Distributional Impacts of Dynamic Responses to Climate Policy in the Electricity Industry

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Research Question & Motivation

How does a cap-and-trade program for greenhouses gases impact the distribution of local air pollution?

ENVIRONMENTAL JUSTICE V. **CAP-AND-TRADE.**
Tapped - Feb 28, 2008
In a **cap-and-trade** system, poor communities, where polluting plants are ... But the EJ groups in **California** are taking a hard line: "[O]ur demands ... concerns of the EJ groups regarding pollution trading, like possible **hot spots**, ...

Do **environmental justice** groups have a legitimate beef with ...
Grist Magazine - Apr 5, 2011
Environmental justice groups' beef with emission trading in **California** goes ... It may be that **California** should have passed command-and-control ... that **cap-and-trade** systems do not create **hotspots** or exacerbate inequality.

Cap-and-trade? Not so great if you are black or brown
Grist - Sep 16, 2016
Environmental justice advocates have long warned that ... A preliminary **report** on **California's** cap-and-trade program shows they just might be right. ... **California** EJ groups issued a declaration against cap-and-trade back in **2008**. The **new report** — by researchers at UC Berkeley, the University of Southern ...

Expected responses of the electricity industry to cap-and-trade

1. **Redistribution of market share to low-emission intensity units**

   $\rightarrow$ change in unit capacity factors

2. **Decrease in carbon emissions intensities**

   $\rightarrow$ investments to improve to unit efficiency (reduce heat rate) in natural gas dominated markets; fuel switching in markets with coal

Model and identification

Firms, as single-agents, makes two decisions in each period:

- Decides whether to operate $\rightarrow$ determines production quantity
- Decides whether invest to improve its efficiency $\rightarrow$ determines next period heat rate
- Per period profits constructed a function of state variables including lagged operating state and investment decision

Identification of unknown structural parameters:

- Start-up costs are identified by the willingness of the generator to operate in two states that differ only in last period operating decision
- Investment costs are identified by difference in heat rates across different marginal costs (carbon prices)

- Firm Decision 1 | Firm Decision 2 | Per Period Profits | State Transition and Timing

Estimation approach

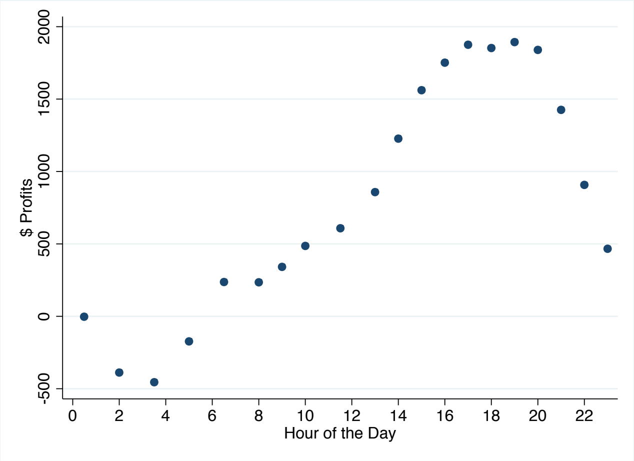
- **Two-step estimation approach**

  Use Bajari, Benkard, and Levin (2007) approach to estimate policy functions for production and investment decisions; develop approximation of electricity price paths in counterfactuals.

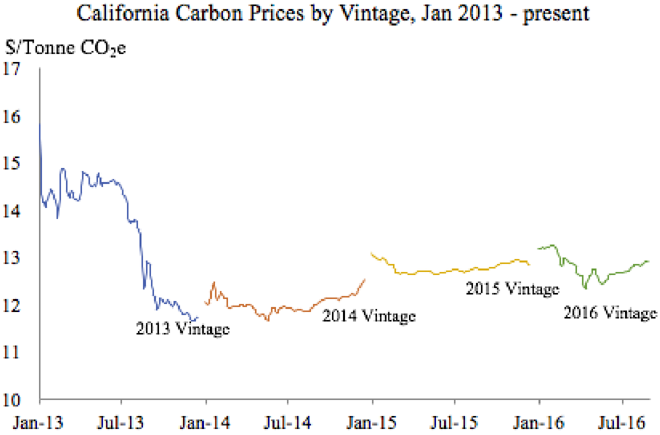
Data

- **Prices:** Hourly wholesale electricity prices from CAISO; carbon allowance prices: ICE; fuel input prices: federal reporting requirements and Bloomberg coal/natural gas spot prices
- **Production quantities:** Unit-specific hourly electricity output from CEMS
- **Emission quantities:** Hourly emissions of NO_x, SO_2, CO_2 from CEMS
- **Unit characteristics:** various EIA reporting requirements

Average profits per hour, 2012-2016

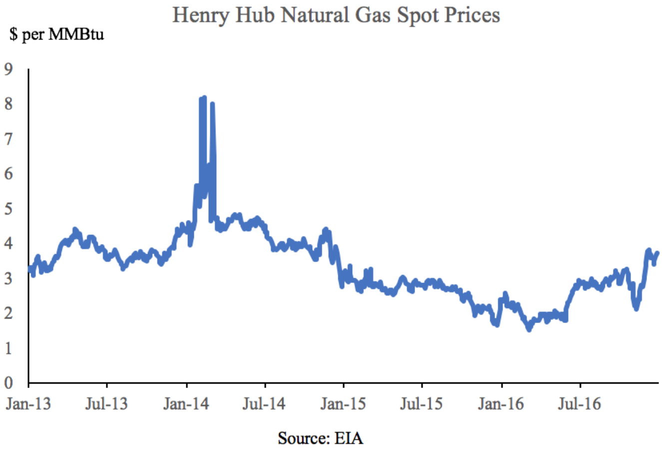


Carbon prices over time

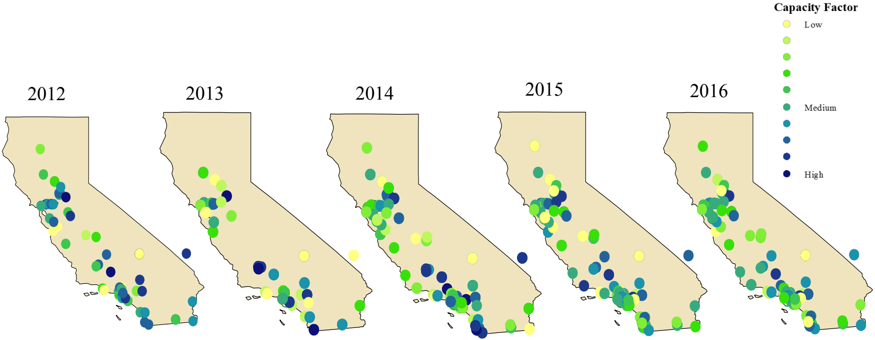


Source: ICE

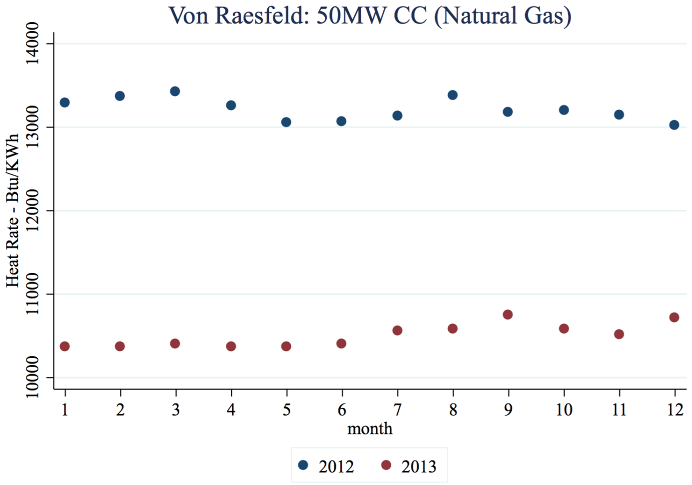
Input fuel prices over time



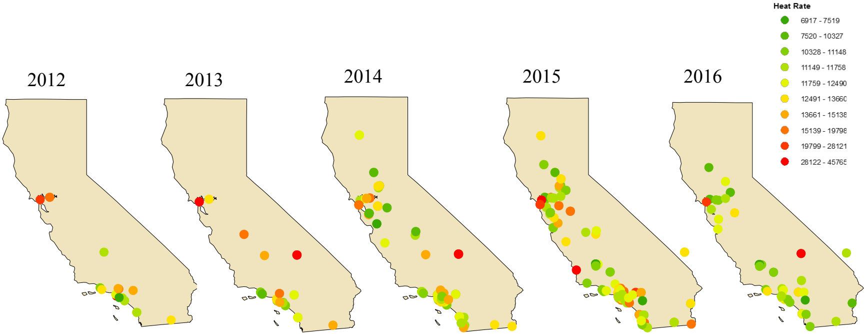
Capacity factors for sample month (Sept.), 2012 - 2016



Unit efficiency by month for example units



Heat rates for sample month (Sept.), 2012 - 2016



Contributions of this work

1. Develop a dynamic model of electric generating behavior that includes both production and investment.
2. Simulate counterfactual outcomes of redistribution and investment in efficiency under different GHG policy scenarios (e.g. a more stringent policy with higher prices, a command and control approach).
3. Map market outcomes across carbon policy scenarios to local air quality outcomes and damages to human health (leveraging epidemiological work and/or AP2 (APEEP) model).

Per Period Profits

$$\pi_t(q(a_{it}), P_t, C_{it}, \Gamma_{it}, L_{it}) =$$

$$\begin{cases} q_{it}(P_t - C_t(hr_{it}, mc_f, e_g, \tau_t)) - \Gamma(z_{it}, v_{it}; \gamma_i), & a_{it} = 1, L_{it} = 1 \\ q_{it}(P_t - C_t(hr_{it}, mc_f, e_g, \tau_t)) - \Gamma(z_{it}, v_{it}; \gamma_i) - start_i, & a_{it} = 1, L_{it} = 0 \\ 0, & a_{it} = 0 \end{cases} \quad (1)$$

- $start_i$: start-up costs incurred when turning on after lagged operating state $L_{it} = a_{it-1} = 0$
- P_t: exogenous hourly price (to be discussed)
- $C_t(\cdot)$: marginal cost function:

$$C_t = hr_{it} * mc_f + hr_{it} * e_f \tau_t \quad (2)$$

- hr_{it}: heat rate, mc_f: marginal costs of fuel, e_g: emissions rate of fuel, τ_t: GHG emissions permit price
- $\Gamma_t(\cdot)$: cost of investment (previous slide)

Firm Decision 1: Operation (production) choice

Firm $i = 1, ..., N$ makes operating decision $a_{it} \in \{0, 1\}$ in each hour t which determines q_{it}

$$
\begin{aligned}
q_{it} &= q_{max,i} \ \textit{if} \ P_t \geq C_{it} \ \textit{and} \ a_{it} = 1 \\
q_{it} &= q_{min,i} \ \textit{if} \ P_t < C_{it} \ \textit{and} \ a_{it} = 1
\end{aligned}
\tag{3}
$$

- q_{it}: MWh produced by firm i if hour t
- $q_{max(min),i}$: unit-specific production constraint
- P_t: wholesale electricity price in hour t
- C_{it}: marginal cost of electricity

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Firm Decision 2: Investment choice

When $a_{it} = 1$, firm makes an investment decisions $z_{it} \in \mathcal{R}^+$, which improves the efficiency (reduces the heat rate) hr_{it+1} with cost $\Gamma(\cdot)$

$$\begin{aligned} hr_{it+1} &= hr_{it}(1+\delta) - z_{it} \\ \Gamma(z_{it}, hr_{it}, \gamma_i, v_{it}) &= 1(z_{it} > 0)(\gamma_{g(i)1} + \gamma_{g(i)2}\frac{z_{it}}{hr_{it}} + v_{it}) \end{aligned} \tag{4}$$

- δ: depreciation rate
- $\gamma_{g(i)1}, \gamma_{g(i)2}$: fixed and variable costs of investment for technology group $g(i)$
- v_{it}: stochastic shock to investment costs

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State Transitions and Timing

Transitions

- $H_{t+1} = H_t + 1 - 1(H_t = 24) * 24$
- $L_{t+1} = a_t$
- $hr_{t+1} = hr_t(1 + \delta) - z_t$
- $P_{t+1} = F(P_{t+1}|P_t, H_t)$ - AR (1), beliefs consistent with equilibrium prices
- $\tau_{t+1} = T(\tau_{t+1}|\tau_t, H_t)$ or $T(\tau_{t+1}|\tau_t, m_t)$ - AR(1), beliefs consistent with equilibrium prices

Timing

- In period t, firm observes $P_t, H_t, L_t, hr_t, \tau_t, \epsilon_t$, and v_t develops expectations about P_{t+1} and τ_{t+1}, decides whether to operate, and conditional on $a_t = 1$, decides z_t.

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Intertemporal Problem

- Firms choose a_t and z_t to maximize the sum of discounted profits:

$$V(s_t) = \max_{a_t, z_t} \Sigma_{j=0}^{\infty} \beta^j \Pi(a_{t+j}, z_{t+j}, s_{t+j} | a_{t+j}, z_{t+j}, s_t)$$
$$s_t = \{x_t; e_t\} = \{P_t, H_t, L_t, hr_t, \tau_t; \epsilon(a_t), v_t\} \quad (5)$$

- The Bellman equation for this dynamic programming problem is:

$$V(s_t) = \max_{a_t, z_t} \{\Pi(s_t, a_t, z_t) + \beta E[V(s_{t+1}) | a_t, z_t, s_t] \quad (6)$$

$$E[V(s_{t+1}) | a_t, z_t, s_t] =$$

$$\int V(P_{t+1}, H_{t+1}, L_{t+1}, hr_{t+1}, \tau_{t+1}; \epsilon_{t+1}(a_{t+1}), v_{t+1} | P_t, H_t, L_t, hr_t, \tau_t)[...]$$
$$dP(\epsilon_{t+1}(a_{t+1}), v_{t+1}, P_{t+1}, \tau_{t+1}) \quad (7)$$

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