Valuing Solar Subsidies

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Durable Goods Involve a Tradeoff

- Upfront cost
- Benefits that are a flow over time

Especially important for green technologies

How Do Consumers Discount Future Payoffs?

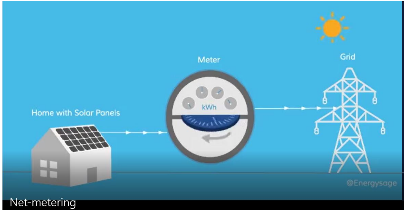
This question is the topic of a long literature

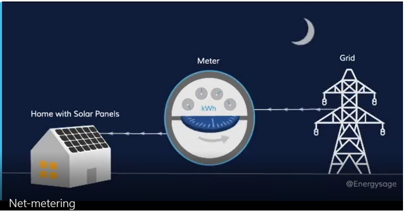
- Experimental: Hyperbolic discounting in the lab (Thaler 1981, Laibson 1997, etc.)
- Field experimental: Consumers may or may not appear to be myopic in the field (e.g., Matousek et al. 2019 review)
- Observational: Some evidence of *high* implicit discount rates for energy-using durables going back to Hausman (1979)

Further, there is evidence of *heterogeneity* in discounting, going back to Lawrence (1991) and Harrison et al. (2002)

Policy Motivation: Rooftop Solar Debates

- Huge amount of policy debate right now around “net metering”
- Key debate: how is solar export compensated?





Policy Motivation: Rooftop Solar Debates

Overcompensation:

- Change in bill from one unit of excess generation ($gen_t > cons_t$) almost always greater than wholesale electricity cost
- Particularly strong under *increasing block pricing*

In Colorado:

- No increasing block pricing
- But yes, net metering
- Wholesale price $\neq$ compensation price

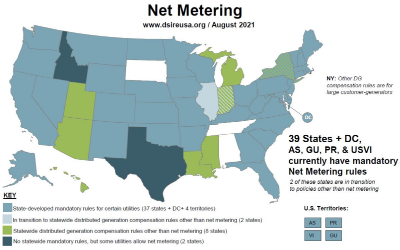
NEM "subsidy" costs are passed onto non-solar customers

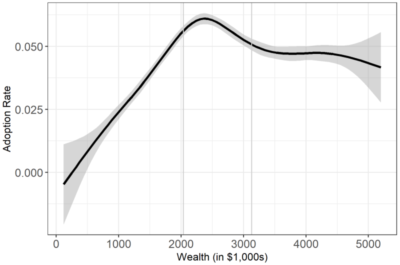
Many States Still Have Net Metering

Concerns:

- Solar adopters tend to be wealthier (Borenstein & Davis 2016; Barbose et al. 2020)
- Overcompensation can lead to a regressive “cost-shift”

Often proposed solution: Compensate exports at a lower rate





Net Metering Provides a Flow Benefit to Adopters

Is a second-best (or third-best) policy

- Indirectly reduces air pollution externalities
  - Not sufficient to justify subsidies (Sexton et al (2021))
- May lead to some learning-by-doing lowering costs (Bollinger & Gillingham 2019)
- May induce some innovation (Gerarden 2022)

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Key point: NPV of solar depends on household discount rates

- And there may be *heterogeneity* in such rates

Research Questions

How do households discount future payoffs from rooftop solar?

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Do discount rates vary systematically over wealth?

- Speaks to whether using a flow incentive (like net metering) exacerbates equity concerns

$\Rightarrow$ Policy lever: Put the subsidy upfront

- Could improve efficiency and equity

Contribution

- Literature on solar subsidies
  - De Groote and Verboven (2019) find a 15% implicit discount rate in Flanders using dynamic model identified with variation in panel costs and subsidies over time
  - We use new sources of (household level) variation in CA context
- Literature on discounting
  - Energy-using durables: implicit discount rates of 10% to 30+% (see Train (1985) for an early summary
  - Heterogeneity by wealth: Lawrence (1991) show variation from 12% to 20%; Houde and Myers (2021); Sinyashin (2022)
  - We find 20% for low wealth vs. 10% for medium and high wealth

Implicit Discount Rates vs. Time Preferences

- The consumer's discount rate should equal the real rate of return only if it lies between their borrowing and lending costs (Coller and Williams 1999)
  - This is further complicated when accounting for consumption smoothing (Cubitt and Read, 2007)
- Potential reasons for the discrepancy in the implicit discount rates across wealth bins include:
  - Differences in lending and borrowing costs
  - Differences in risk aversion
  - Differences in the marginal propensity to consume
    - The effect of risk aversion declines with background consumption

Identifying Discount Rates is Hard

Going back to Magnac and Thesmar (2002):

- Need either:
  1. Variation that affects expected discounted future payoffs without affecting current period utility
  2. Assumption on relative payoffs in different periods (e.g. Chou et al. 2023)

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This study uses:

- Variation in electricity rates over time
- Variation in electricity rates across similar zip codes
- Variation in consumption levels over households
- Variation in **potential generation** by households

Outline

Outline

Empirical Setting: California 2014-2016

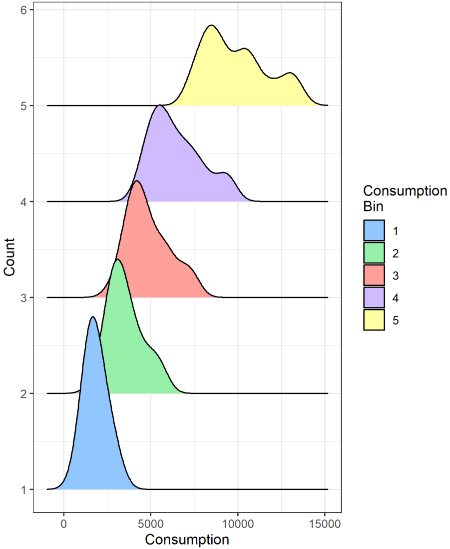
- Address-level data on solar adopters (LBNL)
  - cost, system size, date of installation, lease/purchase
- Address-level data on solar potential (Google Sunroof)
  - solar potential for each roof surface

Empirical Setting: California 2014-2016

- Address-level data on all owner-occupied homes
  - Latitude/Longitude from geocoding
  - sq footage, stories, year built (CoreLogic)
  - *Wealth* (InfoUSA)
  - Owner/Renter, children, length of residence (InfoUSA)
  - Voter registration (CA Sec State)
- Annual household electricity consumption (PG&E)
  - Actual consumption for solar adopters
  - Distribution of consumption in each zip code
  - Calculate quantiles of non-adopter consumption after removing adopters
- Zip code electricity rates & Climate Zone (PG&E)

Empirical Setting: California 2014-2016

Distribution of zip-level consumption



Optimal Sizing

We observe the system size for solar adopters

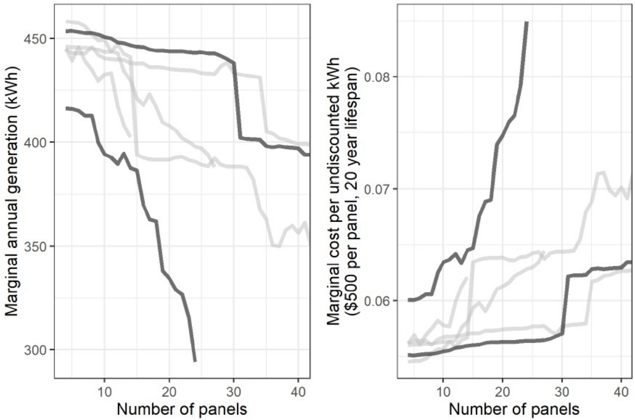
- But what about non-adopters?
- What about adopters under a counterfactual?

$\Rightarrow$ We develop an optimal solar system sizing model

Variation in Cost/kWh Solar Generation

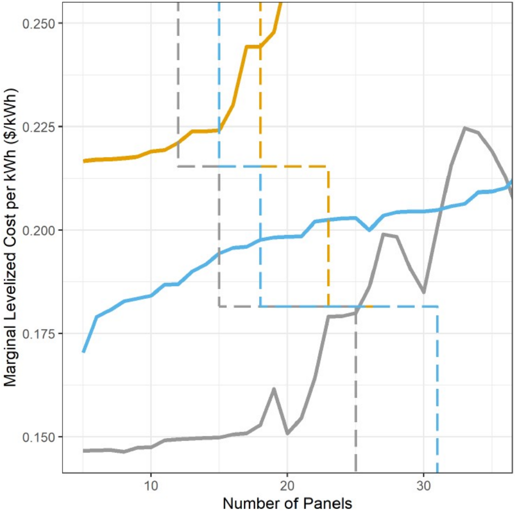
Understanding the Cost/kWh Variation

Roof irradiance affects optimal sizing and flow payoffs



Converting to marginal cost requires fixing the discount rate

Optimal Size for Three Systems in the Data

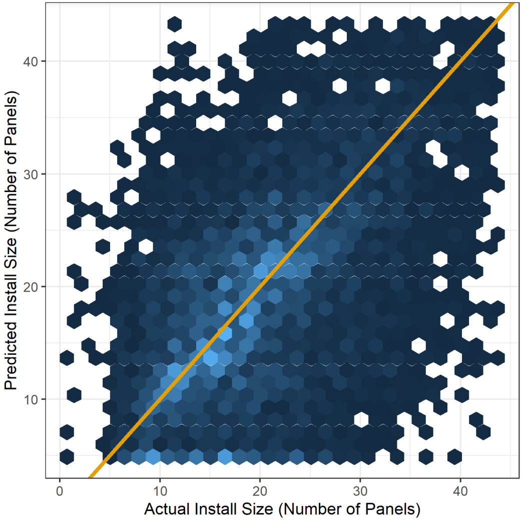


Three systems in different zip codes with very different roof profiles (and different electric rate structures)

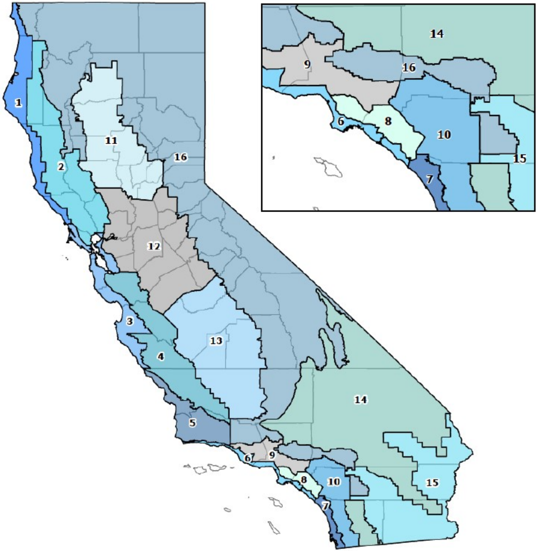
Optimal Sizing Model

- Use sizing rate (rate installer would use / google uses) of 4%
- *Full-offset* for leased systems based on data
- Allow purchased systems to be optimally sized conditional on consumption, roof profile, rates (time)

Optimal Sizing Model Works

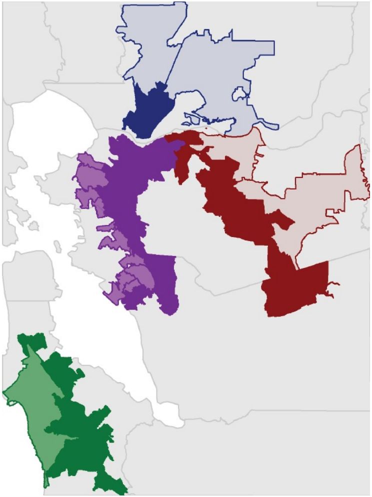


Electric Rates Differ by Climate Zone



Restrict Sample to Zip Codes on Boundary

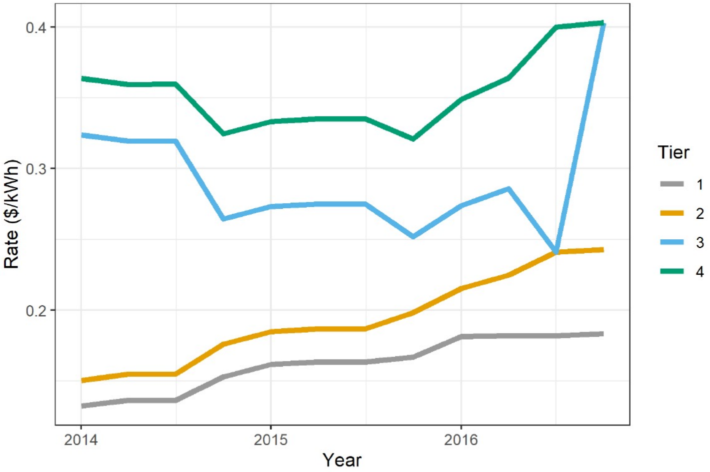
Also restrict sample to zip codes with the same electric rates



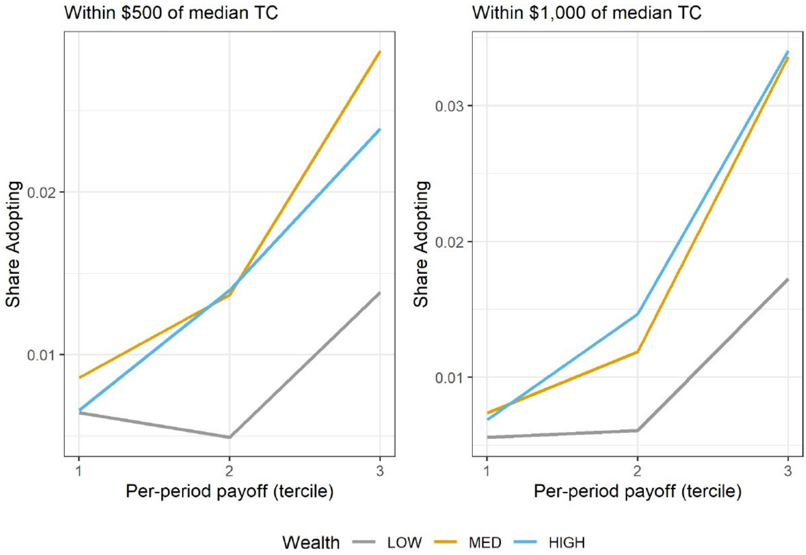
Final sample has just over 279k households and 7k adopters

Variation in Electric Rates Over Time

CA had 4 tiers, which became 3:



Evidence of Response to Flow Payoffs



Outline

Model Overview

Consumers make dynamic decisions of whether to adopt or wait

- Adopting is absorbing state
- Consumers consider upfront cost and discounted flow of payoffs
- Value of waiting depends on state variables
  - State variables differ by solar irradiance
- Tradeoff between flow and upfront cost differs by initial consumption and lease vs own

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$\Rightarrow$ Estimate discount rates as a function of wealth

Modeling Dynamics Requires Specifying Expectations

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  - Avg price is a function of consumption in consumption bin b, which varies by zip code z
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  - So solar revenues ($q^* \bar{p}$) in the next year are $q^* \bar{p}(1 + \zeta_{bz})$
- Variable component of panel cost is a constant proportional change over time
  - Estimated with LBNL data
  - Fixed costs by zip (no decline in real terms)
  - Annual price decline factor η = 0.988 applied to all zip codes

Utility of Adopting

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

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

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

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

- $p_t(x)$ is electric rate step function
- $VC(K^*)$ is the variable cost of adopting, FC is fixed cost
- X includes children, voter reg, sqft, stories, wealth bins (low/med/high), quarter x wealth FE, lease x wealth FE, boundary zone FE
- ϵ_1 is Type 1 extreme value error

Moving Toward Estimation

Normalize outside option:

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

Hotz & Miller (1993) conditional choice probabilities (CCP) approach:

δ_0 is value of adopting in the next period (discounted) minus a ”correction term” that is the log of the probability of adopting in the next period:

$$\begin{aligned}\delta_1 - \delta_0 &= \frac{1-\rho(1+\zeta)}{1-(\rho(1+\zeta))^{4T}}\theta q^* \bar{p} - \frac{1-\rho}{1-(\rho)^{4T}} FC - \frac{1-\rho\eta}{1-(\rho\eta)^{4T}} VC \\ &+ \frac{1-\rho}{1-(\rho)^{4T}} X\beta + \sigma\rho\left(\log(Pr') - \gamma\right)\end{aligned}$$

We account for re-adoption at end-of-life (T=25 years = 100 quarters) by assuming that re-adoption will always occur.

Moving Toward Estimation

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This produces the familiar logit form for probability of adoption (Pr_1) and the likelihood function

- For Pr_1', we estimate a flexible logit with interacted X's and iterate forward

Heterogeneity in Discount Rate by Wealth

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

We can also allow ρ to be a function of income, but we focus on wealth because it seems to better characterize the CA setting

Main Estimation Challenges

1. A reasonable fraction of adopters lease
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2. Initial consumption (q_0) is not observed for nonadopters
   - We do observe the distribution in each zip code

Overcoming the Challenges

1. Lease vs. Own

- Assume a permanent consumer "type" (e)
- Write model conditional on e and integrate over unobserved state
- Incorporate payment to lessor and markups, which changes the relative weights on the upfront vs flow payoffs

$$
\begin{aligned}
\delta_1^l - \delta_0^l \quad = \quad & \frac{1-\rho(1+\zeta)}{1-(\rho(1+\zeta))^{4T}}\left(\theta q^* \bar{p} - \theta^{ppa} q^* \kappa^p\right) \\
- \quad & \frac{\theta^{ppa}}{\theta^l}(1+\kappa^{TC})\left(\frac{1-\rho}{1-(\rho)^{4T}} FC + \frac{1-\rho\eta}{1-(\rho\eta)^{4T}} VC\right) \\
+ \quad & \frac{1-\rho}{1-(\rho)^{4T}} X\beta + \sigma\rho\left(\log(Pr') - \gamma\right)
\end{aligned}
$$

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

Overcoming the Challenges

2. Initial consumption (q_0) is not observed for nonadopters
    - Integrate over the 5 consumption bins x 2 lease types
    - Constrain so weights sum over b within a zip code
    - Weights for unobserved heterogeneity from Arcidiacono and Miller (2011)
    - Modify estimation to account for dependence of weights within zip code on consumption

Estimation

1. Initialize Household x Consumption x Type weights
2. Estimate flexible logit and predict Pr'
3. Estimate model parameters $\rho, \cdots$
4. Update weights
5. Estimate flexible logit and predict Pr'
6. Estimate model parameters
7. Repeat 4-6 until converged

Robustness

We further explore:

- Discount rate used in the sizing model
- Solar rebound
- Control for lines of credit

Outline

Main Result 1: Average Discount Rate

Average rate over all households is 13.0%

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- With government rate of 4%, would be $24,808
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$\Rightarrow$ Suggests efficiency improvements by moving incentives upfront

Main Result 2: Heterogeneity Over Wealth

Annual discount rates vary systematically over wealth

Wealth	Rate (%)	$\bar{\theta}$	Ratio to Low
HIGH	10.8	50	1.8
MED	8.6	60	2.1
LOW	19.7	28	1.0

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$\Rightarrow$ Suggests moving to upfront subsidies might improve equity

Counterfactual: Reduce Upfront Costs by 1%

Reducing upfront costs (same net metering) leads to more adoptions by wealthier households and overall demand elasticity of -2.2

Wealth	Rate (%)	% Change in Installations
HIGH	10.8	2.0
MED	8.6	3.0
LOW	19.7	1.2
ALL		2.2

Note: demand is much more elastic for leases for medium and high wealth

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Note: demand is much more elastic for leases for medium and high wealth

$\Rightarrow$ Moving to upfront incentives will not improve equity

Counterfactual: Reduce Export Compensation

Reduce export compensation to 6.25 cents/kWh (avoided cost)

		Fraction Installs by % Export to Grid				
Wealth	**Rate (%)**	0	30	50	70	100
HIGH	10.8	1	0.90	0.77	0.60	0.37
MED	8.6	1	0.78	0.55	0.33	0.11
LOW	19.7	1	0.96	0.90	0.82	0.67
ALL		1	0.86	0.71	0.54	0.33

$\Rightarrow$ Adjusting net metering can improve equity

Outline

Conclusions

Average household discount rate of 13.0%

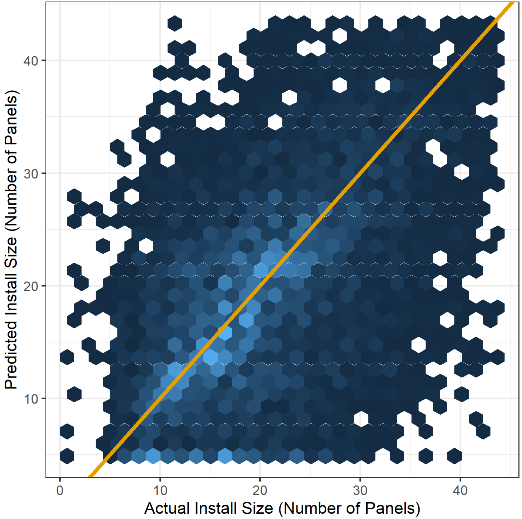
- Exceeds government borrowing rate
- Gains in efficiency from shifting to upfront subsidies
- Could apply to other energy-using durables

Heterogeneity in discount rates across household wealth

- Can at least partly explain disparities in adoption by wealth
- Gains in equity from shifting to upfront subsidies

Thank you!

Optimal Sizing Model Works



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