

Investment, Emissions, and Reliability in Electricity Markets

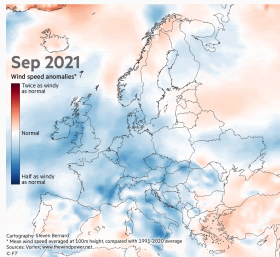
Jonathan Elliott

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Motivation

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Source: Financial Times (October 8, 2021)

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intermittency increases the variability of available capacity
- What policies should we adopt to develop a **clean** and **reliable** electricity industry?

This Paper

- What policies should we adopt to construct a **clean** and **reliable** electricity grid?
- How electricity sector policies affect emissions and blackouts depends on how generator **investments and retirements in all energy sources** respond
- Generator portfolios impact **equilibrium prices and production decisions**

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 - investment and production in variety of energy sources
 - electricity prices
 - blackouts
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- **Quantify** effect of policy tools on emissions, blackouts, & product market welfare and determine **optimal regulation**

Environmental policies

carbon taxes, renewable subsidies

Reliability policies

capacity payments

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- Renewable subsidies substantially less effective at reducing emissions
- Waiting to implement carbon tax after announcement can reduce costs of policy
but for most values of the social cost of carbon, optimal delay just one year

- **Electricity markets:** Reguant (2014), Bushnell et al. (2008), Wolak (2007), Gowrisankaran et al. (2016), Karaduman (2021)
⇒ endogenous investment and market power
- **Investment in electricity markets:** Allcott (2013), Linn and McCormack (2019), Butters et al. (2021)
⇒ dynamics, oligopoly, multiple energy sources
- **Dynamic oligopoly:** Ryan (2012), Fowle et al. (2016), Igami and Uetake (2020)
⇒ heterogeneous production technologies, electricity markets, non-stationary costs
- **Environmental and reliability policy:** Stock and Stuart (2021), Joskow and Tirole (2008), Fabra (2018), McRae and Wolak (2020)
⇒ policies jointly, equilibrium oligopolistic investment

Industry Background & Data

Regulated, Vertically Integrated



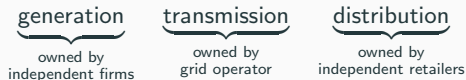
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- investment determined through long-term planning

Regulated, Vertically Integrated



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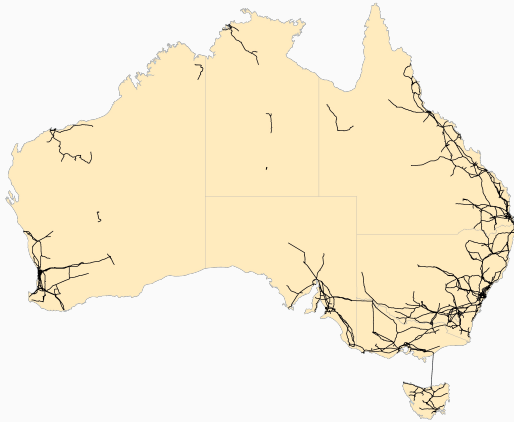
“Restructured”



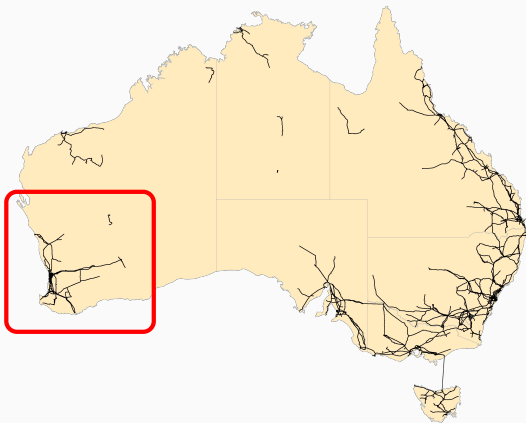
- prices determined by
 - **wholesale price:** generators bidding into day-ahead and real-time wholesale markets
 - **retail price:** electricity retailers
- investment determined through electricity-generating firms' investment decisions based on
 - wholesale market profits
 - (sometimes) capacity payments

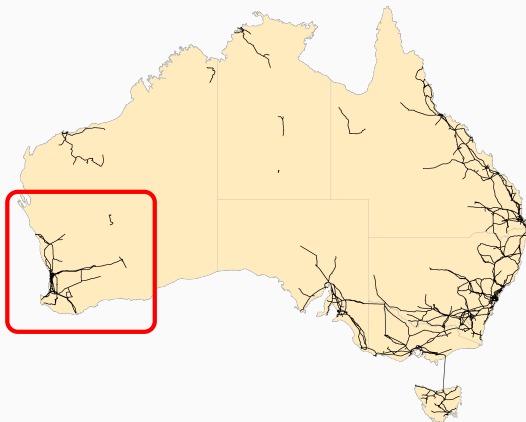
» Details

Western Australian Electricity Market



Western Australian Electricity Market





- 1 million customers, 18 TWh / year
- Restructured from vertically-integrated to independent generators in 2006
- Three energy sources:
 - coal (50.2%)
 - natural gas (42.2%)
 - wind (7.6%)
- Since restructuring, capacity payment program with significant variation over time [▶▶ Graph](#)

Half-hourly

- Demand (virtually) unresponsive to wholesale market price
- Firms submit generator-level step-function bids (AU\$ / MWh)
- Grid operator runs day-ahead and real-time auctions to determine price to equate supply and demand in least cost way

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Yearly

- Each year, grid operator chooses a “capacity price” (AU\$ / MW) for 3 years in future
- Firms choose what fraction of capacity to commit for each of their generators
- 3 years later: firm receives payment
(capacity price \times capacity committed – penalties for unavailability)

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Long-run

- Firms invest in new generators and retire existing ones

From 2007 – 2020:

- Half-hourly wholesale markets
 - prices and generator-level quantities
 - generator outages
- Capacity payments
 - capacity credit prices and assignments
- Generator characteristics
 - capacities
 - energy sources
 - entry/exit dates

» Summary statistics

» Wholesale market variables

- Decline in coal, rise in wind

| Year | Coal | Natural Gas | Wind |
|------|--------|-------------|--------|
| 2007 | 54.24% | 41.68% | 4.08% |
| 2011 | 51.26% | 41.44% | 7.29% |
| 2015 | 50.90% | 42.05% | 7.05% |
| 2019 | 44.74% | 43.04% | 12.21% |

- Decline in coal, rise in wind
- Decline in concentration

| Year | Synergy | Alinta | Bluewaters Power | Others |
|------|---------|--------|------------------|--------|
| 2007 | 79.83% | 15.06% | 0.00% | 5.11% |
| 2011 | 55.29% | 12.09% | 16.22% | 16.40% |
| 2015 | 50.12% | 13.86% | 15.61% | 20.41% |
| 2019 | 38.67% | 20.90% | 18.64% | 21.79% |

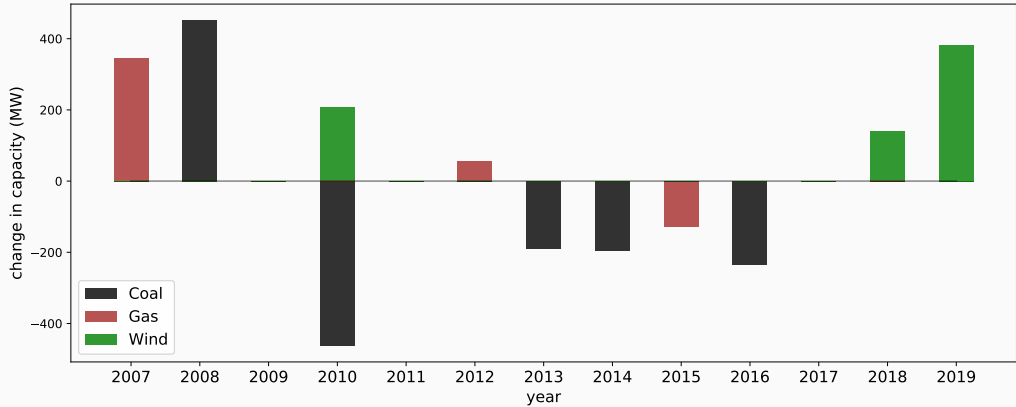
Note: The three listed firms are those with $\geq 10\%$ market share. All other firms are included in "Others."

- Decline in coal, rise in wind
- Decline in concentration
- Prices decline

| | 2007 | 2011 | 2015 | 2019 |
|---------------|-------|-------|-------|-------|
| Average Price | 53.68 | 48.33 | 41.03 | 39.71 |

Note: Prices are in 2015 AU\$.

Capacity Evolution



Model

- Electricity produced by generators $g \in \mathcal{G}$, characterized by
 - capacity K_g
 - energy source $s(g) \in \mathcal{S} = \{\text{coal}, \text{gas}, \text{wind}\}$
 - firm $f(g) \in \left\{ \underbrace{1, \dots, n, \dots, N}_{\text{strategic firms}}, \underbrace{c}_{\text{competitive fringe}} \right\}$

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Short-run (h)

- generators fixed $\mathcal{G}_{t(h)}$
- demand is perfectly inelastic $\bar{Q}_h \sim Q_{t(h)}$

$$\Rightarrow \pi_h(\mathcal{G}_{t(h)}, \bar{Q}_h)$$

Long-run (t)

- firms adjust \mathcal{G}_t
- demand responds to wholesale prices $\bar{P}_{\mathcal{G}}$

$$\Rightarrow \Pi_t(\mathcal{G}, Q(\bar{P}_{\mathcal{G}}))$$

- Firms enter h with generators $\mathcal{G}_{t(h)}$ and distribution of demand $\mathcal{Q}_{t(h)}$
- In each interval h , the following are realized (potentially correlated)
 - inelastic demand $\bar{Q}_h \sim \mathcal{Q}_{t(h)}$
 - production capacity constraints \bar{K}_h
 $\bar{K}_{g,h} = \delta_{g,h} K_g$, where $\delta_{g,h} \in [0, 1]$
 - shocks to generators' costs $\mathbf{c}_h(\cdot)$

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 - shocks to generators' costs $\mathbf{c}_h(\cdot)$
- Strategic firms play a **Cournot game** in quantities, constrained by their **production capacities** in that interval \mathbf{K}_h
- Competitive fringe then produces difference between strategic firms' quantity and $\bar{Q}_h \Rightarrow P_h$
if insufficient capacity ($\sum_g \bar{K}_{g,h} < \bar{Q}_h$) \Rightarrow blackout

►► Details

Over year we get

- firms' profits Π_t

$$\Pi_{f,t}(\mathcal{G}_{f,t}; \mathcal{G}_{-f,t}) = \underbrace{\sum_h \beta^{h/H} \mathbb{E} [\pi_{f,h}(\mathbf{q}_h^*(\mathcal{G}_t))]}_{\text{wholesale profits}} - \underbrace{\sum_{g \in \mathcal{G}_{f,t}} M_{s(g)} K_g}_{\text{maintenance cost}}$$

- emissions level E_t

$$E_t(\mathcal{G}_t) = \sum_h \mathbb{E} \left[\sum_{g \in \mathcal{G}_t} r_{s(g)} q_{g,h}^*(\mathcal{G}_t) \right]$$

- blackout level B_t

$$B_t(\mathcal{G}_t) = \sum_h \mathbb{E} \left[\max \left\{ \bar{Q}_h - \sum_{g \in \mathcal{G}} \bar{K}_{g,h}, 0 \right\} \right]$$

►► Distribution of demand

- Over the long-run (yearly), firms invest in and retire generators
generator composition affect production costs, competition, and distribution of demand
- Generators are long-lived + firms strategic \Rightarrow dynamic game

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 \Rightarrow makes full-solution estimation approaches intractable
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- Difficult to handle non-stationarity (such as declining wind generator costs) using standard estimation approaches
- **Solution:** finite horizon game + sequential moves (Igami and Uetake 2020)
 \Rightarrow unique equilibrium, computationally tractable

- Firms enter t with set of generators \mathcal{G}_{t-1} , costs of new generators \mathbf{C}_t , and capacity price κ_t
- Firms play dynamic game in which in each period t
 1. Nature chooses strategic firm $m \in \{1, \dots, N\}$ to adjust
 2. firm m makes costly adjustment to set of generators $\mathcal{G}_{m,t}$
(other strategic firms keep current sets of generators)
 3. competitive fringe adjusts its set of generators $\mathcal{G}_{c,t}$, *observing firm m 's choice*
 4. receive capacity payments and wholesale profits from \mathcal{G}_t
- In “final” period, firms continue to compete in wholesale markets but can no longer make generator adjustments

►► Assumptions discussion

Long-run: Generator Investment Model

- Value function prior to Nature's selection

$$W_{f,t}(\mathcal{G}_t) = \sum_{m=1}^N \frac{1}{N} V_{f,t}^m(\mathcal{G}_t)$$

where $V_{f,t}^m(\cdot)$ is f 's value function if m is selected to adjust

- If $f = m$:

$$V_{f,t}^f(\mathcal{G}) =$$

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profits
capacity payment

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►► Details

- After “final” period T firms receive profits from wholesale with \mathcal{G}_T

$$W_{f,T}(\mathcal{G}) = \sum_{t=T}^{\infty} \beta^{t-T} \left(\underbrace{\Pi_{f,t}(\mathcal{G})}_{\text{wholesale profit}} + \underbrace{\Upsilon_{f,t}(\mathcal{G}_f)}_{\text{capacity payment}} \right)$$

►► Non-adjustment value function

►► Competitive fringe adjustment

Estimation

Two stages

1. Estimate distribution of wholesale market variables

- ▷ production costs, capacity factors, and demand joint distribution

$$c_{g,h}(q_{g,h}) = \zeta_{1,g,h} q_{g,h} + \zeta_{2,s(g)} \left(\frac{q_{g,h}}{K_g} \right)^2$$

Basic idea: use production FOCs to recover distribution of production costs

» Details

» Results

2. Take estimated distribution to solve for $\hat{\Pi}(\mathcal{G})$ and estimate dynamic parameters

- ▷ sunk costs, maintenance costs, idiosyncratic shock distribution

Stage 2: Dynamic Parameter Estimation

- Construct $\hat{\Pi}(\cdot)$ from first stage estimates [▶▶ Details](#)
- Assume $\eta \stackrel{i.i.d.}{\sim}$ Type I Extreme Value
- We have several dynamic parameters: $\underbrace{\{\mathbf{C}_t\}_t}_{\text{generator costs}}$, $\underbrace{\mathbf{M}}_{\text{maintenance costs}}$, and $\underbrace{\text{Var}(\eta)}_{\eta \text{ shock distribution}} =: \theta$
- Generator costs $\{\mathbf{C}_t\}_t$ taken from engineering estimates
- Estimate using maximum likelihood: [▶▶ Identification](#)

$$\begin{aligned} \mathcal{L}_t(\theta) = & \sum_f \Pr(f \text{ selected to adjust in } t; \mathcal{G}_t) \\ & \times \prod_{\mathcal{G}'_{f,t}} \Pr\left(\mathcal{G}_{f,t} = \mathcal{G}'_{f,t} \middle| \mathcal{G}_{t-1}; \theta\right)^{\mathbb{1}_{\{\mathcal{G}_{f,t} = \mathcal{G}'_{f,t}\}}} \end{aligned}$$

- $\Pr\left(\mathcal{G}_{f,t} = \mathcal{G}'_{f,t} \middle| \mathcal{G}_{t-1}; \theta\right)$ comes from the model

Stage 2: Results

(1): no adjustment after 5 years past 2020

(2): no adjustment after 10 years past 2020

(3): no adjustment after 15 years past 2020

| | (1) $T = 2025$ | (2) $T = 2030$ | (3) $T = 2035$ |
|-------------------------------------|---------------------|---------------------|---------------------|
| Maintenance costs | | | |
| \hat{M}_{coal} (AU\$ / MW) | 0.055 (0.008) | 0.057 (0.007) | 0.058 (0.007) |
| \hat{M}_{gas} (AU\$ / MW) | 0.021 (0.029) | 0.017 (0.030) | 0.016 (0.030) |
| \hat{M}_{wind} (AU\$ / MW) | 0.071 (0.025) | 0.081 (0.048) | 0.086 (0.055) |
| Idiosyncratic costs | | | |
| $\hat{\sigma}$ (variance in AU\$) | 185.700 (54.845) | 184.085 (44.229) | 183.181 (41.091) |

Estimates are in AU\$1 000 000. β set to 0.95.

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- Results stable across T
- Maintenance costs close to engineering estimates

| | estimate | engineering |
|------|------------|-------------|
| coal | AU\$57 000 | AU\$55 000 |
| gas | AU\$17 000 | AU\$10 000 |
| wind | AU\$81 000 | AU\$40 000 |

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- Variance in idiosyncratic shocks pretty high (≈ 1 year of profits)

►► Model fit

Counterfactuals

- How should we design electricity markets so that they are **clean** and **reliable**?
- **Three counterfactuals:**
 1. environmental and reliability policy: carbon tax & capacity payments
 2. alternative environmental policies: renewable subsidies
 3. policy timing
- Begin in 2007 with same state as in data in 2007, simulate market going forward under policy

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- **Welfare:** $\mathbb{E} \left[\sum_{t=0}^{\infty} \beta^t W_t \right]$, where

$$W_t = PS_t + CS_t + G_t - \underbrace{\text{emissions}_t \times SCC}_{\text{emissions cost}} - \underbrace{\text{blackouts}_t \times VOLL}_{\text{blackout cost}}$$

Counterfactual #1: Environmental and Reliability Policy

- **Carbon tax:** tax τ (AU\$ / tonne CO₂-eq) on generator production in proportion to emissions rate r_s (tonne CO₂-eq / MWh)

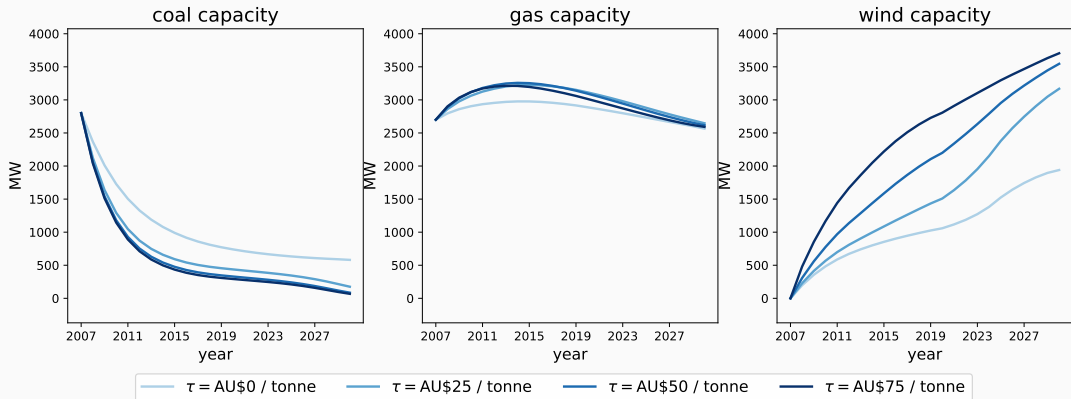
$$c_{g,h}(q_{g,h}) = \zeta_{1,g,h} q_{g,h} + \zeta_{2,g} \left(\frac{q_{g,h}}{K_g} \right)^2 + \tau r_{s(g)} q_{g,h}$$

- **Capacity payment:** payment size κ (AU\$ / MW)

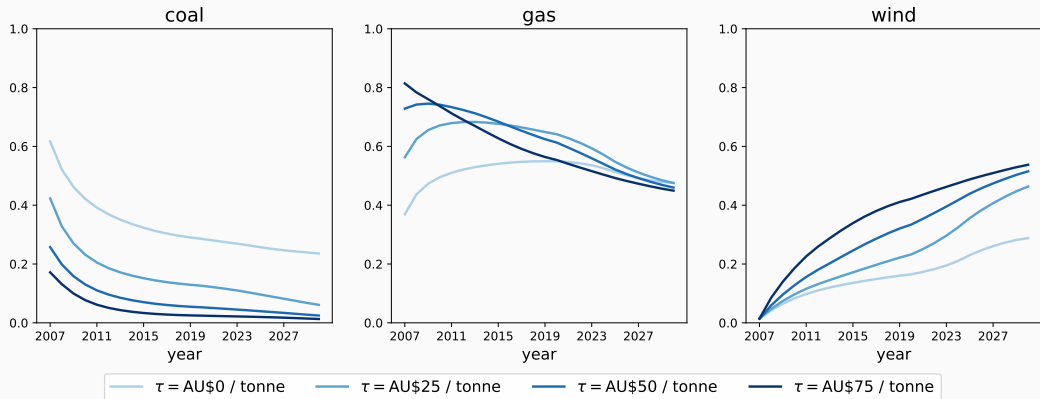
$$\Pi_{f,t}(\mathcal{G}_t) + \Upsilon_f(\mathcal{G}_{f,t}; \kappa)$$

- How do these policies impact production and investment?
- What is the optimal policy in isolation? Jointly?

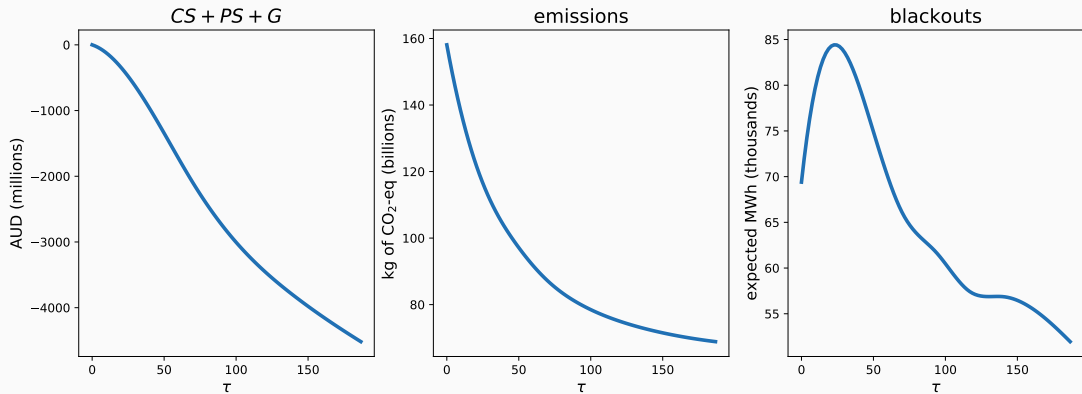
Carbon Tax: Capacity



Carbon Tax: Production Shares

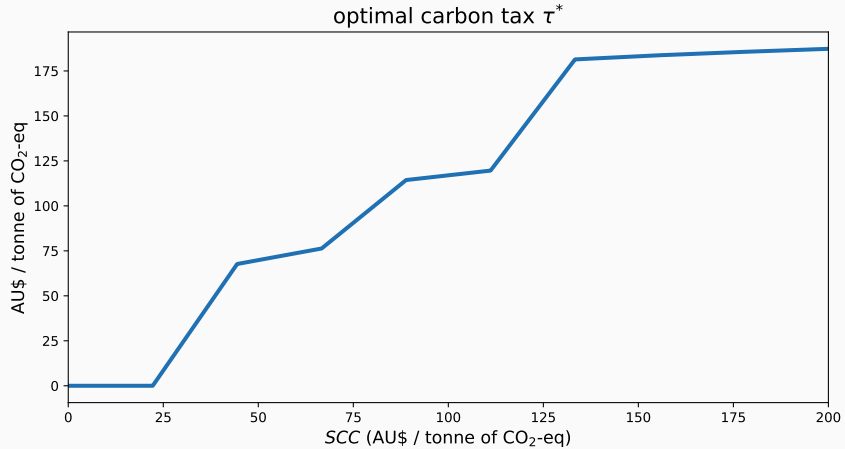


Carbon Tax: Welfare

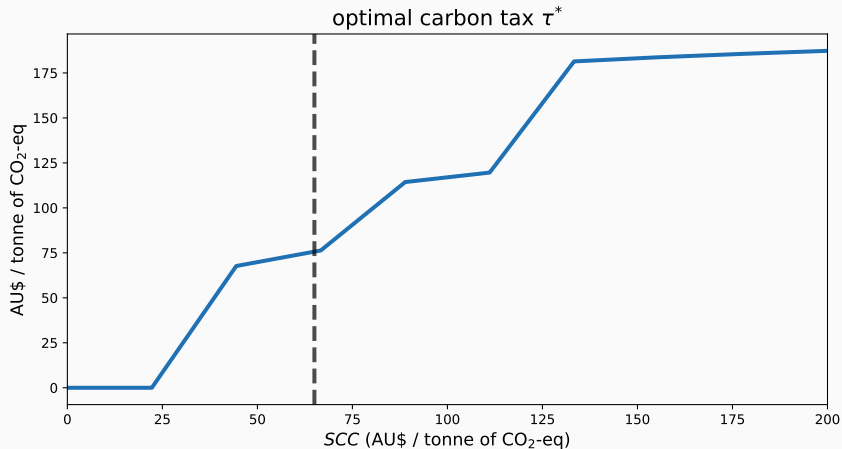


» Breakdown of CS, PS, G

Carbon Tax: Optimal Policy

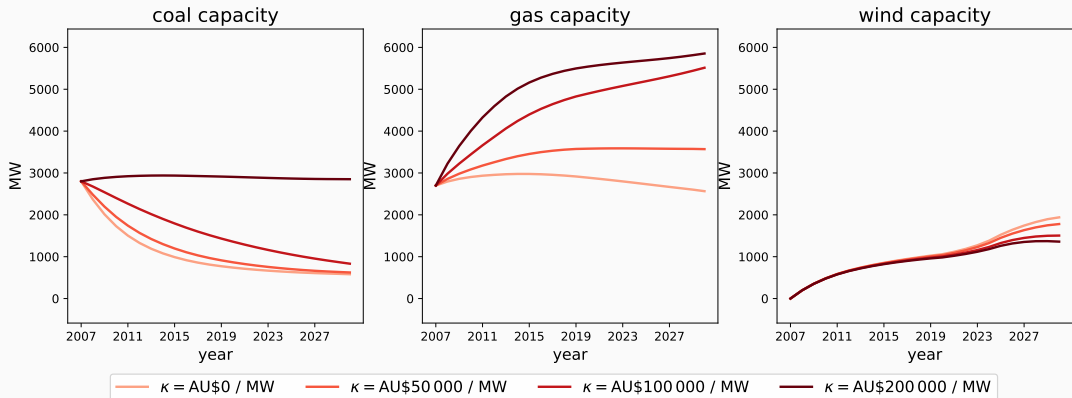


Carbon Tax: Optimal Policy



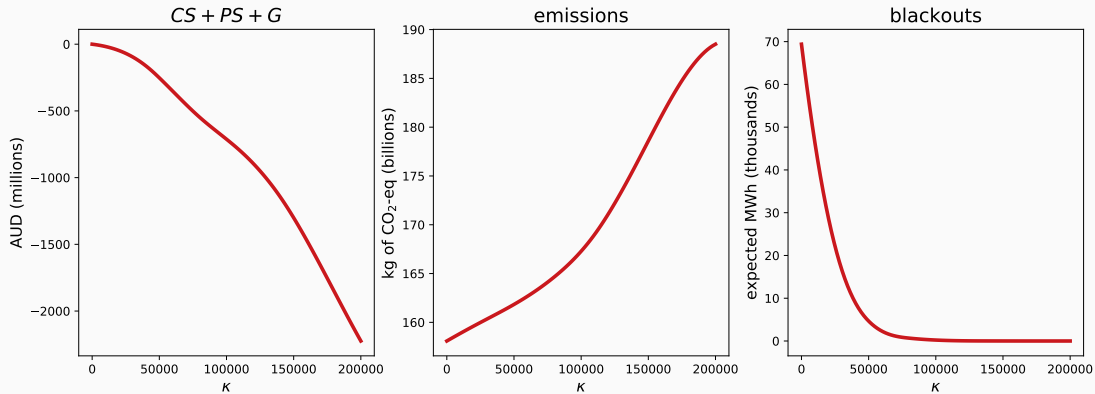
Note: Dashed line represents US government's estimate of SCC.

Capacity Payments: Capacity



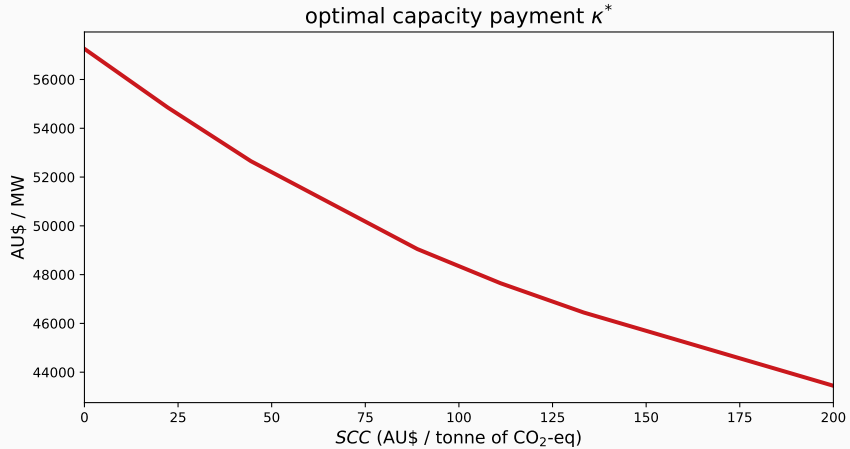
►► Production shares

Capacity Payments: Welfare

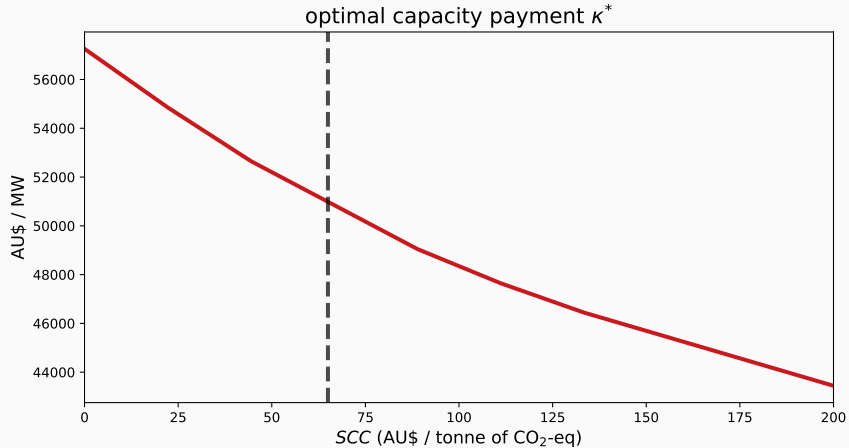


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Capacity Payments: Optimal Policy

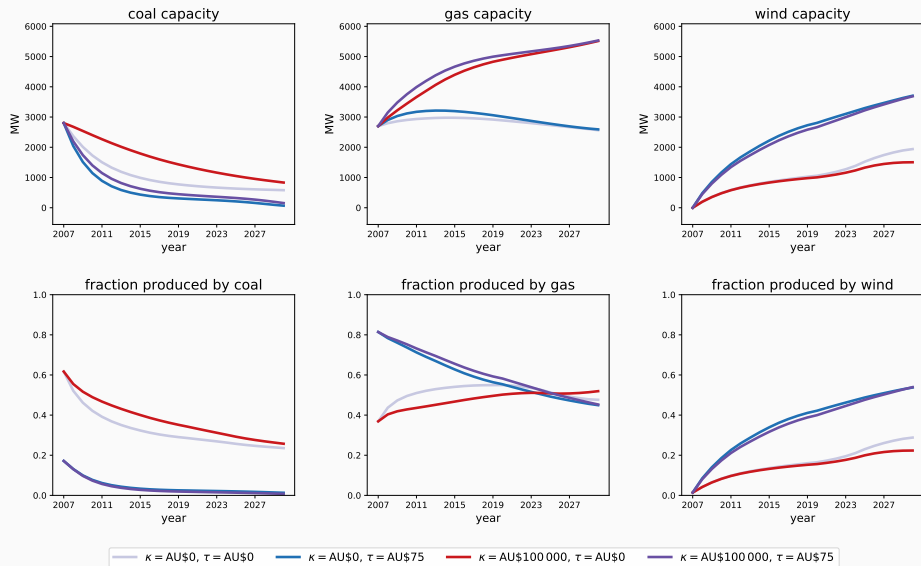


Capacity Payments: Optimal Policy

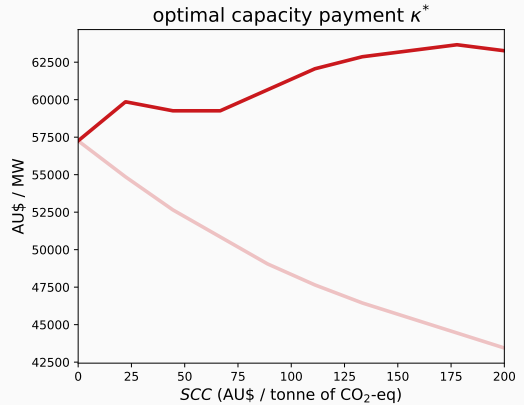
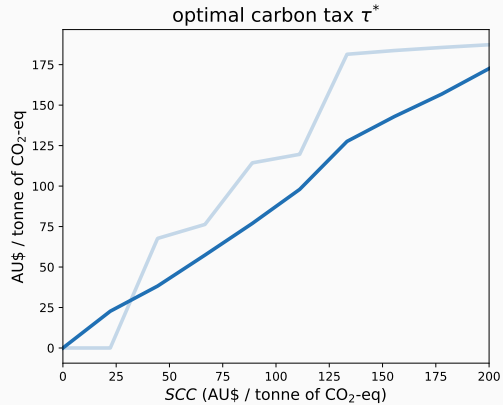


Note: Dashed line represents US government's estimate of *SCC*.

Joint Policies: Capacity and Production



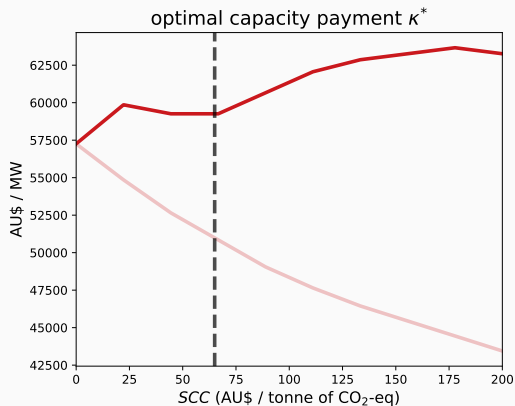
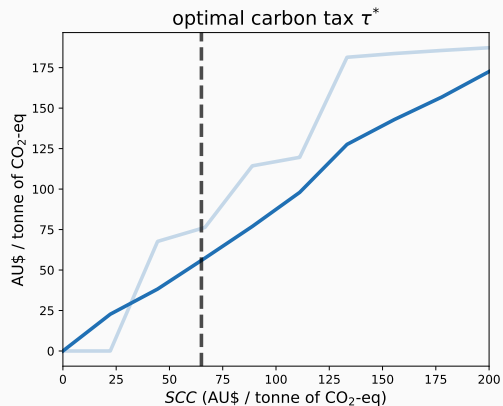
Joint Policies: Optimal Policy



► Changes in welfare

► 2-D function of *SCC* and *VOLL*

Joint Policies: Optimal Policy



Note: Dashed line represents US government's estimate of SCC.

► Changes in welfare

► 2-D function of SCC and VOLL

- Alternative environmental policies [▶▶ Details](#)
 - Predict impact of renewable production and investment subsidies
 - Compared to carbon tax, less effective at reducing emissions
 - investment subsidies fare particularly poorly because they target *investment* instead of *production* margin
 - production subsidies result in significantly more blackouts for level of reduction in emissions

- Alternative environmental policies [» Details](#)
 - Predict impact of renewable production and investment subsidies
 - Compared to carbon tax, less effective at reducing emissions
 - investment subsidies fare particularly poorly because they target *investment* instead of *production* margin
 - production subsidies result in significantly more blackouts for level of reduction in emissions
- Delaying carbon tax implementation [» Details](#)
 - Trade-off: cost-savings vs. delayed emissions reductions
 - ↓ production costs \Rightarrow ↓ wholesale prices
 - ↑ emissions
 - For most values of *SCC*, optimal delay is one year

- Develop and estimate a dynamic model of equilibrium oligopolistic investment in electricity markets
- Consider trade-off between environmental and reliability policies
 - carbon taxes reduce emissions but (for some values) increase blackouts
 - capacity payments reduce blackouts but increase emissions
 - carbon tax + capacity payment reduces blackouts *and* emissions
 - characterize optimal policies based on *SCC*
- Renewable subsidies less effective at reducing emissions, especially renewable *investment* subsidies
- No evidence of it being optimal to wait long time to implement carbon tax after announcement

Capacity Payments

- Payments to generators in proportion to generators' capacities
e.g., if “price” of capacity is \$100 000 / MW, then 100 MW coal plant receives \$10 million for the year *in addition to profits in wholesale electricity markets*
- Payments *not* dependent on amount of electricity produced

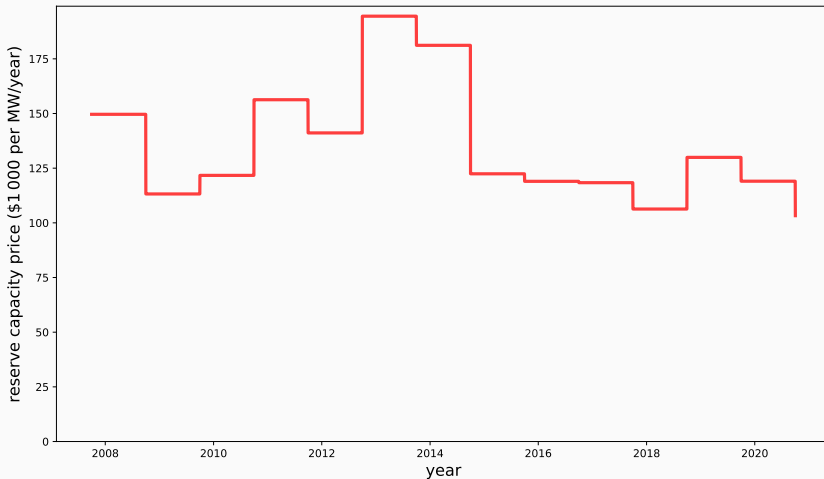
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inability to ration based on valuation \Rightarrow firms don't receive value to consumers of avoiding blackout
- Goal of payments is to ensure sufficient capacity during peak demand
- Payments are substantial portion of generators' revenues ($\sim 20\%$)
- Widely used in “restructured” electricity markets throughout the world

Capacity Payments in Western Australia

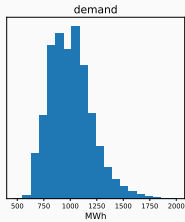


Summary Statistics

| | Mean | Std. Dev. | Min. | Max. | Num. Obs. |
|----------------------------|--------------|-------------|-------------|--------------|------------|
| Half-hourly data | | | | | |
| Price | \$48.87 | \$33.98 | -\$68.03 | \$498.0 | 258 576 |
| Quantity (aggregate) | 1 004.72 | 200.26 | 476.04 | 2 002.95 | 258 576 |
| Fraction capacity produced | 0.26 | 0.29 | 0.0 | 1.0 | 66 195 456 |
| Facility data | | | | | |
| Capacity (coal) | 161.83 | 79.17 | 58.15 | 341.51 | 17 |
| Capacity (natural gas) | 95.37 | 85.78 | 10.8 | 344.79 | 20 |
| Capacity (wind) | 59.42 | 75.54 | 0.95 | 206.53 | 16 |
| Capacity price data | | | | | |
| Capacity price | \$130 725.56 | \$24 025.49 | \$97 834.89 | \$186 001.04 | 14 |
| Capacity commitments | 54.57 | 229.64 | 0.0 | 3 350.6 | 1 274 |

[◀ Go back](#)

Wholesale Market Data

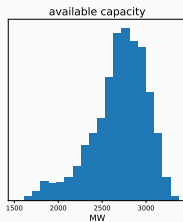
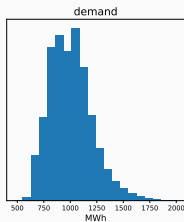


demand

demand
1

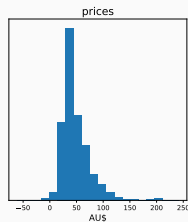
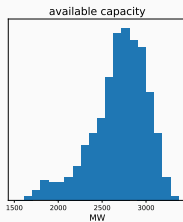
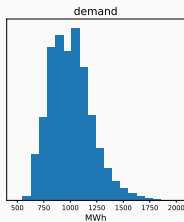
◀ Go back

Wholesale Market Data



| | demand | available capacity |
|--------------------|--------|--------------------|
| demand | 1 | 0.26 |
| available capacity | | 1 |

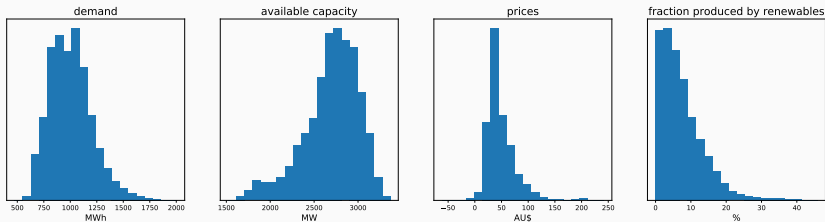
Wholesale Market Data



| | demand | available capacity | prices |
|--------------------|--------|--------------------|--------|
| demand | 1 | 0.26 | 0.4 |
| available capacity | | 1 | -0.23 |
| prices | | | 1 |

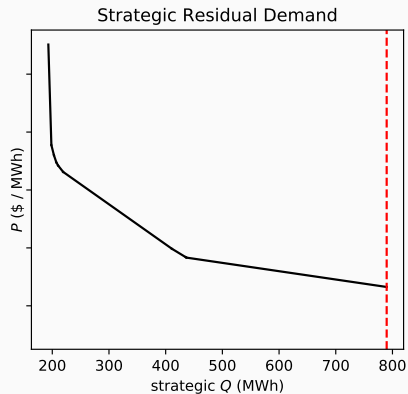
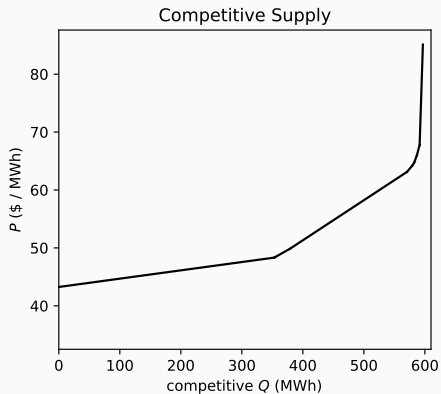
◀ Go back

Wholesale Market Data



| | demand | available capacity | prices | fraction renewables |
|---------------------|--------|--------------------|--------|---------------------|
| demand | 1 | 0.26 | 0.4 | -0.2 |
| available capacity | | 1 | -0.23 | 0.28 |
| prices | | | 1 | -0.23 |
| fraction renewables | | | | 1 |

Example Competitive Supply / Residual Demand



Short-run: Wholesale Market Model

- Firm f makes profits

$$\pi_{f,h}(\mathbf{q}_{f,h}; \mathbf{q}_{-f,h}) = P_h(\mathbf{q}) \sum_{g \in \mathcal{G}_{f,t(h)}} q_{g,h} - c_{f,h}(\mathbf{q}_{f,h})$$

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- In equilibrium, $\sum_g q_{g,h} = \bar{Q}_h$, so strategic firms face downward-sloping inverse demand

► Example

$$P_h(Q_{s,h}) = Q_{c,h}^{-1}(\bar{Q}_h - Q_{s,h})$$

- Strategic firms choose quantities to maximize profits

$$\mathbf{q}_{f,h}^*(\mathbf{q}_{-f,h}) = \arg \max_{0 \leq \mathbf{q}_{f,h} \leq \bar{\mathbf{K}}_{f,h}} \{\pi_{f,h}(\mathbf{q}_{f,h}, \mathbf{q}_{-f,h})\}$$

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- If $\sum_g \bar{K}_{g,h} < \bar{Q}_h$, a blackout results, and consumers are rationed

- If $f \neq m$:

$$V_{f,t}^m(\mathcal{G}) =$$

- If $f \neq m$:

$$V_{f,t}^m(\mathcal{G}) = \mathbb{E} \left[\Pi_{f,t}(\mathcal{G}') \right]$$

profits

Non-adjustment Strategic Value Function

- If $f \neq m$:

$$V_{f,t}^m(\mathcal{G}) = \mathbb{E} \left[\Pi_{f,t}(\mathcal{G}') + \Upsilon_{f,t}(\mathcal{G}'_f) \right]$$

profits

capacity payment

◀ Go back

Non-adjustment Strategic Value Function

- If $f \neq m$:

$$V_{f,t}^m(\mathcal{G}) = \mathbb{E} \left[\begin{aligned} &\Pi_{f,t}(\mathcal{G}') \\ &+ \Upsilon_{f,t}(\mathcal{G}'_f) \\ &+ \eta_{f,\mathcal{G}'_f,t} \end{aligned} \right]$$

profits

capacity payment

idiosyncratic shock

◀ Go back

- If $f \neq m$:

$$V_{f,t}^m(\mathcal{G}) = \mathbb{E} \left[\begin{aligned} &\Pi_{f,t}(\mathcal{G}') && \text{profits} \\ &+ \Upsilon_{f,t}(\mathcal{G}'_f) && \text{capacity payment} \\ &+ \eta_{f,\mathcal{G}'_f,t} && \text{idiosyncratic shock} \\ &+ \beta \mathbb{E} [W_{f,t+1}(\mathcal{G}')] && \text{continuation value} \end{aligned} \right]$$

Competitive Fringe Adjustment

- Nature chooses an energy source s to adjust
- First, incumbent competitive generators of source s exit if and only if

$$\mathbb{E}[v_{g,t}(\text{in}, \mathcal{G})] < \mathbb{E}[v_{g,t}(\text{out}, \mathcal{G} \setminus \{g\})]$$

- Second, potential entrant competitive generators of source s enter if and only if

$$v_{g,t}(\text{in}, \mathcal{G} \cup \{g\}) > v_{g,t}(\text{out}, \mathcal{G})$$

- The equilibrium \mathcal{G}^* determined by a free entry condition: competitive generators enter (or exit) up to the point where it ceases to be profitable
- Competitive generators of source $s' \neq s$ cannot adjust in / out status in the current period

Long-run: Dynamic Game Assumptions

- One strategic firm (randomly chosen) and competitive fringe of one source (randomly chosen) make sequential investment decisions
- After T periods, firms can no longer adjust generators
- Firms have perfect foresight over the path of generator costs and capacity payments

- The expected net revenue received from capacity payment is

$$\Upsilon_{f,t}(\mathcal{G}_f) = \max_{\gamma \in [0,1]^{\mathcal{G}_f}} \left\{ \underbrace{\sum_{g \in \mathcal{G}_f} \gamma_g K_g \kappa_t}_{\text{capacity payment revenue}} - \underbrace{\mathbb{E} \left[\sum_h \psi_{f,h}(\gamma; \mathcal{G}_f) \right]}_{\text{total expected penalties}} \right\}$$

where the penalty formula is given by

$$\psi_{f,h}(\gamma; \mathcal{G}_f) = \sum_{g \in \mathcal{G}_f} \underbrace{\lambda_{s(g)} \rho}_{\text{refund factor}} \underbrace{\kappa_{t(h)}}_{\text{cap. credit price}} \underbrace{\gamma_g \delta_{g,h}}_{\text{capacity deficit}}$$

Stage 1: Wholesale Market Estimation

- Cost function

$$c_{g,h}(q_{g,h}) = \zeta_{1,g,h} q_{g,h} + \zeta_{2,s(g)} \left(\frac{q_{g,h}}{K_g} \right)^2$$

where

$$\zeta_{1,g,h} = \beta_{0,s(g)} + \varepsilon_{g,h}$$

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 1. unconstrained \mathcal{G}_h^u
 2. constrained from above \mathcal{G}_h^+
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1. unconstrained \mathcal{G}_h^u
2. constrained from above \mathcal{G}_h^+
3. constrained from below \mathcal{G}_h^-

- **General idea:** [▶▶ Identification](#)

1. use FOCs to back out cost shocks for *unconstrained* generators
2. use those shocks to bound shocks for *constrained* generators
3. maximize Tobit likelihood $f(\varepsilon) = f^u(\varepsilon^u) F^{-u|u}(\varepsilon^{-u} | \varepsilon^u)$

assume $\varepsilon_h \sim \mathcal{N}(\mathbf{0}, \Sigma)$

Stage 1: Results

| | |
|---------------------------------------|---------------------|
| Capacity utilization costs | |
| $\hat{\zeta}_{2,\text{coal}}$ | 893.452 (73.900) |
| $\hat{\zeta}_{2,\text{gas}}$ | 206.966 (30.963) |
| Deterministic components of ζ_1 | |
| $\hat{\beta}_{0,\text{coal}}$ | 21.831 (1.523) |
| $\hat{\beta}_{0,\text{gas}}$ | 32.648 (1.025) |
| Cost shock components of ζ_1 | |
| $\hat{\sigma}_{\text{coal}}$ | 18.334 (0.460) |
| $\hat{\sigma}_{\text{gas}}$ | 18.652 (0.491) |
| $\hat{\rho}_{\text{coal,coal}}$ | 0.764 (0.032) |
| $\hat{\rho}_{\text{gas,gas}}$ | 0.806 (0.041) |
| $\hat{\rho}_{\text{coal,gas}}$ | 0.774 (0.034) |
| year | |
| 2015 | |
| num. obs. | |
| 2 500 | |

[◀ Go back](#)

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- per-MWh cost of gas larger than coal (AU\$32.65 vs AU\$21.83)
- using high fraction of capacity more expensive for coal than for gas (AU\$893 vs AU\$206)

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- per-MWh cost of gas larger than coal (AU\$32.65 vs AU\$21.83)
- using high fraction of capacity more expensive for coal than for gas (AU\$893 vs AU\$206)
- substantial correlation both across and within sources

►► Estimates of other variables

◀ Go back

Stage 1: Cost Shock Identification

- Dispersion of prices can come from dispersion in ζ_1 or from ζ_2
- Separately identifying ζ_1 from ζ_2 comes from the covariance between prices and capacity utilization
 - if P and \mathbf{q}/\mathbf{K} highly correlated \Rightarrow low σ_ε , high ζ_2
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 - levels determined by the range of prices observed in the data

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 - if P and \mathbf{q}/\mathbf{K} weakly correlated \Rightarrow high σ_ε , low ζ_2
 - levels determined by the range of prices observed in the data
- While identification of cost shocks is nonparametric, helpful to use **parametric distribution**
 1. need to calculate conditional probabilities (i.e., $F^{-u|u}(\varepsilon^{-u}|\varepsilon^u)$)
 2. reduces dimension of correlation among shocks in an interval
- Assume

$$\varepsilon_h \sim \mathcal{N}(\mathbf{0}, \Sigma_\varepsilon)$$

where correlation varies at the energy-source level

- Show in the paper that unconstrained prices and quantities are locally linear in cost shocks

$$\begin{bmatrix} \mathbf{q}_h^u \\ P_h \end{bmatrix} = \mathbf{M}_h(\beta, \zeta_2) \varepsilon_h^u + \mathbf{n}_h(\beta, \zeta_2)$$

therefore

$$\varepsilon_h^u(\beta, \zeta_2) = \mathbf{M}_h(\beta, \zeta_2)^{-1} \left(\begin{bmatrix} \mathbf{q}_h^u \\ P_h \end{bmatrix} - \mathbf{n}_h(\beta, \zeta_2) \right)$$

- This controls for the fact that \mathbf{q}_h^u is a function of ε_h^u

Stage 1: Backing out / Bounding Cost Shocks

- Invert prices and unconstrained quantities to get $\epsilon_h^u(\beta, \zeta_2)$ [» Details](#)

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Stage 1: Backing out / Bounding Cost Shocks

- Invert prices and unconstrained quantities to get $\varepsilon_h^u(\beta, \zeta_2)$ [▶ Details](#)

- Use $\varepsilon_h^u(\beta, \zeta_2)$ to construct strategic firms' (local) residual demand curve

$$\begin{array}{lll} \text{Strategic:} & MR_{g,h}(\beta, \zeta_2) & \geq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{\bar{K}_{g,h}}{K_g^2} + \varepsilon_{g,h} \quad \text{if } g \in \mathcal{G}_h^+ \\ \text{Competitive:} & P_h & \geq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{\bar{K}_{g,h}}{K_g^2} + \varepsilon_{g,h} \quad \text{if } g \in \mathcal{G}_h^+ \end{array}$$

Stage 1: Backing out / Bounding Cost Shocks

- Invert prices and unconstrained quantities to get $\varepsilon_h^u(\beta, \zeta_2)$ [Details](#)
- Use $\varepsilon_h^u(\beta, \zeta_2)$ to construct strategic firms' (local) residual demand curve

$$\begin{array}{lll} \text{Strategic:} & MR_{g,h}(\beta, \zeta_2) & \leq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{K_{g,h}}{K_g^2} + \varepsilon_{g,h} \quad \text{if } g \in \mathcal{G}_h^- \\ \text{Competitive:} & P_h & \leq \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{K_{g,h}}{K_g^2} + \varepsilon_{g,h} \quad \text{if } g \in \mathcal{G}_h^- \end{array}$$

Stage 1: Backing out / Bounding Cost Shocks

- Invert prices and unconstrained quantities to get $\varepsilon_h^u(\beta, \zeta_2)$ [▶ Details](#)
- Use $\varepsilon_h^u(\beta, \zeta_2)$ to construct strategic firms' (local) residual demand curve

$$\begin{array}{lll} \text{Strategic:} & MR_{g,h}(\beta, \zeta_2) & \begin{array}{l} \geq \\ \leq \end{array} & \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{?}{K_g^2} + \varepsilon_{g,h} & \text{if } g \in \mathcal{G}_h^? \\ \text{Competitive:} & P_h & \begin{array}{l} \geq \\ \leq \end{array} & \beta'_{s(g)} \mathbf{x}_{g,h} + 2\zeta_{2,s(g)} \frac{?}{K_g^2} + \varepsilon_{g,h} & \text{if } g \in \mathcal{G}_h^? \end{array}$$

- Likelihood

$$\mathcal{L}_h(\beta, \zeta_2, \Sigma_\varepsilon) = \phi(\varepsilon_h^u) \cdot \Pr\left(\varepsilon_h^+ \leq \nu_h^+ \text{ and } \varepsilon_h^- \geq \nu_h^- \mid \varepsilon_h^u\right)$$

where ν_h is the inversion from above

Stage 1: Other Wholesale Market Variables

- In addition to cost shocks, we have
 - demand shocks \bar{Q}
 - capacity factor shocks δ
- Allow for (unobserved) correlation between demand shocks and capacity factor shocks [▶▶ Details](#)

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Stage 1: Other Variables Details

- Demand and wind capacity factors are allowed to be correlated

$$\underbrace{\begin{bmatrix} \log(\bar{Q}_h) \\ \log\left(\frac{\delta_{\text{wind},h}}{1-\delta_{\text{wind},h}}\right) \end{bmatrix}}_{=: \omega} \sim \mathcal{N}(\mathbf{X}\beta_{\omega}, \Sigma_{\omega})$$

- Thermal generator capacity factors are binary and distributed

$$\delta_{g,h} = \begin{cases} 1 & \text{with probability } p_{s(g)} \\ 0 & \text{with probability } 1 - p_{s(g)} \end{cases}$$

Stage 1: Results (Other Variables)

| | |
|---|-------------------|
| Demand distribution | |
| $\hat{\text{const}}_{\log(\bar{Q})}$ | 6.941 (0.003) |
| $\hat{\sigma}_{\log(\bar{Q})}$ | 0.172 (0.002) |
| Wind outage distribution | |
| $\hat{\text{const}}_{f-1}(\delta_{\text{wind}})$ | -1.274 (0.021) |
| $\hat{\sigma}_{f-1}(\delta_{\text{wind}})$ | 1.779 (0.013) |
| $\hat{\rho}_{f-1}(\delta_{\text{wind}}), f-1(\delta_{\text{wind}})$ | 0.528 (0.008) |
| $\hat{\rho}_{f-1}(\delta_{\text{wind}}), \log(\bar{Q})$ | -0.038 (0.022) |
| Thermal outage probabilities | |
| $\hat{\rho}_{\delta_{\text{coal}}}$ | 0.987 (0.001) |
| $\hat{\rho}_{\delta_{\text{gas}}}$ | 0.987 (0.001) |
| year | 2015 |
| num. obs. | 2 500 |

[◀ Go back](#)

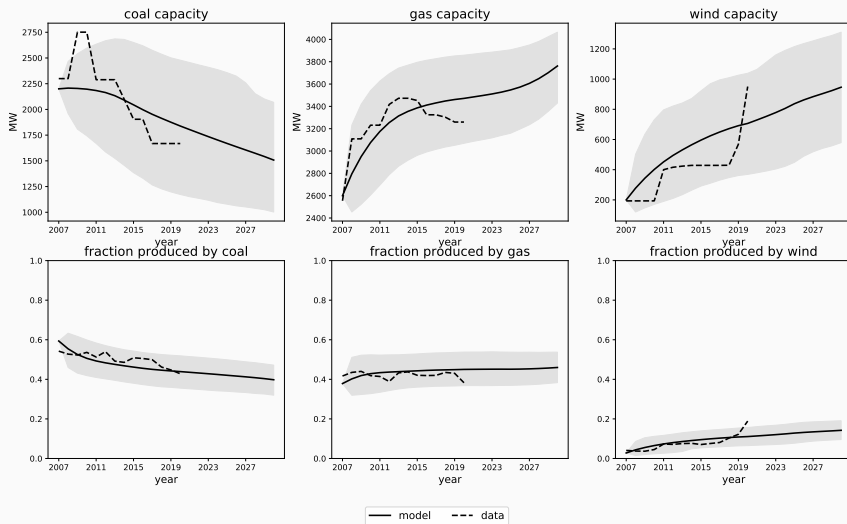
Constructing $\hat{\Pi}(\mathcal{G})$

- $\Pi(\cdot)$ is
 - an expectation over the random variables in the wholesale market under simultaneously determined demand distribution
- To solve, consider candidate \bar{P} and associated $\mathcal{Q}(\bar{P})$
 - sample many draws of shocks
 - solve for equilibrium
 - tricky because 3^G combinations, but in paper provide algorithm that reduces the problem to checking at most $2G$ combinations (reduces number of equilibrium computations by factor of $\sim 10^{30}!$)
 - average over draws of the shocks
- Use new implied \bar{P} and iterate until convergence $\Rightarrow \hat{\Pi}(\cdot)$

Stage 2: Dynamic Parameter Identification

- **Maintenance costs:** identification comes from **level of capacity** for a source conditional on profits and investment costs
 - investments determined by: profits, investment costs, and maintenance costs
 - retirements determined by: profits and maintenance costs
- **Cost shock variance:** identification comes from **covariance between investment and profitability** (stream of profits – investment cost)
 - if profitability and investment highly correlated \Rightarrow low variance
 - if profitability and investment weakly correlated \Rightarrow high variance

Model Fit



Note: The model path in each plot is the expectation over realizations of the idiosyncratic shocks given the initial state. The shaded region corresponds to the area in between the 10th and 90th percentiles.

Demand

- Measure 1 of consumers with utility in interval h

$$u_h(q, P) = \frac{\xi_h}{1 - 1/\varepsilon} q^{1-1/\varepsilon} - Pq$$

where P is the *price consumer faces*

- $\bar{Q}_h(P) = \int_0^1 q^*(P, \xi_h) di$
 $\log(\xi_h) \sim \mathcal{N}(\mu, \sigma^2)$ (possibly correlated with wholesale market variables)

Demand

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where P is the *price consumer faces*

- $\bar{Q}_h(P) = \int_0^1 q^*(P, \xi_h) di$
 $\log(\xi_h) \sim \mathcal{N}(\mu, \sigma^2)$ (possibly correlated with wholesale market variables)
- Constant elasticity of demand: $\frac{d \log \mathbb{E}[\bar{Q}_h(P)]}{d \log P} = -\varepsilon$
- Price elasticity of demand: -0.09 (Deryugina, MacKay, and Reif (2020))

- Measure 1 of consumers with utility in interval h

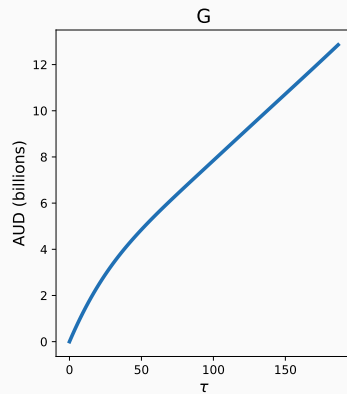
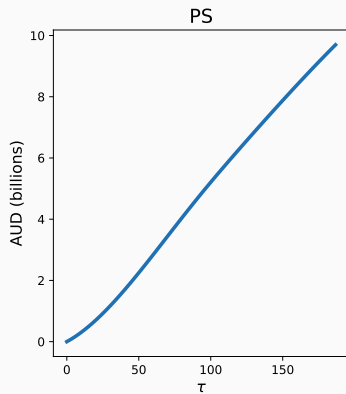
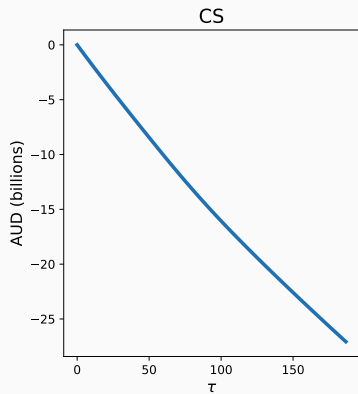
$$u_h(q, P) = \frac{\xi_h}{1 - 1/\varepsilon} q^{1-1/\varepsilon} - Pq$$

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- Constant elasticity of demand: $\frac{d \log \mathbb{E}[\bar{Q}_h(P)]}{d \log P} = -\varepsilon$
- Price elasticity of demand: -0.09 (Deryugina, MacKay, and Reif (2020))
- Average quantity-weighted wholesale prices \bar{P}_t (price consumers pay)
- In equilibrium, $\bar{P}_t(\mathcal{G})$ is implicitly defined by

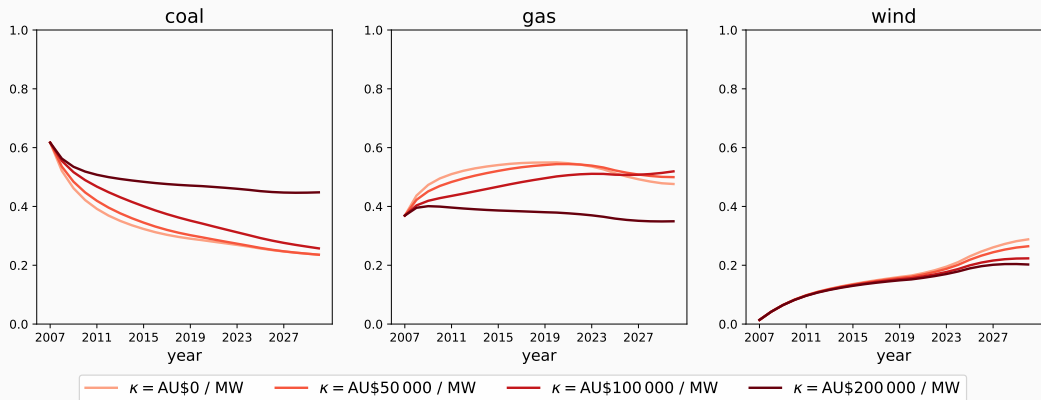
$$\bar{P} = \mathbb{E} \left[P_h(\mathbf{q}_h^*(\mathcal{G}, \bar{Q}_h(\bar{P}))) \frac{\bar{Q}_h(\bar{P})}{\mathbb{E}[\bar{Q}_h(\bar{P})]} \right]$$

Carbon Tax: Welfare

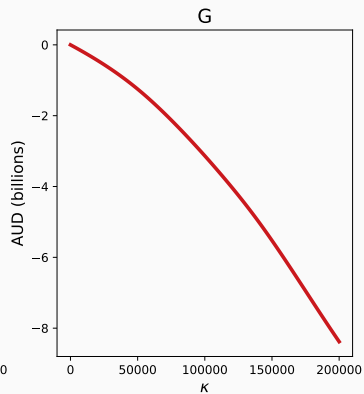
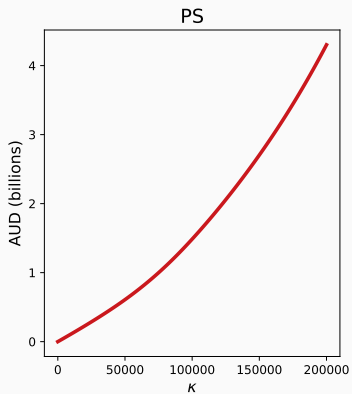
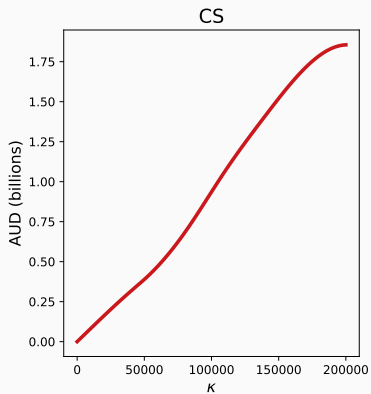


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Capacity Payments: Production Shares

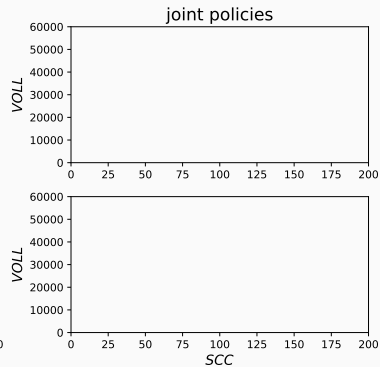
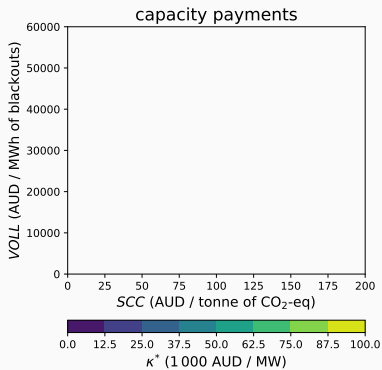
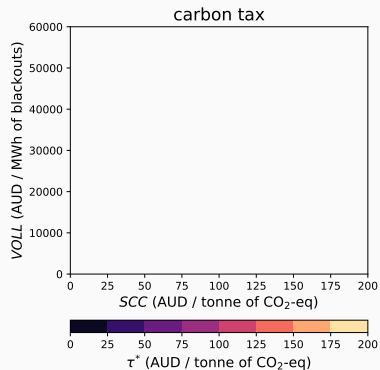


Capacity Payments: Welfare

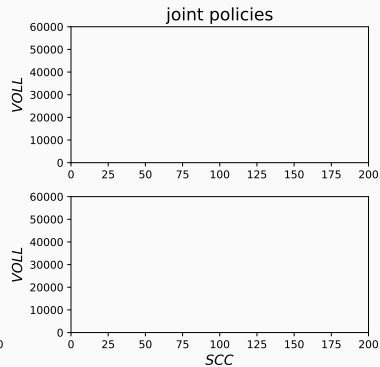
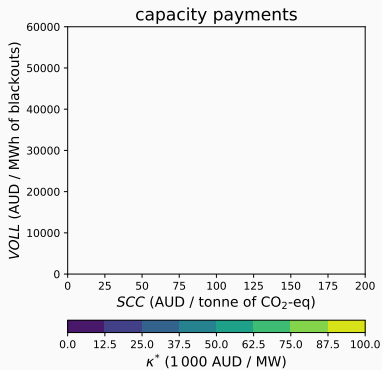
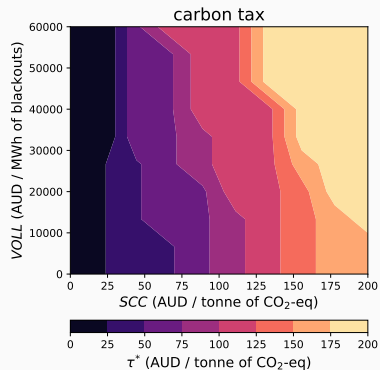


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Optimal Policy

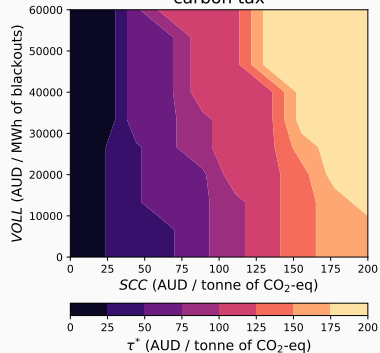


Optimal Policy

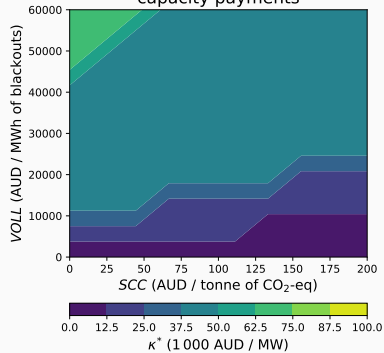


Optimal Policy

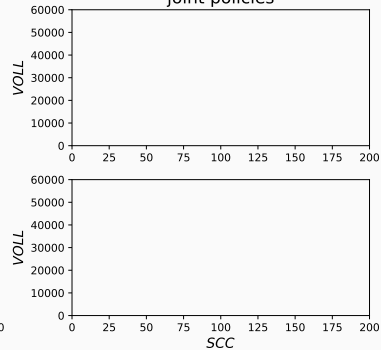
carbon tax



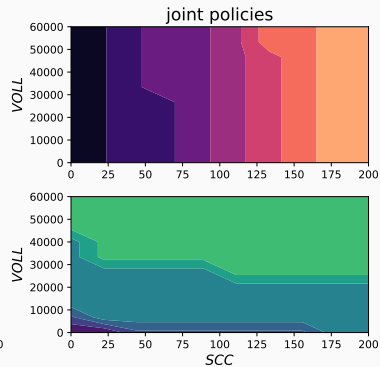
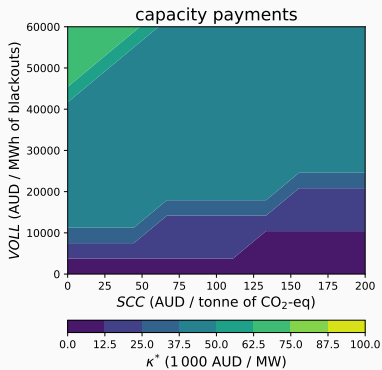
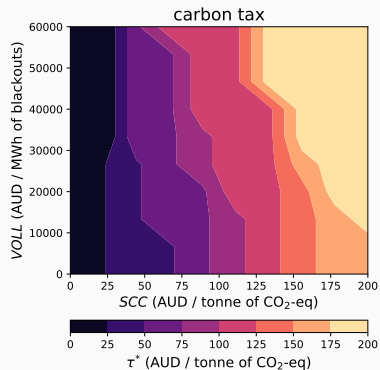
capacity payments



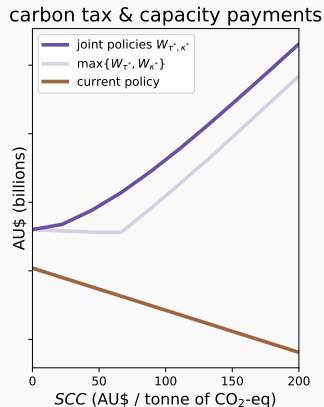
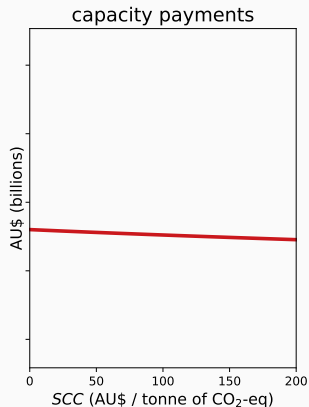
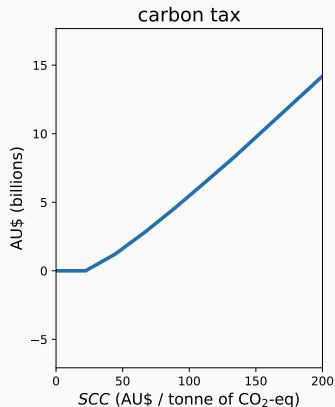
joint policies



Optimal Policy



Changes in Welfare from Optimal Policy



Note: *VOLL* set to 50 000 AU\$ / MW (WEM estimate)

Welfare Impact of Different Policies

| τ | κ | ΔCS (billions AUD) | ΔPS (billions AUD) | ΔG (billions AUD) | Δ emissions (billions kg CO ₂ -eq) | Δ blackouts (thousands MWh) |
|--------|----------|-------------------------------|-------------------------------|------------------------------|---|---------------------------------------|
| 0 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 25 000 | 0.22 | 0.32 | -0.63 | 2.1 | -50.44 |
| | 50 000 | 0.39 | 0.61 | -1.25 | 3.75 | -64.75 |
| | 100 000 | 1.06 | 1.71 | -3.57 | 10.91 | -69.29 |
| 50 | 0 | -7.9 | 2.06 | 4.63 | -58.96 | 7.23 |
| | 25 000 | -7.61 | 2.36 | 4.05 | -58.77 | -42.66 |
| | 50 000 | -7.4 | 2.62 | 3.48 | -58.64 | -60.11 |
| | 100 000 | -6.94 | 3.64 | 1.4 | -57.85 | -67.61 |
| 100 | 0 | -15.12 | 4.83 | 7.46 | -78.13 | -7.64 |
| | 25 000 | -14.77 | 5.1 | 6.89 | -78.1 | -43.15 |
| | 50 000 | -14.49 | 5.33 | 6.34 | -78.11 | -60.03 |
| | 100 000 | -14.05 | 6.26 | 4.24 | -77.71 | -68.01 |
| 150 | 0 | -21.33 | 7.36 | 10.15 | -85.57 | -12.53 |
| | 25 000 | -20.92 | 7.6 | 9.58 | -85.6 | -43.59 |
| | 50 000 | -20.61 | 7.8 | 9.01 | -85.7 | -60.35 |
| | 100 000 | -20.13 | 8.68 | 6.9 | -85.6 | -68.32 |

Counterfactual #2: Alternative Environmental Policies

In addition to carbon tax, several other tools are commonly used

- **renewable production subsidy** ▶▶ Capacity ▶▶ Production ▶▶ Welfare

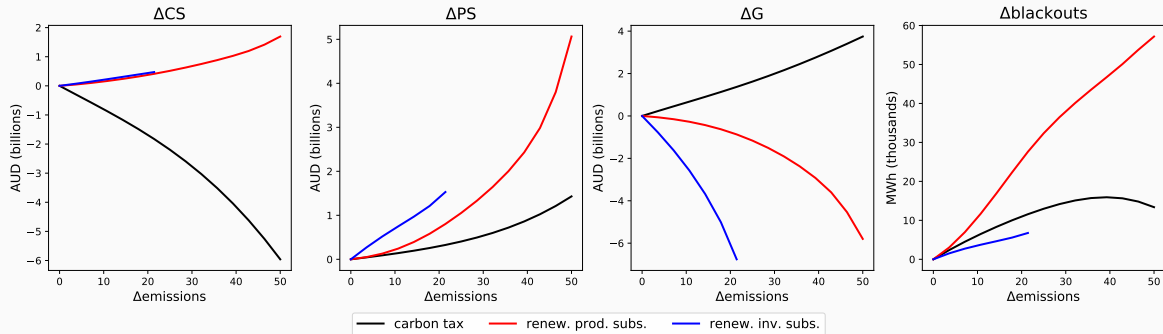
renewable generators receive ς AU\$ per MWh produced

- **renewable investment subsidy** ▶▶ Capacity ▶▶ Production ▶▶ Welfare

firms pay $(1 - s) C_{\text{wind},t}$ for new wind generators

- How does welfare change with these tools?
- Do these tools have different distributional impacts?

Alternative Environmental Policy Comparison



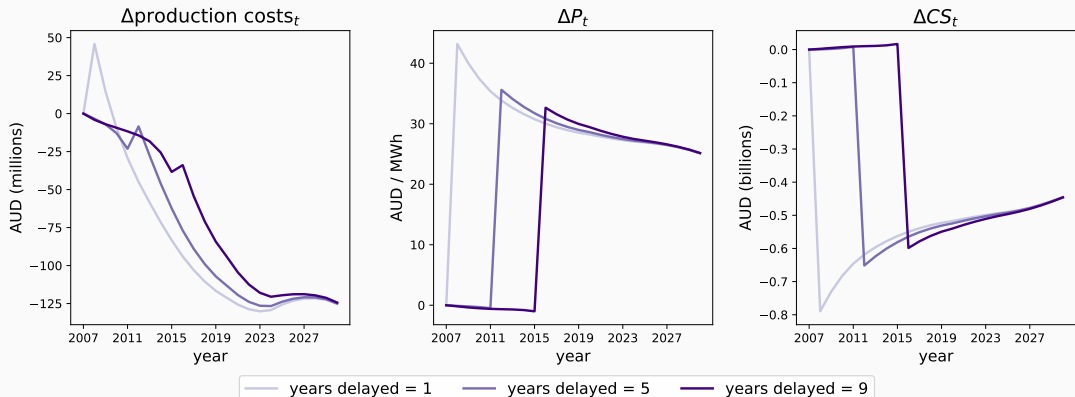
» with capacity payments

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Counterfactual #3: Policy Timing

- Policies are not typically implemented immediately after announcement
- Policy delay allows firms to adjust generator portfolios, yielding cost savings
- Simulate the market from 2007 in which carbon tax announced at beginning and implemented T_{delay} years into future

Policy Timing: CS over Time

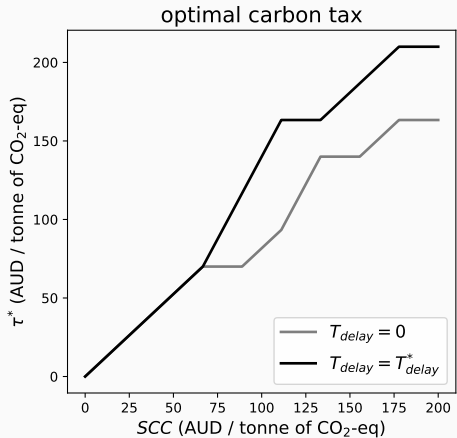
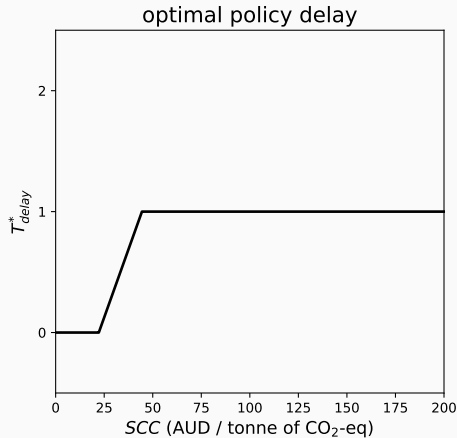


Note: $\tau = 70$, $\kappa = 50\,000$

►► Capacity over time

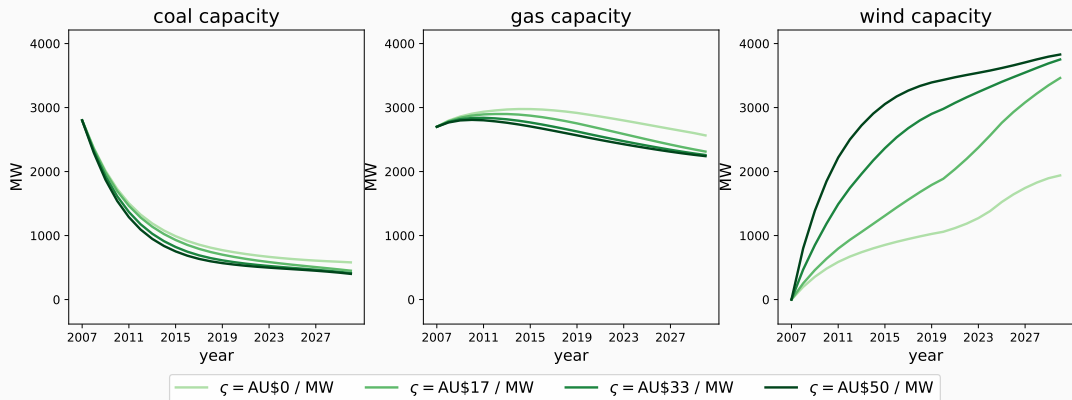
►► Welfare

Policy Timing: Optimal Timing

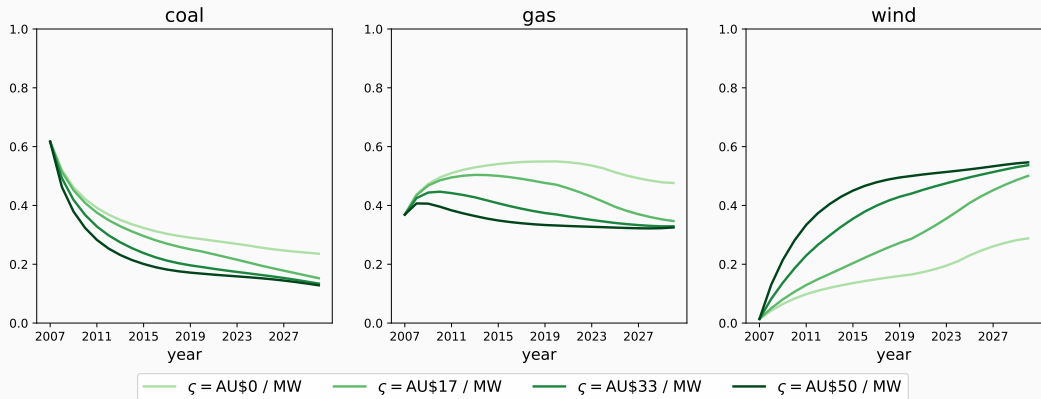


Note: VOLL set to 50 000 AU\$ / MW (WEM estimate)

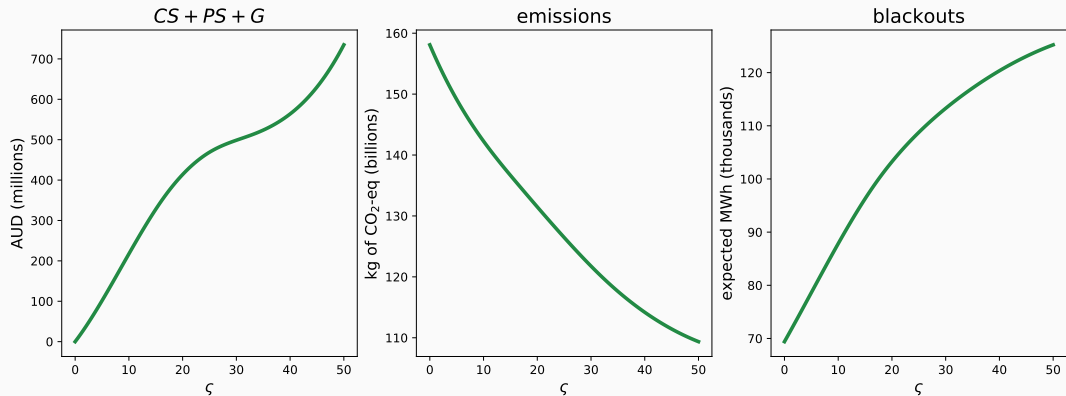
Renewable Production Subsidy: Capacity



Renewable Production Subsidy: Production Shares



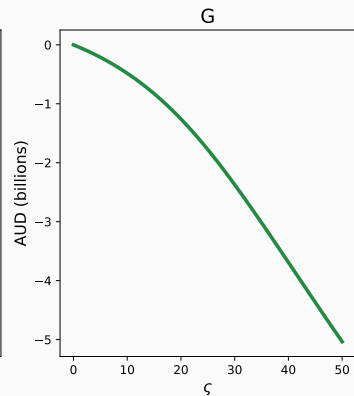
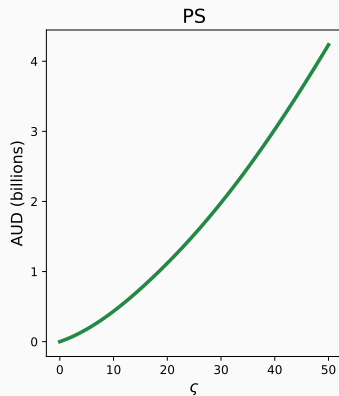
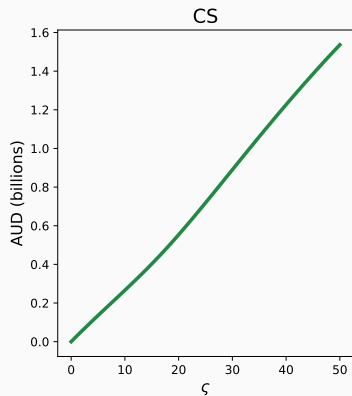
Renewable Production Subsidy: Welfare



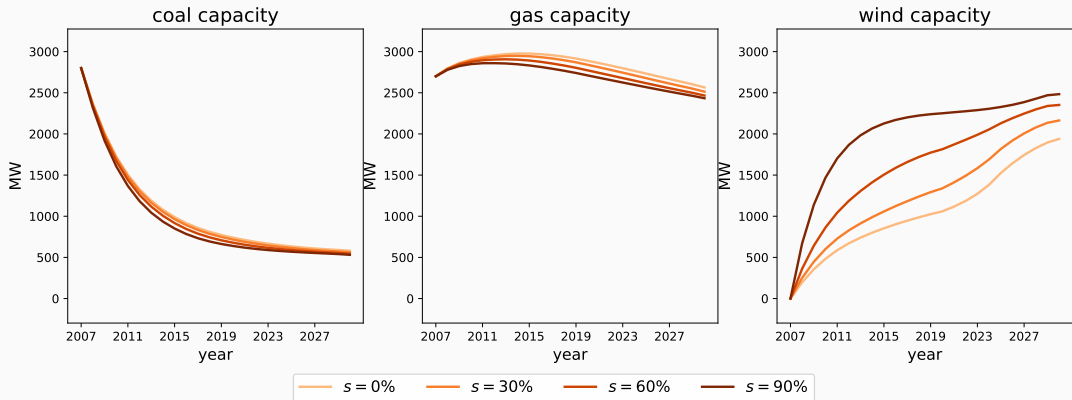
» Breakdown of CS, PS, G

◀ Go back

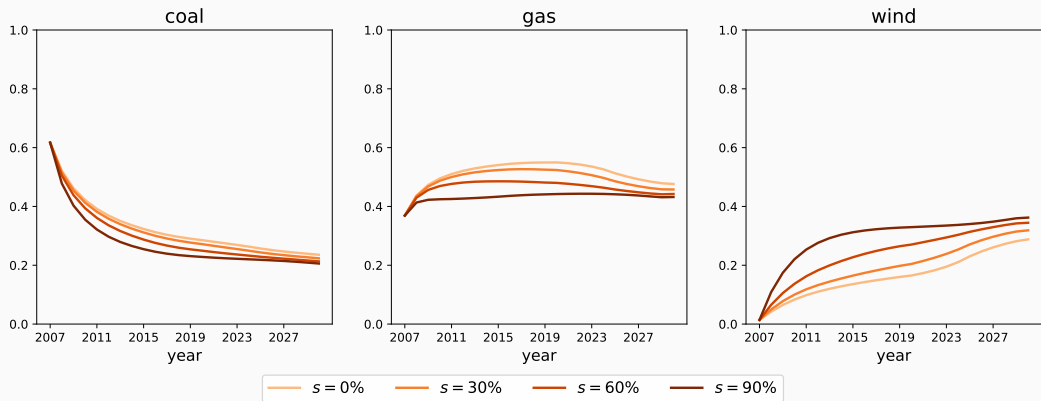
Renewable Production Subsidy: Welfare



Renewable Investment Subsidy: Capacity

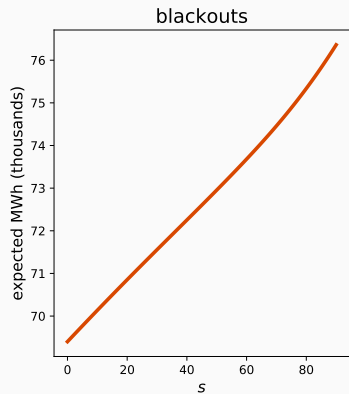
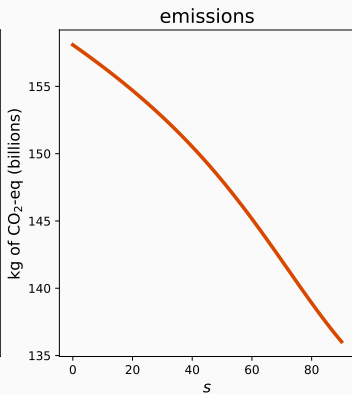
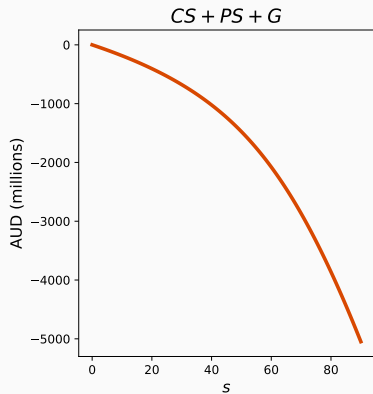


Renewable Investment Subsidy: Production Shares



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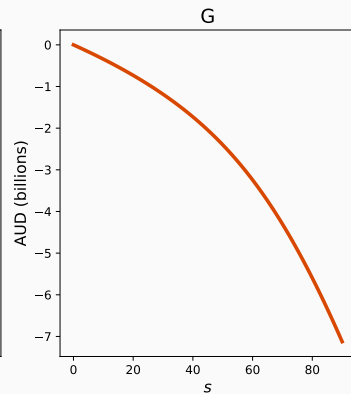
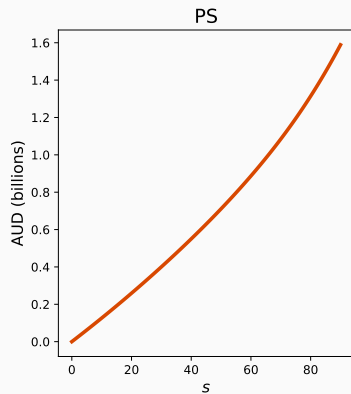
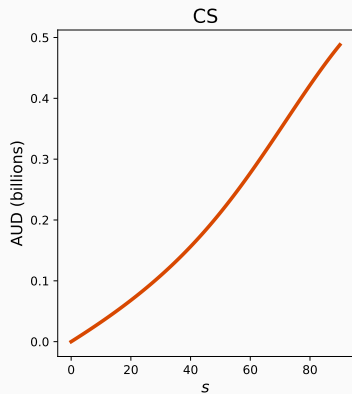
Renewable Investment Subsidy: Welfare



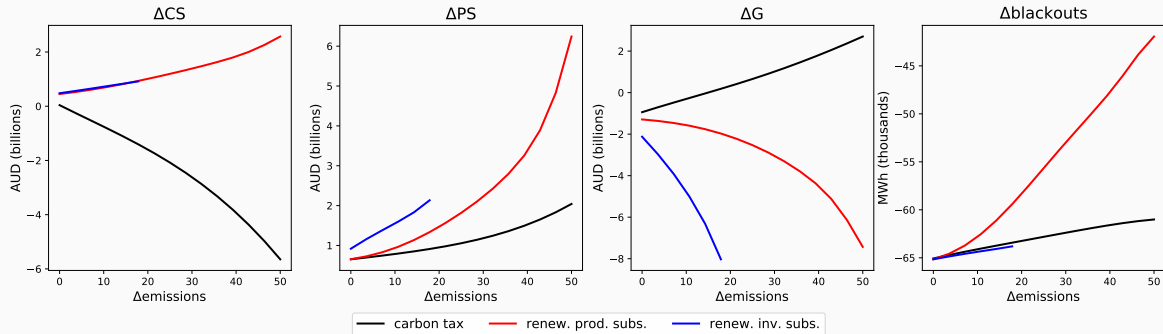
» Breakdown of CS, PS, G

◀ Go back

Renewable Investment Subsidy: Welfare

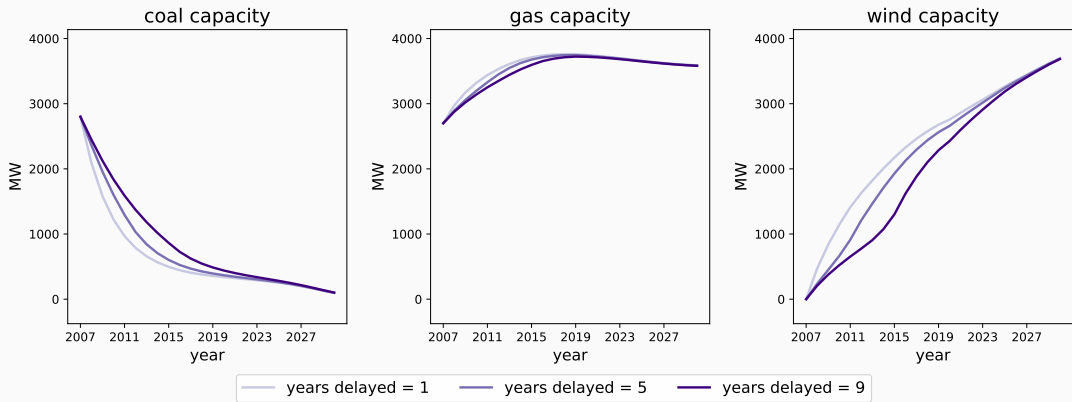


Alternative Environmental Policy Comparison with $\kappa = 50\,000$



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Policy Timing: Capacity



Note: $\tau = 70$, $\kappa = 50\,000$

Policy Timing: Welfare

