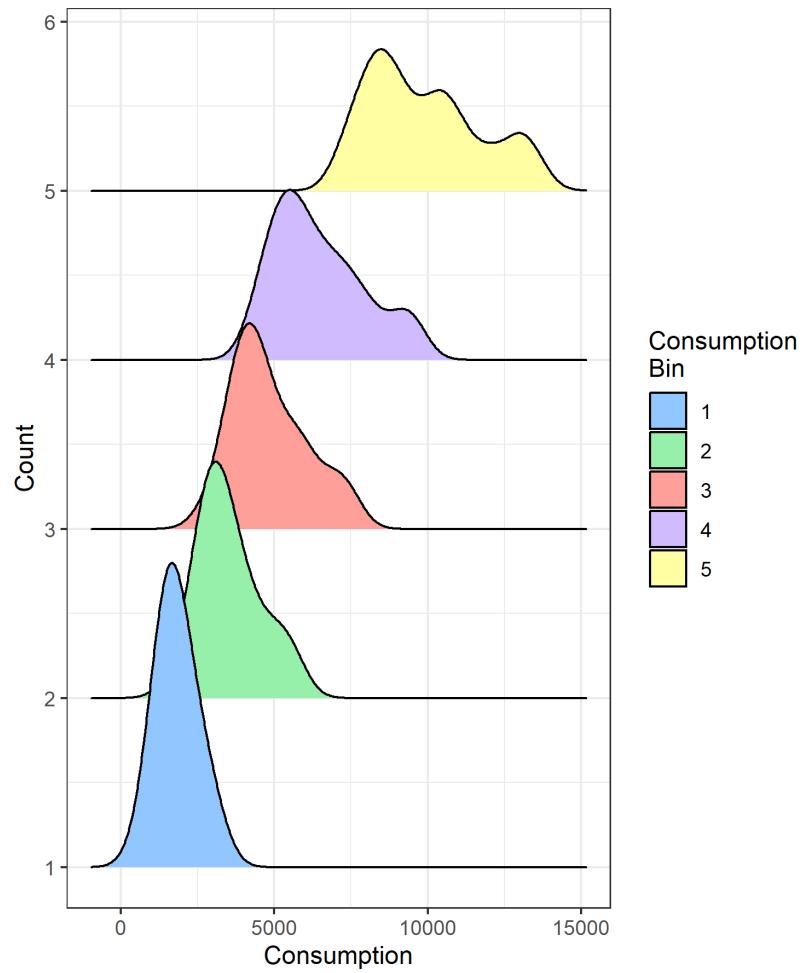
Heterogeneity across wealth in discount rates

- Explains disparity in adoption
- Suggests possible gains in distributional equity across wealth from upfront payments

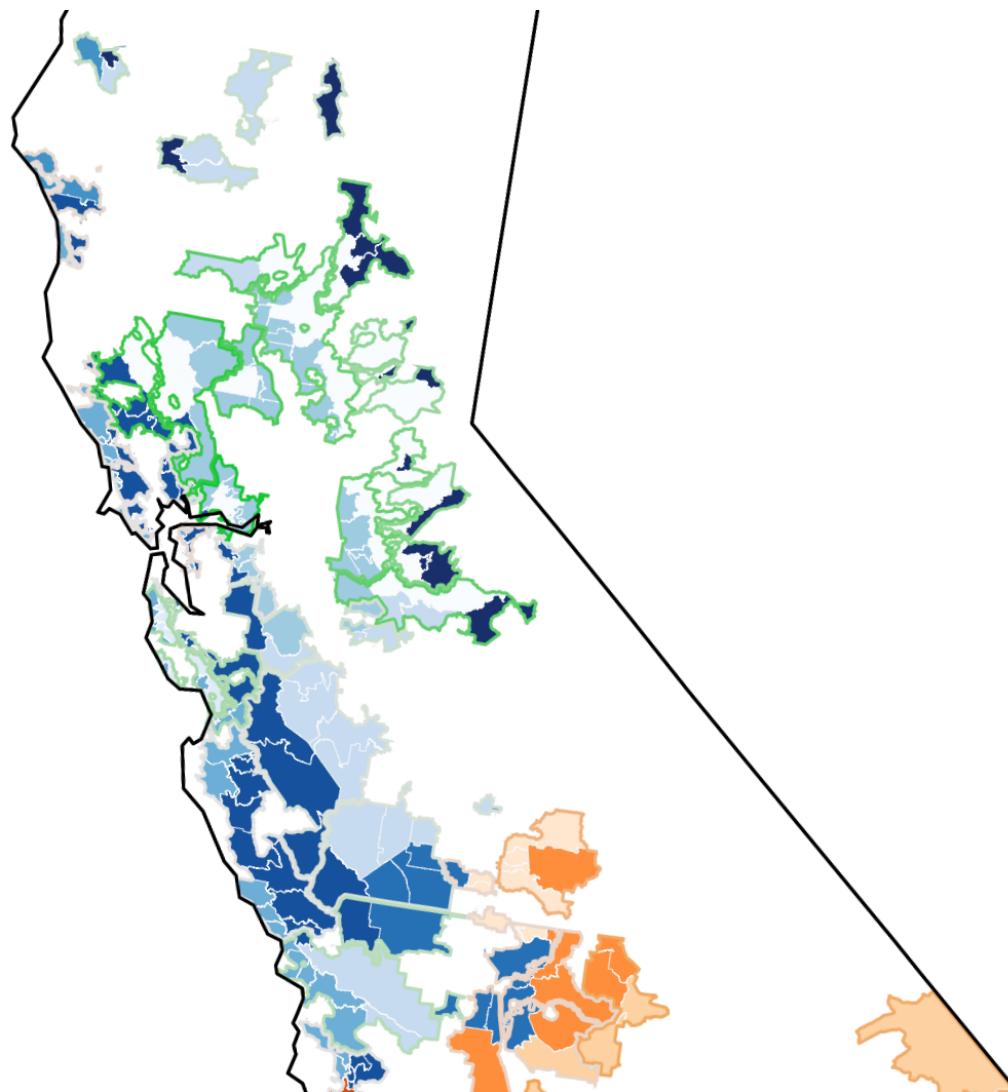
Thanks

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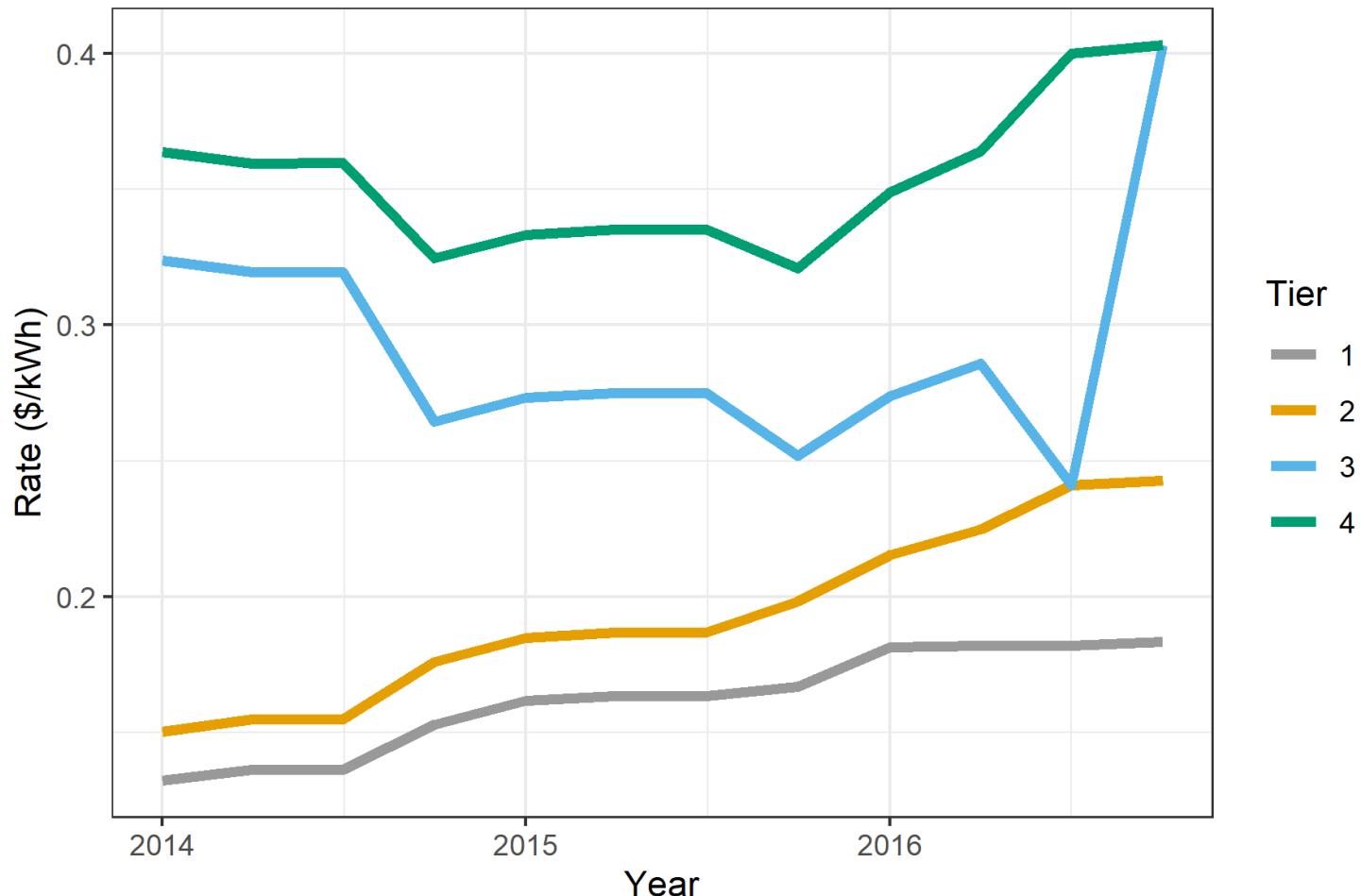
Zip-level annual consumption bins



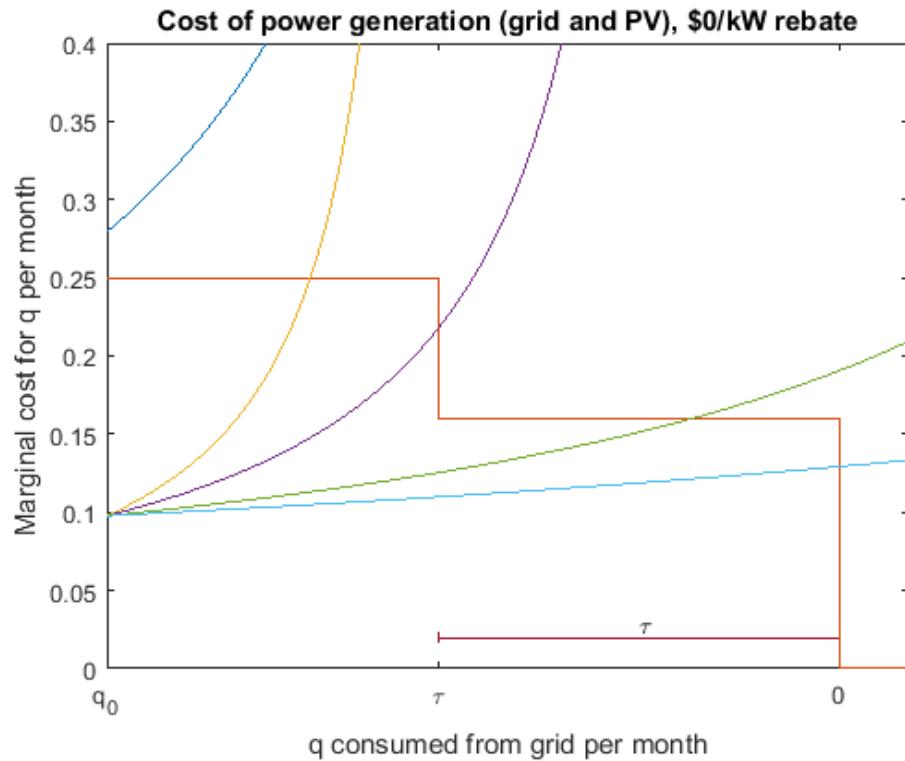
Rate zone boundaries from Bollinger, Gillingham, Kirkpatrick, and Sexton (2017) [Back](#)



Rates: PG&E has 4 (later 3) tiers of pricing. Back



Optimal sizing

[Back](#)

Given consumption, rate structure, and Google Sunroof profile, find optimal capacity to install.

1. Calculate marginal cost per kWh of solar generation
 - Starts low
 - Increases based on roof
 - Reflects cost of panels
2. Calculate marginal cost per kWh from the grid
 - Based on annual consumption
 - Decreases as solar generation increases
3. Optimal is when $MC_{grid} = MC_{solar}$
 - May be "lumpy" due to steps

K^* is optimal size; q^* is optimal generation; $q^* \bar{p}$ is annual value of generation

Results (old)

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Param. Grp	Parameter	Estimate	δ	se	t	pval
σ	σ	-0.505		0.145	-3.490	0.000***
	ρ_{high}	1.961	10.6%***	0.058	33.807	0.000***
	α_{med}	-0.025	11.3%	0.050	-0.493	0.622
	α_{low}	-0.322	23.1%***	0.050	-6.465	0.000***
β	Wealth: lowest 1/3rd	-11.626		1.712	-6.792	0.000***
	Wealth: middle 1/3rd	-2.868		1.700	-1.687	0.092.
	Voter Affiliation: D	-0.301		0.454	-0.662	0.508
	Length of residence	0.019		0.023	0.796	0.426
	Child	-0.053		0.463	-0.114	0.909
	Sqft	1.428		1.173	1.217	0.224
	Sqft ²	-0.184		0.226	-0.813	0.416
	β_0	0.018		0.593	0.031	0.975
	Race: Hispanic	-0.819		0.742	-1.103	0.270
	Race: Black and Other	-1.116		0.802	-1.392	0.164
$\phi_{consumption}$	Race: Asian	15.009		2.270	6.613	0.000***
	Lease Wealth: β_0	-13.893		2.230	-6.229	0.000***
	Lease Wealth: middle 1/3rd	5.091		2.174	2.341	0.019*
	Lease Wealth: lowest 1/3rd	2.837		1.936	1.465	0.143
	ϕ_{bin1}	-20.898		2.249	-9.293	0.000***
$\phi_{consumption}$	ϕ_{bin2}	-6.839		1.214	-5.632	0.000***
	ϕ_{bin3}	2.478		0.833	2.974	0.003**
	ϕ_{bin4}	5.535		0.706	7.836	0.000***

¹ Std. errors from Information Matrix

² Result in disc. rates of 10.6% for high wealth, 11.3% for med wealth, and 23.1% for low wealth

Following Hotz and Miller (1993) and treating solar adoption as an exit state: [Back](#)

$$\begin{aligned}v_0 &= \delta_0 + \sigma\epsilon_0 \\ \delta_0 &= \rho \left(.5772 + \int \delta'_1 - \ln(Pr'_1) dF(TC'|TC) \right)\end{aligned}$$

Using estimated change in: $VC' = \eta VC$:

$$\begin{aligned}\delta_1 - \delta_0 &= (1 - \rho(1 + \zeta))\theta q^* \bar{p} - (1 - \rho\eta)VC(K^*) - (1 - \rho)FC + \\ &\quad (1 - \rho)X\beta + \rho(\log(Pr'_1) - .5772)\end{aligned}$$

And

$$Pr_1 = \Lambda \left(\frac{1}{\sigma} (\delta_1 - \delta_0) \right)$$

Household heterogeneity in ρ :

$$\rho_i = \rho + \alpha_{low} \mathbf{1}(\text{wealth}_i < \tau_{33}^{wealth}) + \alpha_{med} \mathbf{1}(\tau_{33}^{wealth} < \text{wealth}_i < \tau_{67}^{wealth})$$

- Cross-sectional variation in $q^* \bar{p}$ allows identification of α_{low} , α_{med} , ρ .
- Both income and value dummies included in X as well.
 - Main effect = information/inattention

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