Investment, Emissions, and Reliability in Electricity Markets

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January 19, 2022

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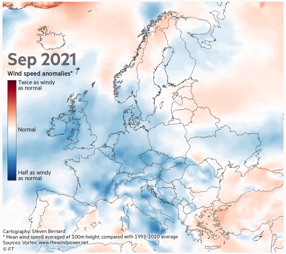

Source: Financial Times (October 8, 2021)

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- How electricity sector policies affect emissions and blackouts depends on how generator investments and retirements in all energy sources respond
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  - investment and production in variety of energy sources
  - electricity prices
  - blackouts
  - emissions
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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

Preview of Results

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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

Literature

- **Electricity markets**: Reguant (2014), Bushnell et al. (2008), Wolak (2007), Gowrisankaran et al. (2016), Karaduman (2021)

  $\Rightarrow$ endogenous investment and market power

- **Investment in electricity markets**: Allcott (2013), Linn and McCormack (2019), Butters et al. (2021)

  $\Rightarrow$ dynamics, oligopoly, multiple energy sources

- **Dynamic oligopoly**: Ryan (2012), Fowlie et al. (2016), Igami and Uetake (2020)

  $\Rightarrow$ 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)

  $\Rightarrow$ policies jointly, equilibrium oligopolistic investment

Industry Background & Data

Regulated, Vertically Integrated

$$\underbrace{\text{generation} \quad \text{transmission} \quad \text{distribution}}_{\text{owned by utility}}$$

- prices determined through regulation
- investment determined through long-term planning

Electricity Markets

Regulated, Vertically Integrated

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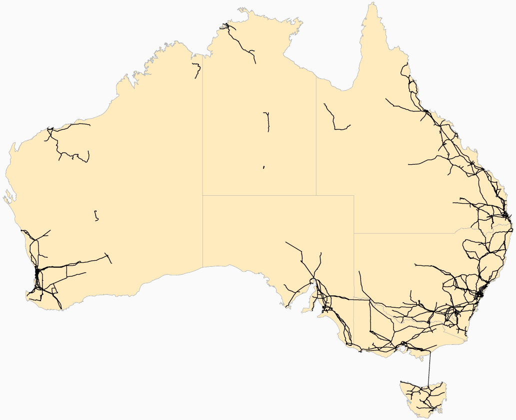
"Restructured"

$\underbrace{\text{generation}}_{\substack{\text{owned by} \\ \text{independent firms}}} \quad \underbrace{\text{transmission}}_{\substack{\text{owned by} \\ \text{grid operator}}} \quad \underbrace{\text{distribution}}_{\substack{\text{owned by} \\ \text{independent retailers}}}$

- 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



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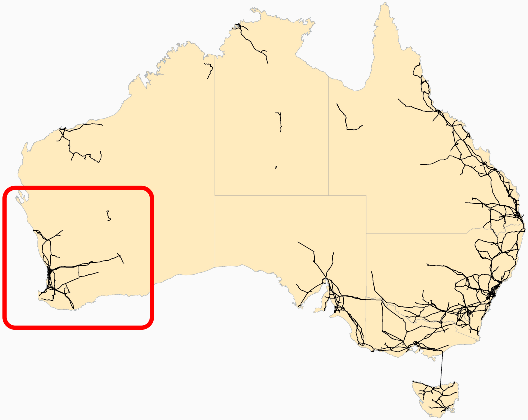

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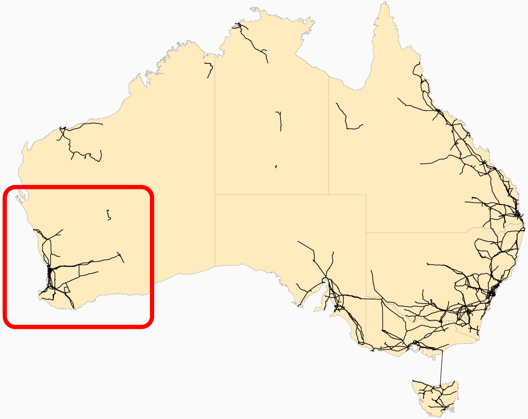

- 1 million customers, 18 TWh / year
- Restructured from vertically-integrated to independent generators in 2006
- Three energy sources:
  coal (50.2%)
  natural gas (42.2%)
  wind (7.6%)
- Since restructuring, capacity payment program with significant variation over time ⏩ Graph

Market Operations

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

Data

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

Market Evolution

- 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%

Market Evolution

- 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."

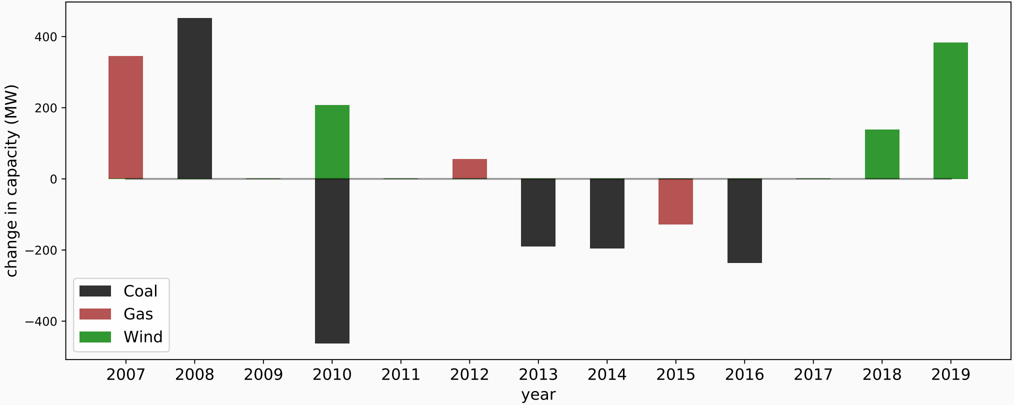
Market Evolution

- 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

Model Overview

- 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 $f(g) \in \left\{ \underbrace{1, \ldots, n, \ldots, N}_{\substack{\text{strategic} \\ \text{firms}}}, \underbrace{c}_{\substack{\text{competitive} \\ \text{fringe}}} \right\}$

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Short-run (h)

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

$$\Rightarrow \boldsymbol{\pi}_h \left(\mathcal{G}_{t(h)}, \bar{Q}_h \right)$$

Long-run (t)

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

$$\Rightarrow \mathbf{\Pi}_t \left(\mathcal{G}, \mathcal{Q} \left(\bar{P}_{\mathcal{G}} \right) \right)$$

Short-run: Wholesale Market Overview

- 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 $\bar{\mathbf{K}}_h$

    $\bar{K}_{g,h} = \delta_{g,h} K_g$, 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

Short-run: Wholesale Market Outcomes

Over year we get

- firms' profits $\boldsymbol{\Pi}_t$

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

- emissions level E_t

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

- blackout level B_t

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

Distribution of demand

Long-run: Modeling Choices

- 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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- **Challenges**: dynamic games generally have multiple equilibria and are computationally very difficult
  ⇒ makes full-solution estimation approaches intractable
- 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)
  ⇒ unique equilibrium, computationally tractable

Long-run: Generator Investment Overview

- 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 $m \in \{1, \ldots, N\}$ 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 $f = m$:

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

Non-adjustment value function   Competitive fringe adjustment

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▸▸ Non-adjustment value function ▸▸ Competitive fringe adjustment

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Details

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

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

Non-adjustment value function

Competitive fringe adjustment

Estimation

Model Estimation

Two stages

1. Estimate distribution of wholesale market variables
   - production costs, capacity factors, and demand joint distribution

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

   Basic idea: use production FOCs to recover distribution of production costs ⏩ Details ⏩ Results

2. Take estimated distribution to solve for $\hat{\Pi}\left(\mathcal{G}\right)$ 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 $\boldsymbol{\eta} \overset{i.i.d.}{\sim}$ Type I Extreme Value
- We have several dynamic parameters: $\underbrace{\{\mathbf{C}_t\}_t}_{\text{generator costs}}, \underbrace{\mathbf{M}}_{\text{maintenance costs}}$, and $\underbrace{Var(\eta)}_{\boldsymbol{\eta}\text{ shock distribution}} =: \boldsymbol{\theta}$
- Generator costs $\{\mathbf{C}_t\}_t$ taken from engineering estimates
- Estimate using maximum likelihood: Identification

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

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

Stage 2: Results

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

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

(1): no adjustment after 5 years past 2020

(2): no adjustment after 10 years past 2020

(3): no adjustment after 15 years past 2020

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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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Idiosyncratic costs			
$\hat{\sigma}$ (variance in AU\$)	185.700	184.085	183.181
	(54.845)	(44.229)	(41.091)

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

(1): no adjustment after 5 years past 2020

(2): no adjustment after 10 years past 2020

(3): no adjustment after 15 years past 2020

- 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

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

Model fit

Counterfactuals

Counterfactual Environment

- 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

$$W_t = \mathrm{PS}_t + \mathrm{CS}_t + \mathrm{G}_t - \underbrace{\mathrm{emissions}_t \times SCC}_{\text{emissions cost}} - \underbrace{\mathrm{blackouts}_t \times VOLL}_{\text{blackout cost}}$$

Counterfactual #1: Environmental and Reliability Policy

- **Carbon tax**: tax τ (AU\$ / tonne CO_2-eq) on generator production in proportion to emissions rate r_s (tonne CO_2-eq / MWh)

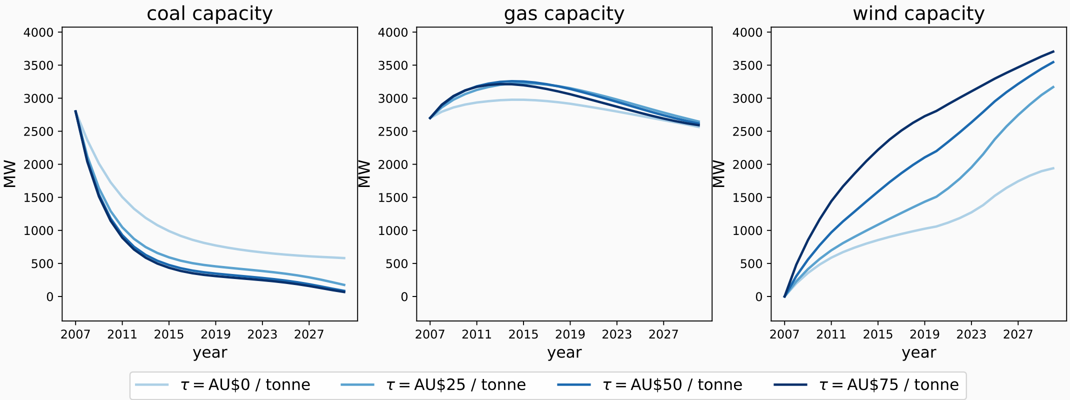
$$c_{g,h}\left(q_{g,h}\right) = \zeta_{1,g,h} q_{g,h} + \zeta_{2,g} \left(\frac{q_{g,h}}{K_g}\right)^2 + \tau r_{s(g)} q_{g,h}$$

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

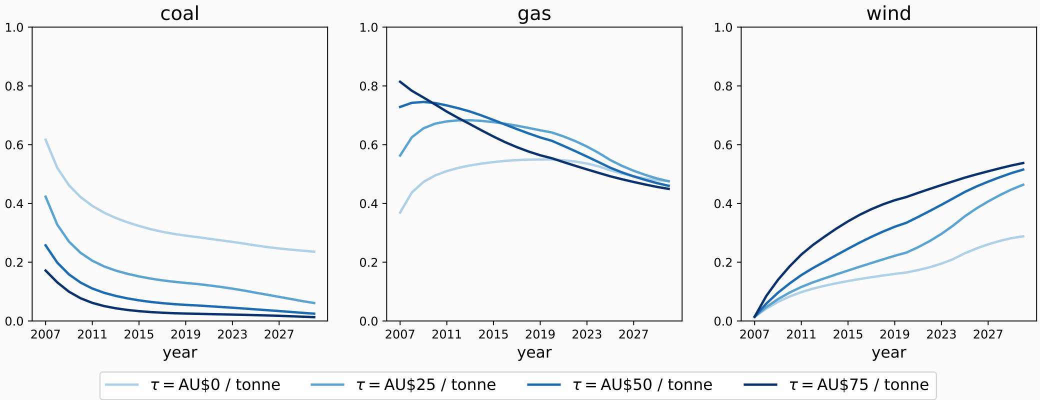
$$\Pi_{f,t}\left(\mathcal{G}_t\right) + \Upsilon_f\left(\mathcal{G}_{f,t}; \kappa\right)$$

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

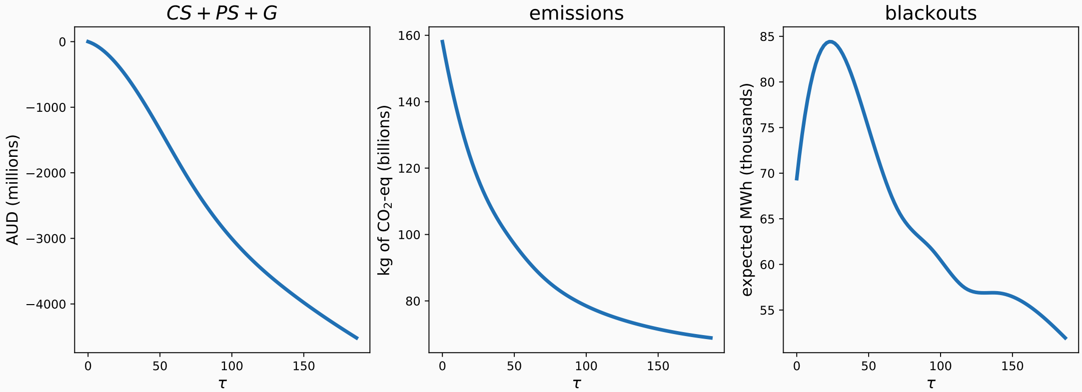
Carbon Tax: Capacity



Carbon Tax: Production Shares

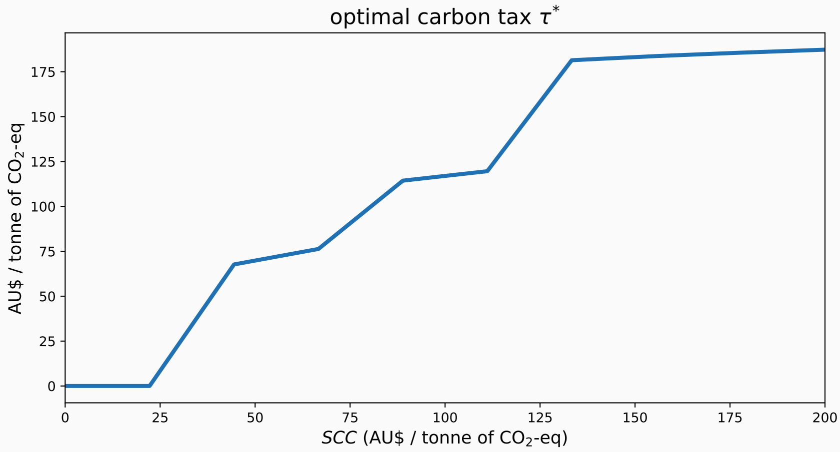


Carbon Tax: Welfare



⏩ Breakdown of CS, PS, G

Carbon Tax: Optimal Policy



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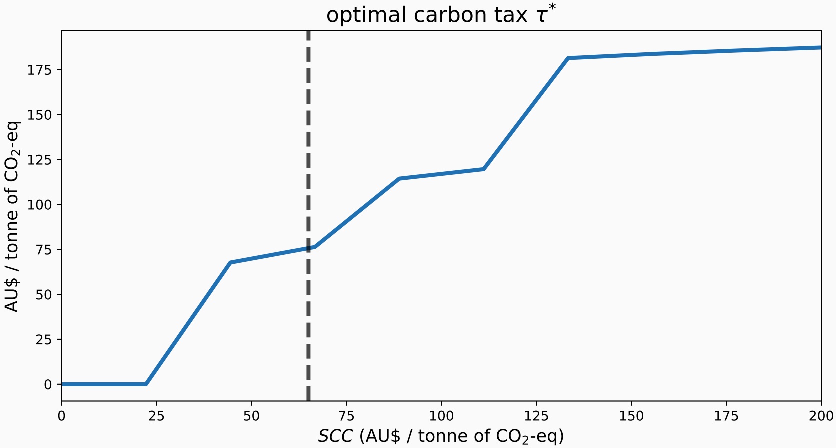
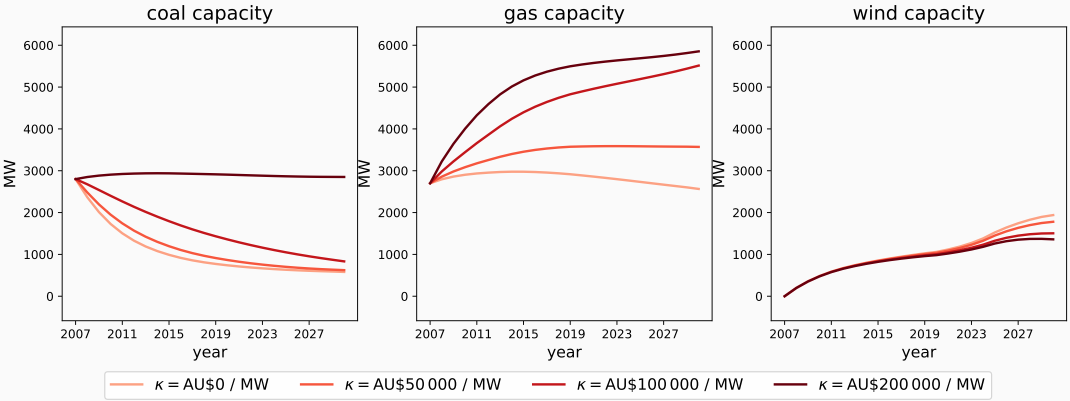


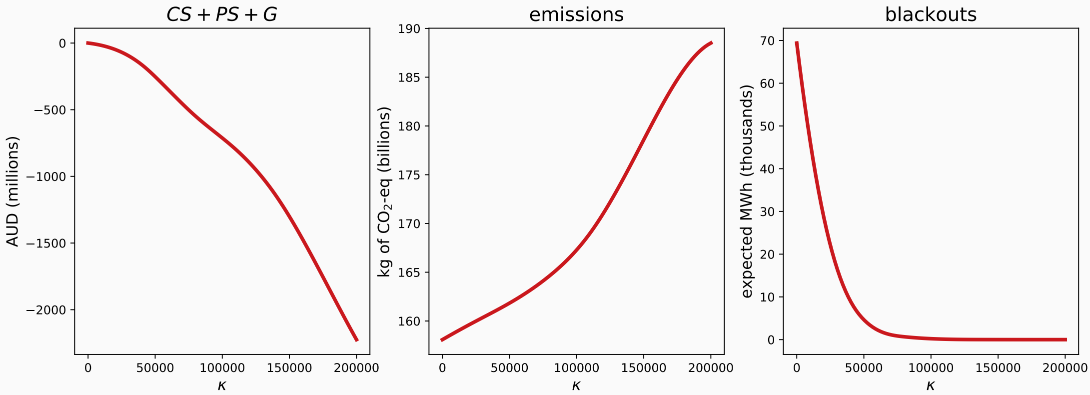
Note: Dashed line represents US government's estimate of *SCC*.

Capacity Payments: Capacity



⏩ Production shares

Capacity Payments: Welfare



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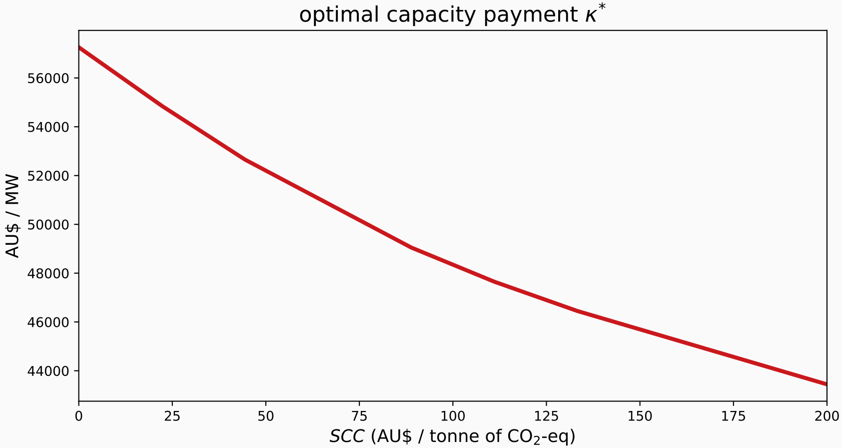

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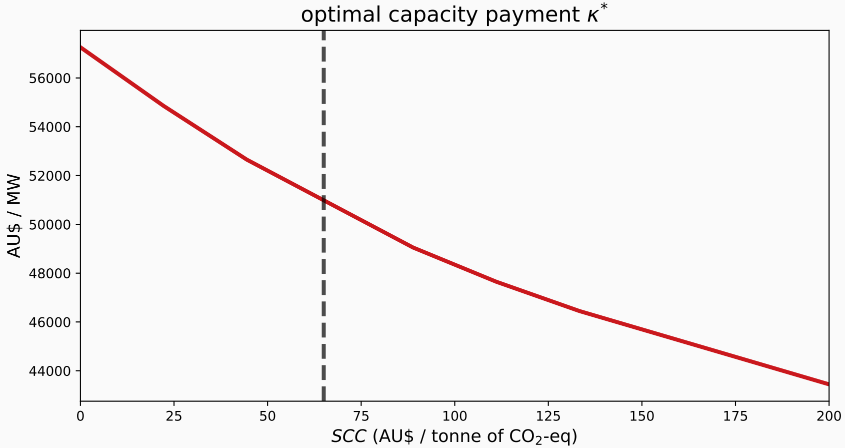

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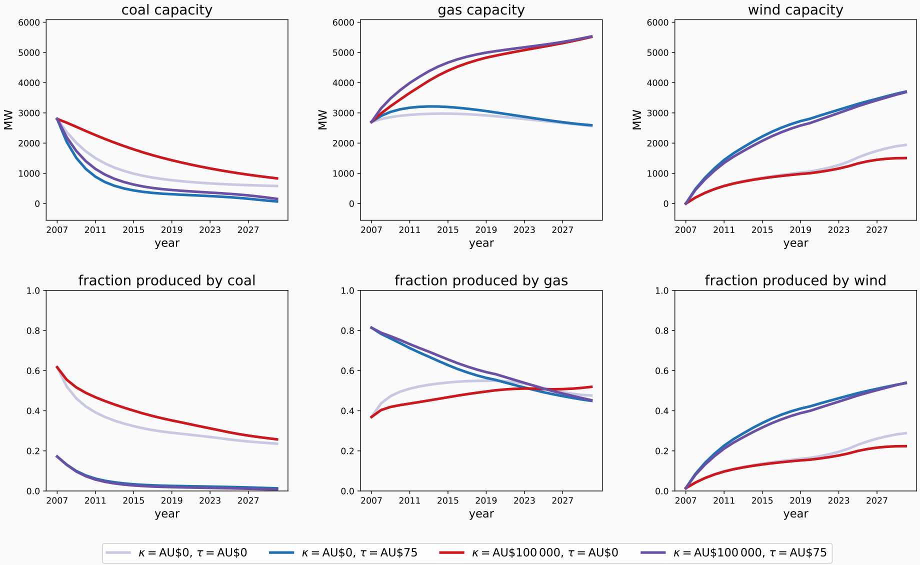
Joint Policies: Capacity and Production



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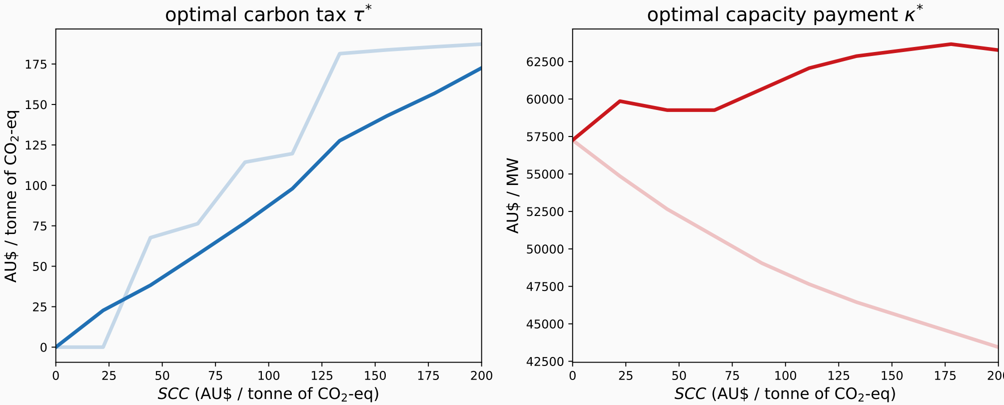
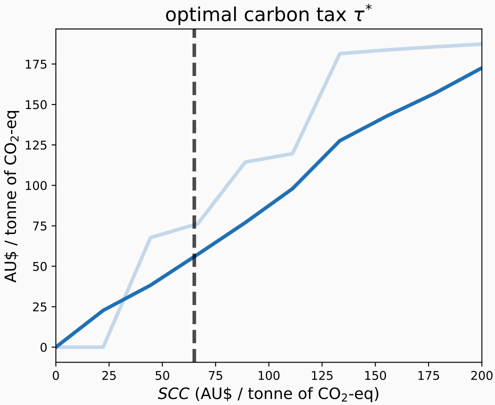
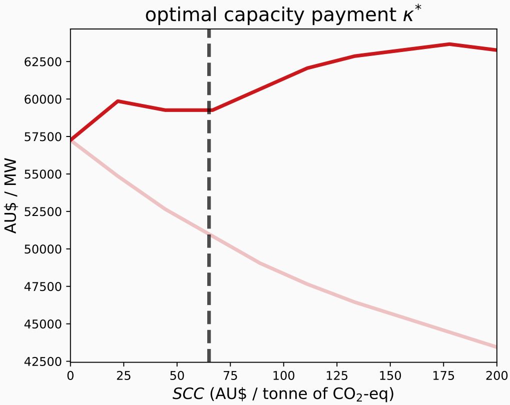


⏩ Changes in welfare
⏩ 2-D function of *SCC* and *VOLL*

Joint Policies: Optimal Policy





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▸▸ Changes in welfare ▸▸ 2-D function of *SCC* and *VOLL*

Additional Counterfactuals

- 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

Additional Counterfactuals

- 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
    - $\downarrow$ production costs $\Rightarrow$ $\downarrow$ wholesale prices
    - $\uparrow$ emissions
  - For most values of SCC, optimal delay is one year

Conclusion

- 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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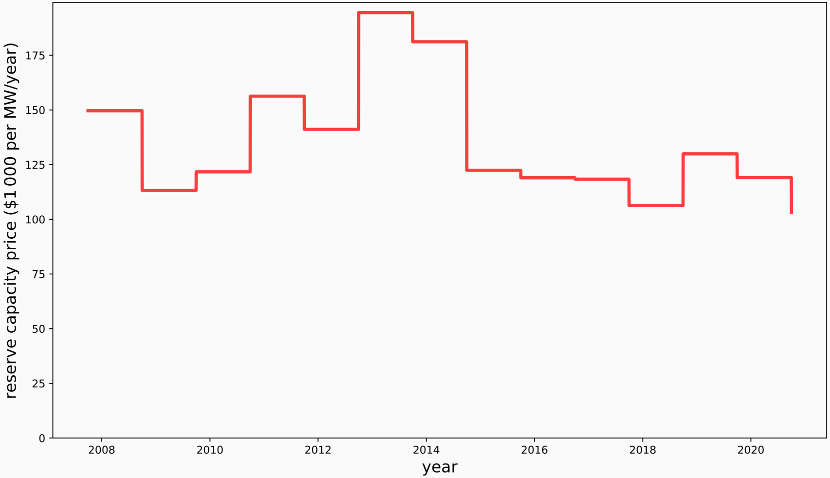
- Goal of payments is to ensure sufficient capacity during peak demand
- Payments are substantial portion of generators' revenues ($\sim$20%)
- Widely used in "restructured" electricity markets throughout the world

Go back

Capacity Payments in Western Australia



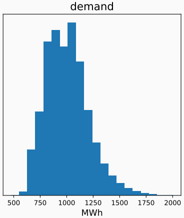
Go back

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

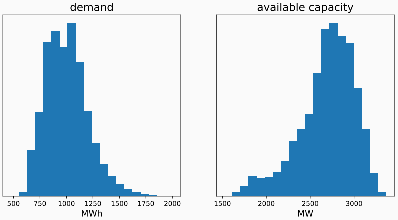
Wholesale Market Data



	demand
demand	1

Go back

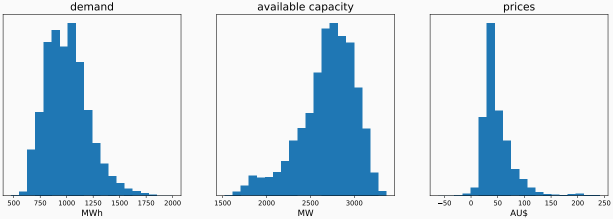
Wholesale Market Data



	demand	available capacity
demand	1	0.26
available capacity		1

Go back

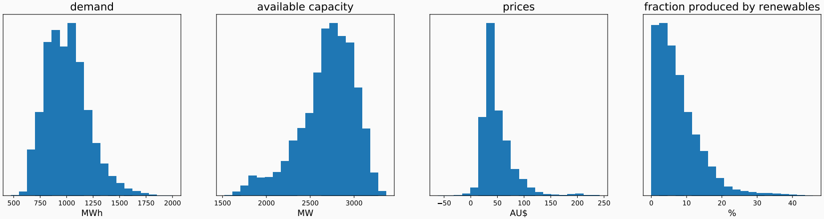
Wholesale Market Data



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

Go back

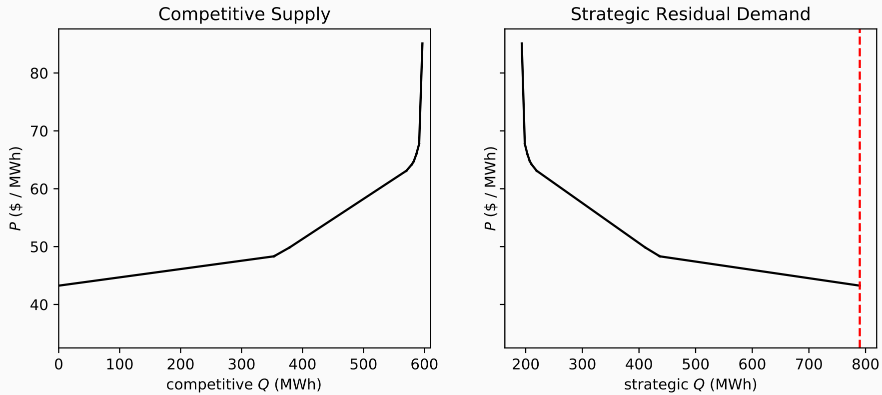
Wholesale Market Data



	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

Go back

Example Competitive Supply / Residual Demand



Go back

Short-run: Wholesale Market Model

- Firm f makes profits

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

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

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

- Stratgic firms choose quantities to maximize profits

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

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

Go back

Non-adjustment Strategic Value Function

- If $f \neq m$:

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

◂ Go back

Non-adjustment Strategic Value Function

- If $f \neq m$:

$$V^{m}_{f,t}(\mathcal{G}) = \quad \mathbb{E}\Big[\Pi_{f,t}(\mathcal{G}')$$

profits

Go back

Non-adjustment Strategic Value Function

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$$
\begin{aligned}
V^m_{f,t}(\mathcal{G}) = \quad & \mathbb{E}\Big[\Pi_{f,t}(\mathcal{G}') && \text{profits} \\
& \quad + \Upsilon_{f,t}(\mathcal{G}'_f) && \text{capacity payment}
\end{aligned}
$$

Go back

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& \quad + \eta_{f,\mathcal{G}'_f,t} && \text{idiosyncratic shock}
\end{aligned}
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Go back

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& \quad + \eta_{f,\mathcal{G}'_f,t} && \text{idiosyncratic shock} \\
& \quad + \beta\mathbb{E}\left[W_{f,t+1}(\mathcal{G}')\right]\Big] && \text{continuation value}
\end{aligned}
$$

Go back

Competitive Fringe Adjustment

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

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

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

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

- 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

Go back

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

Go back

Capacity Payments

- The expected net revenue received from capacity payment is

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

where the penalty formula is given by

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

Go back

Stage 1: Wholesale Market Estimation

- Cost function

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

where

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

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- Three types of generators in an interval h
  1. unconstrained $\mathcal{G}_h^u$
  2. constrained from above $\mathcal{G}_h^+$
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- Three types of generators in an interval h
  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 $f\left(\varepsilon\right) = f^u\left(\varepsilon^u\right) F^{-u|u}\left(\varepsilon^{-u}\middle|\varepsilon^u\right)$

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

Other wholesale variables
Estimation details
Go back

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
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$\hat{\sigma}_{\text{gas}}$	18.652
	(0.491)
$\hat{\rho}_{\text{coal,coal}}$	0.764
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$\hat{\rho}_{\text{gas,gas}}$	0.806
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year	2015
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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
    - 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

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- 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
  - 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., $F^{-u|u}\left(\varepsilon^{-u}\middle|\,\varepsilon^{u}\right)$)
  2. reduces dimension of correlation among shocks in an interval
- Assume
$$\varepsilon_h \sim \mathcal{N}\left(\mathbf{0}, \boldsymbol{\Sigma}_\varepsilon\right)$$
  where correlation varies at the energy-source level

Go back

ε_h^u Inversion Details

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

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

therefore

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

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

Go back

Stage 1: Backing out / Bounding Cost Shocks

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

Go back

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

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

Go back

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

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

Go back

Stage 1: Backing out / Bounding Cost Shocks

- Invert prices and unconstrained quantities to get $\varepsilon^u_h(\beta, \zeta_2)$ ⏩ Details
- Use $\varepsilon^u_h(\beta, \zeta_2)$ to construct strategic firms' (local) residual demand curve

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

- Likelihood

$$\mathcal{L}_h(\beta, \zeta_2, \mathbf{\Sigma}_\varepsilon) = \phi(\varepsilon^u_h) \cdot \Pr\left(\varepsilon^+_h \leq \nu^+_h \text{ and } \varepsilon^-_h \geq \nu^-_h \,\middle|\, \varepsilon^u_h\right)$$

where ν_h is the inversion from above

◀ Go back

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

Go back

Stage 1: Other Variables Details

- Demand and wind capacity factors are allowed to be correlated

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

- Thermal generator capacity factors are binary and distributed

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

Go back

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	
$\hat{p}_{\delta_{\text{coal}}}$	0.987
	(0.001)
$\hat{p}_{\delta_{\text{gas}}}$	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 $\Rightarrow \hat{\Pi}(\cdot)$

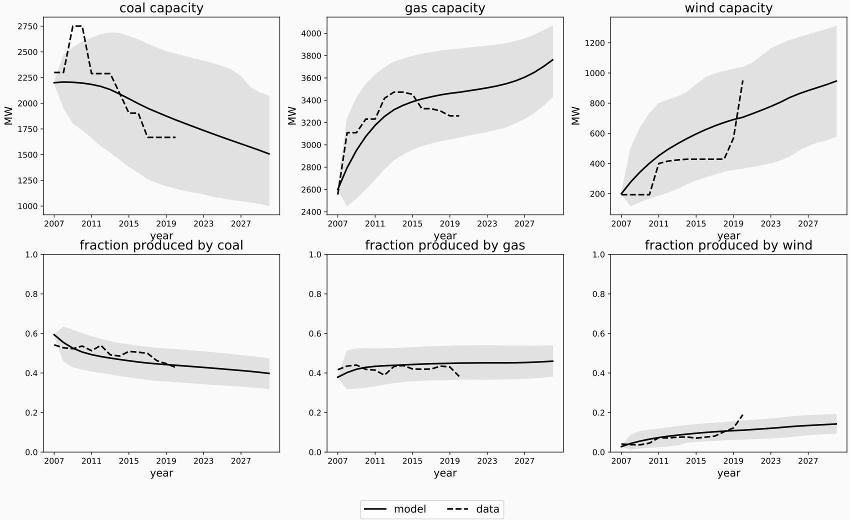
Go back

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

Go back

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.

Go back

Demand

- Measure 1 of consumers with utility in interval h

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

  where P is the *price consumer faces*

- $\bar{Q}_h\left(P\right) = \int_0^1 q^*\left(P, \xi_h\right) di$

  $\log\left(\xi_h\right) \sim \mathcal{N}\left(\mu, \sigma^2\right)$ (possibly correlated with wholesale market variables)

Demand

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  $\log\left(\xi_h\right) \sim \mathcal{N}\left(\mu, \sigma^2\right)$ (possibly correlated with wholesale market variables)

- Constant elasticity of demand: $\frac{d \log \mathbb{E}\left[\bar{Q}_h(P)\right]}{d \log P} = -\varepsilon$

- Price elasticity of demand: -0.09 (Deryugina, MacKay, and Reif (2020))

Demand

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- Price elasticity of demand: -0.09 (Deryugina, MacKay, and Reif (2020))

- Average quantity-weighted wholesale prices $\bar{P}_t$ (price consumers pay)

- In equilibrium, $\bar{P}_t\left(\mathcal{G}\right)$ is implicitly defined by

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

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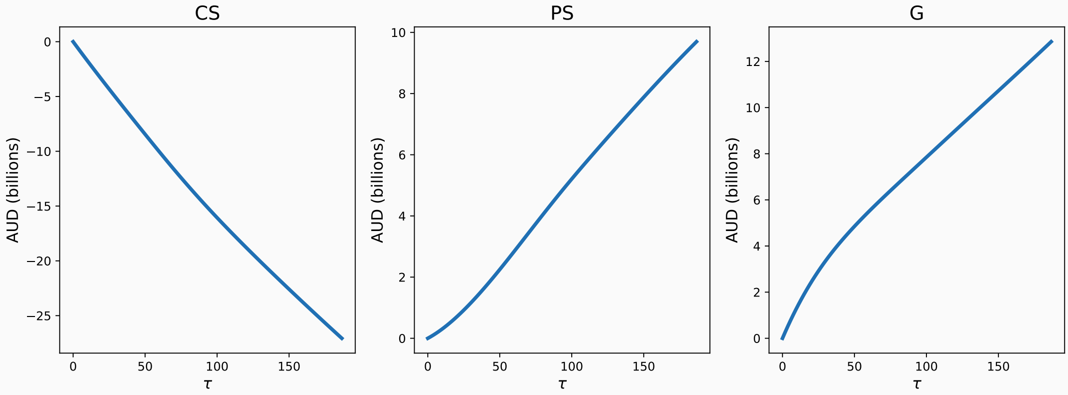
Carbon Tax: Welfare



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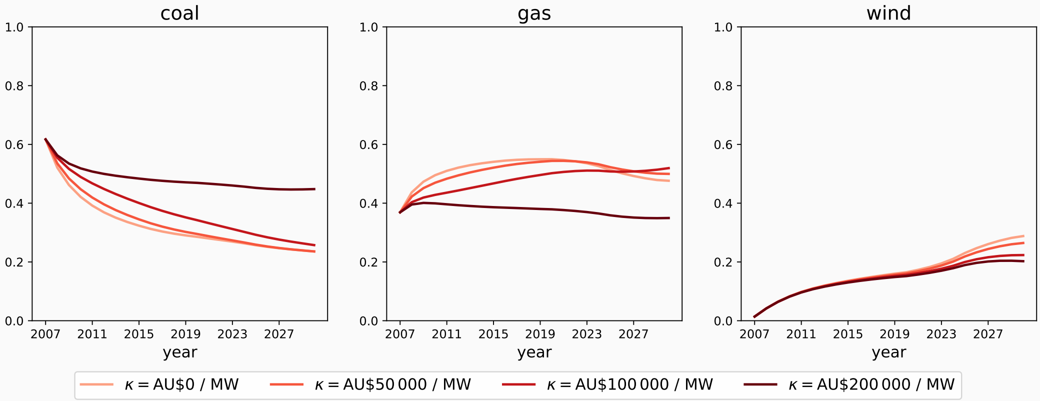
Capacity Payments: Production Shares



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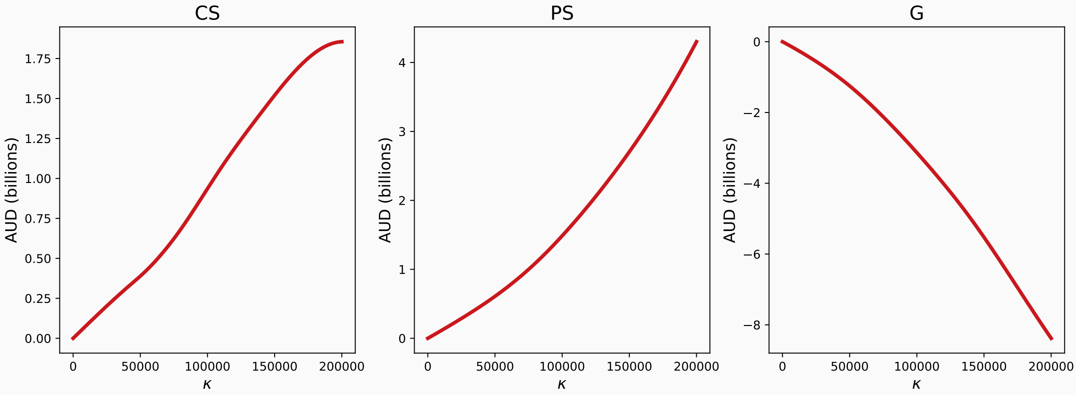
Capacity Payments: Welfare



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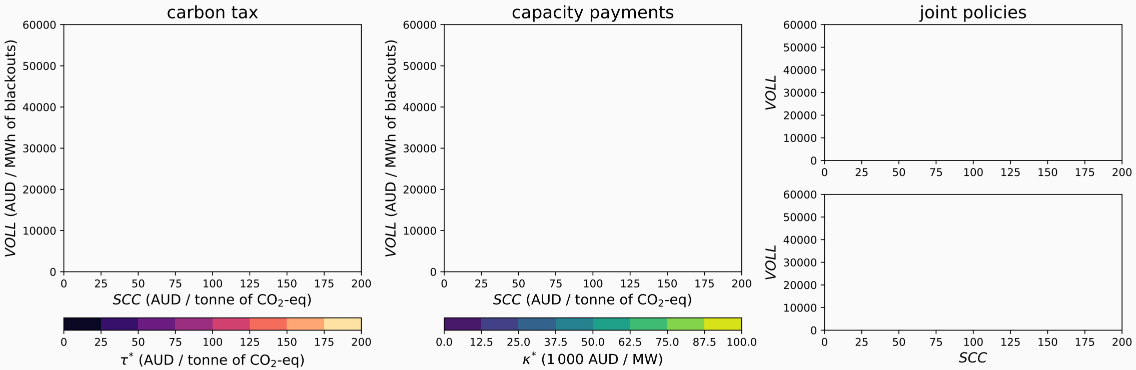
Optimal Policy



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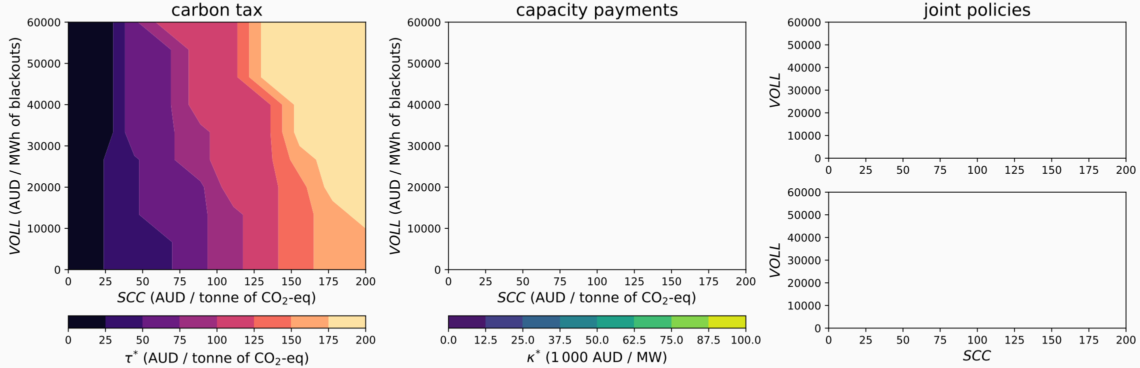
Optimal Policy



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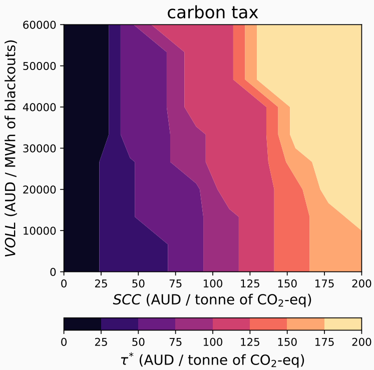
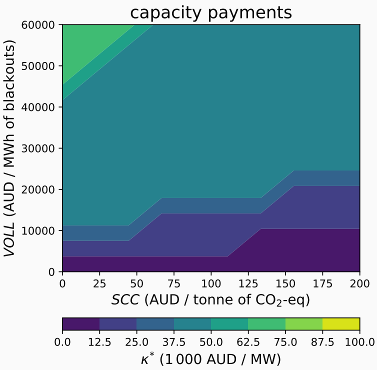
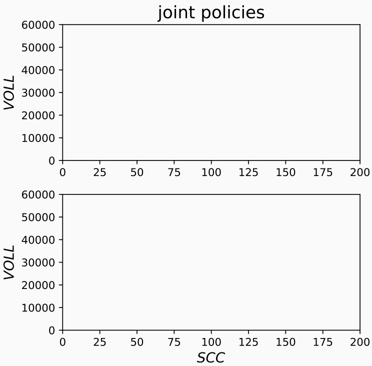
Optimal Policy







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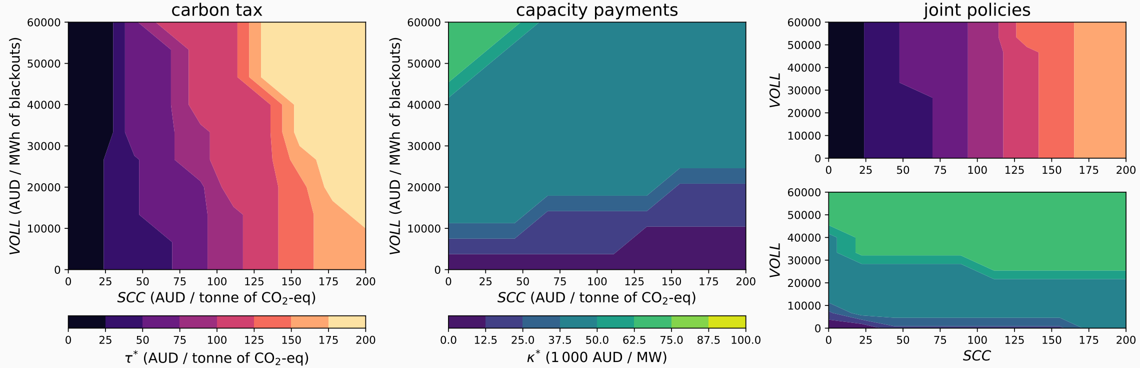
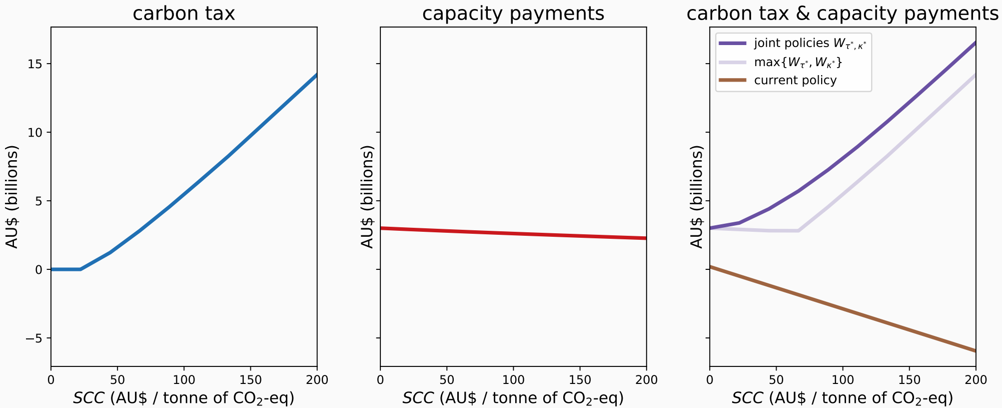
Optimal Policy



◂ Go back

Changes in Welfare from Optimal Policy



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

Welfare by category

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Welfare Impact of Different Policies

τ	κ	ΔCS (billions AUD)	ΔPS (billions AUD)	ΔG (billons 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

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Counterfactual #2: Alternative Environmental Policies

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

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

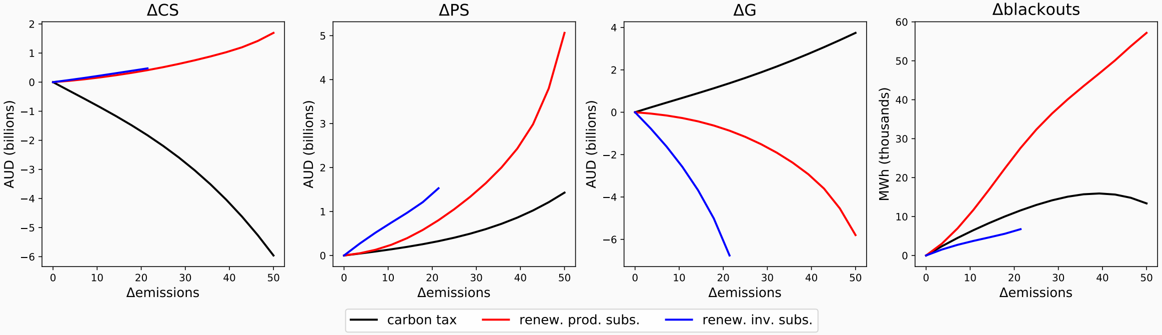
  renewable generators receive ς AU$ per MWh produced

- **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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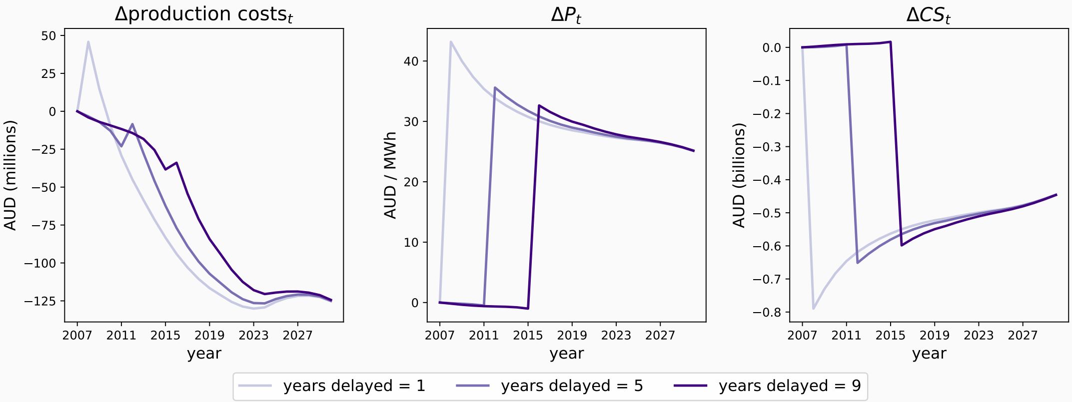
Counterfactual #3: Policy Timing

- 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

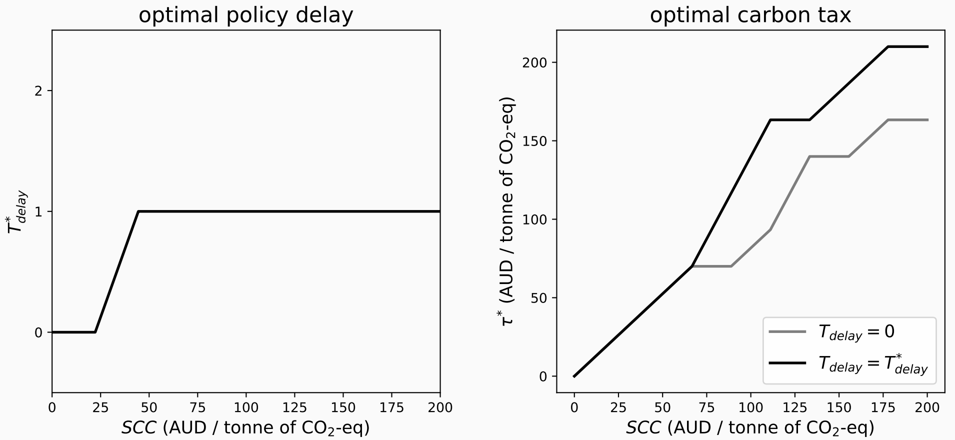
Policy Timing: CS over Time



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

Capacity over time
Welfare

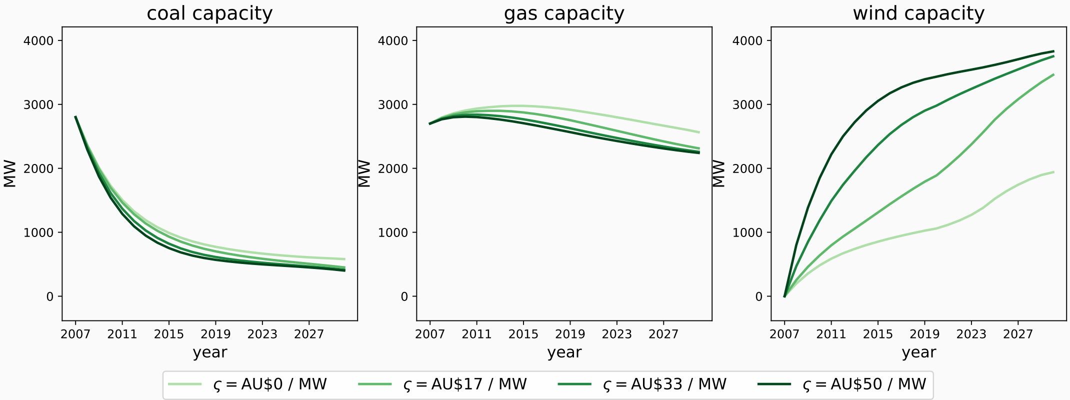
Policy Timing: Optimal Timing



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

◂ Go back

Renewable Production Subsidy: Capacity



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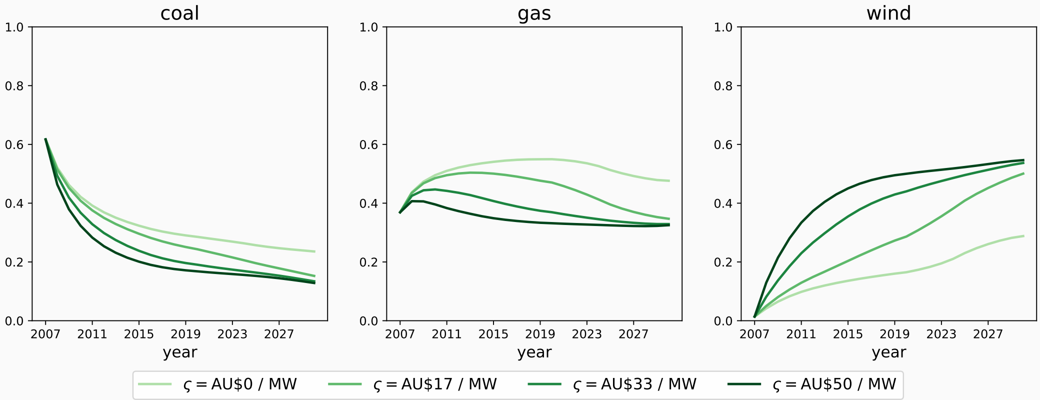
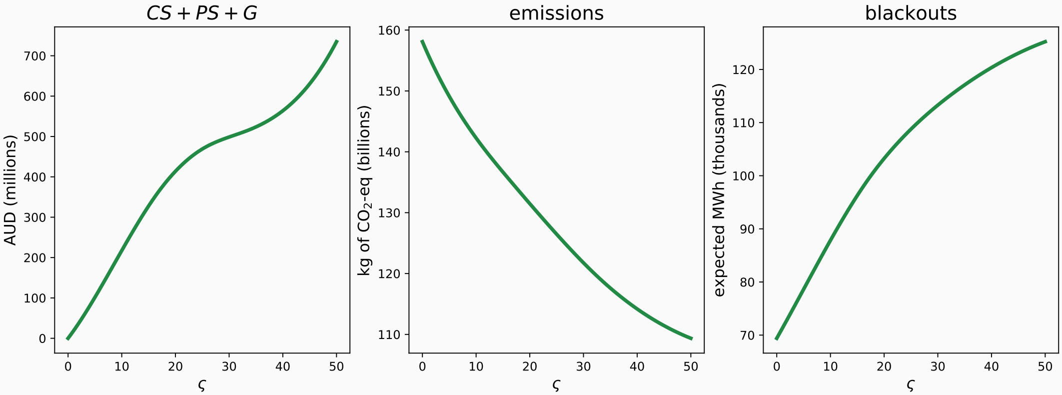
Renewable Production Subsidy: Production Shares



Go back

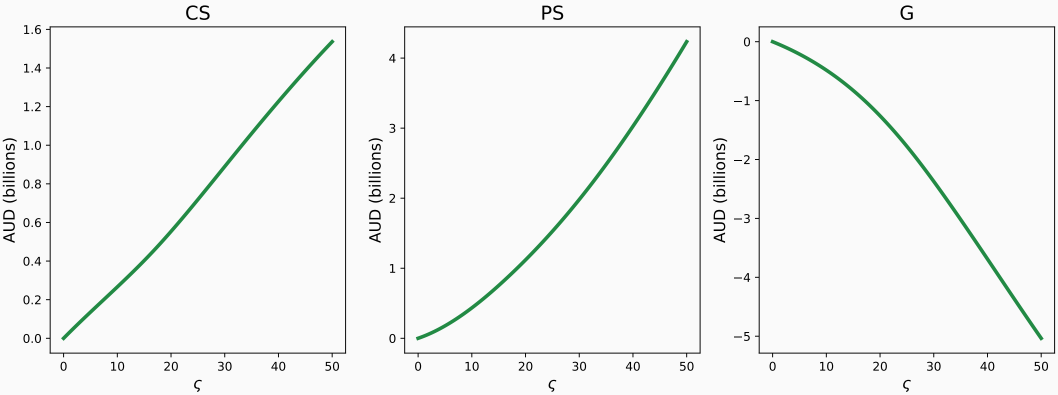
Renewable Production Subsidy: Welfare



Breakdown of CS, PS, G

Go back

Renewable Production Subsidy: Welfare



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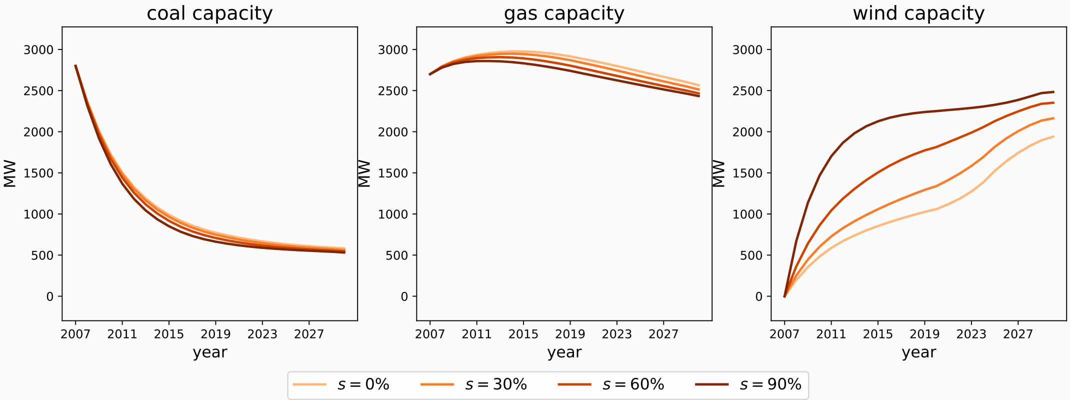
Renewable Investment Subsidy: Capacity



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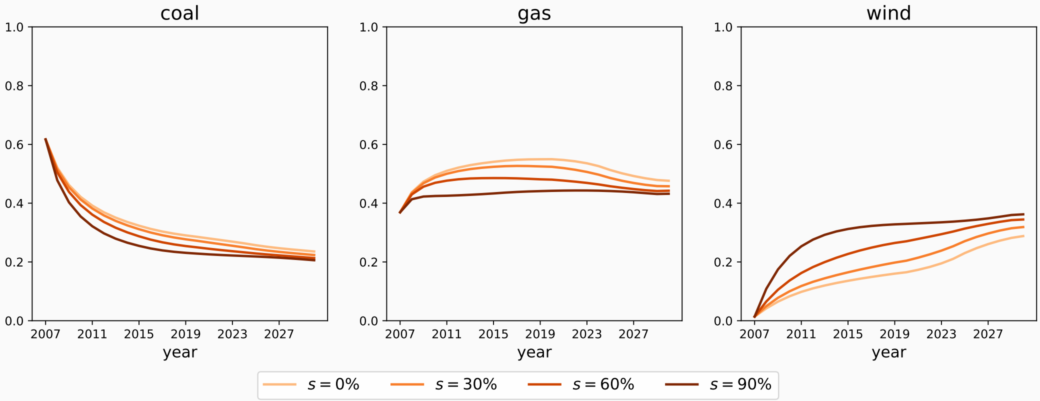
Renewable Investment Subsidy: Production Shares



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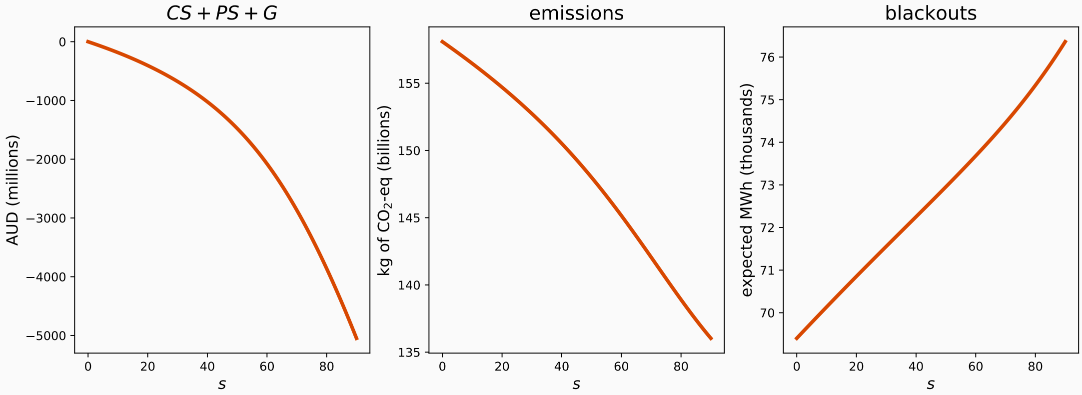
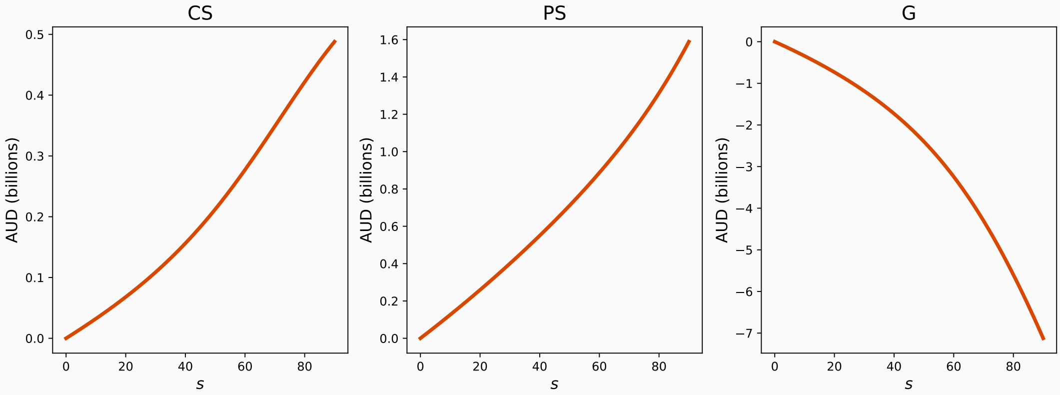
Renewable Investment Subsidy: Welfare



Breakdown of CS, PS, G

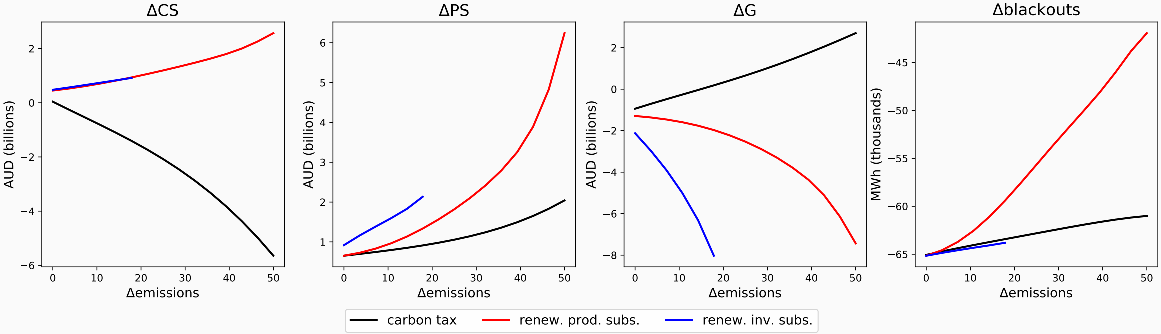
Go back

Renewable Investment Subsidy: Welfare



◂ Go back

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



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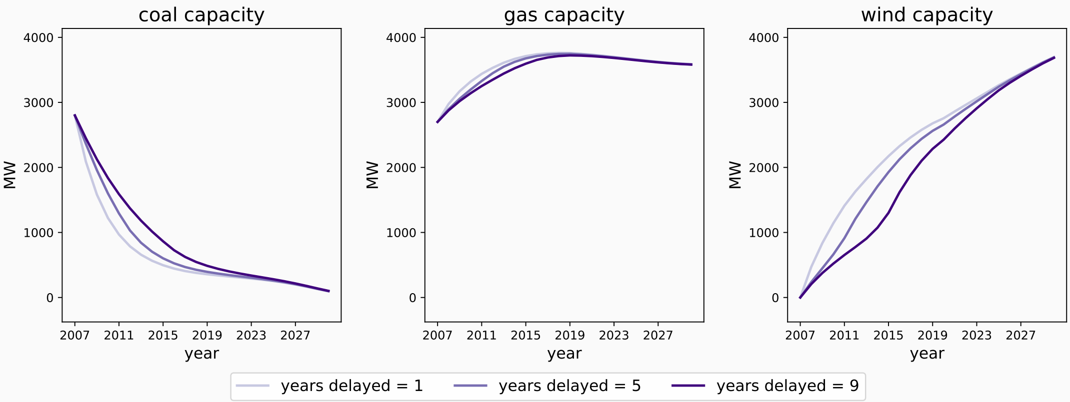
Policy Timing: Capacity



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

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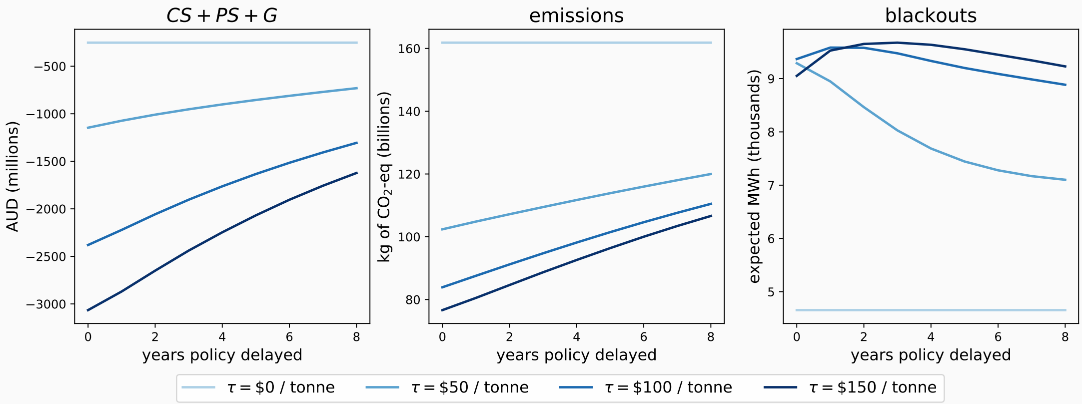
Policy Timing: Welfare



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