Valuing Solar Subsidies

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Focus on 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
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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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  - If each kWh reduces bill by higher tier rates that are above wholesale rates, then net metering is a **flow (monthly) subsidy**
- 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

Context

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NPV of flow payoff depends on household discount rate

Household **heterogeneity** in rate $\longrightarrow$ 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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Research Questions

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Q2: Do discount rates vary systematically over wealth?

This speaks to whether or not the choice to use a potentially inefficient flow incentive (like net metering) exacerbates distributional differences.

Research Questions

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Q2: Do discount rates vary systematically over wealth?

This speaks to whether or not the choice to use a potentially inefficient flow incentive (like net metering) exacerbates distributional differences.

Policy lever: put the subsidy up front

- Increase efficiency with up-front subsidies
- If discount rates vary systematically $\longrightarrow$ 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

- Lawrance (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

- Household-level variation allows for credible estimates of heterogeneous discount rates

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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

Overview

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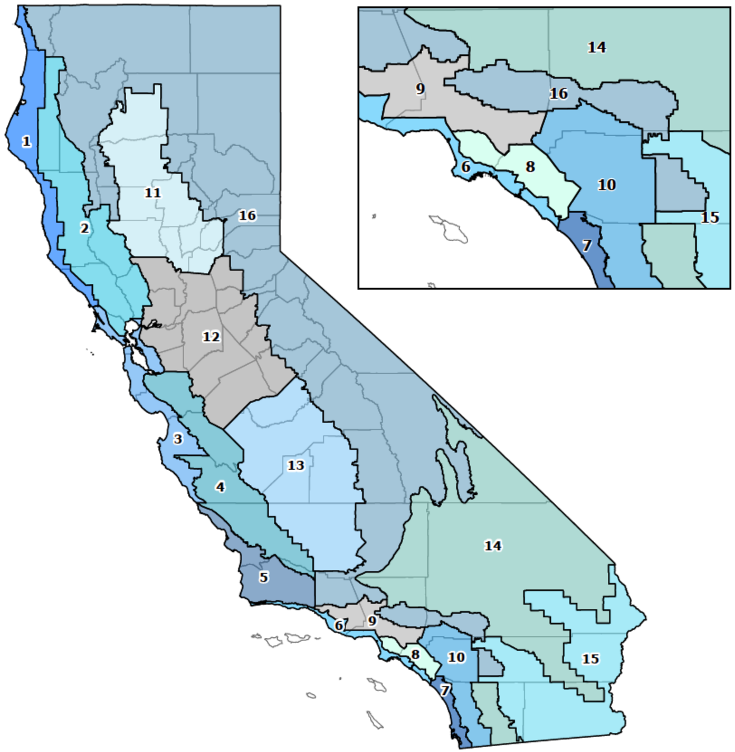
Roadmap

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

Sources of Identifying Variation

Identifying Variation

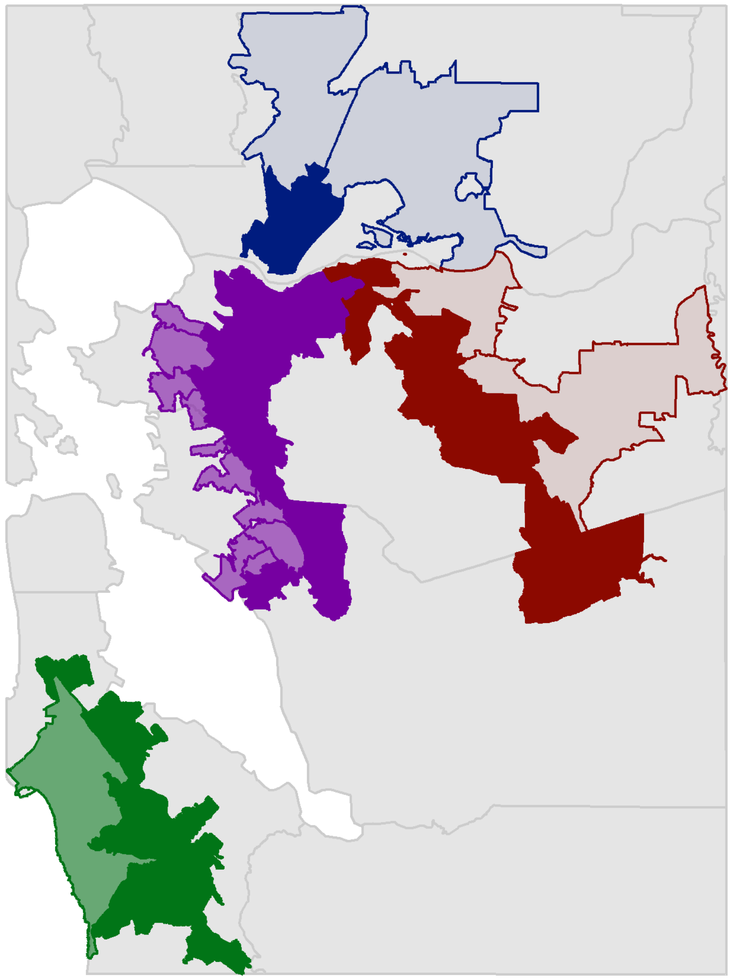


Climate zones allow different thresholds for block pricing steps.

- 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.

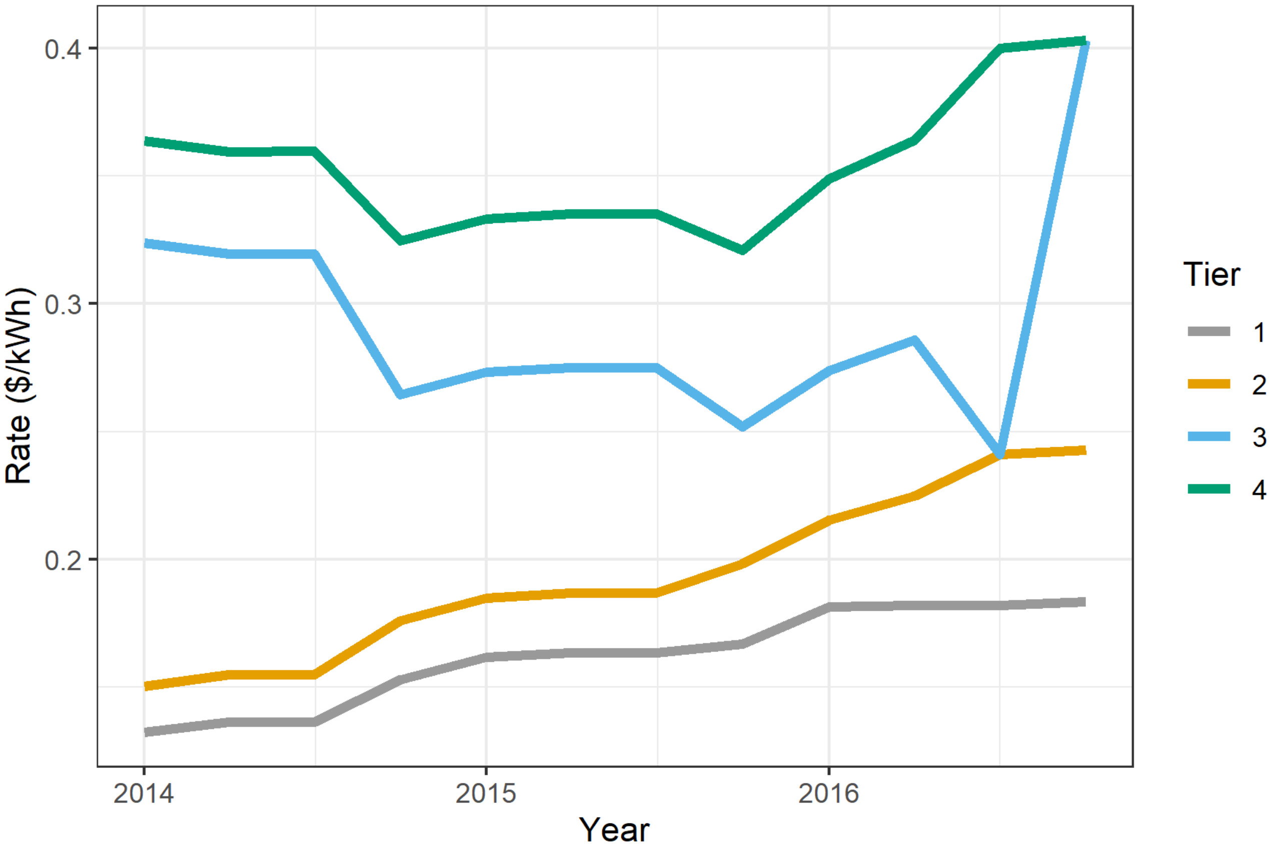
Identifying Variation

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



Identifying Variation

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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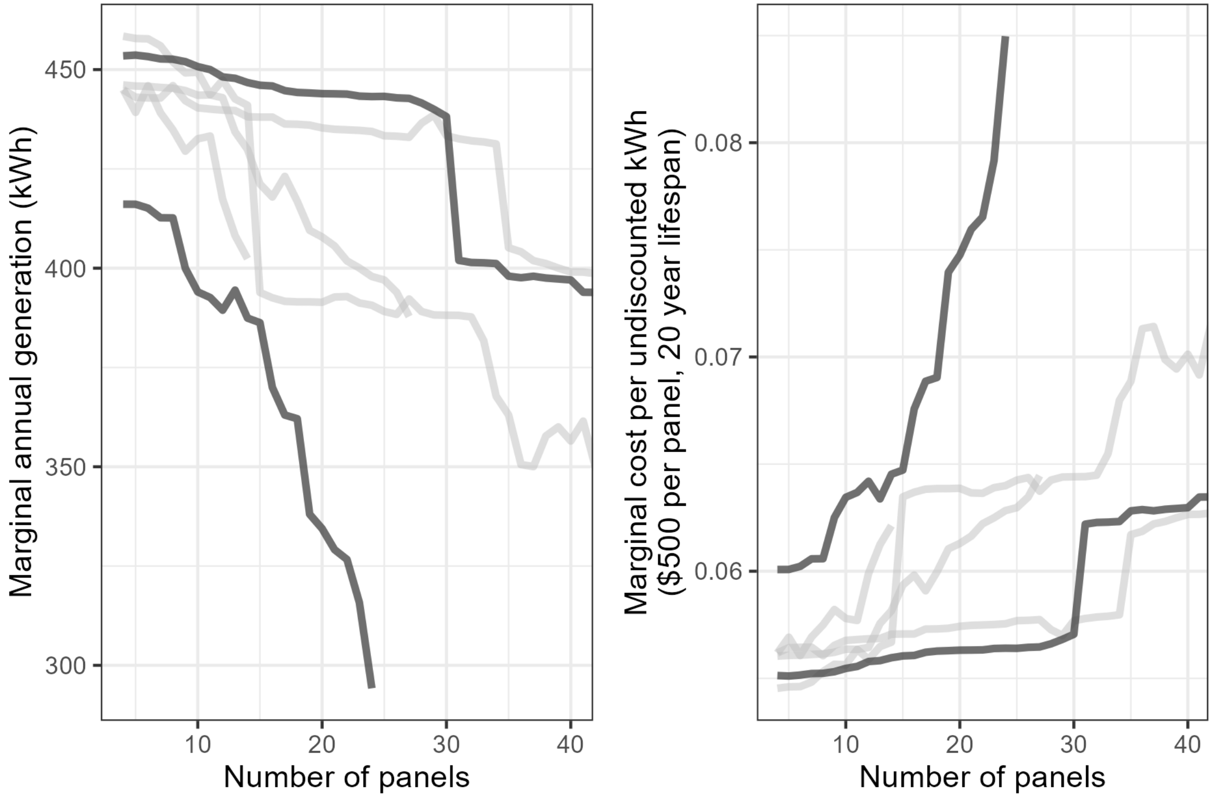
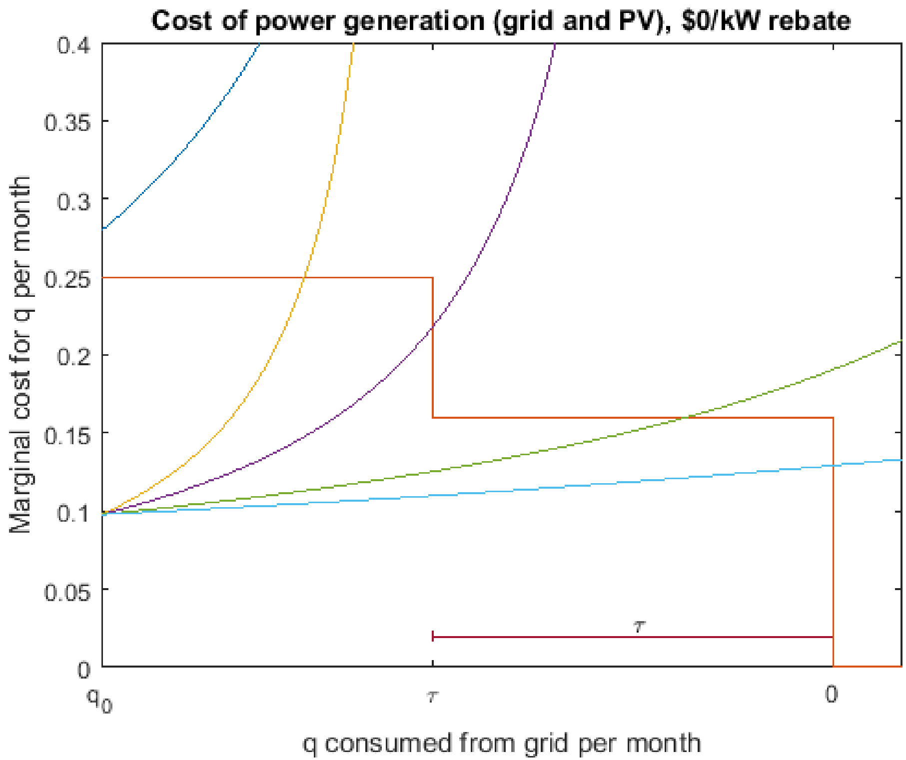
Google Sunroof roof irradiance

- 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

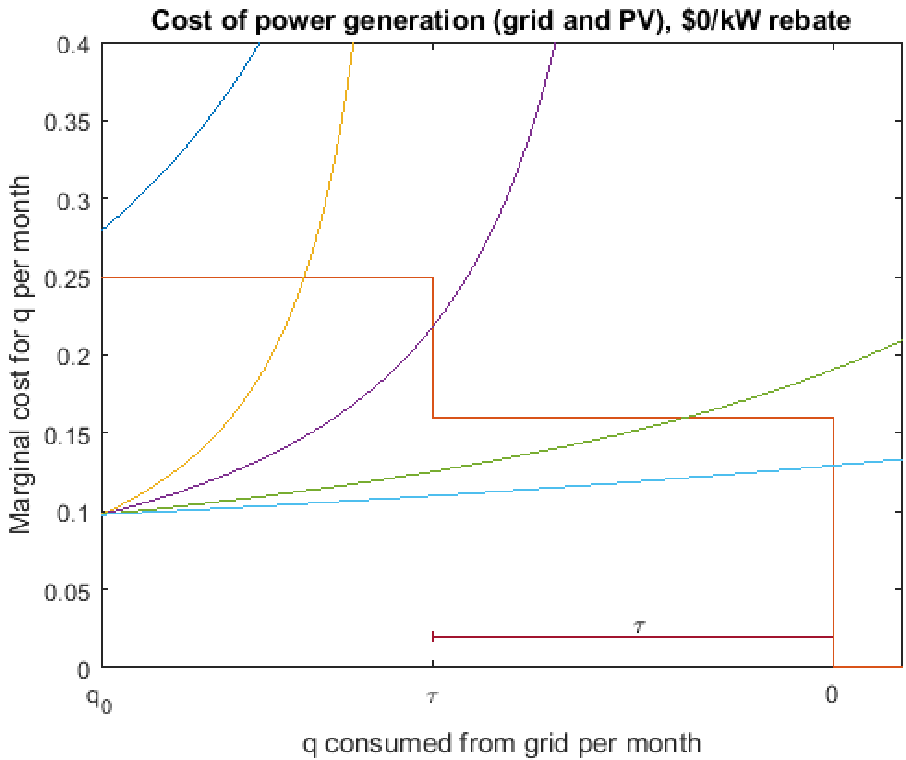


1. Dark blue is a shady roof
2. Yellow-orange is a sunny roof with few high-irradiance segments
3. Purple is a sunny roof with moderate high-irradiance segments
4. Green is a sunny roof with many high-irradiance segments
5. Light blue is a sunny roof on a flat, south-oriented roof.

Example is two-tier pricing with step at τ.

Increasing q^0 slides steps to right.

Optimal sizing

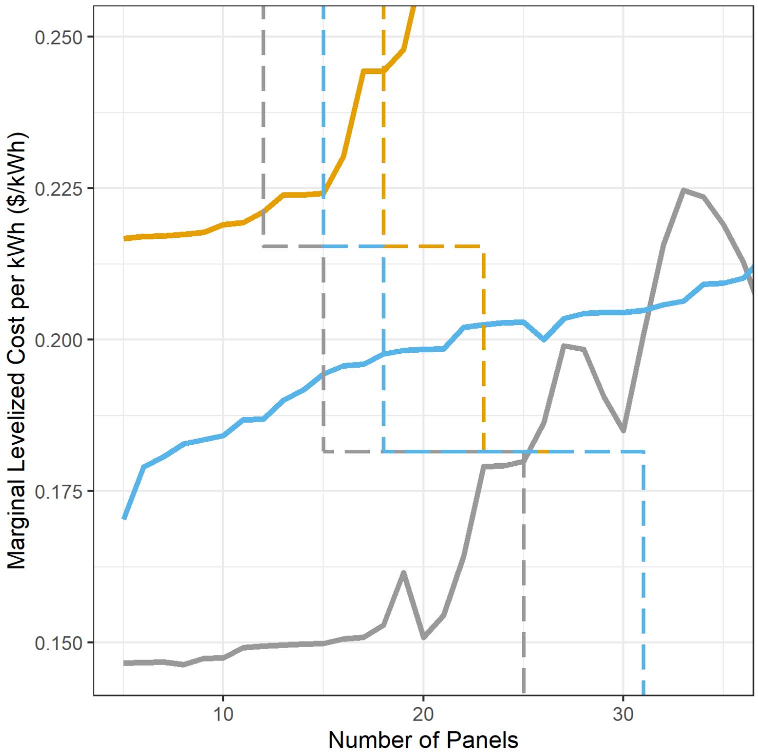


Given consumption, rate structure, and Google Sunroof profile, find capacity K^* to install.

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

Data

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)

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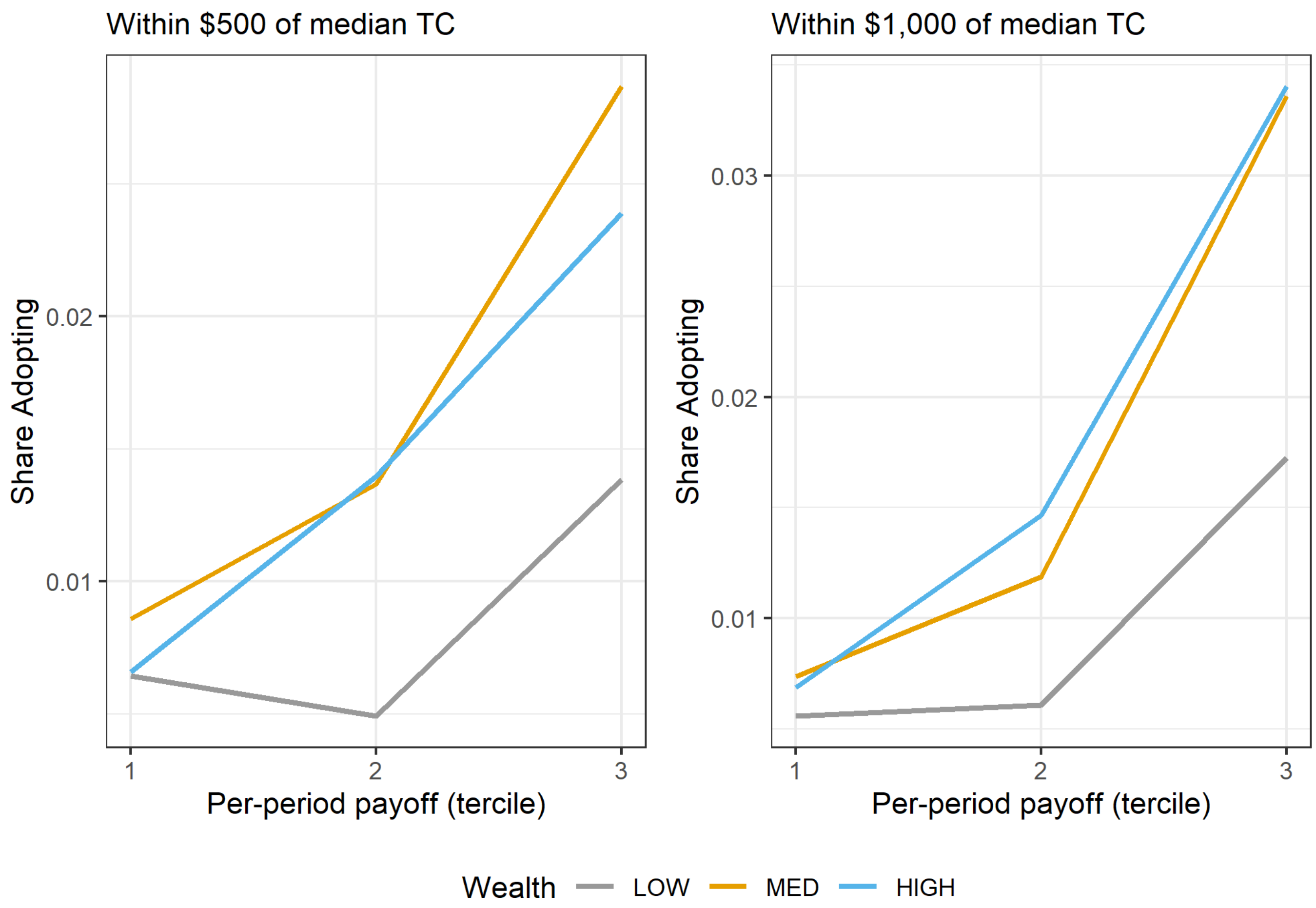
Observed Consumption (adopters)

For adopters, we observe $\boldsymbol{q}^0$

- Place in bin $\boldsymbol{b}_z$
- Calculate same as non-adopters

Model Inputs

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



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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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Model

Utility of adopting:

$$
\begin{aligned}
v_1 &= \delta_1 + \sigma\epsilon_1 \\
\delta_1 &= \underbrace{\int_{q_0-q^*}^{q_0} \sum_{t=1}^{T} \frac{1}{(1+\delta)^{t-1}} p_t(x)dx}_{\text{Discounted value of offset electricity}} - VC(K^*) - FC + X\beta \\
\delta_1 &= \overbrace{\theta q^* \bar{p}} - VC(K^*) - FC + X\beta
\end{aligned}
$$

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

- $p_t(x)$ 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
- $\epsilon \sim$ 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

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

$\boldsymbol{\rho}$ 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)

Model

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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$$\begin{aligned}\delta_1^l - \delta_0^l = {} & (1-\rho(1+\zeta))\theta q^* \bar{p} - \\ & \frac{\theta^{ppa}}{\theta^I}(1+\kappa^{TC})\left((1-\rho\eta)VC(K^*) + (1-\rho)FC\right) + \\ & (1-\rho)X\beta + \sigma\rho(\log(Pr_1') - .5772)\end{aligned}$$

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:

$$\begin{aligned}\delta_1^l - \delta_0^l = {} & (1-\rho(1+\zeta))\left(\theta q^* \bar{p} - \theta^{ppa} q^* \kappa^p\right) - \\ & \frac{\theta^{ppa}}{\theta^I}(1+\kappa^{TC})\left((1-\rho\eta)VC(K^*) + (1-\rho)FC\right) + \\ & (1-\rho)X\beta + \sigma\rho(\log(Pr_1') - .5772)\end{aligned}$$

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Unobserved states: consumption and lease/purchase type

- Conditional on consumption b and type e (and given parameter vector), we can calculate $Pr(adopt)$ 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 $w_z^{(r)} = \frac{\Pi_{i \in z} L_{ib^{(r)}}}{\sum_r \Pi_{i \in z} L_{ib^{(r)}}}$
  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
11.25%	49.87	95.22	1.91

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

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

$\mathbf{11.25\%}$ implies $\boldsymbol{\theta} = \mathbf{49.87}$, or 1.91x 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	49.87	\$10,840.98	\$20,702.55
Adopters Only	\$13,658.51	\$329.55	49.69	\$16,376.41	\$29,831.90

The average present value of average flow $\boldsymbol{q^*\bar{p}}$ is \$10,841. 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	$\bar{\bar{\theta}}$	ratio
High	9.6%	54.6	1.5
Med	8.4%	60.9	1.7
Low	15.5%	35.2	1.0

Counterfactuals

Reduce up-front costs by 1%

		1% Decrease in Up-Front Variable Cost		
Wealth	Rate	Counterfactual Installations	Counterfactual Purchases	Counterfactual Leases
Low	15.5%	1.048	1.051	1.041
Med	8.4%	1.041	1.045	1.037
High	9.6%	1.020	1.029	1.013
All	–	1.037	1.044	1.030

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Wealth	Rate	1% Decrease in Up-Front Variable Cost				
		Households	Observed Adopt	Share Obs. Adopt	Counterfactual Adopt	Share Counterfactual Adopt
Low	15.5%	50298	2009	3.99%	2105	4.19%
Med	8.4%	67631	3272	4.84%	3405	5.03%
High	9.6%	65738	1963	2.99%	2002	3.05%
All	–	183667	7244	3.94%	7513	4.09%

Proposed NEM Rate of $.0625/kWh

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

		NEM Proposed $.0625/kWh Rate		
Wealth	Rate	Counterfactual Installations	Counterfactual Purchases	Counterfactual Leases
Low	15.5%	0.079	0.083	0.069
Med	8.4%	0.074	0.076	0.072
High	9.6%	0.299	0.289	0.306
All	–	0.136	0.122	0.151

[a] Avg. offset price in sample: $0.17/kWh. Avg. offset price for adopters: $0.20/kWh.

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High	9.6%	65738	1963	2.99%	587	0.89%
All	–	183667	7244	3.94%	982	0.53%

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

		NEM $.0625, Difference as Up-front Subsidy		
Wealth	Rate	Counterfactual Installations	Counterfactual Purchases	Counterfactual Leases
Low	15.5%	6.330	7.032	4.769
Med	8.4%	5.235	6.339	4.107
High	9.6%	3.479	6.365	1.510
All	–	5.077	6.601	3.352

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		NEM $.0625, Difference as Up-front Subsidy				
Wealth	Rate	Households	Observed Adopt	Share Obs. Adopt	Counterfactual Adopt	Share Counterfactual Adopt
Low	15.5%	50298	2009	3.99%	12718	25.29%
Med	8.4%	67631	3272	4.84%	17128	25.33%
High	9.6%	65738	1963	2.99%	6830	10.39%
All	–	183667	7244	3.94%	36779	20.02%

Conclusion

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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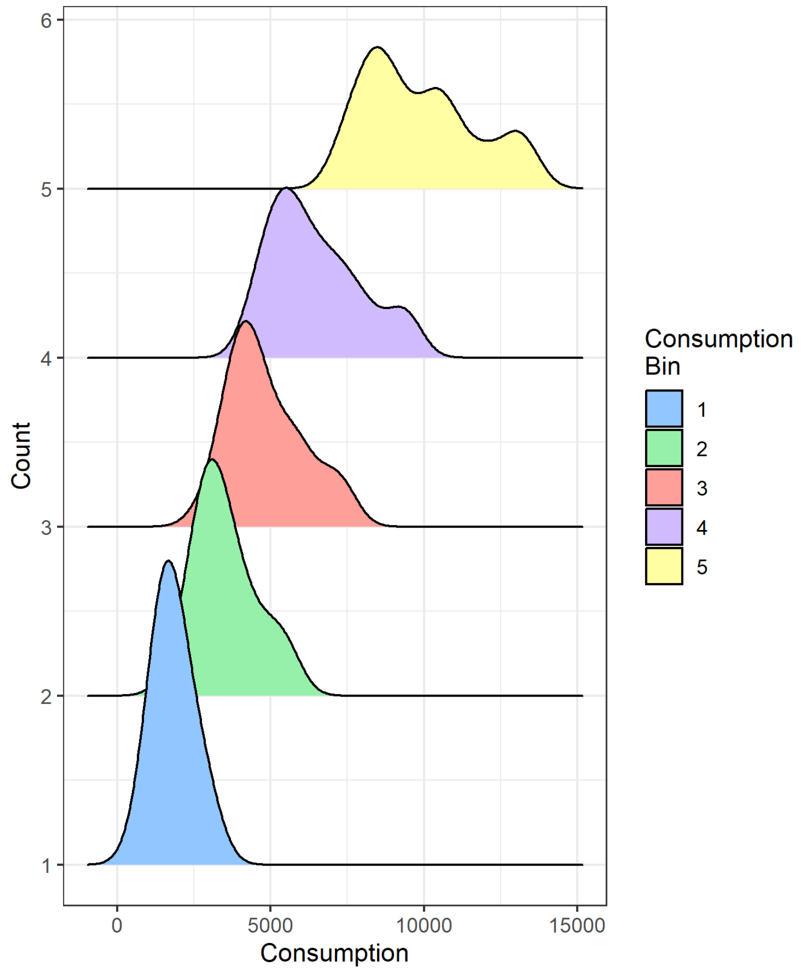
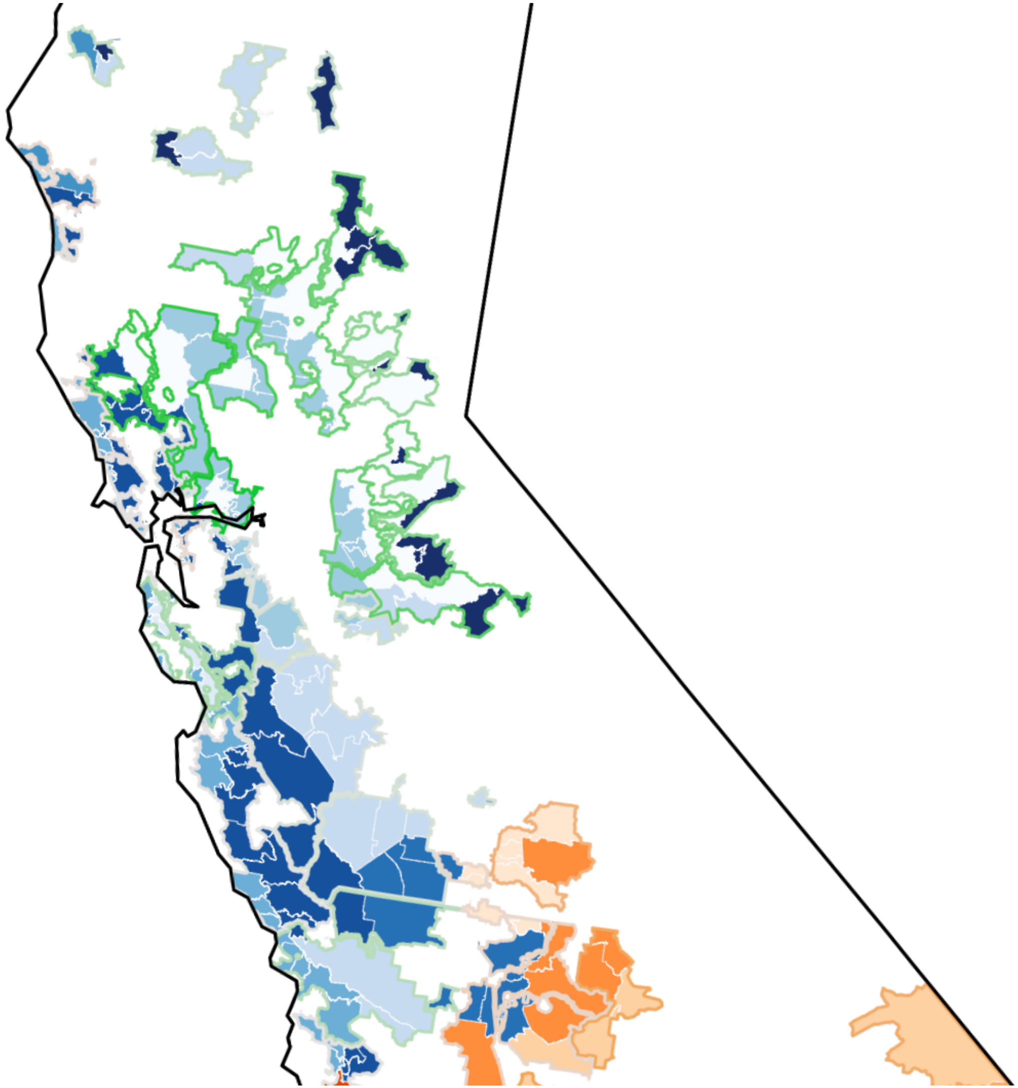
Zip-level annual consumption bins

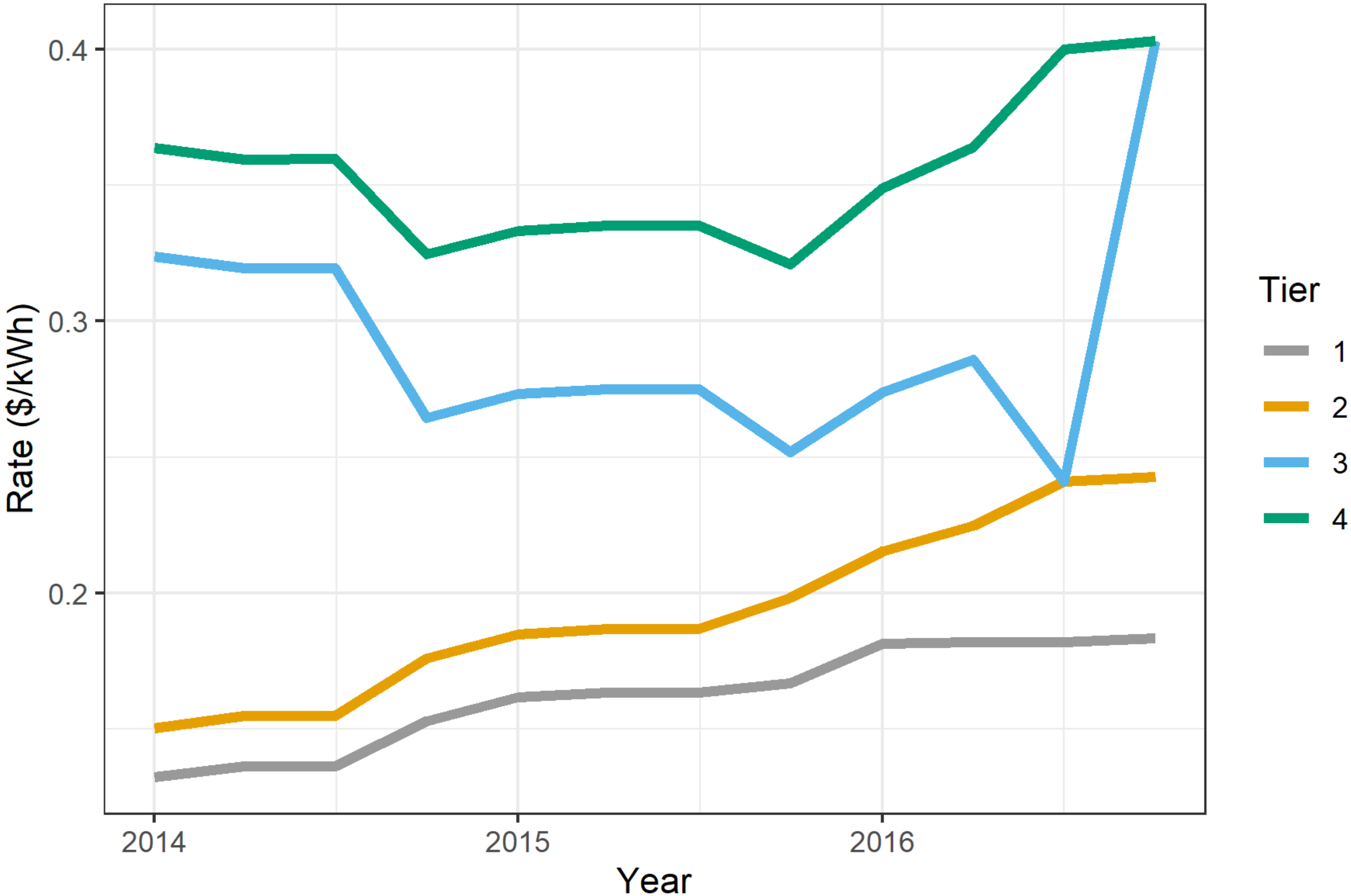


Data

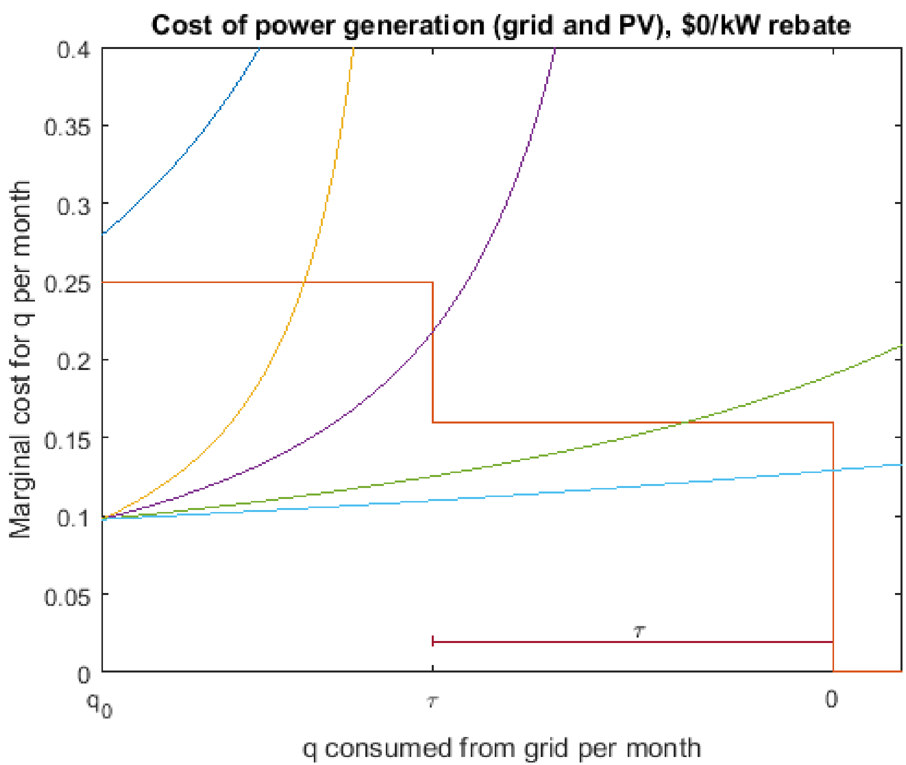
Rate zone boundaries from Bollinger, Gillingham, Kirkpatrick, and Sexton (2017) Back



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)

Back

Param. Grp	Parameter	Estimate	δ	se	t	pval
σ	σ	-0.505		0.145	-3.490	0.000***
ρ	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
	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
$\phi_{consumption}$	ϕ_{bin1}	-20.898		2.249	-9.293	0.000***
	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

Model

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

$$v_0 = \delta_0 + \sigma\epsilon_0$$
$$\delta_0 = \rho\left(.5772 + \int \delta_1' - ln(Pr_1')dF(TC'|TC)\right)$$

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

$$\delta_1 - \delta_0 = (1-\rho(1+\zeta))\theta q^*\bar{p} - (1-\rho\eta)VC(K^*) - (1-\rho)FC + \\ (1-\rho)X\beta + \rho(\log(Pr_1') - .5772)$$

And

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

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Household heterogeneity in ρ:

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

- 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

Back