# Complementarities and Optimal Targeting of Technology Subsidies

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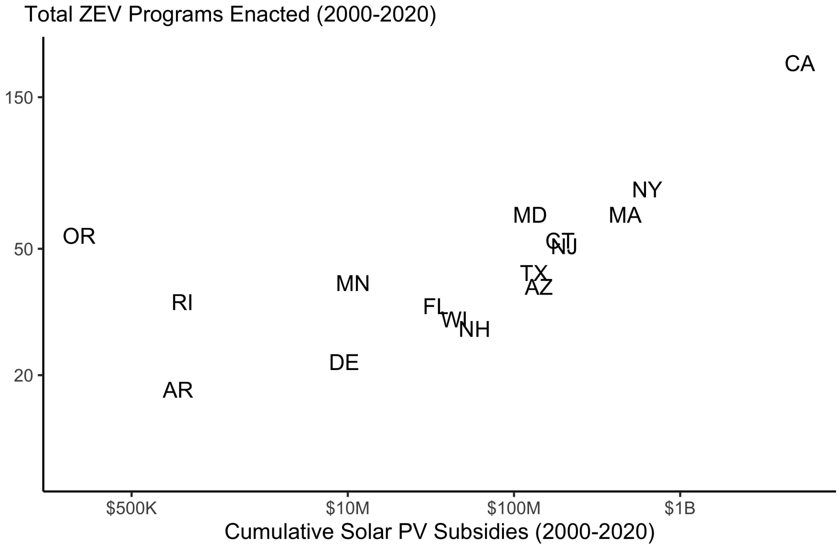
*The views expressed in this presentation are those of the authors and do not necessarily reflect those of the Federal Trade Commission or any individual Commissioner.

# Substantial overlap in public funding for solar, PEV adoption




Sources: Lawrence Berkeley National Lab (LBNL), US Department of Energy (DOE)

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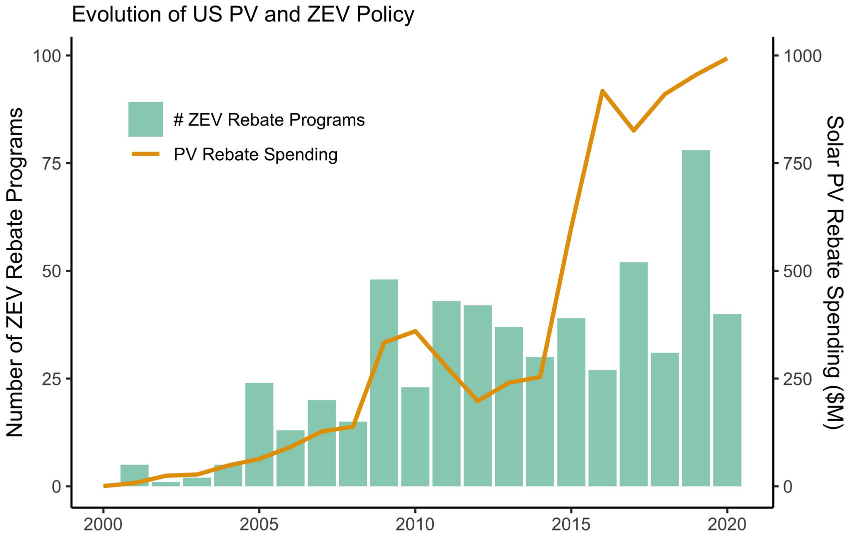


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# But what if solar, PEVs are complementary goods?

1. Technology complementarity: Low marginal fuel costs
    - Depends on consumption/charging behavior, PV output
2. Policy complementarity: Net-metering
    - Excess solar generation can "roll back the meter"
3. Correlated preferences:
    - Unobservable preference for "green" goods

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- Application: Residential solar and PEV markets in California (CA)
- Today:
  1. Provide empirical evidence of existing complementarity between PV and PEV adoption in CA
  2. Develop model of optimal second-best policies with complementary, clean goods
     - $\rightarrow$ Independent Pigouvian subsidies are sub-optimal
  3. Find evidence of likely welfare losses from observed overlapping policy regime in CA

# Related literature

- Public finance and optimal taxation
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- Product complementarities
  - Bollinger et al., 2023; Crawford and Yurukoglu, 2012; Crawford et al., 2018; Dubé, 2004; Gentzkow, 2007; Grzybowski and Verboven, 2016; Hendel, 1999; Hicks and Allen, 1934; Iaria and Wang, 2020; Kwak et al., 2015; Lee et al., 2013; Liu et al., 2010; Manski and Sherman, 1980; Nevo et al., 2005 . . .

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- Economics of clean technologies and solar/PEV subsidies
  - Borenstein, 2017; De Groote and Verboven, 2019; Gillingham and Tsvetanov, 2019; Lyu, 2023; E. Muehlegger and Rapson, 2022; E. J. Muehlegger and Rapson, 2023 ...

# Outline

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Data and Descriptives

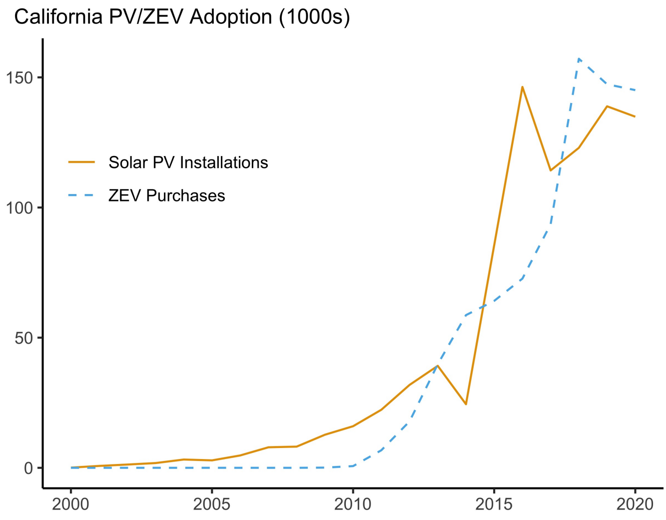
Are Solar and PEV's Complements? A Basic Model of Co-adoption

Implications: A Model of Optimal Second Best Subsidies

Optimal versus Observed Subsidy Policies in CA

Next Steps

# Setting: Solar and EV adoption in California




- CA: Largest market for residential PV and EV in US
- Substantial state-level subsidies:
  - PV: California Solar Initiative (2007-2013)
  - EV: Clean Vehicle Rebate Project (2009-2023)

Sources: Lawrence Berkeley National Lab (LBNL), CA Energy Commission (CEC))

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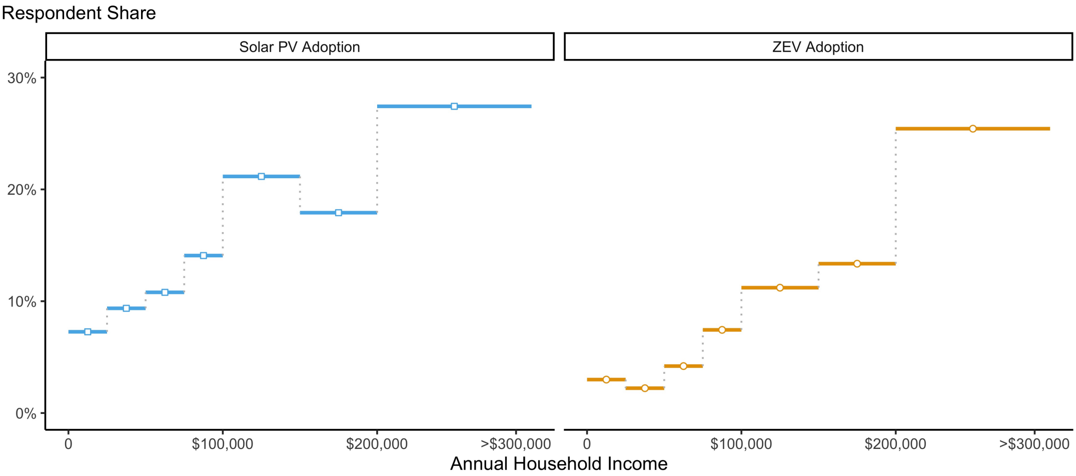
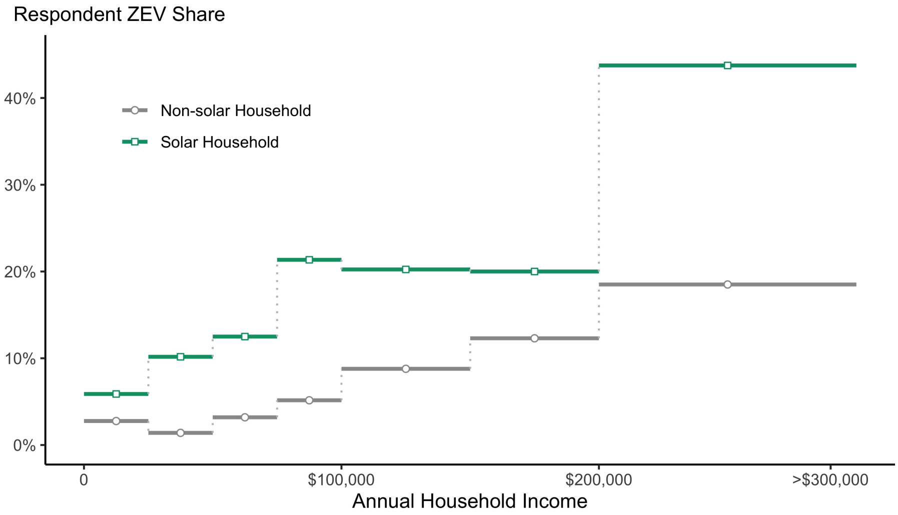
- California Public Utilities Commission $\longrightarrow$ California solar PV rebate data (2007-2013)

# Fact #1: Adoption ↑ w/ income



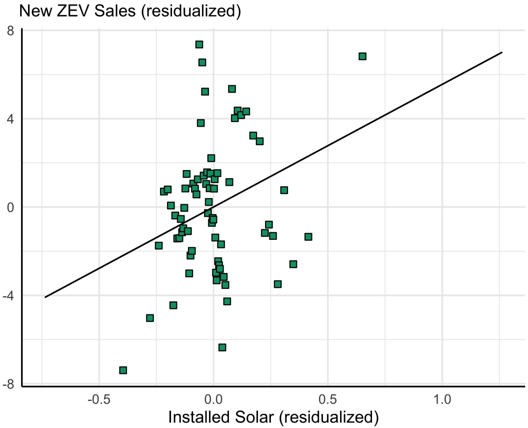

Source: California Energy Commission, CA Vehicle Survey

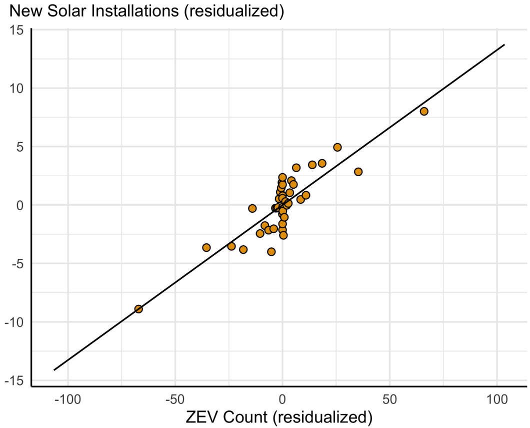
# Fact #2: ZEV adoption ↑ 4× among PV households




Source: California Energy Commission, CA Vehicle Survey

# Fact #3: Stocks and flows are correlated




▸ Regressions ▸ PV policy variation ▸ ZEV policy variation ▸ Full results (PV) ▸ Full results (ZEV)

# Outline

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- Complementary goods $\Longleftrightarrow$ positive compensated cross-price elasticities of demand
- Relationship between adoption levels:
  1. Does not define complementarity
  2. Is not a sufficient statistic for welfare

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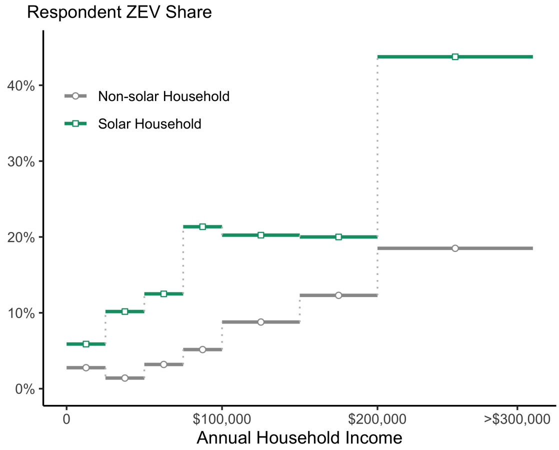
- Limitations:
  - For vehicle adoption decision, use choice experiment with no outside option
  - Source(s) of potential complementarity?
  - Dynamics!

# California Vehicle Surveys (2013, 2017)




- Random survey of nearly 7,000 CA households
- Includes data on solar adoption
  - → Combine with LBNL/CPUC data on solar prices, rebates
- Use vehicle choice experiment with randomized prices, attributes (e.g., fuel type), and policies
- Choice set: 4 vehicles (combination of PEVs/ICEs), each with a solar/no-solar alternative

# Model of co-adoption with complementarity

- Follow static discrete choice model of Gentzkow, 2007
- Individual $i$'s indirect utility from consuming goods $j$ in bundle $b$ (i.e., $j \in b$) is

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- $\varepsilon_{ib} \overset{\text{i.i.d.}}{\sim}$ T1EV bundle-specific preference shock

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- Identification:
  - $\alpha$ identified from experimental variation in vehicle prices/rebates + variation in PV rebates
  - $\Gamma_b$ identified from inclusion of 'controls' $X_{ij}$ which only shift utility of adoption for one technology (e.g., HOV lane access, solar irradiance)

# Solar PV and PEVs are complements: $\Gamma > 0$ (Gentzkow, 2007)

| | Estimate (SE) | | Estimate (SE) |
|---|---|---|---|
| **Common Parameters** | | **Vehicle Attributes** | |
| (Price – Subsidy) / Income | $-1.904$ (0.033) | Acceleration Rate | $-0.060$ (0.002) |
| Complementarity Term ($\Gamma$) | 0.771 (0.030) | Fueling Time | $-0.139$ (0.004) |
| | | Fuel Cost/Mile | $-0.047$ (0.015) |
| **Solar PV Attributes** | | Miles/Gallon | 0.391 (0.018) |
| $\mathbb{1}$\{Solar PV\} | $-6.374$ (0.404) | Range | 0.533 (0.012) |
| Solar Radiation | 0.058 (0.018) | Trunk Space | 0.198 (0.013) |
| Module Efficiency | 0.205 (0.012) | Vehicle Age | $-0.037$ (0.004) |
| | | $\mathbb{1}$\{Small Car\} | $-0.157$ (0.015) |
| **Income Interactions** | | $\mathbb{1}$\{SUV\} | $-0.039$ (0.022) |
| Income $\times$ $\mathbb{1}$\{PEV\} | 0.028 (0.002) | $\mathbb{1}$\{Truck\} | $-0.692$ (0.024) |
| Income $\times$ $\mathbb{1}$\{Solar PV\} | 0.015 (0.002) | $\mathbb{1}$\{Van\} | $-1.280$ (0.036) |
| | | $\mathbb{1}$\{PEV\} | $-0.213$ (0.032) |
| | | $\mathbb{1}$\{Hybrid\} | 0.130 (0.014) |
| Log Likelihood | | $-85\,665.49$ | |
| Individuals | | 6754 | |
| Choices | | 54 032 | |

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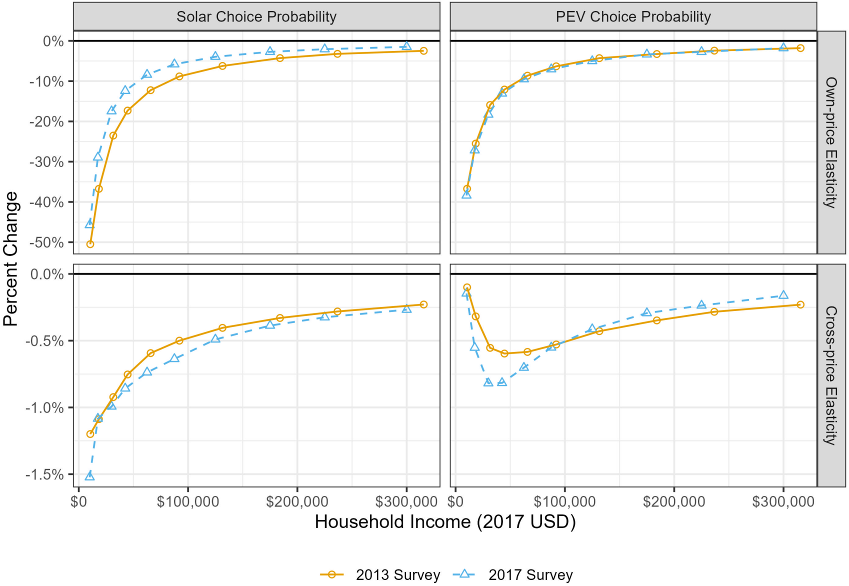
# Positive cross-price elasticities: Demand response when price ↑10%



# Outline

# Model of optimal second best subsidies

- Develop stylized model to demonstrate the implications of cross-technology complementarity for optimal (constrained) policy

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    2. $\uparrow$ complementarity, $\downarrow$ optimal constrained policy
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- Generalizes to other settings with overlapping subsidies for complementary goods

# Model setup

- $N$ identical households consume a numeraire and four goods:

$$x_1 = \text{clean electricity} \qquad x_2 = \text{dirty electricity}$$
$$y_1 = \text{clean transportation} \qquad y_2 = \text{dirty transportation}$$

- Households face prices $\boldsymbol{p} = \left(p_1^x, p_2^x, p_1^y, p_2^y, 1\right)$

▸ HH problem

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- Assume $x_1$ is a substitute for $x_2$ and $y_1$ is a substitute $y_2$, i.e.

$$\frac{\partial x_1}{\partial p_2^x} > 0 \qquad \frac{\partial x_2}{\partial p_1^x} > 0 \qquad \frac{\partial y_1}{\partial p_2^y} > 0 \qquad \frac{\partial y_2}{\partial p_1^y} > 0$$

▸ HH problem

# Social planner's problem

- Social planner chooses per-unit taxes or subsidies, $\boldsymbol{\tau} = (\tau_1^x, \tau_2^x, \tau_1^y, \tau_2^y)$ to maximize utility, accounting for externalities

- First-best policy: With no constraints on $\boldsymbol{\tau}$, the following portfolio is first-best

$$\tau_1^{x*} = 0 \qquad \tau_2^{x*} = e_x N \qquad \tau_1^{y*} = 0 \qquad \tau_2^{y*} = e_y N$$

  - Standard Pigouvian taxation result
  - Tinbergen independence still holds

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  - Standard Pigouvian taxation result
  - Tinbergen independence still holds

- But what if we constrain $\tau_2^x = \tau_2^y = 0$?
  $\rightarrow$ Could arise due to due political constraints on direct Pigouvian taxation

▸ HH problem ▸ Planner's problem

# Takeaway #1: Policymaker needs to know full substitution matrix

- Naive constrained policy: If government ignores potential interactions between electricity and transportation, will set the following subsidies

$$\tilde{\tau}_1^x = e_x N \left( \frac{\partial x_2}{\partial p_1^x} \right) \left( \frac{\partial x_1}{\partial p_1^x} \right)^{-1} \qquad \tilde{\tau}_1^y = e_y N \left( \frac{\partial y_2}{\partial p_1^y} \right) \left( \frac{\partial y_1}{\partial p_1^y} \right)^{-1}$$

▸ Naive policy

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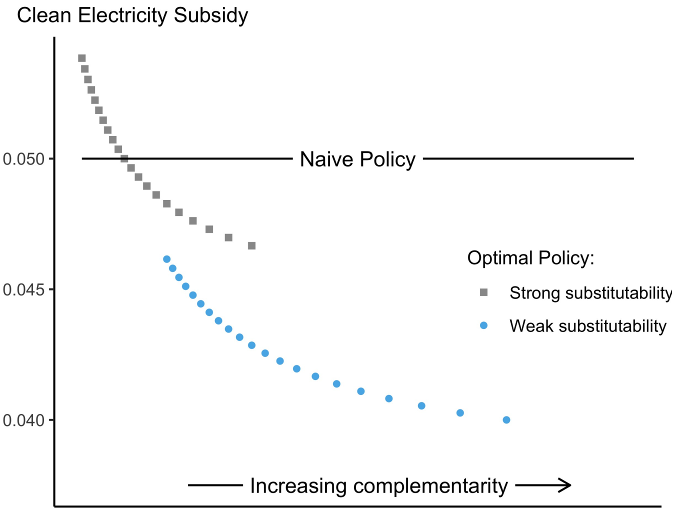
- Second-best policy: If government considers potential interactions between electricity and transportation, will set the following subsidies

$$\bar{\tau}_1^x = \frac{e_x N}{|\tilde{\Omega}|}\left(\frac{\partial x_2}{\partial p_1^x}\frac{\partial y_1}{\partial p_1^y} - \frac{\partial x_2}{\partial p_1^y}\frac{\partial y_1}{\partial p_1^x}\right) + \frac{e_y N}{|\tilde{\Omega}|}\left(\frac{\partial y_2}{\partial p_1^x}\frac{\partial y_1}{\partial p_1^y} - \frac{\partial y_2}{\partial p_1^y}\frac{\partial y_1}{\partial p_1^x}\right)$$

$$\bar{\tau}_1^y = \frac{e_x N}{|\tilde{\Omega}|}\left(\frac{\partial x_2}{\partial p_1^y}\frac{\partial x_1}{\partial p_1^x} - \frac{\partial x_2}{\partial p_1^x}\frac{\partial x_1}{\partial p_1^y}\right) + \frac{e_y N}{|\tilde{\Omega}|}\left(\frac{\partial y_2}{\partial p_1^y}\frac{\partial x_1}{\partial p_1^x} - \frac{\partial y_2}{\partial p_1^x}\frac{\partial x_1}{\partial p_1^y}\right)$$

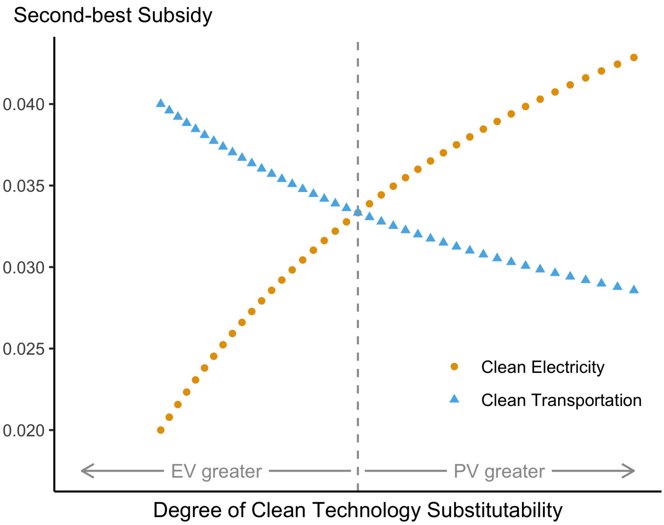
▸ Naive policy ▸ Second-best

# Takeaway #2: ↑ complementarity, ↓ optimal constrained policy




- Assume clean electricity and clean transportation are complements
- Optimal constrained policy > naive policy when:
  - Strong within-technology substitution
  - Weak cross-technology complementarity

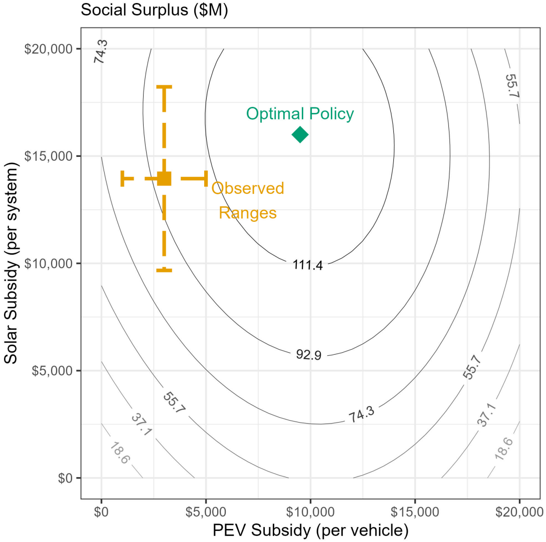
# Takeaway #3: Emphasize clean technology with greatest impact




- Assume clean electricity and clean transportation are complements
- Result depends on both
  - Direct substitution
  - Effect of complementarity between clean goods

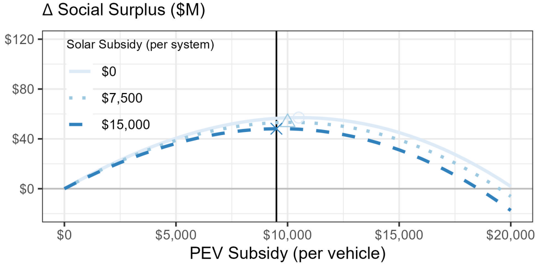
# Outline

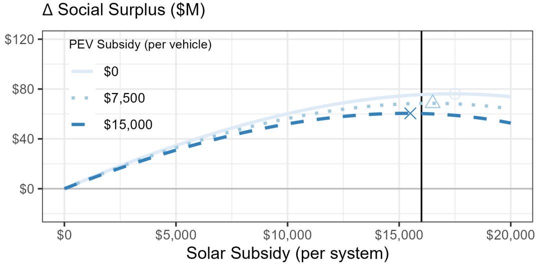
# Comparing "optimal" and observed subsidies in CA




- Use model estimates to calculate "social surplus" for different subsidy portfolios
  - Consumer surplus
  - Environmental damages
  - Government revenues
- Max $\Delta$surplus (relative to no subsidies):
  - PEV subsidy: $9,000/vehicle
  - Solar subsidy: $16,500/system
- Observed Ranges (2013, 2017):
  - PEV subsidies from CVRP
  - PV subsidies from CSI, federal ITC

# Welfare losses from ignoring interactions




- Max Δsurplus (relative to no subsidies):
  - PEV subsidy: $9,000/vehicle
  - Solar subsidy: $16,500/system
- Validates results from theory model:
  1. Emphasize more the technology with larger behavioral response
  2. Likely to over-subsidize if ignore complementarity

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# Next steps

- Today:
  - Suggestive evidence of PV-PEV complementarity
  - Theory of optimal constrained subsidy policy for interacting technologies
  - Possible efficiency implications for CA subsidy policy
- Possible next steps: Aggregate model of PV/PEV adoption to recover substitution matrix
  - Leverage finite dependence to model/estimate dynamic adoption decisions

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  - Document distributional impacts of naive vs second-best policies
- Stepping back: What is the source of the complementarity?

  $\rightarrow$ Looking for access to utility billing data to get sufficient variation in NEM, charging benefits

# Thank you!

Please reach out with comments/questions

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# Backup Slides

# Are solar PV and EV complements?

- Goal: Estimate likelihood of adopting one technology conditional on adopting the other
  $\rightarrow$ Empirical challenge: Unobservable factors affecting *both* PV and EV adoption
- Solution: Instrument adoption with relevant policy variation
  - PV: Spatial and temporal variation in solar rebates
  - ZEV: Temporal variation in EV rebate program $\times$ proximity to HOV lanes
- Estimate the following via two-stage least squares for ZCTA $z$ in year $t$:

$$\underbrace{\Delta q^{EV}_{zt}}_{\text{EV sales}} = \alpha_1 \underbrace{q^{PV}_{z,t-1}}_{\text{PV stock}} + \gamma_{c(z)t} + \lambda_z + \varepsilon_{zt}$$

$$\underbrace{\Delta q^{PV}_{zt}}_{\text{PV installs}} = \alpha_2 \underbrace{q^{EV}_{z,t-1}}_{\text{EV stock}} + \eta_{c(z)t} + \mu_z + \epsilon_{zt}$$

  - $\gamma_{c(z)t}, \eta_{c(z)t}$ are county-by-year FE; $\lambda_z, \mu_z$ are ZCTA FE

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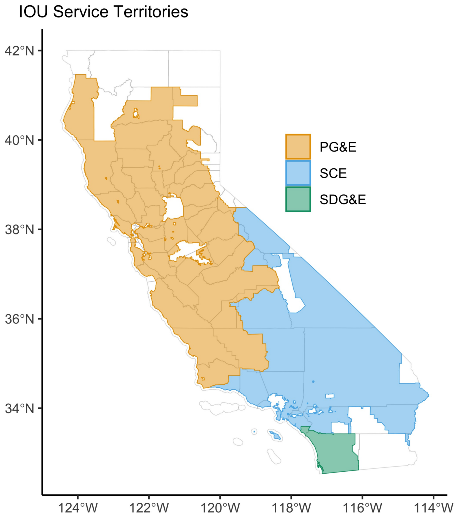
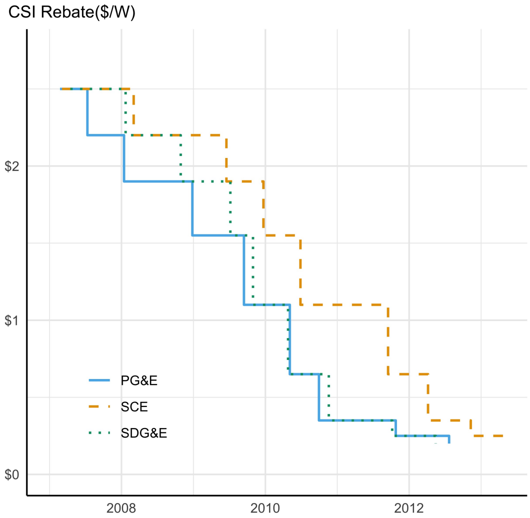
# Solar PV policy variation: CSI rebates

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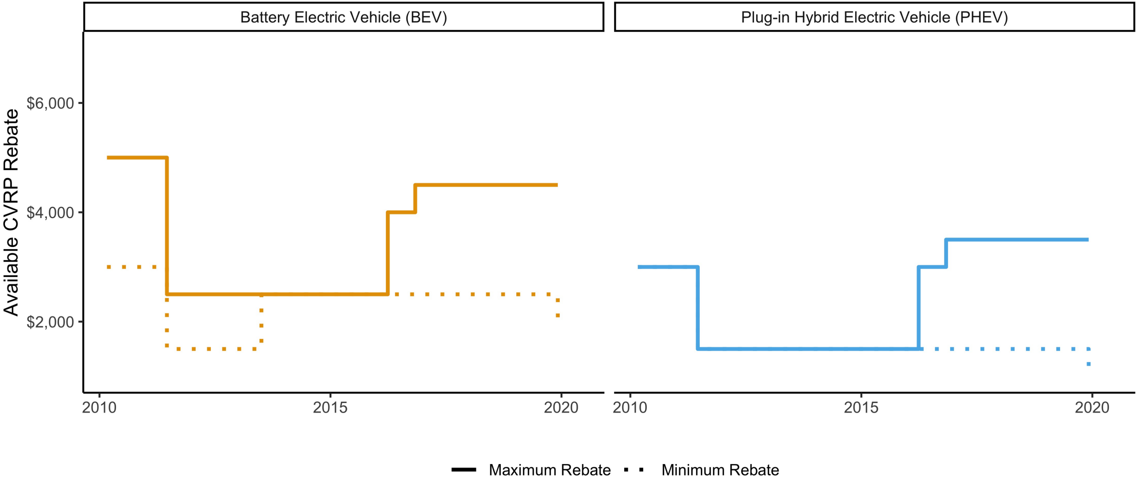
# EV policy variation: CVRP rebates

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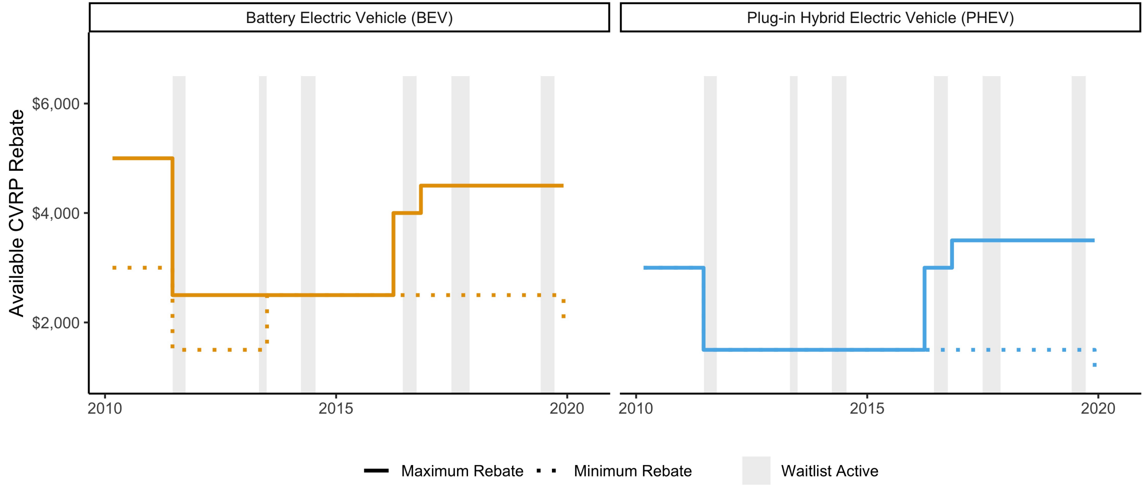
# EV policy variation: CVRP rebates

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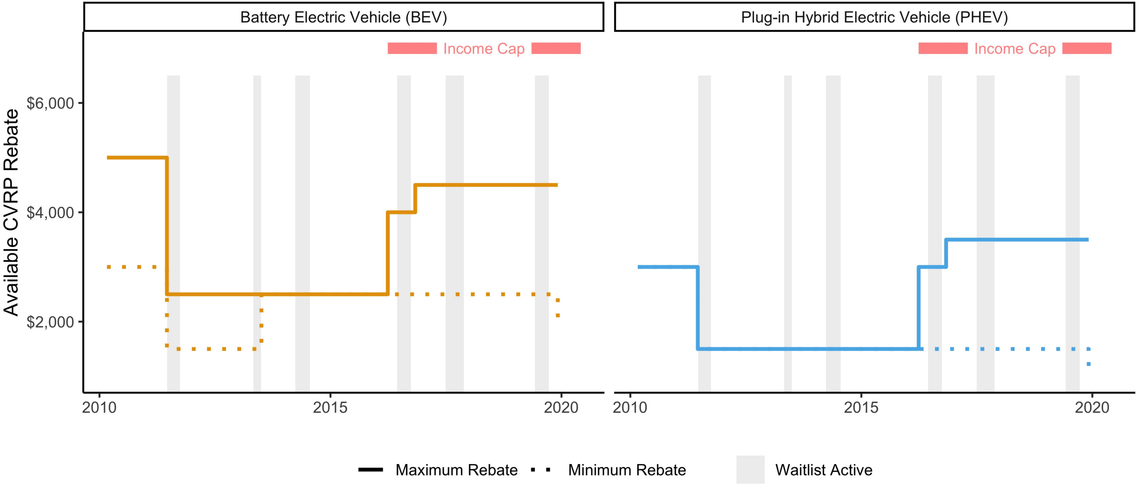
# EV policy variation: CVRP rebates

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# Full results: EV adoption

| | First Stage: Installed Solar (1) | Second Stage: ZEV Sales (2) |
|---|---|---|
| $(\text{CSI Rebate})_t$ | -21.4 | |
| | (4.14) | |
| $(\text{CSI Rebate})_{t-1}$ | -33.1 | |
| | (3.25) | |
| $(\text{CSI Rebate})_t \times \log(\text{GHI})$ | 2.93 | |
| | (0.553) | |
| $(\text{CSI Rebate})_{t-1} \times \log(\text{GHI})$ | 4.48 | |
| | (0.435) | |
| Installed Solar | | 5.55 |
| | | (2.20) |
| Observations | 46,464 | 46,464 |
| F-test (IV only) | 58.444 | 22.564 |
| ZCTA fixed effects | ✓ | ✓ |
| County-Year fixed effects | ✓ | ✓ |

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# Full results: PV adoption

| | First Stage: ZEV Count (1) | Second Stage: PV Installations (2) |
|---|---|---|
| CVRP Waitlist Length $\times$ HOV Miles | -0.080 | |
| | (0.009) | |
| CVRP Income Cap $\times$ HOV Miles | 36.7 | |
| | (3.99) | |
| Max CVRP Rebate $\times$ HOV Miles | -0.004 | |
| | (0.0005) | |
| Gas Price $\times$ HOV Miles | -2.15 | |
| | (0.378) | |
| ZEV Count | | 0.133 |
| | | (0.019) |
| Observations | 46,464 | 46,464 |
| F-test (IV only) | 177.45 | 86.374 |
| ZCTA fixed effects | ✓ | ✓ |
| County-Year fixed effects | ✓ | ✓ |

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# Toy model: Household's problem

- The representative household maximizes:

$$U = u(x_1, x_2, y_1, y_2) - N[e_x x_2 + e_y y_2] + \mu$$

where $u(\cdot)$ is a concave, $C^2$ function; subject to the following budget constraint:

$$(p_1^x + \tau_1^x)x_1 + (p_2^x + \tau_2^x)x_2 + (p_1^y + \tau_1^y)y_1 + (p_2^y + \tau_2^y)y_2 + \mu = m$$

- Assume that $N$ is sufficiently large such that households do not internalize their impact on aggregate consumption of the dirty goods:

$$x_1\left(\frac{\partial u}{\partial x_1} - p_1^x - \tau_1^x\right) = 0 \qquad x_2\left(\frac{\partial u}{\partial x_2} - p_2^x - \tau_2^x\right) = 0$$

$$y_1\left(\frac{\partial u}{\partial y_1} - p_1^y - \tau_1^y\right) = 0 \qquad y_2\left(\frac{\partial u}{\partial y_2} - p_2^y - \tau_2^y\right) = 0$$

- FOCs imply demand functions:

$$x_1 = x_1(\boldsymbol{p}, \boldsymbol{\tau}) \qquad x_2 = x_2(\boldsymbol{p}, \boldsymbol{\tau}) \qquad y_1 = y_1(\boldsymbol{p}, \boldsymbol{\tau}) \qquad y_2 = y_2(\boldsymbol{p}, \boldsymbol{\tau})$$

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# Toy model: Social planner's problem

- Government chooses a portfolio of per-unit taxes or subsidies, $\boldsymbol{\tau} = (\tau_1^x, \tau_2^x, \tau_1^y, \tau_2^y) \in \mathbb{R}^4$, with tax revenues: $N[x_1\tau_1^x + x_2\tau_2^x + y_1\tau_1^y + y_2\tau_2^y]$

- Assuming lump-sum revenue recycling, government problem is

$$
\begin{aligned}
W(\boldsymbol{\tau}) = u(x_1, x_2, y_1, y_2) - N[e_x x_2 + e_y y_2] + m \\
- (p_1^x + \tau_1^x)x_1 - (p_2^x + \tau_2^x)x_2 - (p_1^y + \tau_1^y)y_1 \\
- (p_2^y + \tau_2^y)y_2 + \tau_1^x x_1 + \tau_2^x x_2 + \tau_1^y y_1 + \tau_2^y y_2
\end{aligned}
$$

- Government's FOC:

$$
\underbrace{\begin{bmatrix}
\frac{\partial x_1}{\partial p_1^x} & \frac{\partial x_2}{\partial p_1^x} & \frac{\partial y_1}{\partial p_1^x} & \frac{\partial y_2}{\partial p_1^x} \\
\frac{\partial x_1}{\partial p_2^x} & \frac{\partial x_2}{\partial p_2^x} & \frac{\partial y_1}{\partial p_2^x} & \frac{\partial y_2}{\partial p_2^x} \\
\frac{\partial x_1}{\partial p_1^y} & \frac{\partial x_2}{\partial p_1^y} & \frac{\partial y_1}{\partial p_1^y} & \frac{\partial y_2}{\partial p_1^y} \\
\frac{\partial x_1}{\partial p_2^y} & \frac{\partial x_2}{\partial p_2^y} & \frac{\partial y_1}{\partial p_2^y} & \frac{\partial y_2}{\partial p_2^y}
\end{bmatrix}}_{\equiv \Omega}
\begin{bmatrix} \tau_1^x \\ \tau_2^x \\ \tau_1^y \\ \tau_2^y \end{bmatrix}
= e_x N \begin{bmatrix} \frac{\partial x_2}{\partial p_1^x} \\ \frac{\partial x_2}{\partial p_2^x} \\ \frac{\partial x_2}{\partial p_1^y} \\ \frac{\partial x_2}{\partial p_2^y} \end{bmatrix}
+ e_y N \begin{bmatrix} \frac{\partial y_2}{\partial p_1^x} \\ \frac{\partial y_2}{\partial p_2^x} \\ \frac{\partial y_2}{\partial p_1^y} \\ \frac{\partial y_2}{\partial p_2^y} \end{bmatrix}
$$

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# Toy model: “Naive” constrained policy

- “Naive” constrained policy: Government sets policy ignoring all interactions between the electricity and transportation goods

- In this case, the government's problem becomes

$$\begin{bmatrix} \frac{\partial x_1}{\partial p_1^x} & 0 \\ 0 & \frac{\partial y_1}{\partial p_1^y} \end{bmatrix} \begin{bmatrix} \tau_1^x \\ \tau_1^y \end{bmatrix} = e_x N \begin{bmatrix} \frac{\partial x_2}{\partial p_1^x} \\ 0 \end{bmatrix} + e_y N \begin{bmatrix} 0 \\ \frac{\partial y_2}{\partial p_1^y} \end{bmatrix}$$

- The government sets the following policies:

$$\tilde{\tau}_1^x = e_x N \left( \frac{\partial x_2}{\partial p_1^x} \right) \left( \frac{\partial x_1}{\partial p_1^x} \right)^{-1} \qquad \tilde{\tau}_1^y = e_y N \left( \frac{\partial y_2}{\partial p_1^y} \right) \left( \frac{\partial y_1}{\partial p_1^y} \right)^{-1}$$

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# Toy model: Second-best policy

- Second-best policy: Government sets policy accounting for all interactions between the electricity and transportation goods

- In this case, the government's problem becomes

$$\underbrace{\begin{bmatrix} \frac{\partial x_1}{\partial p_1^x} & \frac{\partial y_1}{\partial p_1^x} \\ \frac{\partial x_1}{\partial p_1^y} & \frac{\partial y_1}{\partial p_1^y} \end{bmatrix}}_{\equiv \tilde{\Omega}} \begin{bmatrix} \tau_1^x \\ \tau_1^y \end{bmatrix} = e_x N \begin{bmatrix} \frac{\partial x_2}{\partial p_1^x} \\ \frac{\partial x_2}{\partial p_1^y} \end{bmatrix} + e_y N \begin{bmatrix} \frac{\partial y_2}{\partial p_1^x} \\ \frac{\partial y_2}{\partial p_1^y} \end{bmatrix}$$

- The government sets the following policies:

$$\bar{\tau}_1^x = \frac{e_x N}{|\tilde{\Omega}|} \left( \frac{\partial x_2}{\partial p_1^x} \frac{\partial y_1}{\partial p_1^y} - \frac{\partial x_2}{\partial p_1^y} \frac{\partial y_1}{\partial p_1^x} \right) + \frac{e_y N}{|\tilde{\Omega}|} \left( \frac{\partial y_2}{\partial p_1^x} \frac{\partial y_1}{\partial p_1^y} - \frac{\partial y_2}{\partial p_1^y} \frac{\partial y_1}{\partial p_1^x} \right)$$

$$\bar{\tau}_1^y = \frac{e_x N}{|\tilde{\Omega}|} \left( \frac{\partial x_2}{\partial p_1^y} \frac{\partial x_1}{\partial p_1^x} - \frac{\partial x_2}{\partial p_1^x} \frac{\partial x_1}{\partial p_1^y} \right) + \frac{e_y N}{|\tilde{\Omega}|} \left( \frac{\partial y_2}{\partial p_1^y} \frac{\partial x_1}{\partial p_1^x} - \frac{\partial y_2}{\partial p_1^x} \frac{\partial x_1}{\partial p_1^y} \right)$$

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