Dynamic Models of Photovoltaic System Installations and Upgrades

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Motivation

Most literature treats solar energy adoption as a terminal action

Real world: option to upgrade leads to “stopping problem”

How does that change estimates of installation rates, effects of incentives, etc.?

Probability of agents upgrading their existing photovoltaic system?

Literature

De Groote and Verboven (2019) account for the intertemporal nature of solar energy adoption in their DDC model. Find that consumers excessively discount the future, so upfront incentives are better.

Langer & Lemoine’s (2022) DDC model studies optimal dynamic subsidy paths in CA. Find the most effective subsidy should increase over time as such a path effectively avoids over subsidizing agents.

Data

Lawrence Berkeley Lab’s Tracking the Sun Report includes more than 2 million PV systems.

Focus:

County level solar panel installation data from California, Connecticut, Massachusetts & Minnesota

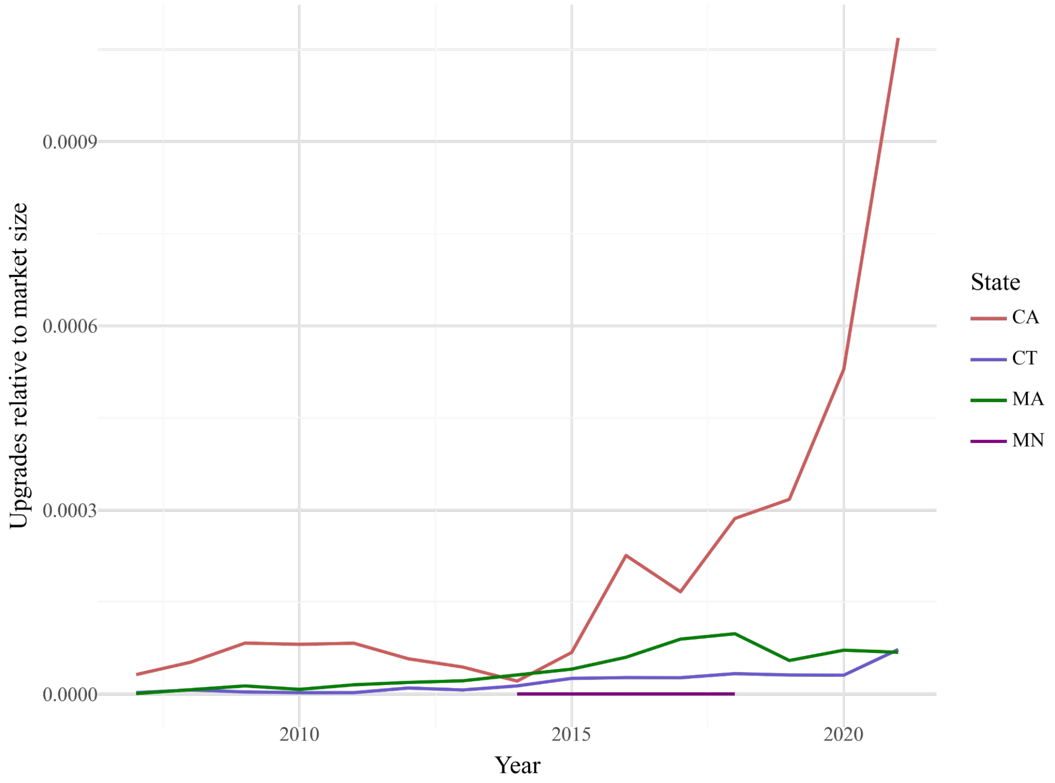
Non third party owned residential P.V. systems

Installed between 2007 and 2021

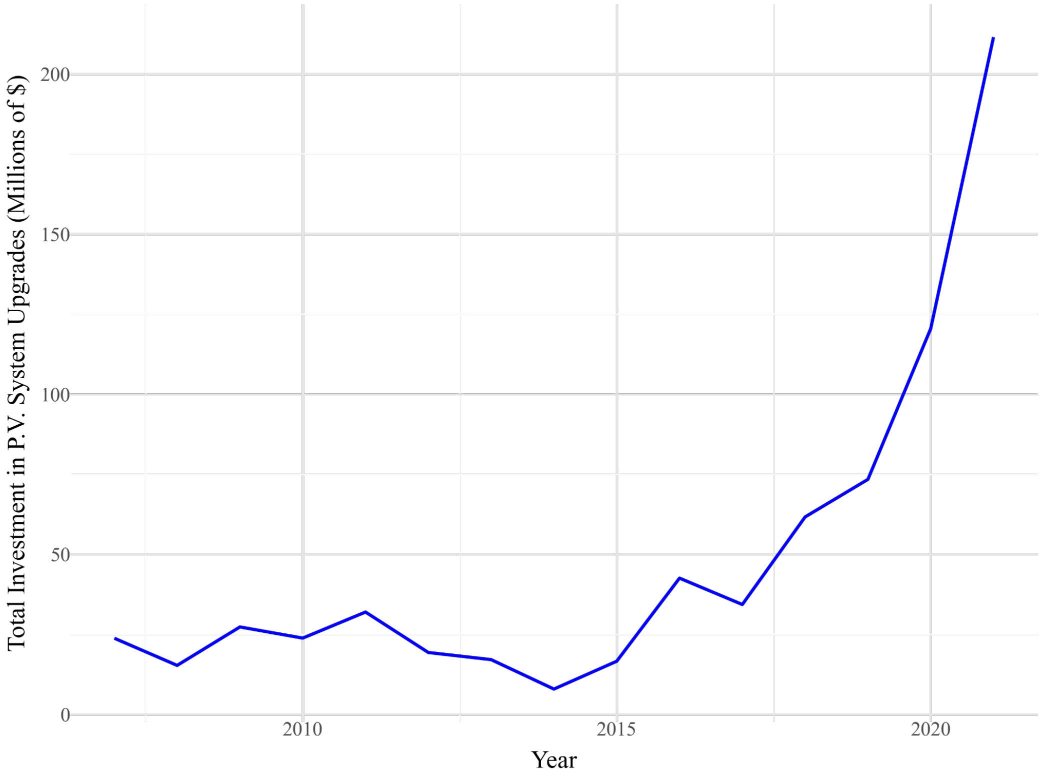
Table 1: Summary Statistics of Key Variables

Variable	Min	Max	Mean	Median	Std
New Installations	115.00	116990.00	73844.98	86553.00	36284.72
Expansions	0.00	7839.00	2647.38	2025.00	2534.03
Price per kW	0.00	545978.18	4862.47	4389.78	2532.92
Rebate per kW	0.00	12034.91	168.53	0.00	554.80
System Size	0.04	4043.66	7.32	6.46	11.11
Module Efficiency	0.07	0.23	0.19	0.19	0.02

Trends in Upgrades



Investment in Upgrades



Incident Energy & Adjusting size

$$IE_c = \frac{\text{Mean size (kW)}_{c,y}}{\eta_{c,y}}$$

Then, for every year t,

$$\text{Effective Size}_{c,t} = \eta_{c,t} \cdot IE_c$$

y= first observed year

η= system efficiency (in %)

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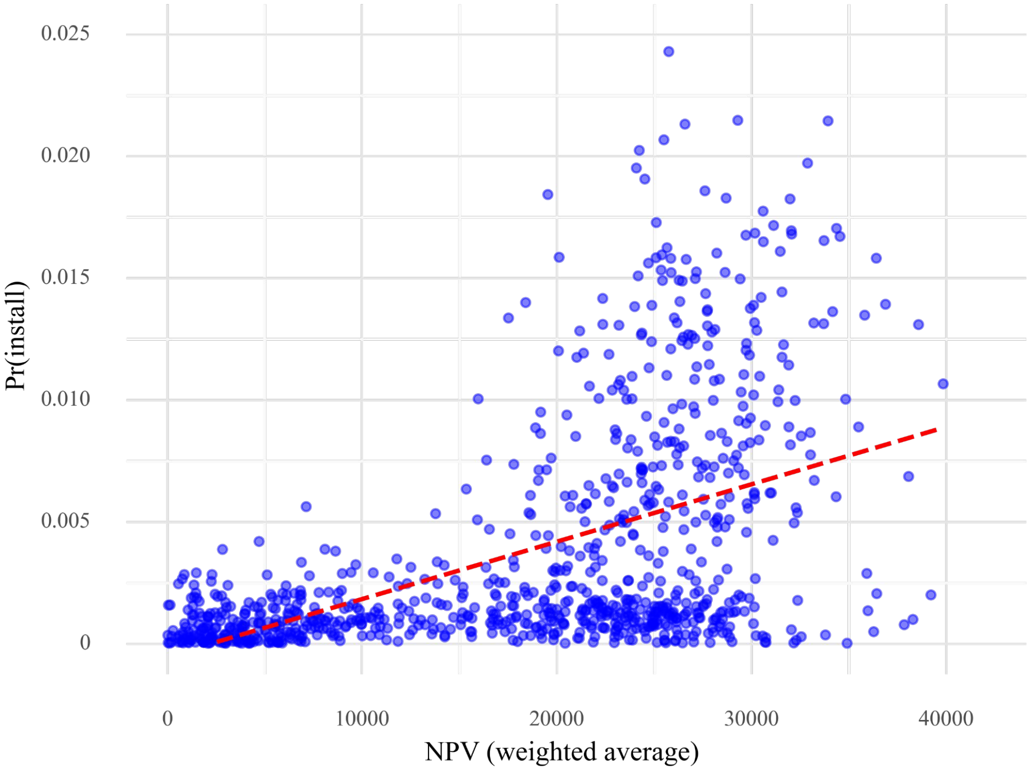
Net Present Value Variable

$$NPV = (\frac{1}{1-\beta} \text{ Electricity savings}) - \text{Installation cost net of incentives}$$

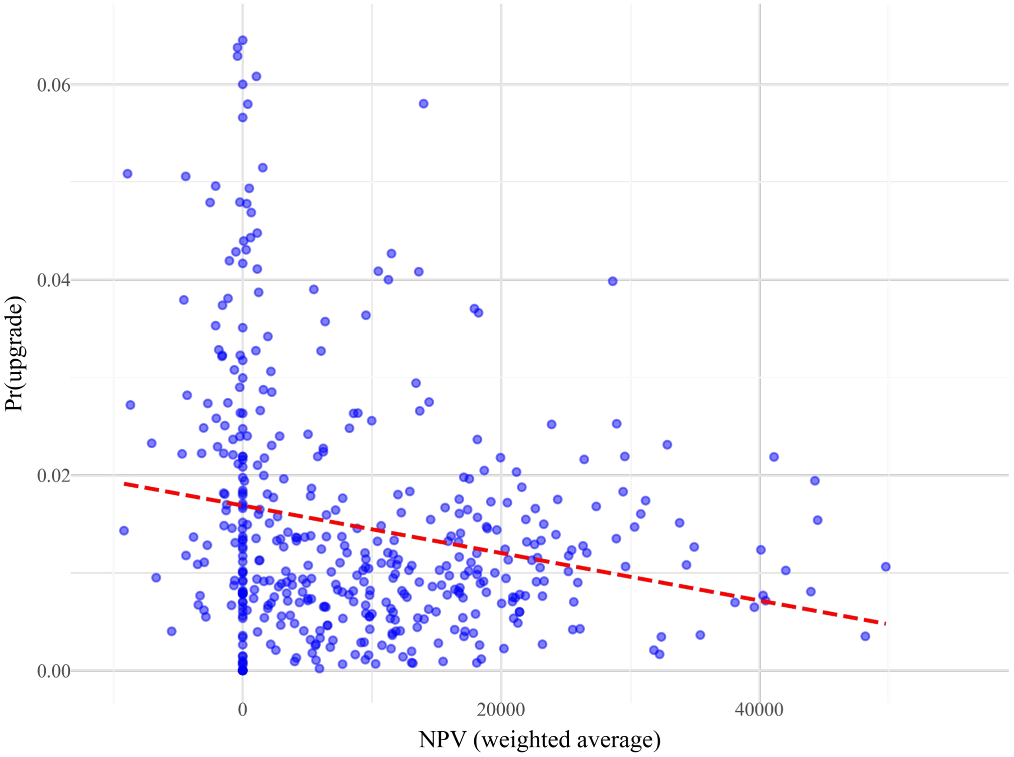
Accounts for:

1. Improvement in system efficiency (relative to first year)
2. Installation costs
3. Subsidy received (upfront)
4. Tax benefits (ITC)
5. Electricity savings from net metering

Relationship between NPV & P(install)



Relationship between NPV & Pr(upgrade)



Dynamic Model #1- Terminal action

Profit function

$$\pi_t(d;\theta) = \begin{cases} a + b(NPV)_t & \text{if } d_t = 1 \text{ i.e. agent decides to install} \\ 0 & \text{if } d_t = 0 \text{ i.e. agent decides to wait} \end{cases}$$

Per period utility

$$u_t(d,\epsilon;\theta) = \begin{cases} a + b(NPV_t) + \epsilon(d_t) & \text{if } d_t = 1 \\ 0 + \epsilon(d_t) & \text{if } d_t = 0 \end{cases}$$

Choice specific value function

$$\tilde{v}_t(d;\theta) = \begin{cases} a + b(NPV_t) + \frac{\gamma}{1-\beta}, & \text{if } d_t = 1 \\ \beta EV_{t+1}(d,\epsilon;\theta) & \text{if } d_t = 0 \end{cases}$$

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Optimal Stopping Problem

$$V_t(\epsilon;\theta) = \max_{\{d_t, d_{t+1}, \ldots\}} \mathbb{E}\left[\sum_{j=t}^{\infty} \beta^{j-t} u_j(d;\theta_j) \middle| NPV_t\right]$$

Bellman Equation reformulation

$$V_t(\epsilon;\theta) = \max_{d_t} \left[u_t(d,\epsilon;\theta) + \beta EV_t(d,\epsilon;\theta)\right]$$

$$EV_t(d,\epsilon;\theta) = ln(\sum_d exp(\tilde{v}_t(d;\theta))) + \gamma$$

Last period T

$$\tilde{v_T}(d;\theta) = \begin{cases} a + b(NPV_T) + \frac{\gamma}{1-\beta}, & \text{if } d_T = 1 \\ \beta EV_T(d,\epsilon;\theta), & \text{if } d_T = 0 \end{cases}$$

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Solve for period T then iterate backwards

Model predicts:

$$\tilde{Pr}(install)_t = \tilde{Pr}(d = 1; \theta)_t$$

$$= \frac{exp(\tilde{v}_t(d = 1; \theta))}{exp(\tilde{v}_t(d = 1; \theta)) + exp(\tilde{v}_t(d = 0; \theta))}$$

Estimation

Static estimates (2021 data) as initial guess:

a= -15.4, b= 3.8e-4

Maximize log likelihood of observing the predicted probabilities for each county, then sum over counties

$$l(N, n, \tilde{Pr}, t) = \prod_t binom(N_t, \tilde{Pr}_t) = \prod_t \binom{N_t}{n_t} \tilde{Pr}(install)_t^{n_t} \ (1 - \tilde{Pr}(install)_t)^{N_t - n_t}$$

N= owner occupied households , n= new installations, $\tilde{Pr}$ = Pr(new installation)

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Dynamic Model #2- Upgrade Option

y= first year with observed expansions $\eta_{y-1} = 0 \text{ and } NPV_{y-1} = 0$

Agents start with (y-1) vintage or, equivalently, no solar panels

Upgrading from a (y-1) vintage = installing P.V. system for the first time

In year t with vintage i:

Decision space

$$d_t = \begin{cases} 1 & \text{if agent decides to upgrade to vintage } t \\ 0 & \text{if agent decides to keep existing vintage } i \end{cases}$$

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Profit function

$$\pi_{t,i}(d;\theta) = \begin{cases} a + b(NPV_t' - NPV_i') - IC_i & \text{if } d_t = 1 \\ m\mathbb{1}[i \neq y-1] & \text{if } d_t = 0 \end{cases}$$

Per period utility

$$u_{t,i}(d,\epsilon;\theta) = \begin{cases} a + b(NPV_t' - NPV_i') - IC_i + \epsilon_t(d=1) & \text{if } d_t = 1 \\ m\mathbb{1}[i \neq 2006] + \epsilon_t(d=0) & \text{if } d_t = 0 \end{cases}$$

Choice specific value function

$$\tilde{v}_{t,i}(d;\theta) = \begin{cases} a + b(NPV_t' - NPV_i' - IC_i) + \beta EV_{\theta,t+1,t} & \text{if } d_t = 1 \\ m\mathbb{1}[i \neq 2006] + \beta EV_{\theta,t+1,i} & \text{if } d_t = 0 \end{cases}$$

Optimal Stopping Problem

$$V_{t,i}(\epsilon_t;\theta) = \max_{\{d_t, d_{t+1}, \dots\}} \mathbb{E}\left[\sum_{j=t}^{\infty} \beta^{j-t} u_{j,i}(d;\theta) \middle| NPV_t, NPV_i, IC_i\right]$$

Bellman Equation reformulation

$$V_{t,i}(\epsilon;\theta) = \max_{d_t} \left[u_{t,i}(d,\epsilon;\theta) + \beta EV_{t,i}(d,\epsilon;\theta)\right]$$

$$EV_{t,i}(d,\epsilon;\theta) = ln(\sum_{d_t} exp(\tilde{v}_{t,i}(d;\theta))) + \gamma$$

Last period T+1

$$\tilde{v}_{T+1,i}(d;\theta) = \begin{cases} a + b(NPV_T' - NPV_i' - IC_i) + \beta EV_{T+1,T}(d,\epsilon;\theta) & \text{if } d_T = 1 \\ m\mathbb{1}[i \neq 2006] + \beta EV_{T+1,i}(d,\epsilon;\theta) & \text{if } d_T = 0 \end{cases}$$

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Model predicts:

$$\tilde{Pr}(\text{upgrade in } t|\text{vintage } i) = \tilde{P}_{up,t}(i) = \tilde{Pr}(d = 1|X_{t,i};\theta)$$

$$= \frac{exp(\tilde{v}_{t,i}(d = 1;\theta))}{exp(\tilde{v}_{t,i}(d = 1;\theta)) + exp(\tilde{v}_{t,i}(d = 0;\theta))}$$

$$\tilde{Pr}(upgrade)_t = \sum_{i=y}^{t} \tilde{Pr}(\text{upgrade in } t \cap \text{have vintage } i)$$

$$= \sum_{i=y}^{t} \tilde{P}_{up,t}(i) \cdot \mu_t(i)$$

$\mu_t(i)$ = share of agents in year t that have vintage i

Estimation

Static estimates (2021 data) as initial guess:

a= -8.3, b= 1.28e-4

Maximize log likelihood of observing the predicted probabilities (initial installations - Pr and upgrades- q) for each county, then sum over counties

$$L(N, N', n, u, \tilde{Pr}, q, t) = \prod_{t=2007}^{2021} \binom{N_t}{n_t} \tilde{Pr_t}^{n} (1 - \tilde{Pr}_t)^{N-n} \prod_{t=2008}^{2021} \binom{N'_t}{u_t} q_t^{u_t} (1 - q_t)^{N'_t - u_t}$$

N= owner occupied households , n= new installations, $\tilde{Pr}$ = Pr(new installation)

N'= installed base of P.V systems, u= upgrades, q= Pr(upgrade)

Parameter Estimates

Terminal Action Model

a= disutility= 12.666

b= NPV effect= 3.361e-07

a/b = implied installation **benefit** (in $)

= 37,667,360

Model with Upgrade Option

a= -1.487

b= 1.538e-06

m= -0.6986$

Implied installation **cost** = a/b = -$966,840

Policy implications

Inelasticity to NPV:

a) no difference due to modeling choices in policies that shift NPV returns
b) counterintuitive but consistent- more work required!

Installation cost vs benefit:

a) parameters are biased from ignoring the possibility of upgrades
  - policies that compensate for disutility
  - measures of switching costs

b) large magnitudes - consistent

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Thank You!

Questions/comments/feedback

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