Optimal Subsidies for Residential Solar

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TWEEDS

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HTML version

Residential Solar Panels

Solar panel **subsidies** and **installation rates** vary significantly across states.

The **environmental benefits** also vary geographically.

- Variation in sunlight ☀
- Variation in the marginal damage of electricity production 🏭

1. How should residential solar subsidies **optimally vary across space**?
2. To what extent has the current system of subsidies led to a **spatial misallocation** of solar panels?

Our approach

A structural model

- Heterogeneous **households** choose whether to install solar panels
- Households can also purchase electricity from the grid, which is produced by a set of heterogeneous **power plants**
- Installation of solar panels generates **positive externalities** by offseting production from fossil-fuel power plants

Data and Estimation

Structurally estimate the model using data on

1. **Residential solar installations**
   - Deepsolar database, a remotely-sensed dataset on universe of US residential solar installations
   - Google Project Sunroof, a remotely-sensed dataset on solar irradiance and rooftops suitable for solar
2. **Power plant production and emissions:** from Open Grid Emissions (OGE), presented at 2022 TWEEDS by Greg Miller!
   - Hourly electricity generation and emissions for over 10,000 power plants across the U.S. in 2019
   - Gives us over 40 million plant-hour observations
   - Pollutants are NO_x, SO_2, $PM2.5$, CO_2, NH_4, and N_2O
3. **Environmental damages** from AP3, a state-of-the-art air pollution model, and the social cost of carbon

Data and Estimation

Our estimated model is consistent with

- Distribution of installation rates
- Causally identified, quasi-experimental estimates on the effect of subsidies on solar panel installations
- Power plant production over the course of the year

Use the model to find optimal subsidies

- Choose set of state level subsidies to maximize the gov't objective
- **Quantify:** How severe is misallocation caused by current system of subsidies? What would be the environmental benefits of switching to the optimal system of subsidies?

Results preview

1. Current subsidies lead to severe **spatial misallocation** of solar panel installations in the U.S.

2. Optimal cost-neutral reform increases aggregate environmental benefits by **6-11%**

3. National funding for subsidies under the current system exceeds the unconstrained optimum by over **ten-fold.**

A brief model overview

Households

Households live in a state

- Face a set of electricity prices, installation prices, and menu of subsidies. Prices are all fixed over time and exogenous.
- Heterogeneity:
    - Sunlight
    - Rooftop space for solar panels
    - Preferences for solar installation
- Make once-and-for-all decision of how many panels to install, taking into account **lifetime costs and benefits**

Electricity production

Nondispatchable power plants (e.g. wind, solar)

- Output driven by exogenous factors
- Don't respond to demand for electricity
- Don't lead to environmental damages

Dispatchable power plants (e.g. coal, natural gas)

- Fill residual demand after nondispatchable plants and residential solar
- Heterogeneity:
    - Environmental damages
    - Production capacity
    - Location
- Specify plant-specific policy functions mapping excess electricity demand across grid ➡ plant-level electricity production

Government

Menu of subsidies at each state

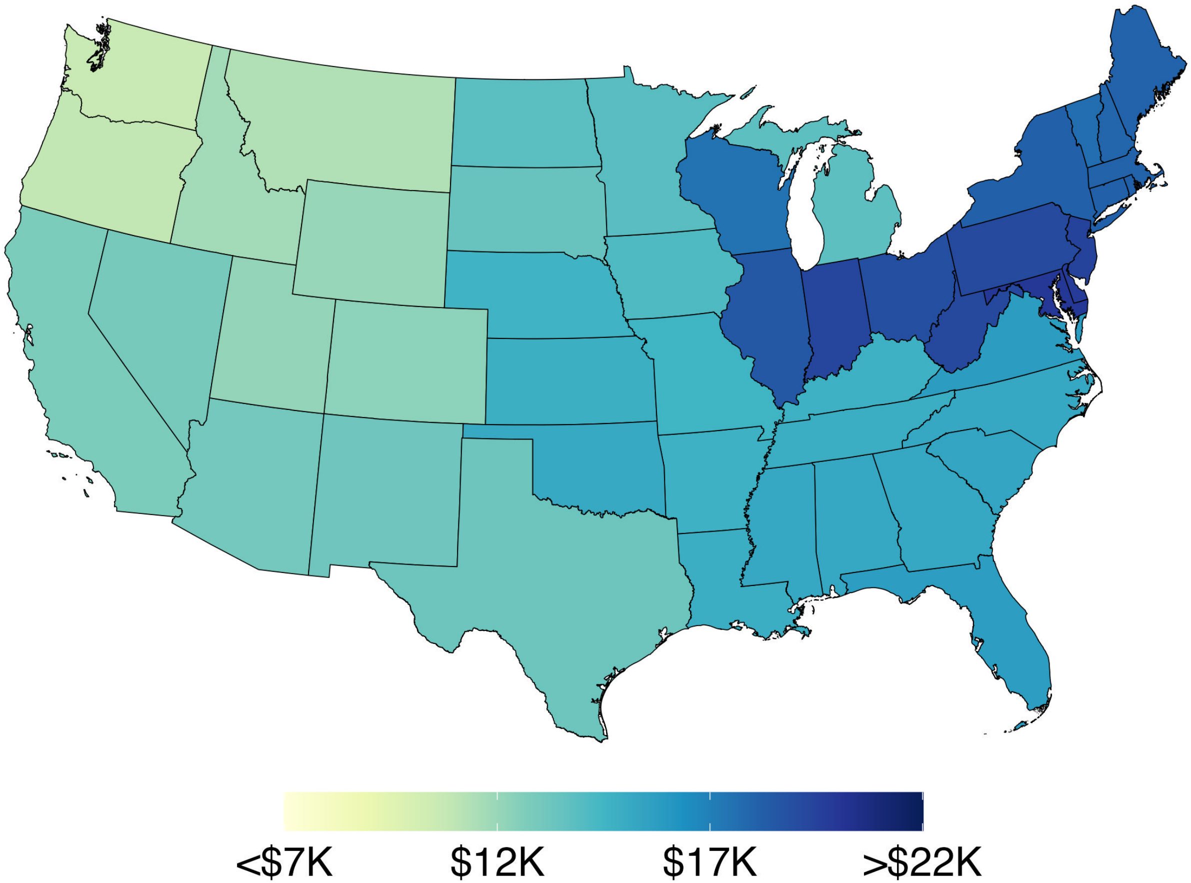
1. Production-based subsidies (e.g. renewable energy certificates)
2. Cost-based subsidies (e.g. federal investment tax credit)
3. Per-panel subsidies

⬆ subsidy ⏩ ⬆ solar installations ⏩ ⬇ dispatchable production ⏩ ⬇ damages

Choose the system of state subsidies to **maximize objective** subject to the government's **budget constraint**

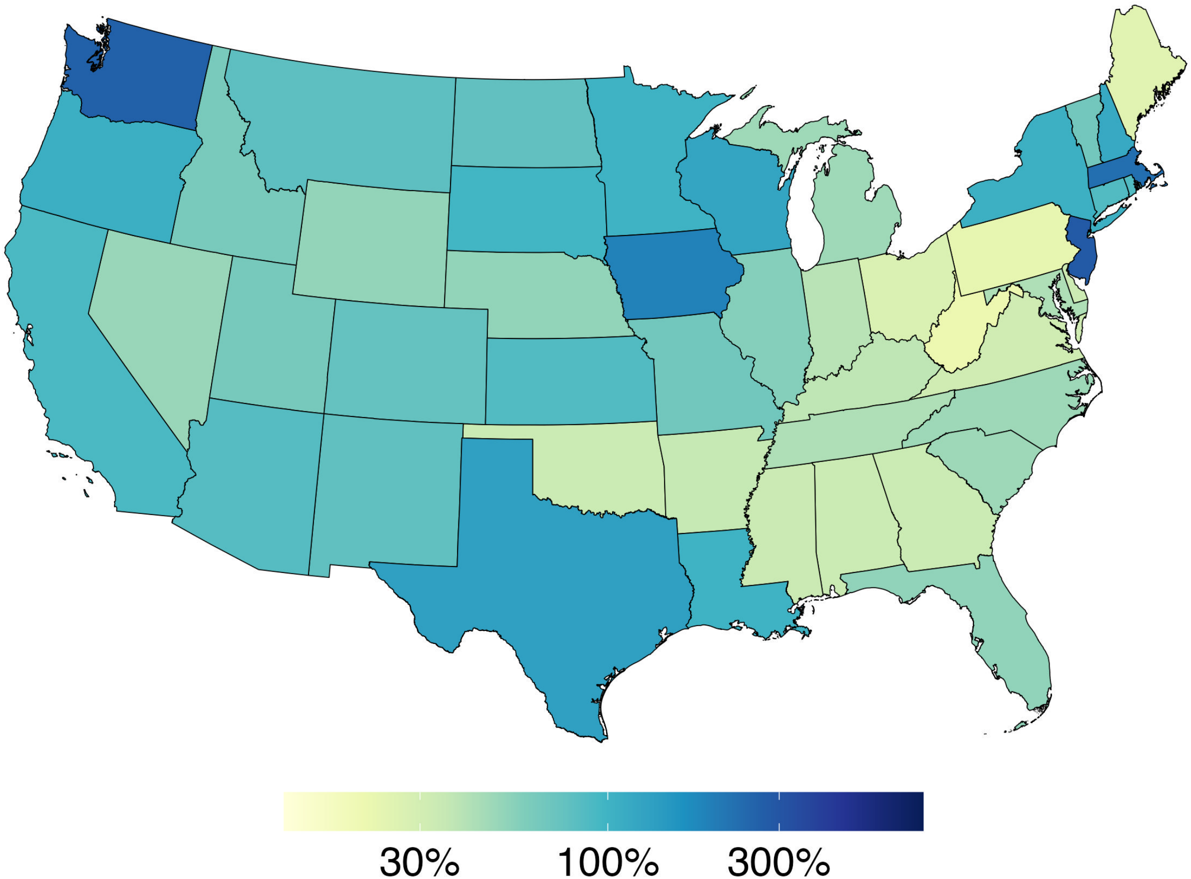
Results

Cost-neutral optimal subsidies



Welfare Maximizing Subsidies

Spatial misallocation of installations



Baseline installations as a percent of optimal

Unconstrained reforms

Optimal subsidy levels drop significantly without cost-neutral constraint.

	SCC = $51			
	Baseline	**Optimal**	**Baseline**	**Optimal**
Damages Offset ($Millions)	**141.7**	**42.3**		
Fiscal Cost ($Millions)	**495.1**	**42.3**		

- We can achieve **30%** of the benefits at **<10%** of the cost

Unconstrained reforms

Optimal subsidy levels drop significantly without cost-neutral constraint.

	SCC = $51		SCC = $185	
	Baseline	**Optimal**	**Baseline**	**Optimal**
Damages Offset ($Millions)	141.7	42.3	**325.1**	**207.3**
Fiscal Cost ($Millions)	495.1	42.3	**495.1**	**207.1**

- We can achieve **30%** of the benefits at **<10%** of the cost
- However...
  - Sensitive to choice of SCC
  - Get **64%** of benefits at **42%** of cost under higher SCC
  - Some potential benefits of residential solar are not included

Much more in the paper!

We also show results for

- Damage minimizing subsidies
- Benefits of marginal subsidy increases around current levels
- Compare tract and state-level subsidies

Robustness checks

Our results hold across various alterations/extensions...

- Alternative household utility functions
- Accounting for line losses
- Improved storage technology (i.e. batteries)
- Cleaner grid

Conclusion

We use a structural model estimated with novel datasets on solar panel installations and power plant emissions to quantify the spatial misallocation in solar installations caused by current subsidies.

- Current subsidies cause a spatial misallocation of solar installations
- Optimal cost-neutral reform increases environmental benefits by **6-11%**
- Subsidy levels are currently an order of magnitude higher than is justified by damages from emissions alone

Appendix

Model

Household setup

Household i in state j

- Choose whether to install solar panels $m_i \in \{0, 1\}$
- Number of panels conditional on installation $N_i \in \left(0, \bar{N}_i\right]$
- Each panel produces stream of electricity $\{A_{it}\}_{t=0}^{T}$ throughout the life of the panel (25 years).
- Choose path of electricity consumption each period $\{e_{it}\}_{t=0}^{T}$
- Assume electricity bought and sold at p_j
- $e_i = \sum_{t=0}^{T} \frac{e_{it}}{(1+r)^t}$ discounted sum of electricity consumed
- $A_i = \sum_{t=0}^{T} \frac{A_{it}}{(1+r)^t}$ discounted sum of electricity produced

Net present value budget constraint

Net present value budget constraint:

$$c_i + \underbrace{p_j\left(e_i - m_i N_i A_i\right)}_{\text{Net cost of electricity}} + \underbrace{m_i \left(1 - s_j^{\text{Cost}}\right) p_j^{\text{Ins}}\left(N_i\right)}_{\text{Net cost of installation}} =$$

$$y_i + \underbrace{m_i N_i A_i s_j^{\text{KWh}}}_{\text{KWh Subsidy}} + \underbrace{m_i N_i s_j^{\text{Unit}}}_{\text{Unit Subsidy}}.$$

- c_i: Consumption of numeraire good
- $p_j^{\text{Ins}}\left(N_i\right)$: Cost of installing N_i panels
- y_i: Income (exogenous)
- s_j^{Cost}: Per dollar installation subsidy
- s_j^{KWh}: Per KWh subsidy
- s_j^{Unit}: Per panel subsidy

Utility Function

Quasilinear utility function

$$c_i + \nu_i \left(\{e_{it}\}_{t=0}^{T} \right) + m_i \gamma_i \left(N_i \right)$$

- $\nu_i \left(\cdot \right)$: Lifetime utility from electricity use
- $\gamma_i \left(N_i \right)$: Nonpecuniary benefit of adding N_i solar panels
- Note that the choice of electricity consumption $\{e_{it}\}_{t=0}^{T}$ is seperable from installation decision: choice of consumption does not affect installation decisions

Utility Function

Households are solving a two step problem

1. Choose stream of electricity usage
2. Make installation decision and number of panels to install

$$V_i = \max_{N_i, m_i \in \{0,1\}} m_i \left[\underbrace{\mu_{ij}(N_i)}_{\text{Monetary}} + \underbrace{\gamma_i(N_i)}_{\text{Nonpecuniary}} \right]$$

where the monetary value is given by

$$\mu_{ij}(N_i) = \underbrace{N_i A_i \left(p_j + s_j^{\text{KWh}}\right)}_{\text{electricity value}} - \underbrace{\left(1 - s_j^{\text{Cost}}\right) p_j^{\text{Ins}}(N_i)}_{\text{installation cost}} + \underbrace{N_i s_j^{\text{Unit}}}_{\text{unit subsidy}}$$

Electricity overview

Three sources of electricity

1. Residential solar
2. Commercial nondispatchable (e.g. wind and solar)
3. Commercial dispatchable (e.g. coal and natural gas)

Excess load: Electricity demand that is not satisfied by residential solar or commercial nondispatchable sources.

Dispatchable Production

Production by dispatchable plant k in time t:

$$y_{kt}^{\text{Disp}} = \begin{cases} 0 & \text{if } f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) \leq 0 \\ f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) & \text{if } 0 < f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) < \bar{y}_k \\ \bar{y}_k & \text{if } f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) \geq \bar{y}_k \end{cases}$$

- f_k is a flexible power-plant specific production function
- ELoad_t is a vector of excess loads across geographic regions in time t
- $\bar{y}_k$ is production capacity of plant

Damages

- $d_k\left(y_{kt}^{\text{Disp}}\right)$: environmental damages by plant k
- $D\left(\text{ELoad}\right) = \sum_{t=0}^{T} \frac{\sum_k d_{kt}\left(y_{kt}^{\text{Disp}}\right)}{(1+r)^t}$: PDV of aggregate damages

Optimal Subsidies

Government maximizes sum of utility less environmental damages:

$$\underbrace{\int_i V_i h(i) di}_{\text{Utility}} - \underbrace{D\left(\text{ELoad}\right)}_{\text{Damages}}$$

subject to budget constraint

$$\underbrace{\sum_j \int_{i \in I_j} s_{ij} m_i^\star h(i) di}_{\text{Government Cost}} \leq G$$

- $h(i)$: density of household type i
- I_j: set of households in state j
- $s_{ij} = s_j^{\text{Unit}} N_i^\star + s_j^{\text{kWh}} A_i N_i^\star + s_j^{\text{Cost}} p_j^{\text{Ins}} \left(N_i^\star\right)$: total subsidy paid to HH i
- Planner chooses s_j^θ for each type of subsidy θ and each state j.

Planner's FOC

Optimal subsidies must satisfy

$$\underbrace{\frac{\partial M_j}{\partial s_j^\theta} \times \left(\overrightarrow{\Delta D}_j^{\theta,\text{ext}} - \lambda \overrightarrow{s}_j^{\theta,\text{ext}} \right)}_{\text{Extensive Margin}} + \underbrace{\left.\frac{\partial N_j}{\partial s_j^\theta}\right|_{M_j^{\text{st}}} \times \left(\overrightarrow{\Delta D}_j^{\theta,\text{int}} - \lambda \overrightarrow{\frac{\partial s}{\partial N}}_j^{\theta,\text{int}} \right)}_{\text{Intensive Margin}} + \underbrace{(1-\lambda)\, M_j \overline{\frac{\partial s_{ij}}{\partial s_j^\theta}}}_{\text{Mechanical Effect}} = 0.$$

- $\frac{\partial M_j}{\partial s_j^\theta}$ is number of marginal installers
- $\overrightarrow{\Delta D}_j^{\theta,\text{ext}}$ is the average damages offset of switchers
- $\overrightarrow{s}_j^{\theta,\text{ext}}$ is the average subsidy received by switchers
- λ is the marginal value of public funds
- $\left.\frac{\partial N_j}{\partial s_j^\theta}\right|_{M_j^{\text{st}}}$ is the number of marginal panels
- $\overrightarrow{\Delta D}_j^{\theta,\text{int}}$ and $\overrightarrow{\frac{\partial s}{\partial N}}_j^{\theta,\text{int}}$ avg damages offset/subsidy paid to marginal panel
- $\overline{\frac{\partial s_{ij}}{\partial s_j^\theta}}$ is the increase in subsidy paid to inframarginal households

Quantitative Model

Households

Household installation decision:

$$V_i = \max_{N_i, m_i \in \{0,1\}} m_i \left[\mu_{ij}(N_i) + \gamma_i(N_i) \right].$$

Parameterize non-pecuniary value of installation as

$$\gamma_i(N_i) = \underbrace{\gamma_0 + \gamma_{1N} N_i + \gamma_{2N} N_i^2}_{\text{Polynomial in } N_i} + \underbrace{\gamma_{dem} X_\ell}_{\text{Local Demographics}} + \underbrace{\sigma \varepsilon_i}_{\text{Idiosyncratic}}$$

- X_ℓ: vector of demographics at household's census tract, ℓ
- ε_i: logit idiosyncratic term

Household choices

Optimal number of panels

Conditional on installation, households will choose $N^\star$ panels

$$N_i^\star = \min\left[\bar{N}_i, -\left(\frac{\frac{\partial \mu_{ij}}{\partial N_i} + \gamma_{1N}}{2\gamma_{2N}}\right)\right]$$

Probability of installation

$$\pi_i = \frac{\exp\left(\frac{\mu_i + \gamma_0 + \gamma X_\ell + \left(\gamma_{1N} N_i^\star + \gamma_{2N} N_i^{\star 2}\right)}{\sigma}\right)}{1 + \exp\left(\frac{\mu_i + \gamma_0 + \gamma X_\ell + \left(\gamma_{1N} N_i^\star + \gamma_{2N} N_i^{\star 2}\right)}{\sigma}\right)}.$$

Dispatchable power plant production

Power plant policy functions

Production by these dispatchable plants k in time t is

$$y_{kt}^{\text{Disp}} = \begin{cases} 0 & \text{if } f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) \leq 0 \\ f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) & \text{if } 0 < f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) < \bar{y}_k \\ \bar{y}_k & \text{if } f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) \geq \bar{y}_k \end{cases}$$

We specify that

$$f_k\left(\text{ELoad}_t, \varepsilon_{kt}\right) = \lambda_k^0 + \sum_{R \in \mathbf{R}_k} \left(\lambda_{Rk}^1 \text{ELoad}_{Rt} + \lambda_{Rk}^2 \text{ELoad}_{Rt}^2\right) + \varepsilon_{kt}$$

- $\mathbf{R}_k$ is the set of NERC regions within the interconnection which contains plant k
- ε_{kt} is a normally distributed shifter

Data and Estimation

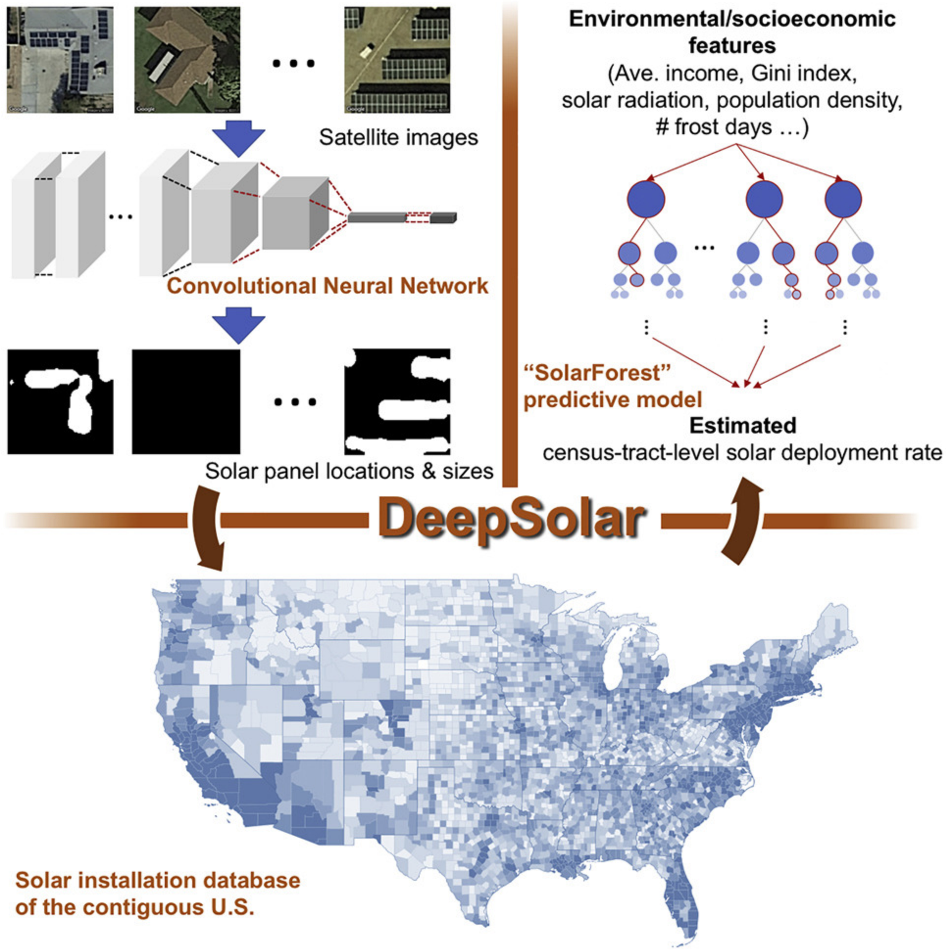
Data overview

- **Solar panel installations:** Deepsolar database (Yu et al. 2018). Overview
  - Tract-level number of residential solar systems
  - Tract-level total installed panel area
- **Rooftop sizes:** Google Project Sunroof (GPS) has area suitable for solar panels within census tracts (analog of $\bar{N}_i$). Example
- **Solar irradiance:** Combination of GPS for annual values, and the System Advisor Model (SAM), for time profile of each hour of the year
- **Current subsidies:** Database of State Incentives for Renewables & Efficiency (DSIRE) assembled by Sexton et. al. (2021)
- **Electricity prices:** average retail price by state from EIA. Map
- **Installation price function:** Estimated regionally using installation data from Tracking the Sun. Regression results

Data overview pt. 2

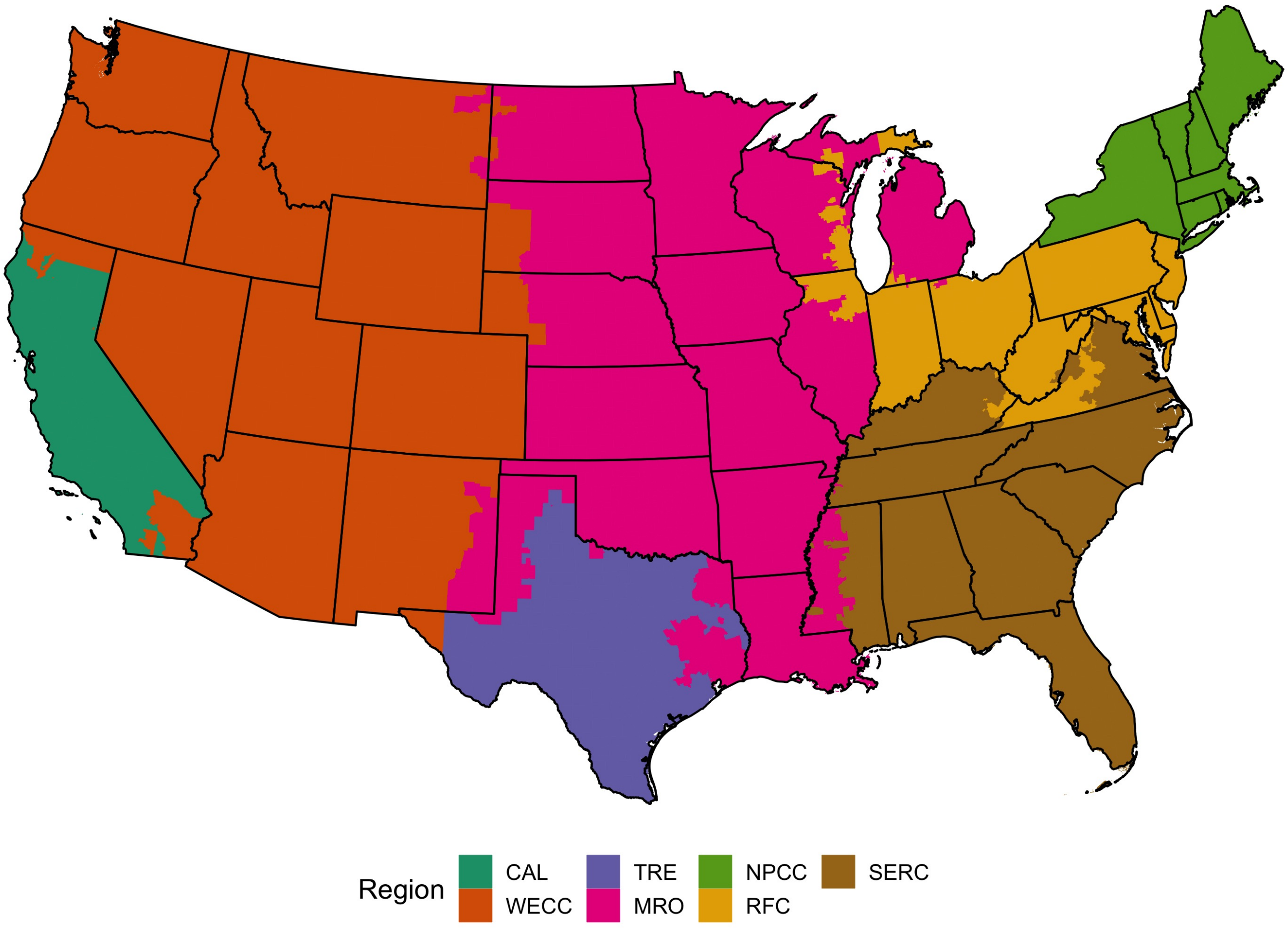
- **Power plant production and emissions:**
  - Open Grid Emissions (OGE) has hourly electricity generation and emissions for over 10,000 power plants across the U.S. in 2019
  - Pollutants are NO_x, SO_2, $PM2.5$, CO_2, NH_4, N_2O
  - Gives us over 40 million plant-hour observations
- **Damages:**
  - AP3 is a state-of-the-art integrated assessment model
  - Accounts only for human health damages
  - Use a $51/ton social cost of carbon

Deepsolar overview



Google Project Sunroof Example

NERC Region Map



Estimation overview

- **Households**
  - GMM using Deepsolar and Google Project Sunroof data
  - Target installation rate and size across all census tracts
  - Identification from cross-sectional variation in returns to installation across tracts (sunlight, subsidies and prices)
- **Power Plants**
  - Production estimated with MLE (Tobit) using OGE data
  - Emissions estimated as (power-plant specific) spline in production
  - Use AP3 to convert emissions to damages

Validation

- Replicate three quasi experimental estimates of the impact of subsidies on solar panel installations
- Replicate power plant production over the course of the year

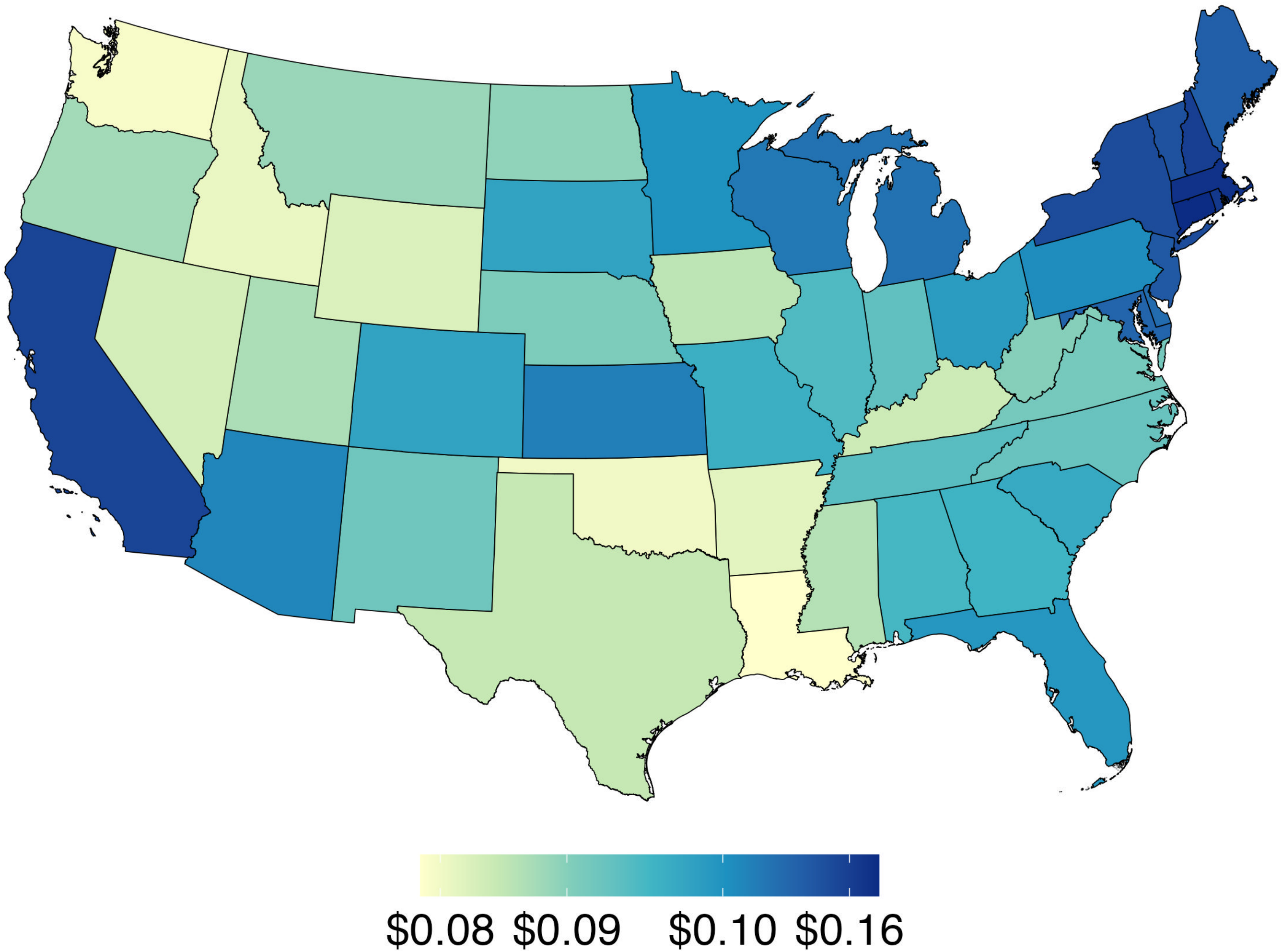
Model fit plots

Estimates and fit

Despite being sparsely parameterized, both the household and power plant models fit the data very well.

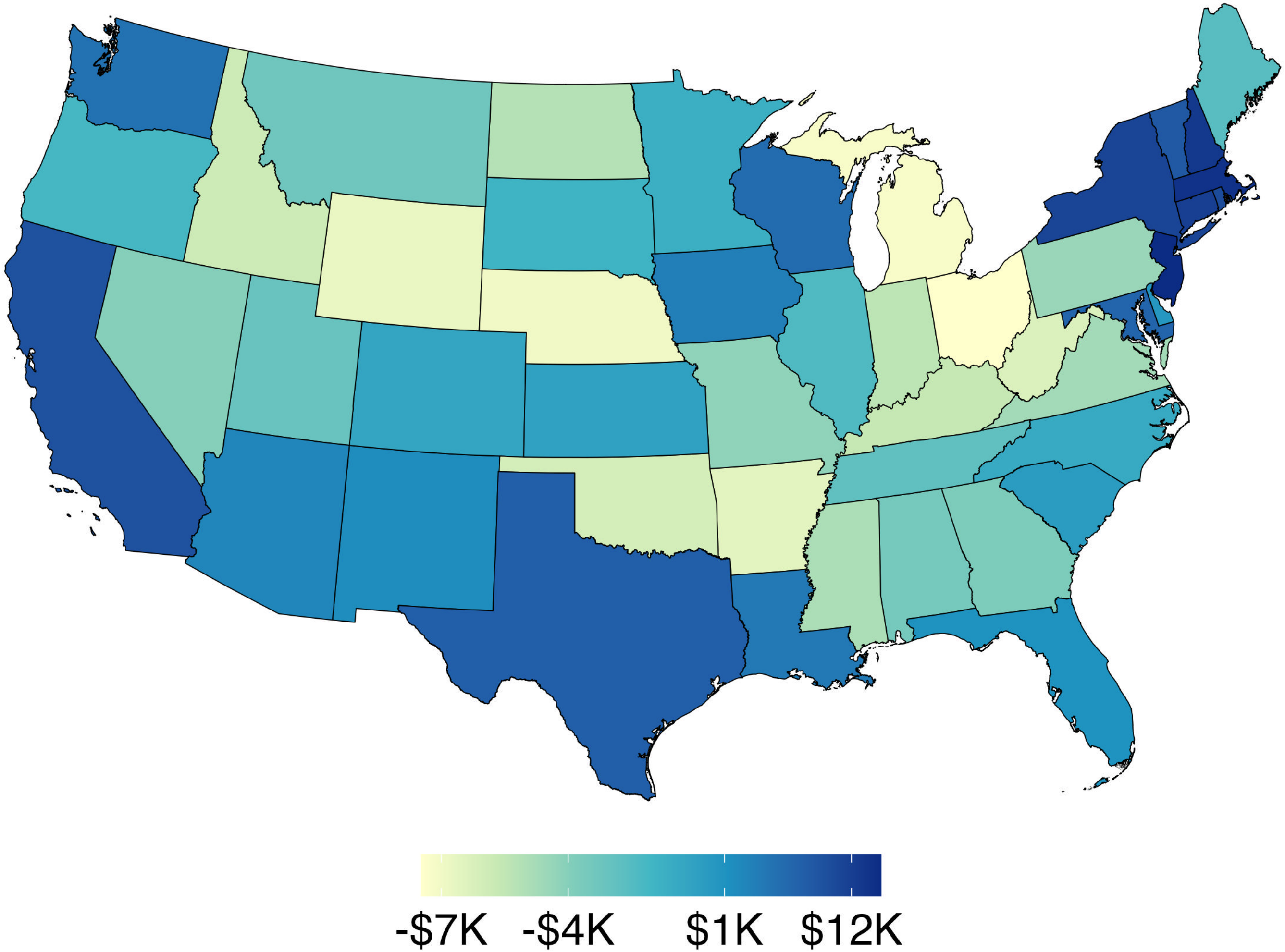
- Household parameter estimates: Details
- Installations across households: Details
- Installations across states: Details
- Quasi-experimental studies on installations: Details
- Why do installation rates vary across states? Details
- Power plant production: Details
- Marginal Damages: Details
- Mix of plant fuel type: Details

Electricity Prices



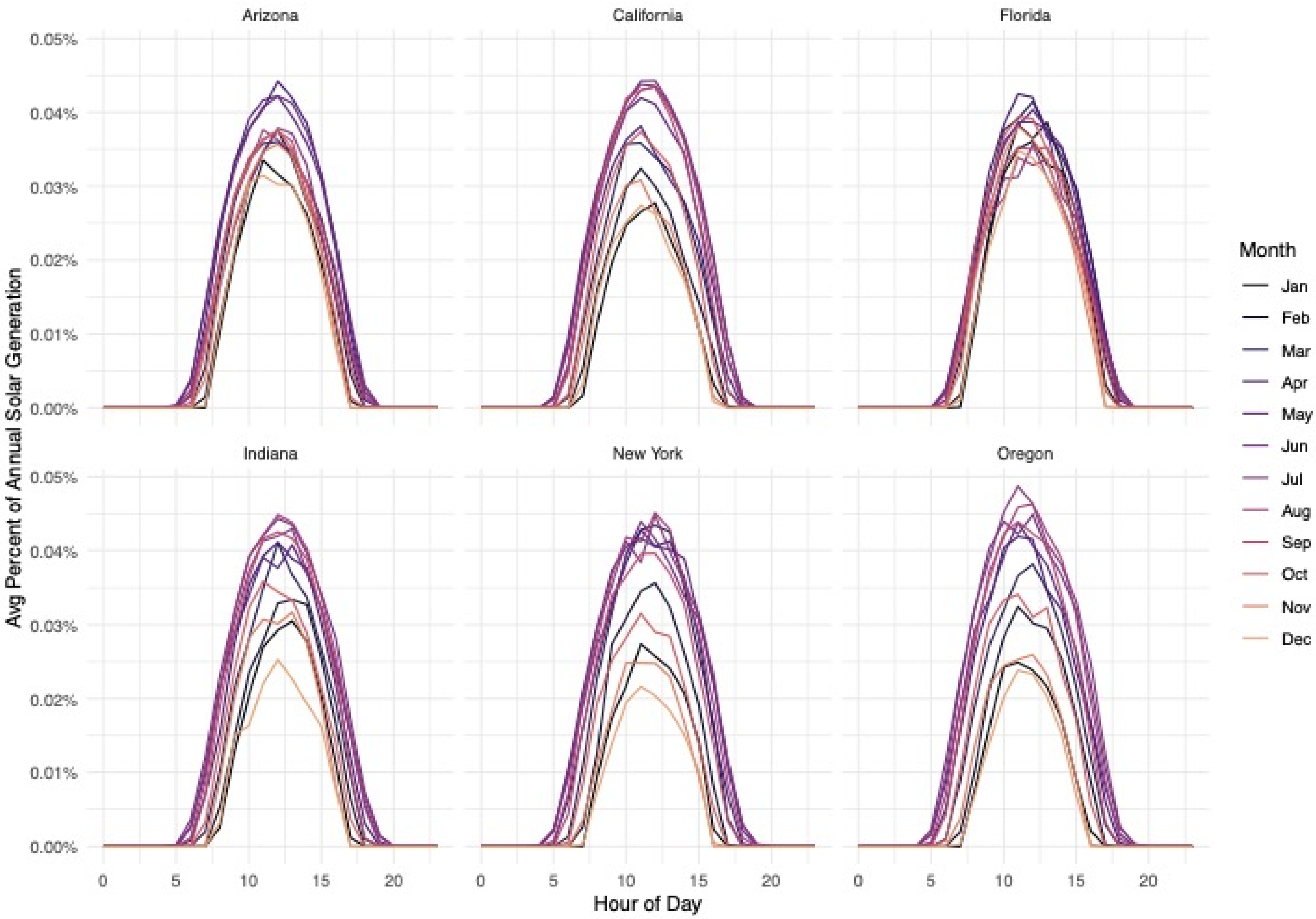
Data

Expected Monetary Benefit



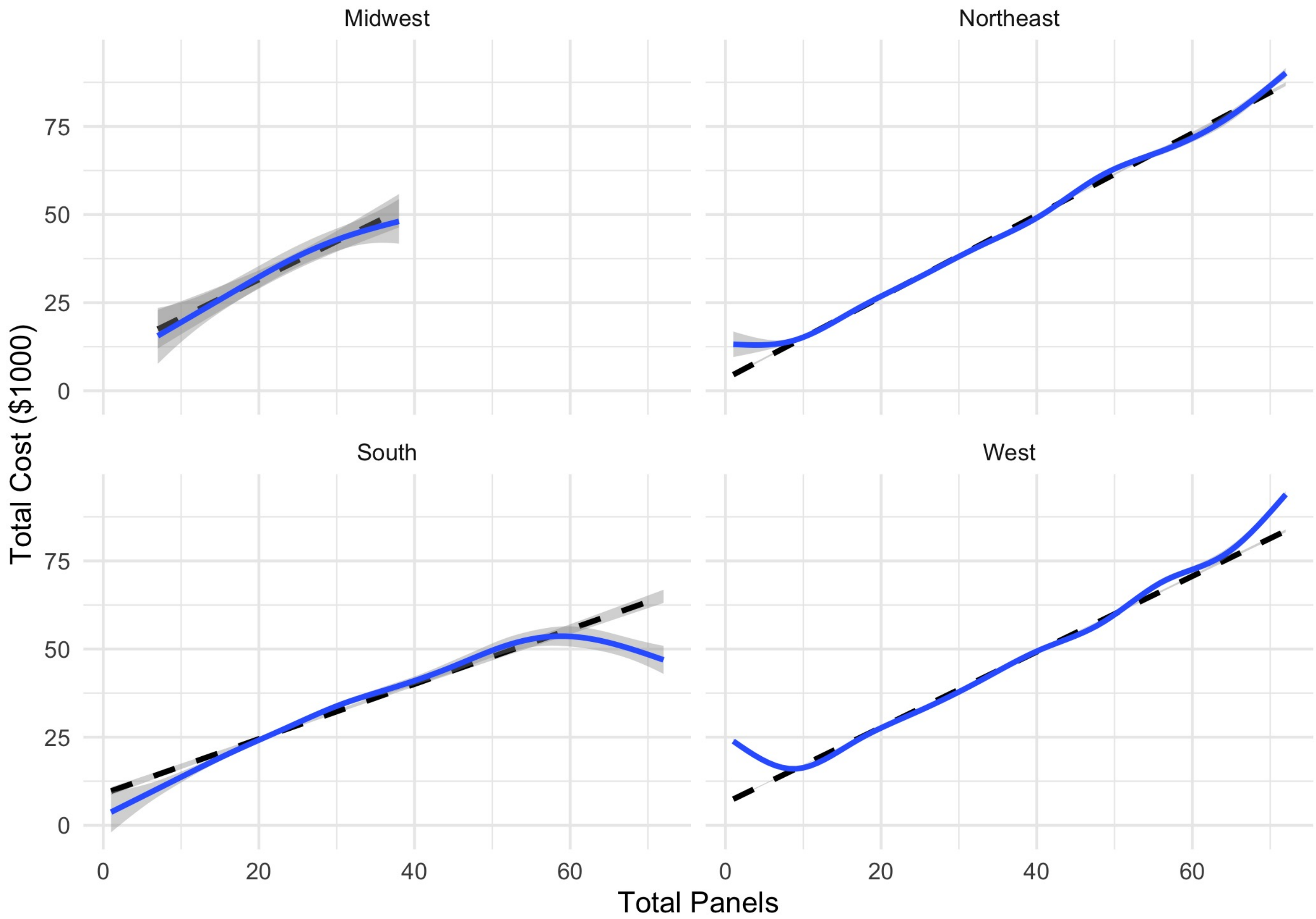
Data

SAM hourly profiles



Data

Installation price estimation

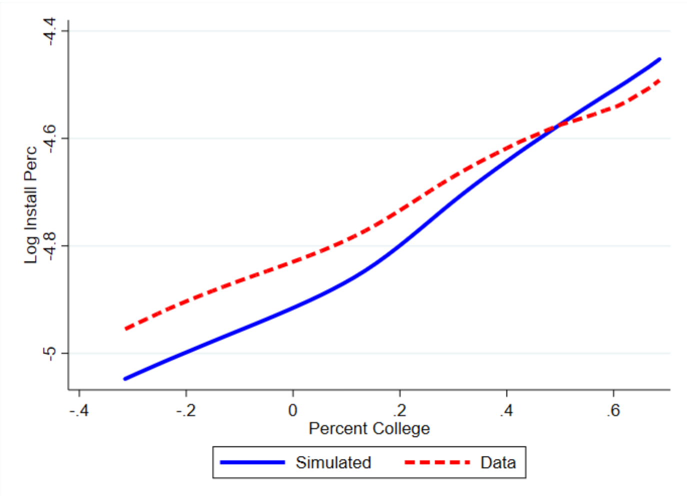


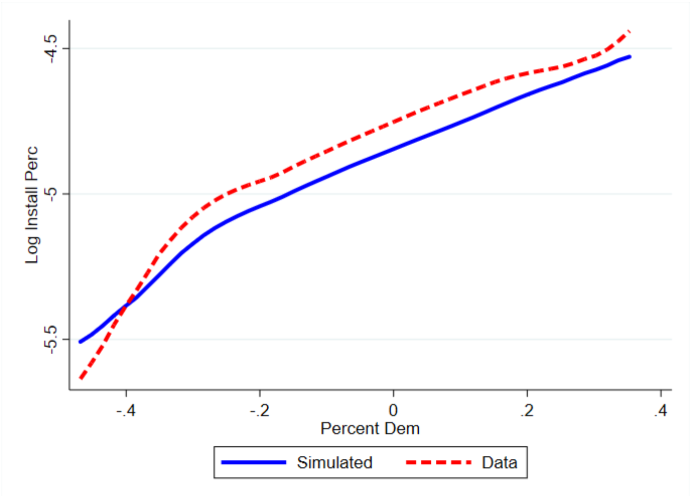
Data

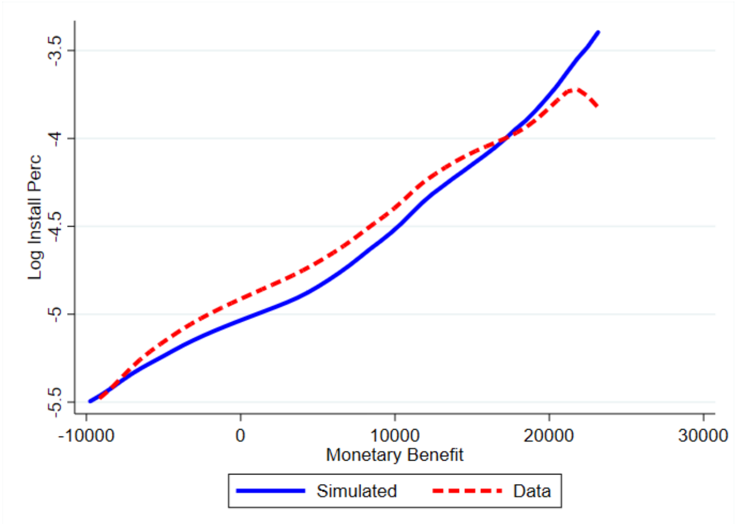
Parameter Estimates

		Estimate	Standard Error
Dispersion of Idiosyncratic Utility	σ	8.55	0.08
Percent College	γ_{Coll}	5.71	0.36
Percent Democrat	γ_{Pol}	10.44	0.50
Constant	γ_0	-1357.03	411.27
Number of Panels	γ_{1N}	177.70	55.65
Number of Panels Squared	γ_{2N}	-6.00	1.88

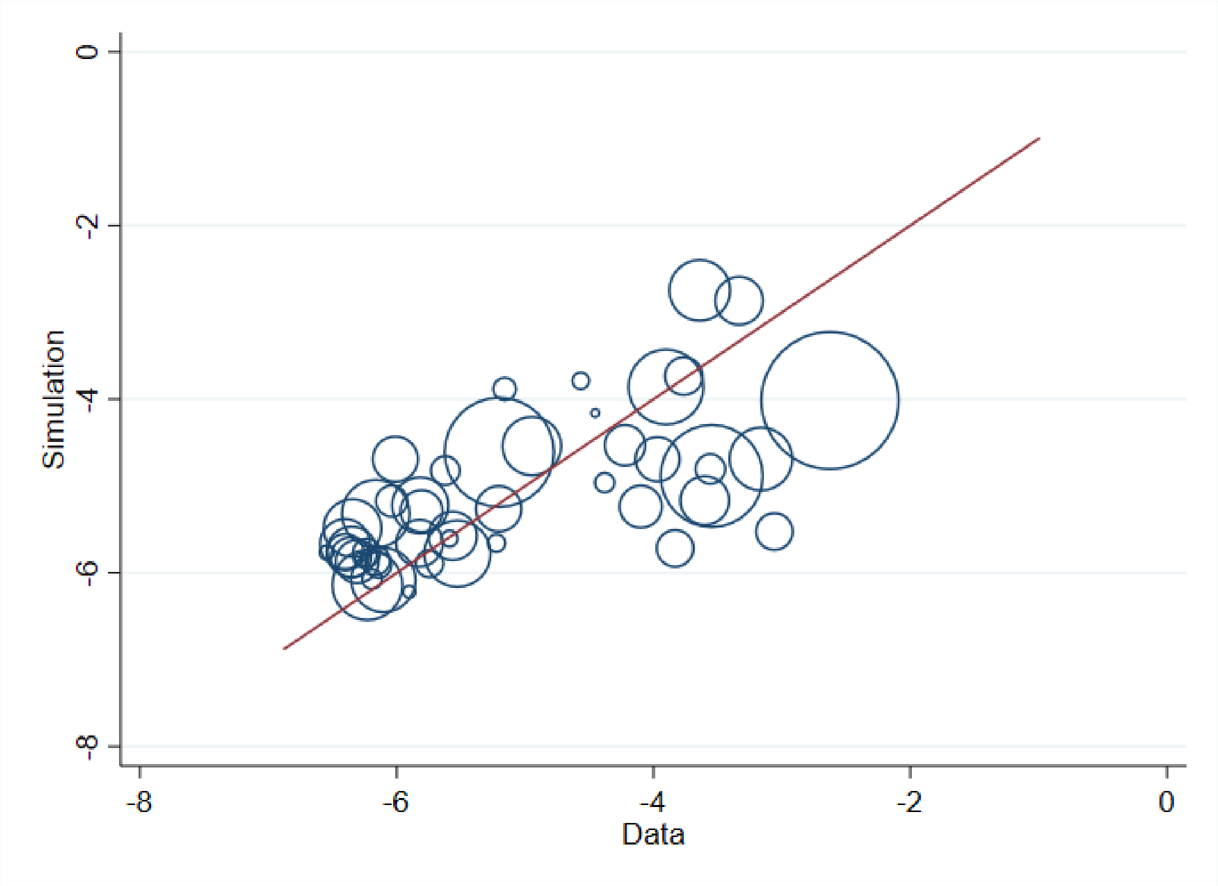
Fit by demographic







Fit by State



Simulated vs actual log installations by state (sized by population)

Quasi-Experimental Evidence

Hughes and Podolefsky, 2015

- Examine the introduction of a solar rebate in California
- **Results:** \$400 to \$500 increase in total rebate leads to a **7 to 15%** increase in installations.
- **Model:** \$500 increase in subsidies leads to a **6%** increase in installations.

Crago and Chernyakhovskiy, 2017

- County-level panel data from 12 states in the US Northeast
- **Results:** Increasing rebates by \$1 per watt increases solar panel installations by **47%**.
- **Model:** increasing rebates by \$1 per watt in these same 12 states increases installations by **51%**.

Fit

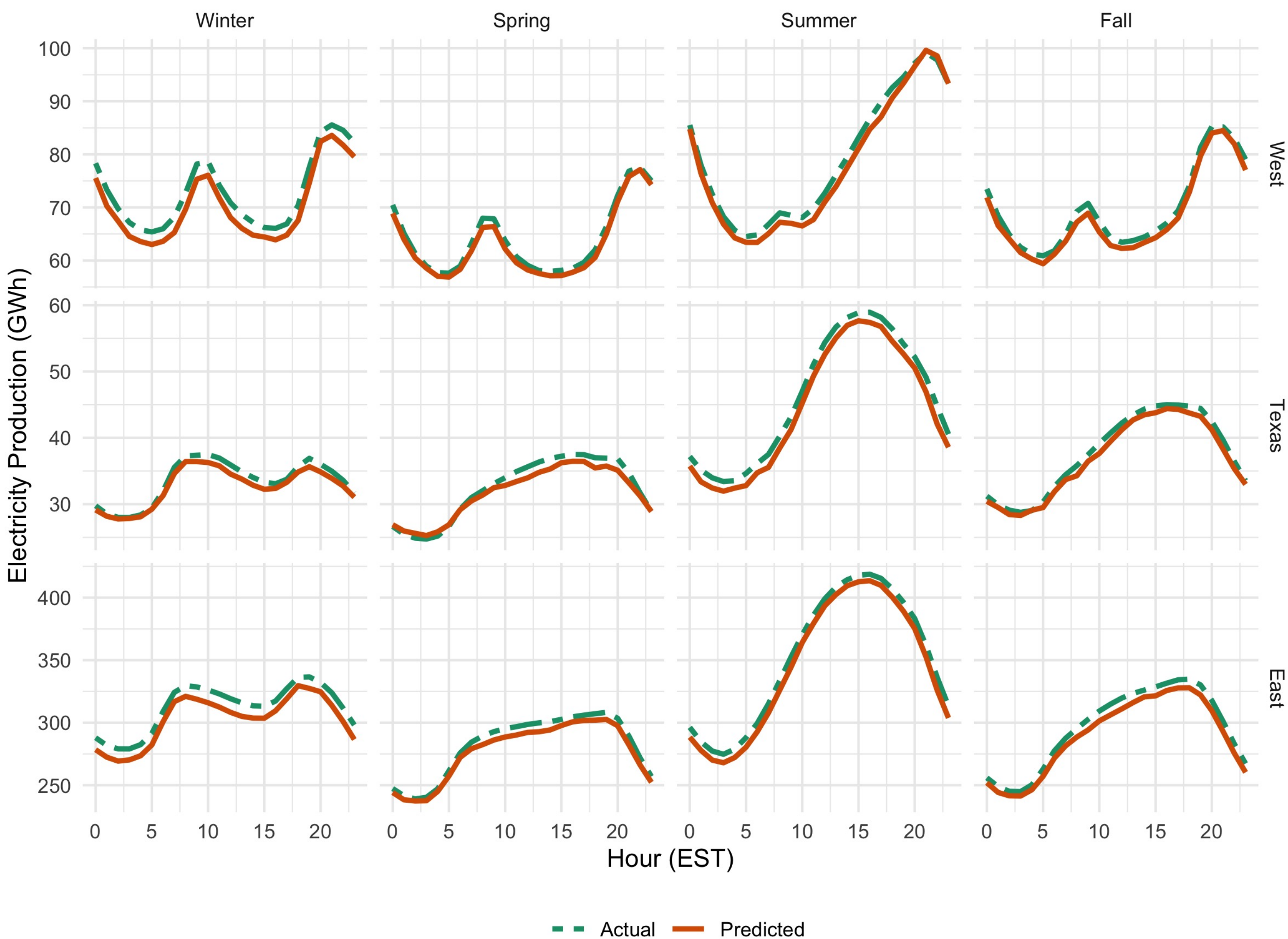
Decomposition

	SD Installs
Baseline	1
Harmonize Subsidies	0.48
Harmonize Electricity Prices	0.25
Harmonize Installation Prices	0.23
Equalize Sunlight	0.09
Harmonize Demographics	0.08

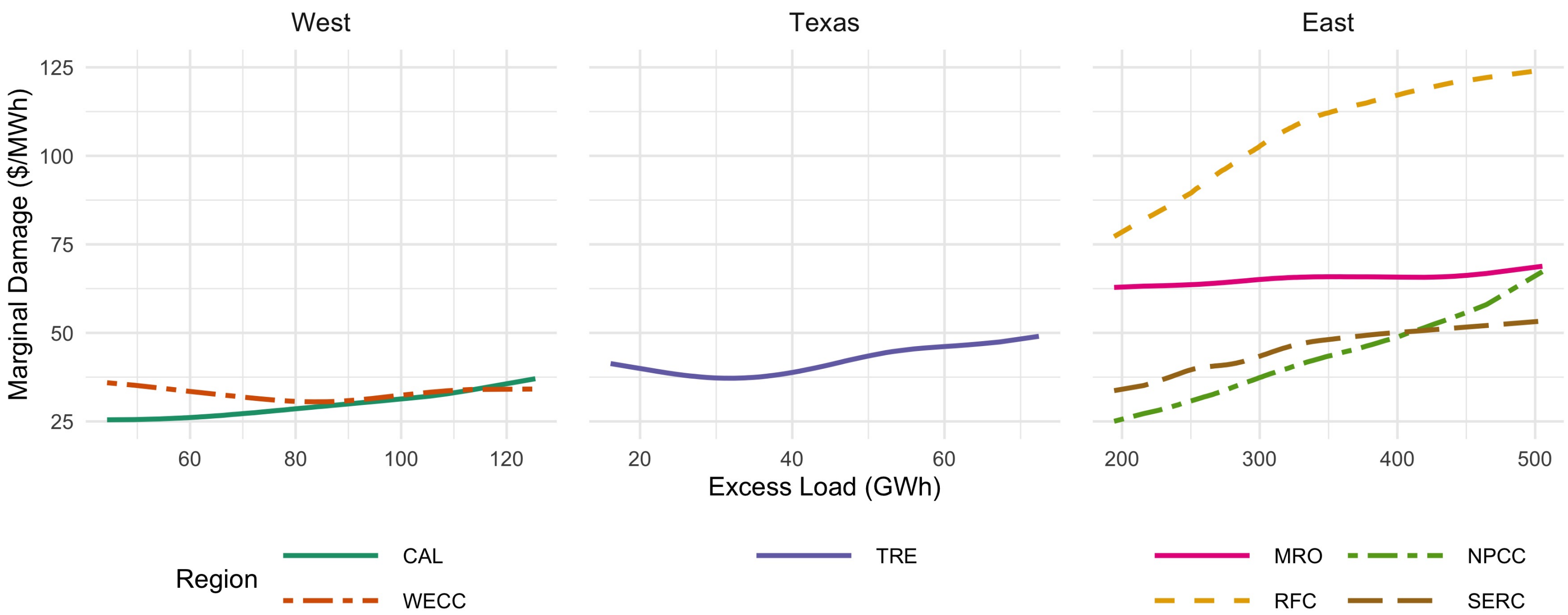
Standard Deviation in Installation Rates Across States: Decomposition. All are relative to baseline.

Fit

Electricity Production Fit



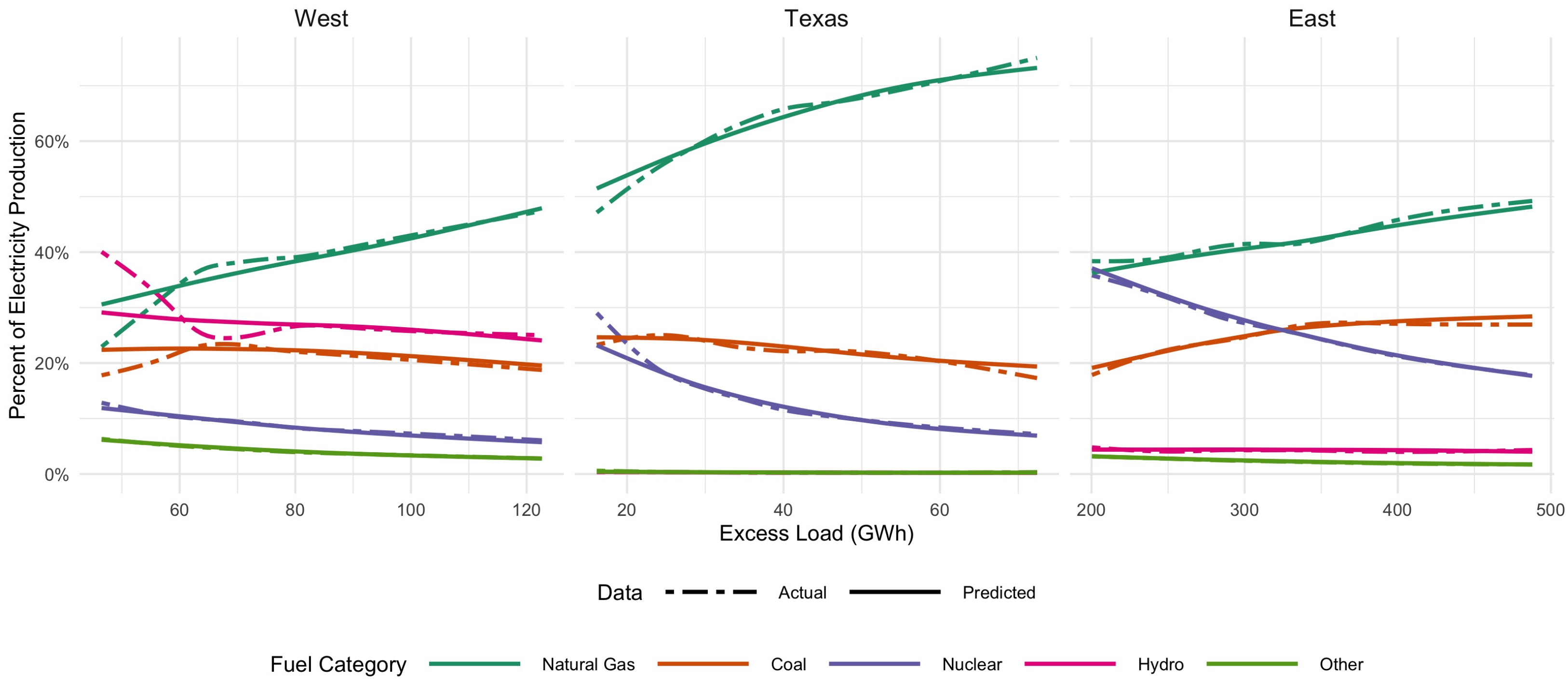
Marginal Damage of electricity



Estimated marginal damage of electricity produced in each region over different levels of demand in each interconnection.

Fit

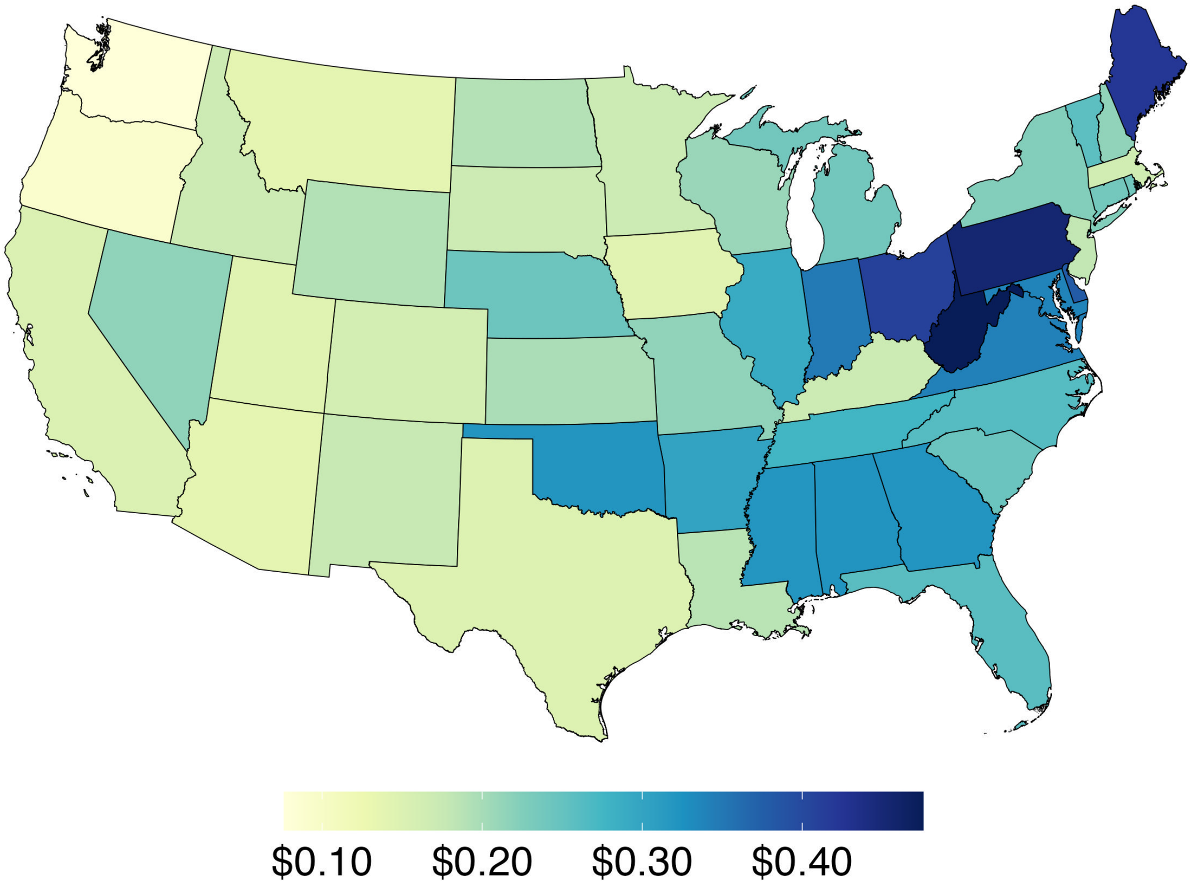
Fuel mix


West
Texas
East
Percent of Electricity Production
0%
20%
40%
60%
60
80
100
120
20
40
60
200
300
400
500
Excess Load (GWh)
Data
Actual
Predicted
Fuel Category
Natural Gas
Coal
Nuclear
Hydro
Other

Fit

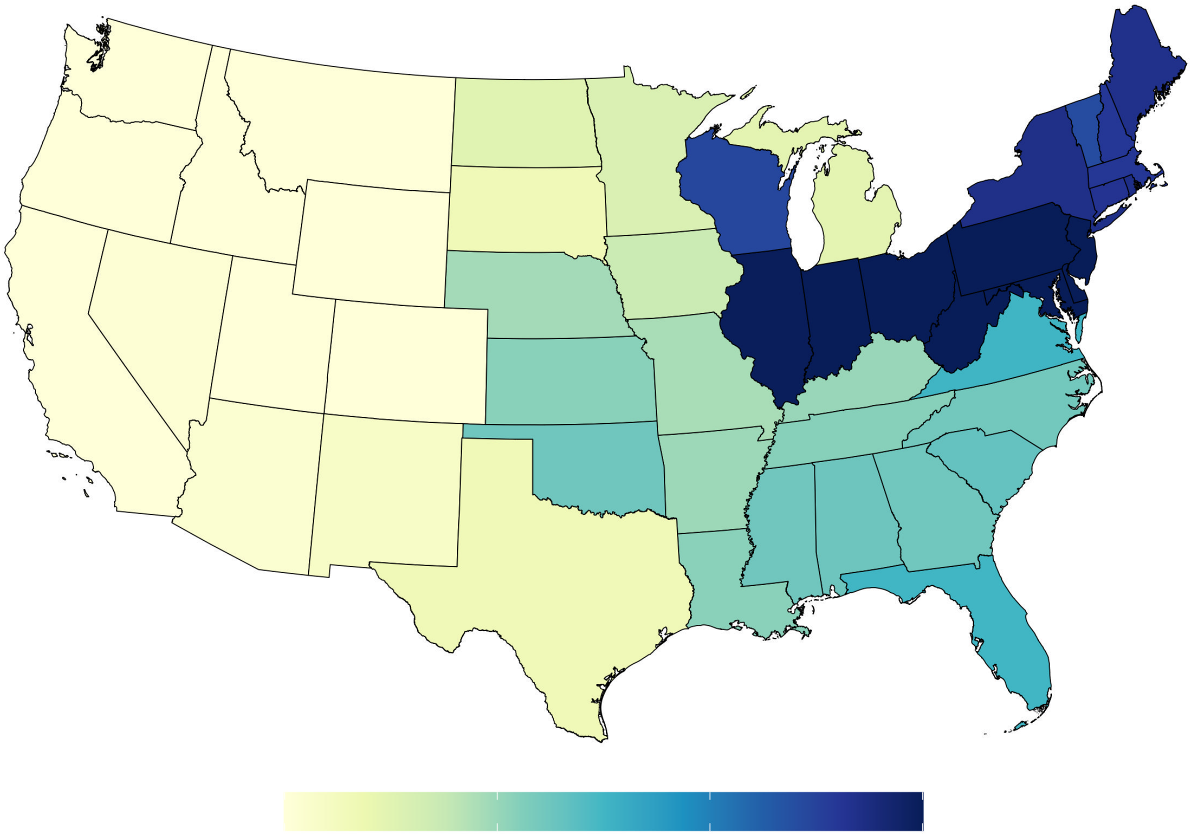
Results Appendix

Marginal subsidy increases



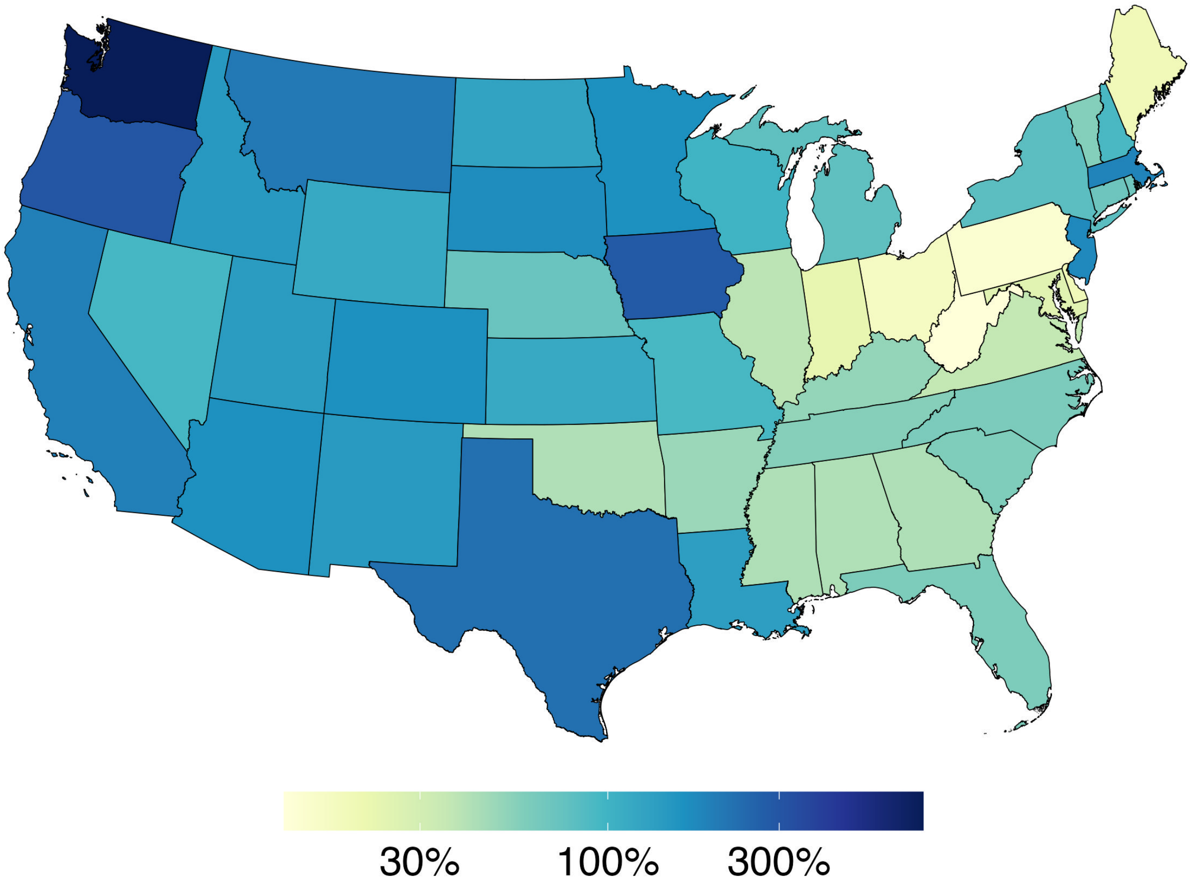
Damages offset by a one dollar increase in subsidies

Damage minimizing subsidies



Damage Minimizing Subsidies

Damage min spatial misallocation



Baseline installations as a percent of damage minimizing installations

Total damages offset (Millions of $)

		Welfare Maximizing		Damage Minimizing	
	Baseline	**State**	**Tract**	**State**	**Tract**
CO2e	69.8	75.9	75.9	72.6	72.5
NOx	18.0	19.3	19.3	18.3	18.2
PM2.5	16.7	16.9	16.9	18.1	18.1
SO2	37.0	38.3	38.8	48.5	49.4
Total	**141.5**	**150.5**	**150.9**	**157.5**	**158.2**

- Most of the offset damages are from CO_2 emissions
- **Tract-level** subsidies only slightly better than state-level subsidies

Subsidy types

Optimal choice involves almost entirely KWh subsidies rather than current dependence on cost based subsidies

Percent of Subsidy Dollars

	Baseline	**Welfare Max**
Unit Subsidies	6.8	0.3
Cost Subsidies	81.6	0.9
KWh Subsides	8.1	98.8
Total	**100.0**	**100.0**