Investment, Emissions, and Reliability in Electricity Markets

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NYU Stern IO Seminar

Motivation

- Electricity makes up 25% of global CO_2 emissions (IPCC, 2014) Breakdown by sector
- Blackouts result when demand for electricity exceeds available supply

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- Develop and estimate a structural dynamic oligopoly model that endogenizes:
  - total investment levels
  - production from different sources (e.g., coal, gas, wind)
  - prices
  - probabilities of blackouts
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- Quantify effect of policy tools on emissions, blackouts, & product market welfare and determine optimal regulation

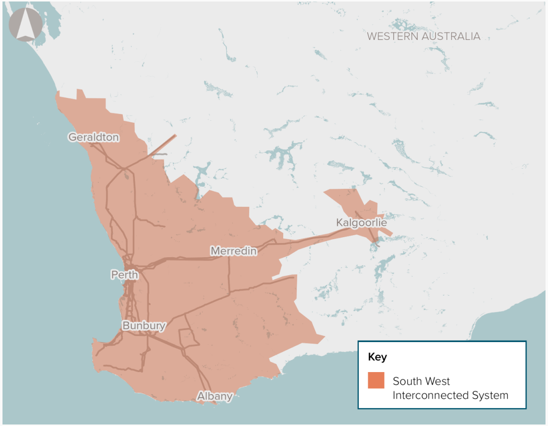
Environmental policies	carbon taxes, renewable subsidies
Reliability policies	capacity payments

Literature

- **Electricity markets**: Reguant (2014), Bushnell et al. (2008), Wolak (2007)
  $\Rightarrow$ endogenous capacity and market power
- **Equilibrium impacts in electricity markets**: Gowrisankaran et al. (2016), Linn and McCormack (2019), Karaduman (2019), Butters et al. (2021)
  $\Rightarrow$ endogenous investment in multiple energy sources, oligopoly
- **Dynamic oligopolistic investment**: Ryan (2012), Fowlie et al. (2016)
  $\Rightarrow$ heterogeneous production technologies, wholesale electricity markets, non-stationary costs
- **Environmental and reliability policy**: Fabra (2018), McRae and Wolak (2020), Joskow and Tirole (2008), Stock and Stuart (2021)
  $\Rightarrow$ policies jointly, equilibrium investment

Institutional Background

- Western Australian Wholesale Electricity Market serves over 1 million customers around the city of Perth, supplies 18 TWh of electricity every year
- Restructured from vertically-integrated monopoly to independent generators selling to grid in 2006
- Geographically isolated (grid unconnected to other markets)
- Three energy sources: coal (2007: 54.2%, 2021: 42.8%), natural gas (2007: 41.7%, 2021: 38.3%), and wind (2007: 4.1%, 2021: 18.9%)
- One firm 53% market share, two others with $> 10\%$


WESTERN AUSTRALIA
Geraldton
Kalgoorlie
Merredin
Perth
Bunbury
Albany
Key
South West Interconnected System

Market Operations

Half-hourly

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

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Yearly

- Each year, grid operator chooses a "capacity price" (\$ / 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 (price $\times$ capacity committed)

Reliability Policy: 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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- **Why use capacity payments?** Positive externality associated with capacity

  inability to ration based on valuation $\Rightarrow$ firms don't receive value to consumers of avoiding blackout

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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

  New England ISO, NYISO, PJM, Western Australia, UK, France, Italy, Colombia

Data

- Wholesale market data
  - prices and quantities produced in each half-hour period
  - generator outages in each half-hour period
- Generator data
  - nameplate capacities
  - energy sources
  - entry / exit dates
- Capacity payment data
  - capacity credit prices
  - capacity credit assignments
- October 2007 – July 2021

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estimate wholesale costs and demand

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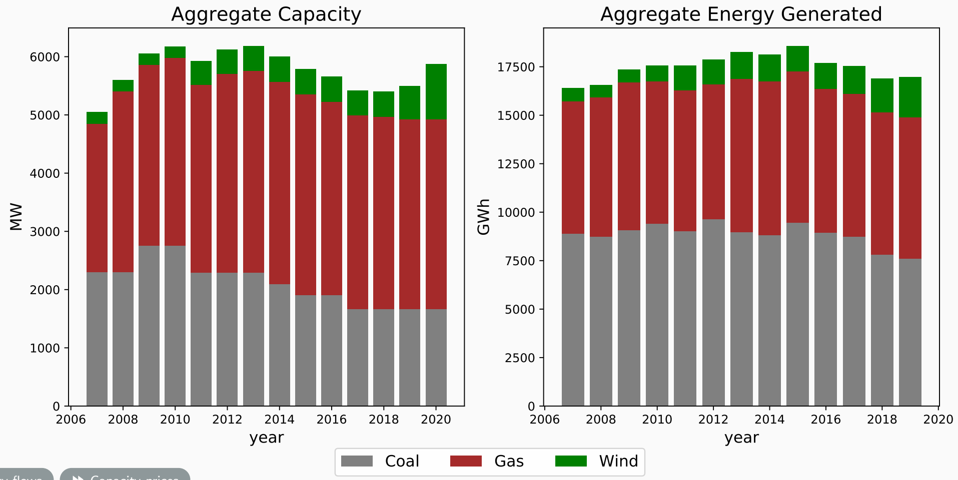

Capacity flows
Capacity prices

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 $\bar{P}_{\mathcal{G}}$

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

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 cost functions $\mathbf{c}_h(\cdot)$
- Strategic firms play a Cournot game in quantities, constrained by their production capacities in that interval

Modeling choices Details

Short-run: Wholesale Market Outcomes

- Over year we get
  - firms' profits $\mathbf{\Pi}_t$

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

  - blackout frequency Ψ_t

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

  - average wholesale prices $\bar{P}_t$

$$\bar{P}_t\left(\mathcal{G}_t\right)=\mathbb{E}\left[P_h\left(\mathbf{q}_h\left(\mathcal{G}_t\right)\right)\right]$$

Long-run: Modeling Choices

- Over the long-run, firms invest and dis-invest in generators in dynamic game

  generator levels affect competition, distribution of demand, and production costs

- A few requirements of the dynamic game: needs to...

  Theoretical: handle non-stationarity
  Computational: be computationally tractable
  Empirical: yield unique equilibrium to do full-solution approach

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- **Solution**: finite game + sequential moves (Igami and Uetake 2020)

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

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

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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Details

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 $\mathcal{G}_T$

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

Non-adjustment value function | Competitive fringe adjustment

Model Summary

- **Short-run**: Each interval, firms enter with generators and inelastic demand, choose quantities to maximize profits

$$\Rightarrow \pi_h\left(\mathcal{G}\right)$$

- **Long-run**: Each year, firms adjust generators $\mathcal{G}$ to maximize long-run present-discounted profits, and demand responds:

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

where $\bar{P}\left(\mathcal{G}\right)$ is implicitly defined by

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

Estimation

Model Estimation

- Two stages
  1. Estimate distribution of wholesale market variables
     - ▷ cost, capacity factor, and demand joint distribution
  2. Take estimated cost distribution to solve for $\hat{\Pi}(\mathcal{G})$ and solve for dynamic parameters
     - ▷ sunk costs, maintenance costs, idiosyncratic shock distribution

Stage 1: Wholesale Market Estimation

- Cost function

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

where

$$\zeta_{1,g,h} = \boldsymbol{\beta}'_{s(g)} \mathbf{x}_{g,h} + \varepsilon_{g,h}$$

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- Three types of generators in an interval h
  1. unconstrained $\mathcal{G}_h^u$
  2. constrained from above $\mathcal{G}_h^+$
  3. constrained from below $\mathcal{G}_h^-$

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

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 quantities
  - 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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  - 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

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

where correlation varies at the energy-source level

Estimation details

Stage 1: Results

	(1)	(2)
Capacity utilization costs		
$\hat{\zeta}_{2,\text{coal}}$	6 354.212	893.452
	(899.311)	(73.900)
$\hat{\zeta}_{2,\text{gas}}$	775.830	206.966
	(63.720)	(30.963)
Deterministic components of ζ_1		
$\hat{\beta}_{0,\text{coal}}$	−69.746	21.831
	(11.945)	(1.523)
$\hat{\beta}_{0,\text{gas}}$	17.339	32.648
	(2.367)	(1.025)
Cost shock components of ζ_1		
$\hat{\sigma}_{\text{coal}}$	71.767	18.334
	(8.995)	(0.460)
$\hat{\sigma}_{\text{gas}}$	44.966	18.652
	(1.428)	(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	2015
num. obs.	2 500	2 500

(1): no correlation in cost shocks

(2): allow correlation in cost shocks

Estimates of other variables

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- using high fraction of capacity more expensive for coal than for gas ($893 vs $206)

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

▶▶ Estimates of other variables

Stage 2: Dynamic Parameter Estimation

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

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

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

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

Stage 2: Results

	(1) $T_{add} = 5$	(2) $T_{add} = 10$	(3) $T_{add} = 15$
Maintenance costs			
$\hat{M}_{\text{coal}}$	0.055	0.057	0.058
	(0.008)	(0.007)	(0.007)
$\hat{M}_{\text{gas}}$	0.021	0.017	0.016
	(0.029)	(0.030)	(0.030)
$\hat{M}_{\text{wind}}$	0.071	0.081	0.086
	(0.025)	(0.048)	(0.055)
Idiosyncratic costs			
$\hat{\sigma}$	185.700	184.085	183.181
	(54.845)	(44.229)	(41.091)

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

(1): no adjustment after 5 years past T_{data}

(2): no adjustment after 10 years past T_{data}

(2): no adjustment after 15 years past T_{data}

Model fit

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- Maintenance costs very close to engineering estimates

	estimate	**engineering**
coal	$57 000	$55 000
gas	$17 000	$10 000
wind	$81 000	$40 000

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coal	\$57 000	\$55 000
gas	\$17 000	\$10 000
wind	\$81 000	\$40 000

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

Model fit

Counterfactuals

Counterfactual Environment

- 3 strategic firms: (Coal, Gas), (Gas, Wind), (Coal, Wind) + competitive fringe
- Begin in 2007 with same state as in data in 2007
- Price elasticity of demand: -0.09 (Deryugina, MacKay, and Reif (2020)) Demand details

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  1. environmental and reliability policy: carbon tax & capacity payments
  2. alternative environmental policies
  3. policy timing

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- **Three counterfactuals**:
  1. environmental and reliability policy: carbon tax & capacity payments
  2. alternative environmental policies
  3. policy timing
- Welfare from policy P to P': $\mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \Delta^{P\to P'} W_t\right]$, where

$$
\begin{aligned}
\Delta^{P\to P'} W_t = \quad & \Delta^{P\to P'} \text{PS}_t && \text{producer surplus} \\
+ \quad & \Delta^{P\to P'} \text{CS}_t && \text{consumer surplus} \\
+ \quad & \Delta^{P\to P'} \text{G}_t && \text{government revenue} \\
- \quad & \Delta^{P\to P'} \text{emissions}_t \times SCC && \text{environmental cost} \\
- \quad & \Delta^{P\to P'} \text{blackouts}_t \times VOLL && \text{blackout cost}
\end{aligned}
$$

Counterfactual #1: Environmental and Reliability Policy

- **Carbon tax**: tax τ (AUD / kg CO_2-eq) on generator production in proportion to emissions rate r_s (kg CO_2-eq / MWh)

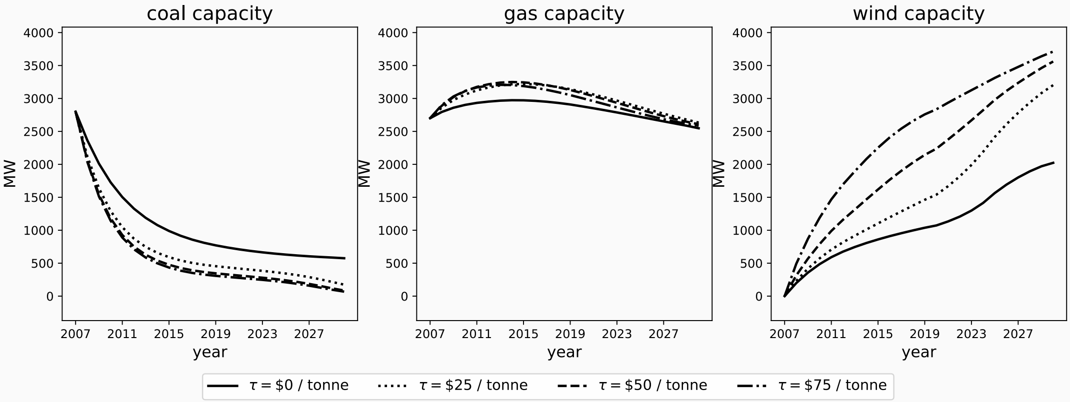
$$c_{g,h}\left(q_{g,h}\right) = \zeta_{1,g,h} q_{g,h} + \zeta_{2,g}\left(\frac{q_{g,h}}{K_g}\right)^2 + \tau r_{s(g)} q_{g,h}$$

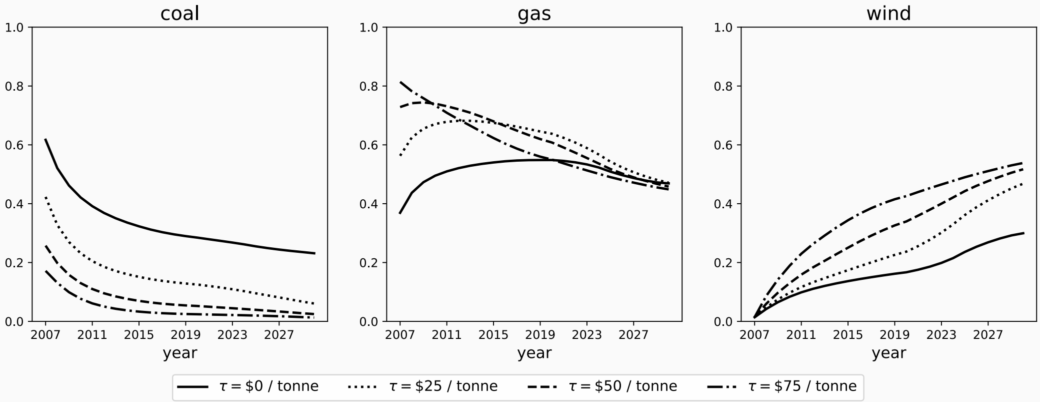
- **Capacity payment**: payment κ (AUD / MW)

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

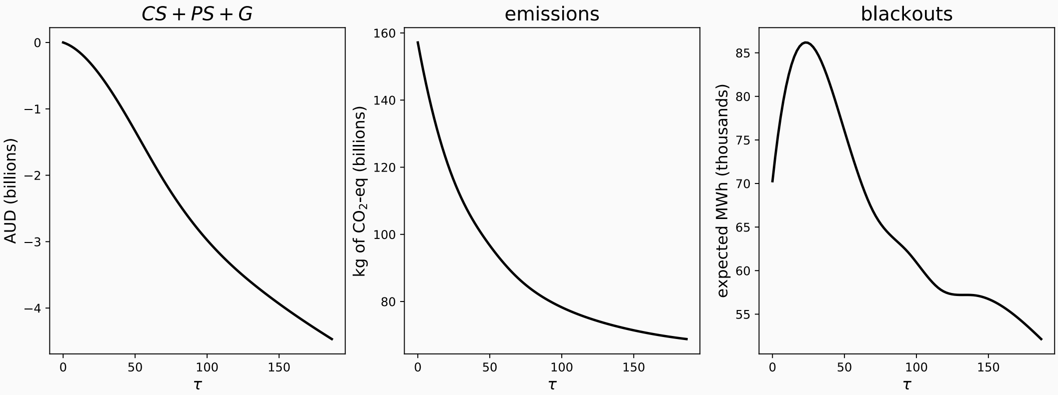
- How do these policies impact production and investment?
- What is the optimal policy in isolation? Jointly?

Carbon Tax: Capacity



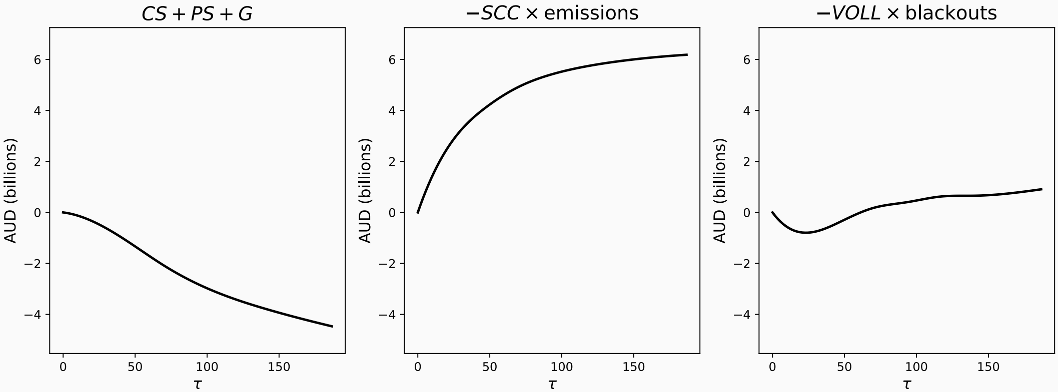

coal
gas
wind
1.0
0.8
0.6
0.4
0.2
0.0
2007
2011
2015
2019
2023
2027
year
$\tau = \$0$ / tonne
$\tau = \$25$ / tonne
$\tau = \$50$ / tonne
$\tau = \$75$ / tonne

Carbon Tax: Welfare



Breakdown of CS, PS, G

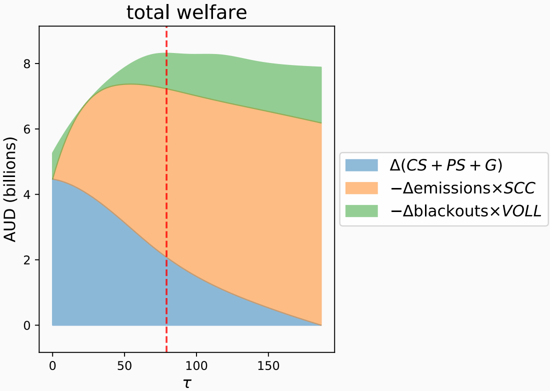
Carbon Tax: Welfare



$VOLL$ set to 50 000 AUD / MW (WEM estimate), SCC set to 70 AUD / tonne.

▶▶ Breakdown of CS, PS, G

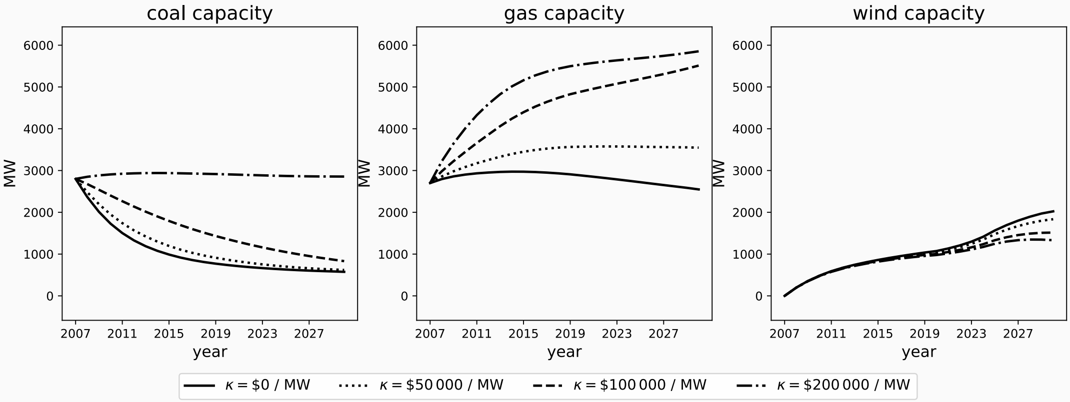
Carbon Tax: Welfare



VOLL set to 50 000 AUD / MW (WEM estimate), *SCC* set to 70 AUD / tonne.

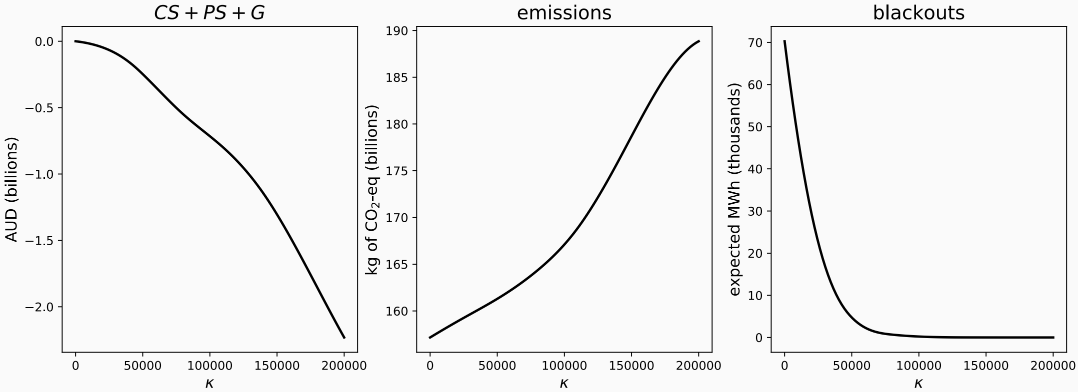
⏩ Breakdown of CS, PS, G

Capacity Payments: Capacity



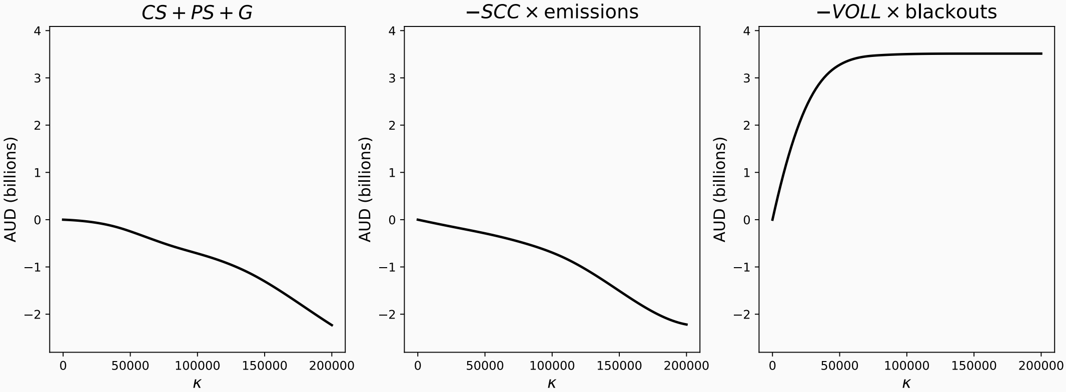
Production shares

Capacity Payments: Welfare



Breakdown of CS, PS, G

Capacity Payments: Welfare



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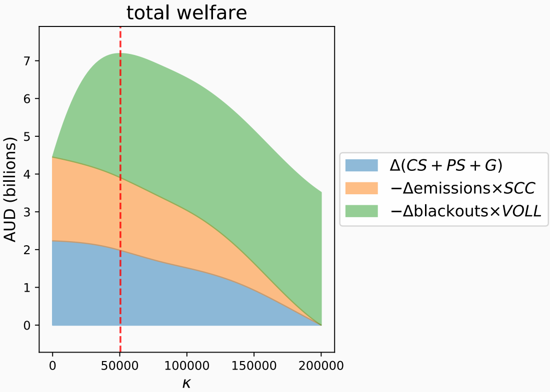
Capacity Payments: Welfare



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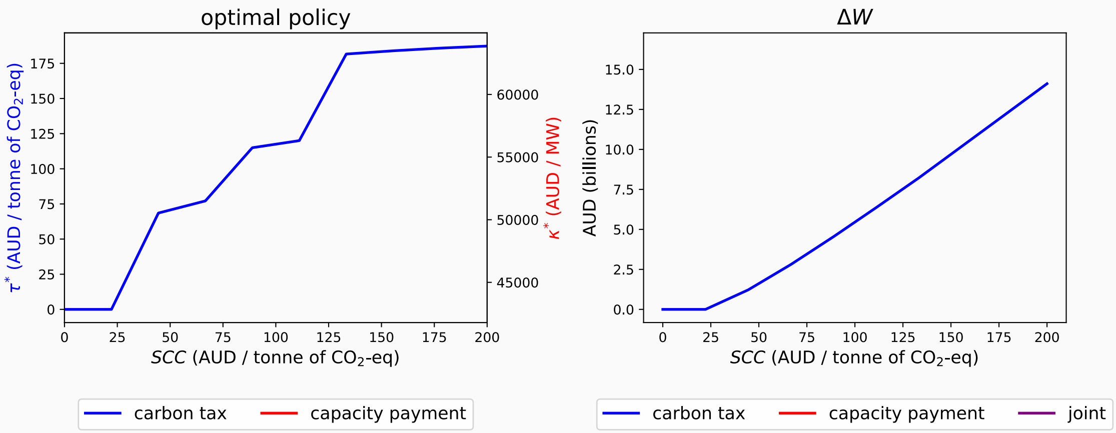
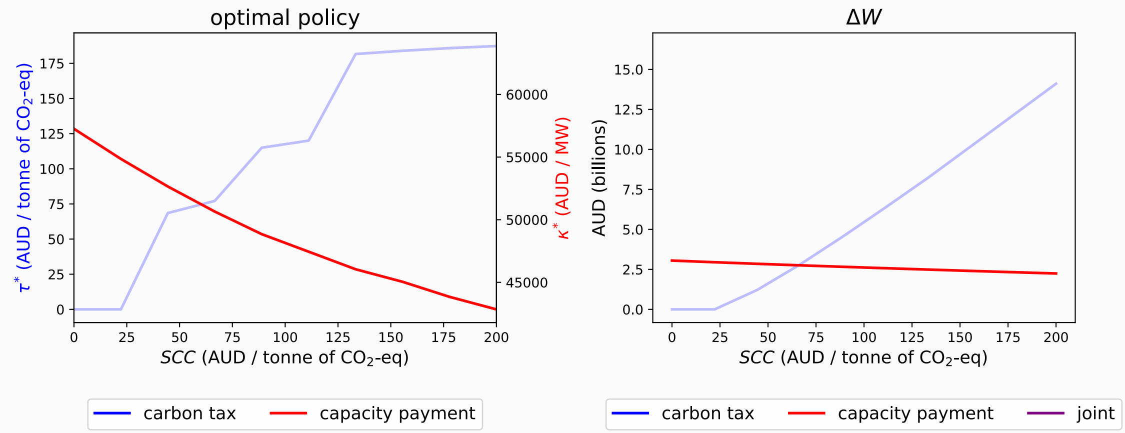
Breakdown of CS, PS, G



Note: *VOLL* set to 50 000 AUD / MW (WEM estimate) ⏩ 2-D function of *SCC* and *VOLL*

⏩ Compare to W. Australia's policy

Optimal Policy



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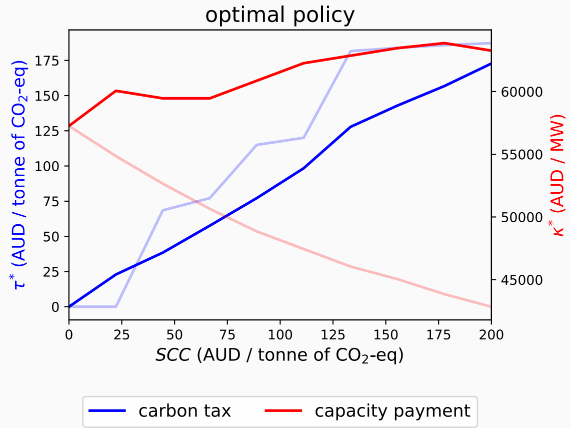
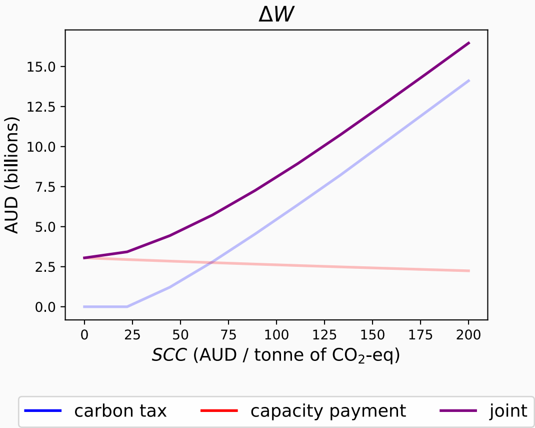




Note: *VOLL* set to 50 000 AUD / MW (WEM estimate) ⏩ 2-D function of *SCC* and *VOLL*

⏩ Compare to W. Australia's policy

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 AUD 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

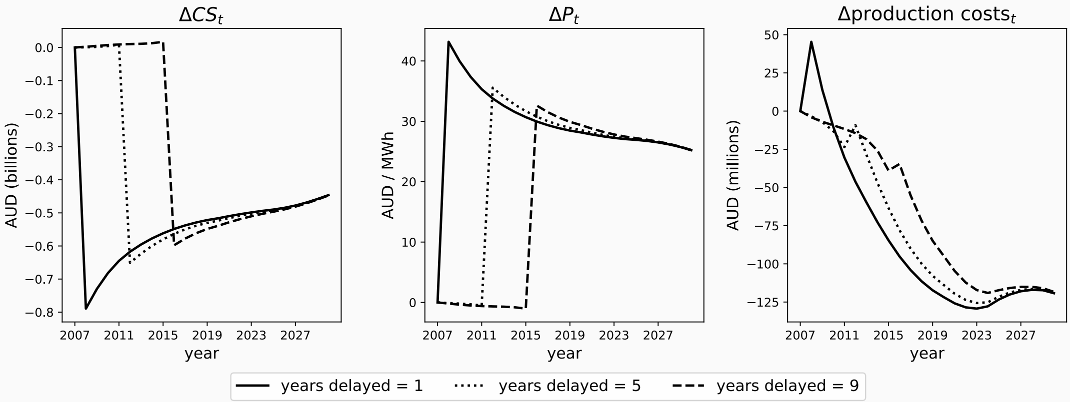
	ΔW w/o cap. pay. (billion AUD)	ΔW w/ cap. pay. (billion AUD)	ΔCS (billion AUD)	ΔPS (billion AUD)	ΔG (billion AUD)	Δemissions (billion kg CO_2)	Δblackouts (thousand MWh)
carbon tax	8.81	11.18	-27.07	9.76	12.85	-88.34	-18.12
renew. prod. subs.	4.72	10.46	1.53	4.29	-5.05	-48.01	55.35
renew. inv. subs.	0.01	2.53	0.03	0.13	-0.35	-1.64	0.74

⏩ Distortions as function of Δemissions

Counterfactual #3: Policy Timing

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

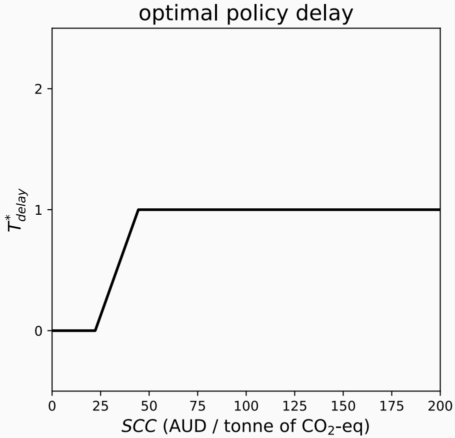
Policy Timing: CS over Time

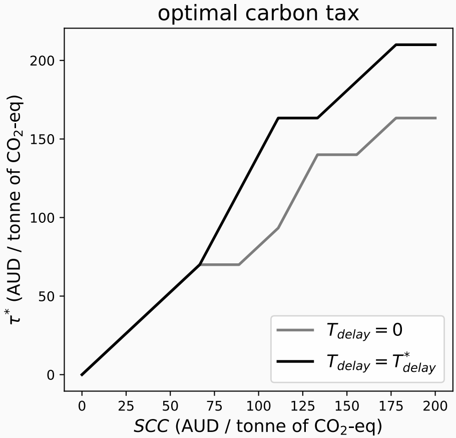


Note: $\tau = 70$, $\kappa = 50\,000$

▸▸ Capacity over time ▸▸ Welfare

Policy Timing: Optimal Timing



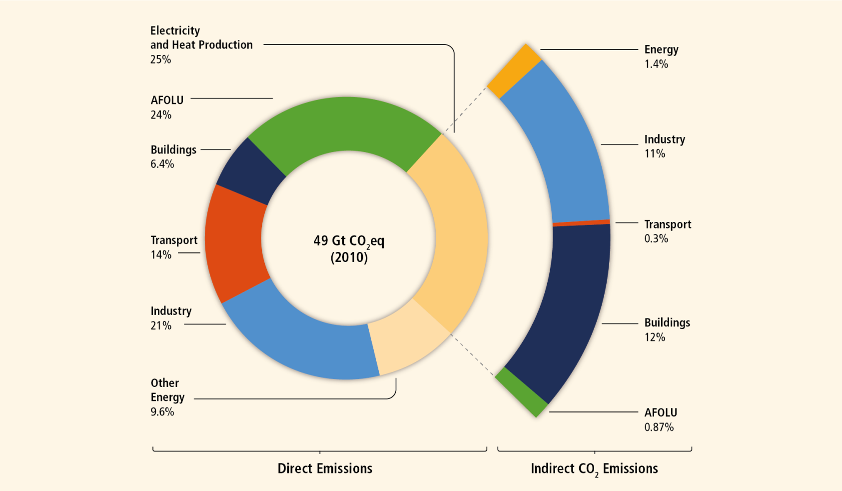


Note: *VOLL* set to 50 000 AUD / MW (WEM estimate)

Conclusion

- Develop and estimate a model of equilibrium, oligopolistic investment in electricity markets
- Capacity payments without accompanying environmental policies substantially increase emissions
    - but capacity payments don't need to be that high to make prob. of blackout ≈ 0
- Carbon taxes effectively reduce emissions but at cost to CS + PS + G
- Carbon tax + capacity payment reduces blackouts and emissions
- Other renewable subsidies not as effective at reducing emissions but lower cost to consumers
- No evidence of it being optimal to wait long time to implement environmental policy

Global Emissions



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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

Prices and Quantities Over Time

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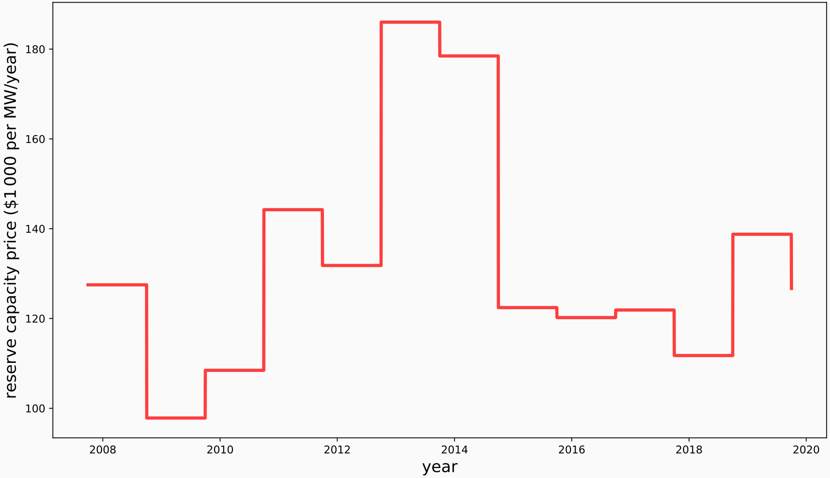
Capacity Price



◂ Go back

Capacity Price

By energy type

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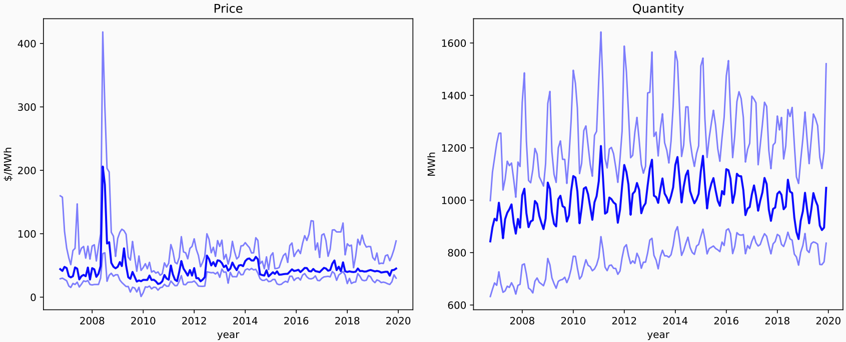
Wholesale Market Data



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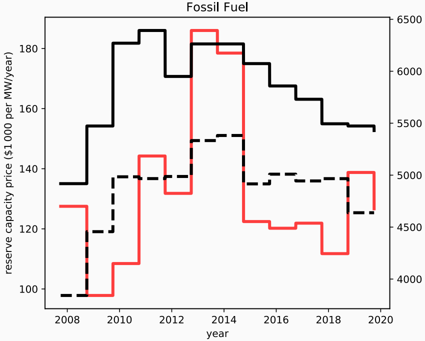
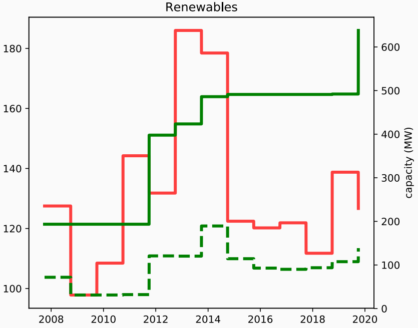
Capacity Price





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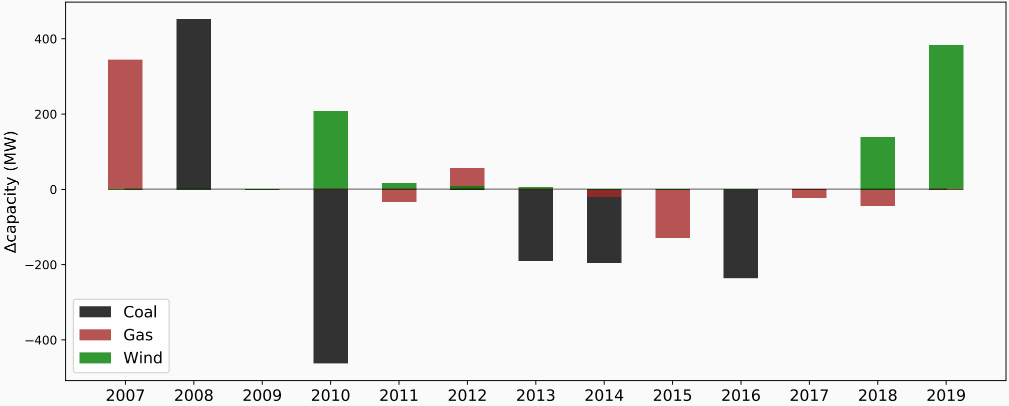
Capacity Evolution



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Why Cournot?

- Supply function equilibrium is neither easy to compute nor unique

  we need to compute over 100 billion equilibria

  we would need to select equilibria in very different states of the world than currently observed

- Supply function equilibrium is bounded between competitive equilibrium and the Cournot equilibrium

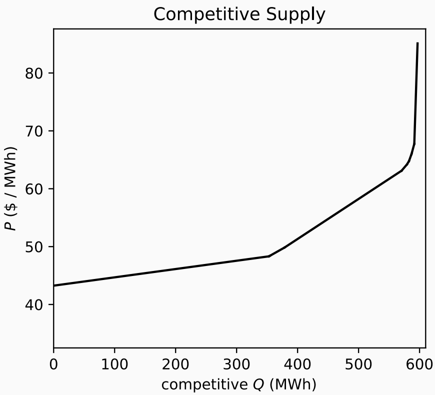
  so we know which direction bias goes in

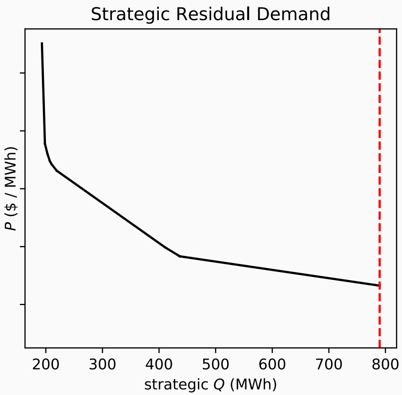
- Bushnell, Mansur, and Saravia (2008) show that the California electricity market does not diverge greatly from Cournot equilibrium

- For tractability, ignore short-run dynamic considerations (e.g. ramp-up costs)

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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- Competitive fringe takes prices as given $\Rightarrow Q_{c,h}\left(P_h\right)$

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- Competitive fringe takes prices as given $\Rightarrow Q_{c,h}\left(P_h\right)$
- 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

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

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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 $f \neq m$ and $f \neq c$:

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

Go back

Non-adjustment Strategic Value Function

- If $f \neq m$ and $f \neq c$:

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

profits

Go back

Non-adjustment Strategic Value Function

- If $f \neq m$ and $f \neq c$:

$$V^{m}_{f,t}(\mathcal{G}) = \mathbb{E}\Big[\Pi_{f,t}(\mathcal{G}') \qquad \text{profits}$$
$$+ \Upsilon_{f,t}(\mathcal{G}'_f) \qquad \text{capacity payment}$$

Go back

Non-adjustment Strategic Value Function

- If $f \neq m$ and $f \neq c$:

$$
\begin{aligned}
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& \quad + \varepsilon_{f,\mathcal{G}'_f,t} && \text{idiosyncratic shock}
\end{aligned}
$$

Go back

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

◂ 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

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

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

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

- 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

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

ε_h^u Inversion Details

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

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

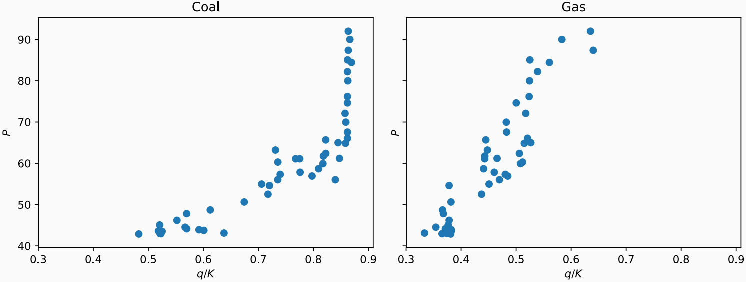
  therefore

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

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

Go back

Stage 1: Cost Shock Identification



Go back

Stage 1: Backing out / Bounding Cost Shocks

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

Other wholesale variables

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

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

⏩ Other wholesale variables

◀ 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

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

Other wholesale variables

Go back

Stage 1: Backing out / Bounding Cost Shocks

- Invert prices and unconstrained quantities to get $\boldsymbol{\varepsilon}_h^u(\boldsymbol{\beta}, \zeta_2)$ Details
- Use $\boldsymbol{\varepsilon}_h^u(\boldsymbol{\beta}, \zeta_2)$ to construct strategic firms' (local) residual demand curve

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

- Likelihood

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

where $\boldsymbol{\eta}_h$ is the inversion from above

Other wholesale variables

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

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

- 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)

	(1)	(2)
Demand distribution		
$\hat{\text{const}}_{\log(\bar{Q})}$	6.941	6.941
	(0.003)	(0.003)
$\hat{\sigma}_{\log(\bar{Q})}$	0.172	0.172
	(0.002)	(0.002)
Wind outage distribution		
$\hat{\text{const}}_{f^{-1}(\delta_{\text{wind}})}$	-1.215	-1.274
	(0.021)	(0.021)
$\hat{\sigma}_{f^{-1}(\delta_{\text{wind}})}$	1.772	1.779
	(0.012)	(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	0.987
	(0.001)	(0.001)
$\hat{p}_{\delta_{\text{gas}}}$	0.987	0.987
	(0.001)	(0.001)
year	2015	2015
num. obs.	2 500	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

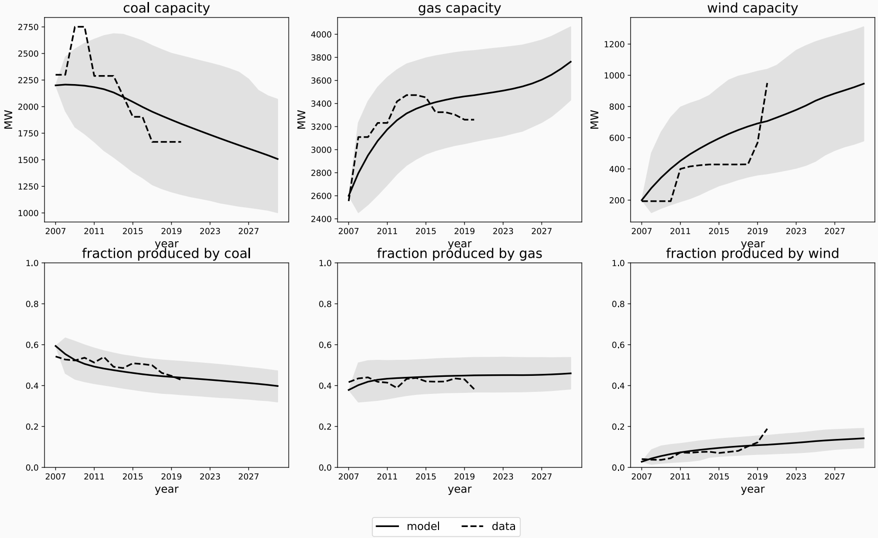
- To solve, consider candidate $\bar{P}$ and associated $\mathcal{Q}(\bar{P})$
  - sample many draws of shocks
  - solve for equilibrium

    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

Model Fit



Go back

Demand

- Measure 1 of consumers with utility in interval h

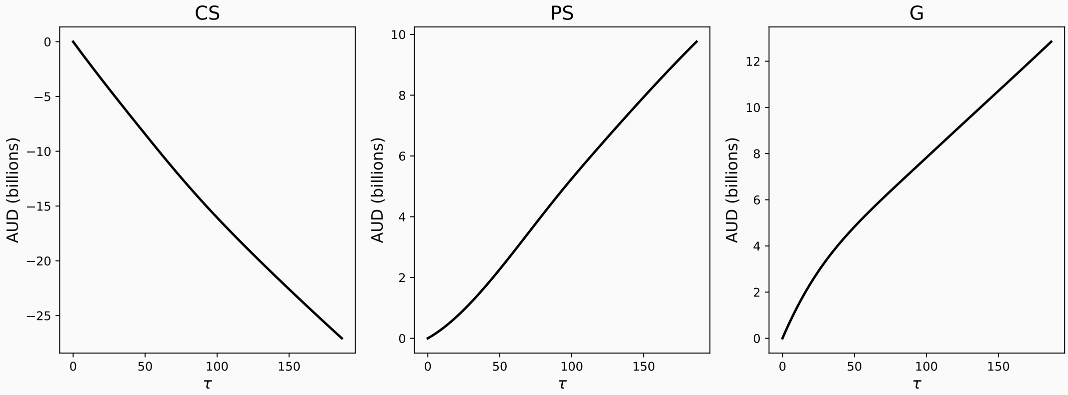
$$u_h(q, P) = \frac{\xi_h}{1 - 1/\varepsilon} q^{1-1/\varepsilon} - Pq$$

  where P is the *price consumer faces*

- $\bar{Q}_h(P) = \int_0^1 q_h^*(P)\, di$
- Competitive retail market $\Rightarrow P_{consumer} = c + \mathbb{E}[P_h]$
- $\log(\xi_h) \sim \mathcal{N}(\mu, \sigma^2)$ (possibly correlated with wholesale market variables)
- Constant elasticity of demand: $\frac{d \log E\left[\bar{Q}_h(P_{consumer})\right]}{dP_{consumer}} = -\varepsilon$

Go back

Carbon Tax: Welfare



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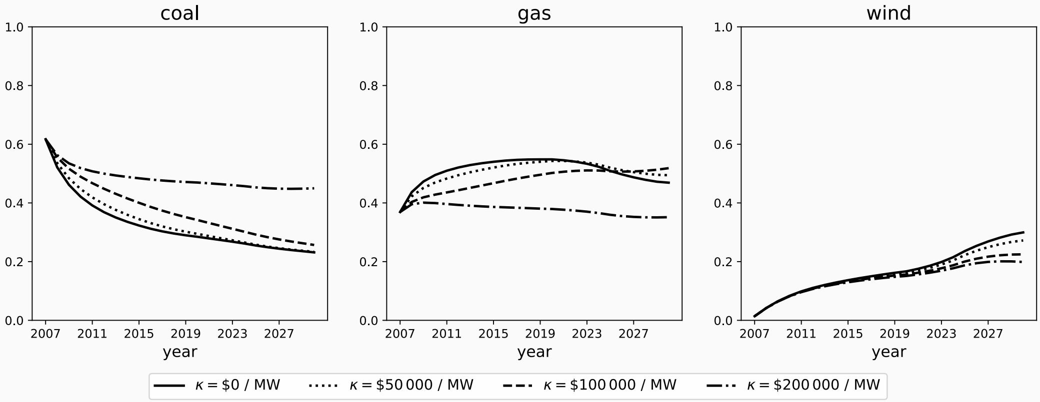
Capacity Payments: Production Shares



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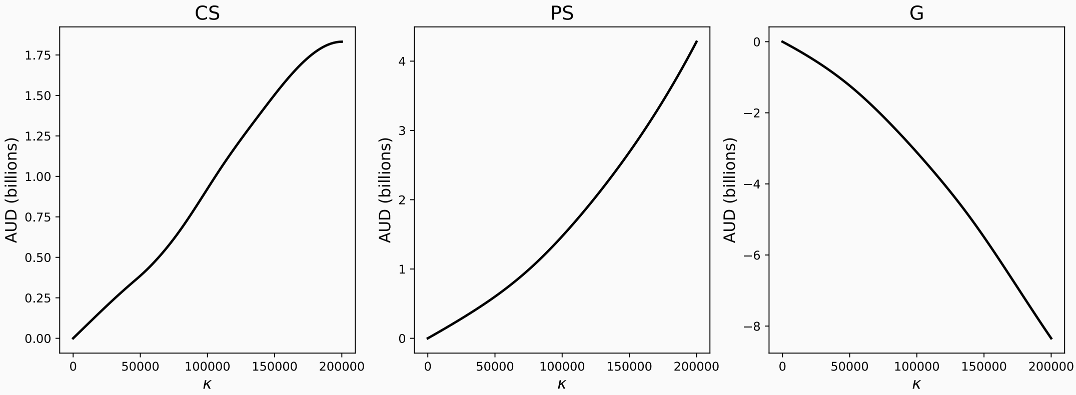
Capacity Payments: Welfare



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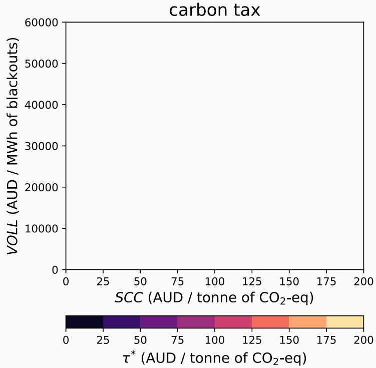
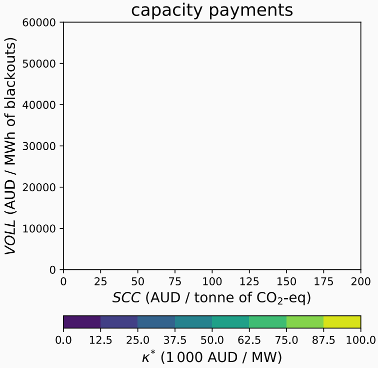
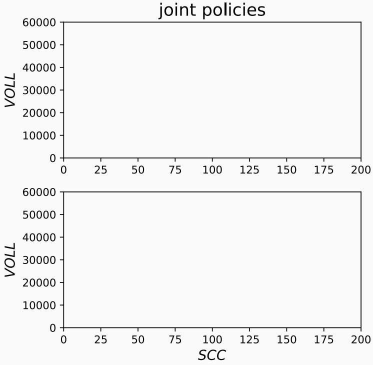
Optimal Policy







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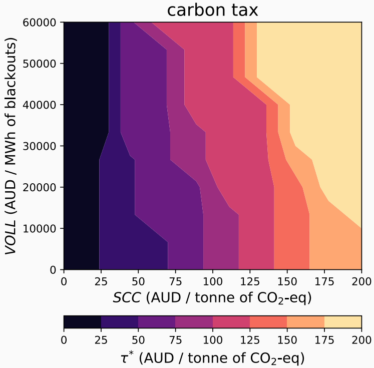
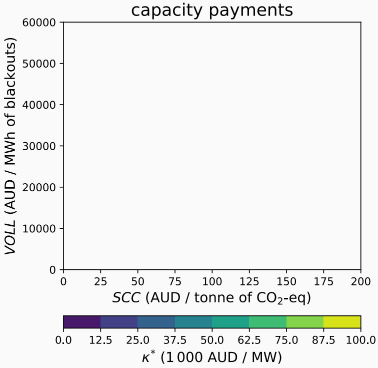
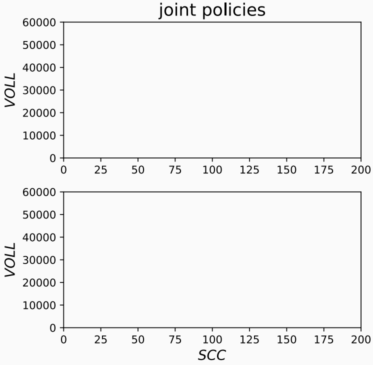
Optimal Policy







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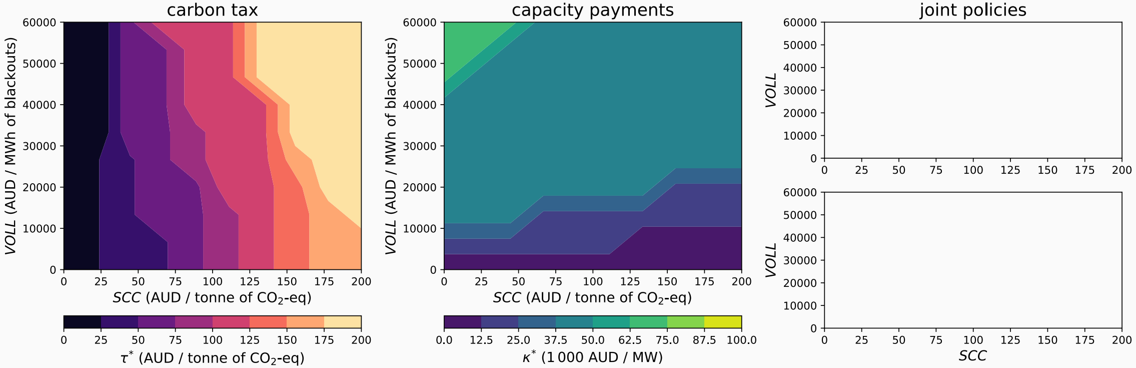
Optimal Policy



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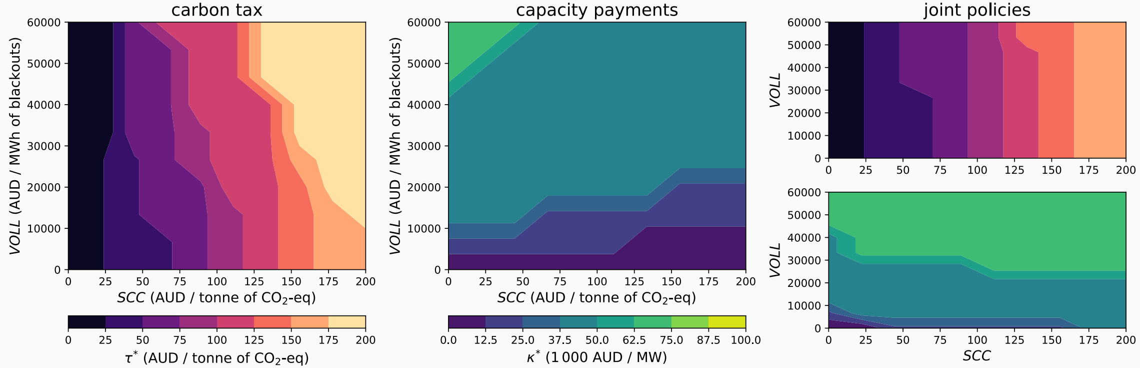
Optimal Policy



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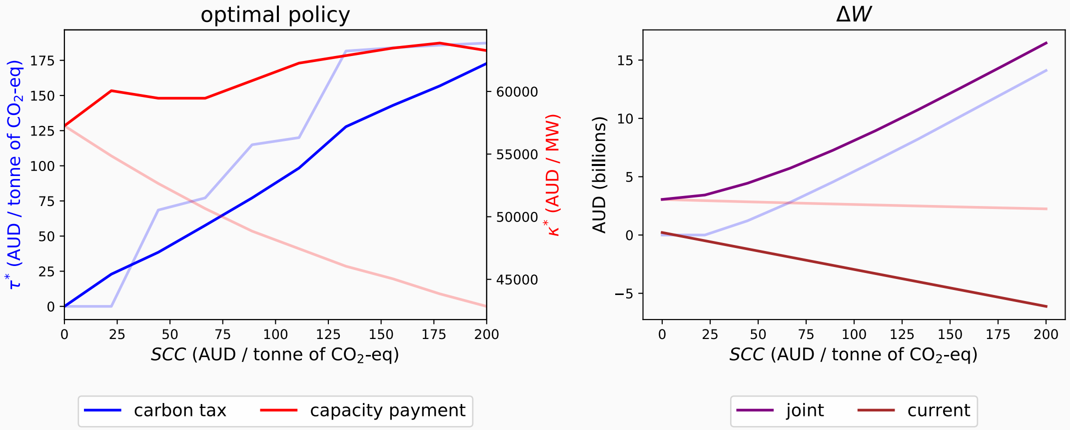
Compare Optimal Policy to Policy in Practice



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

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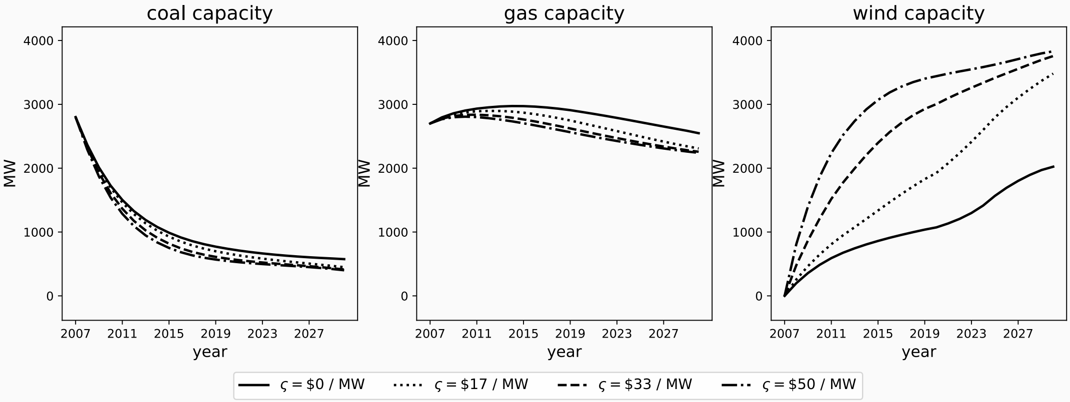
Renewable Production Subsidy: Capacity



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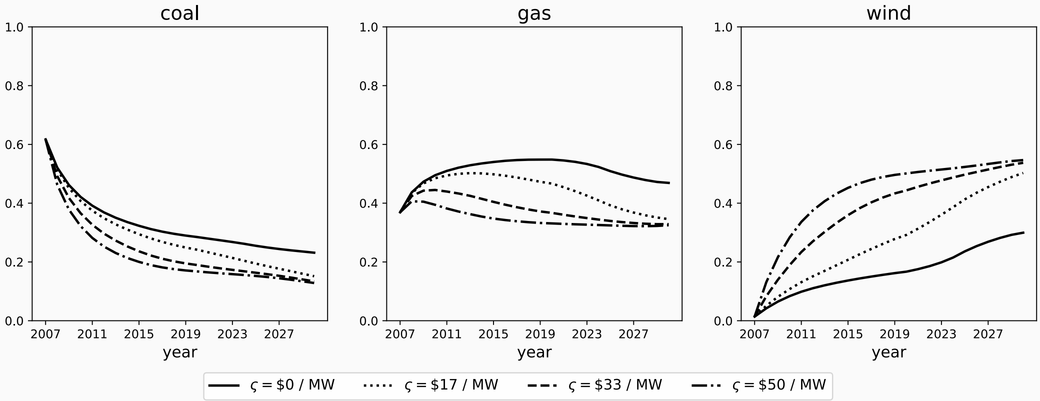
Renewable Production Subsidy: Production Shares



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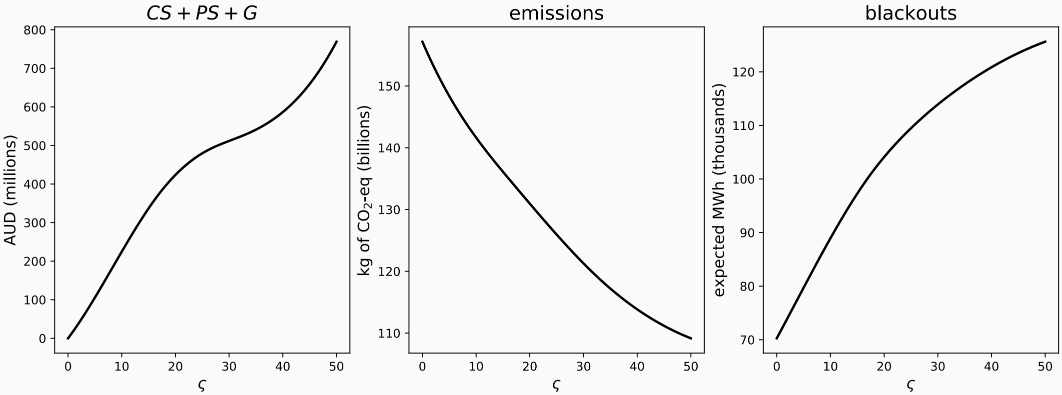
Renewable Production Subsidy: Welfare



Breakdown of CS, PS, G

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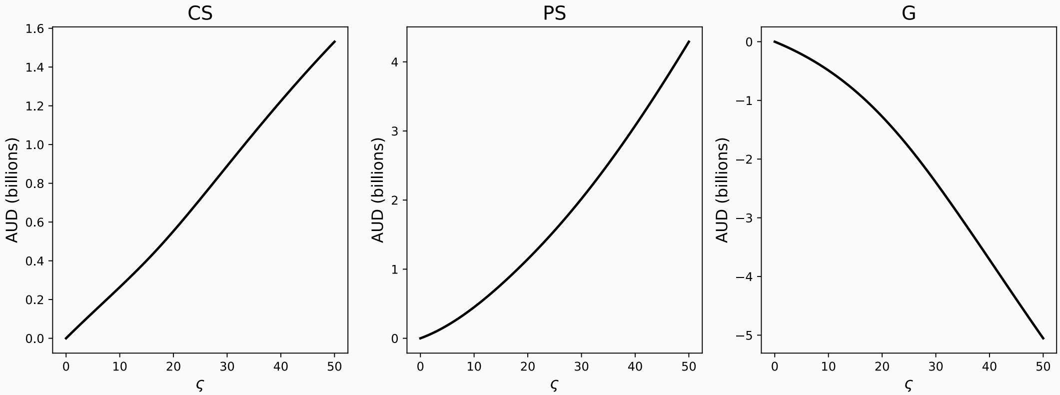
Renewable Production Subsidy: Welfare



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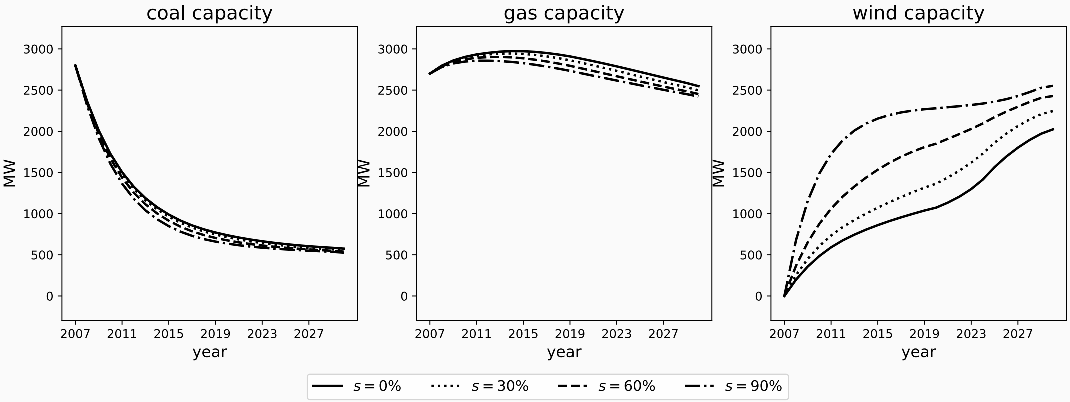
Renewable Investment Subsidy: Capacity



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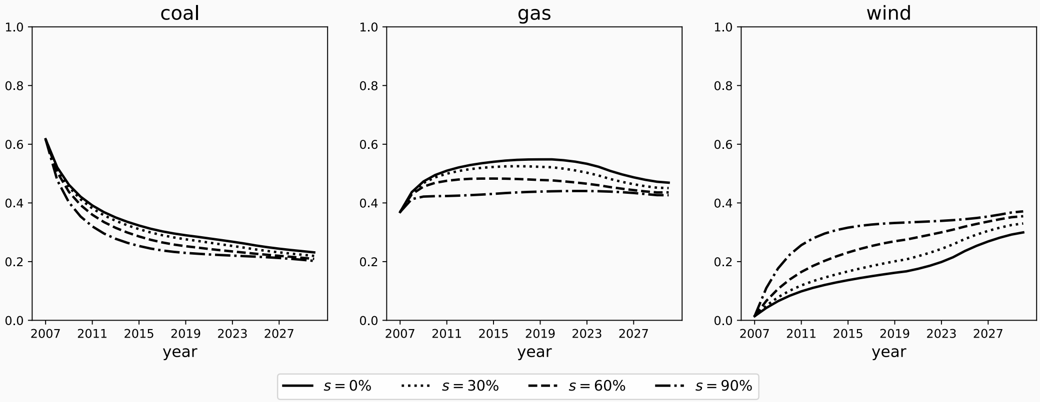
Renewable Investment Subsidy: Production Shares



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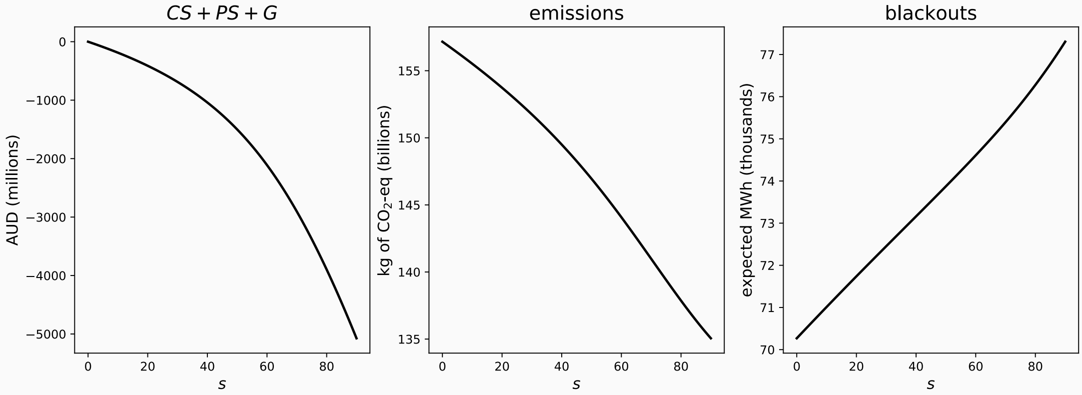
Renewable Investment Subsidy: Welfare



Breakdown of CS, PS, G

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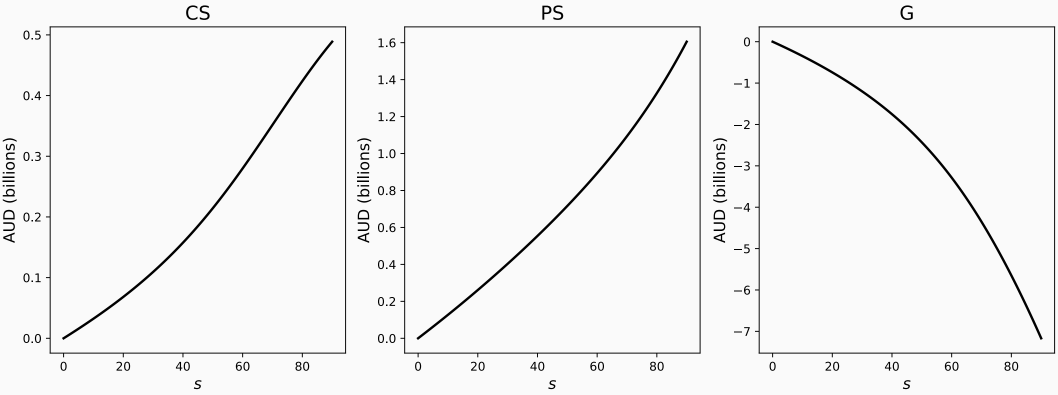
Renewable Investment Subsidy: Welfare



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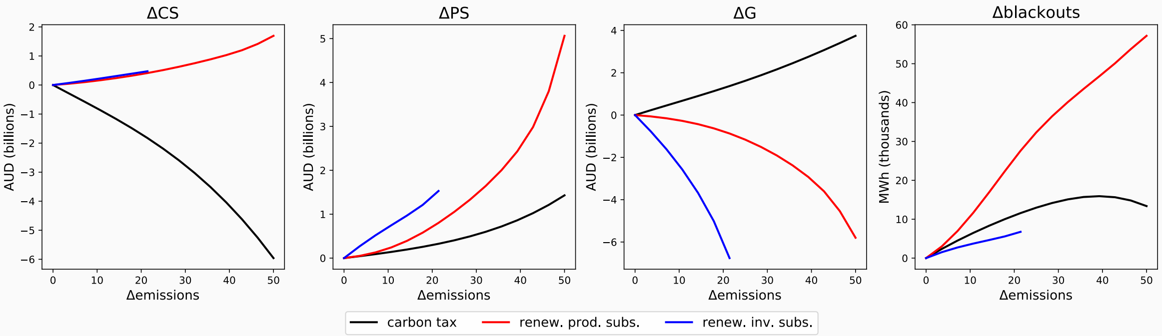
Alternative Environmental Policy Comparison



with Capacity Payments

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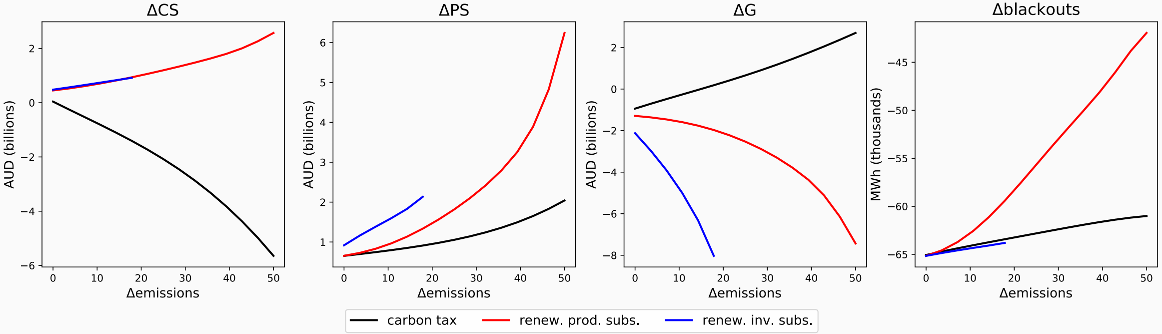
Alternative Environmental Policy Comparison with $\kappa = 50\,000$



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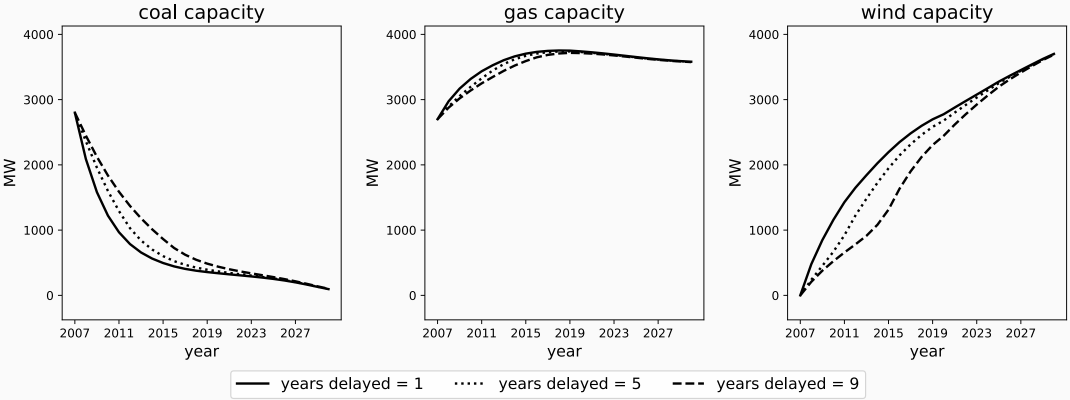
Policy Timing: Capacity



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

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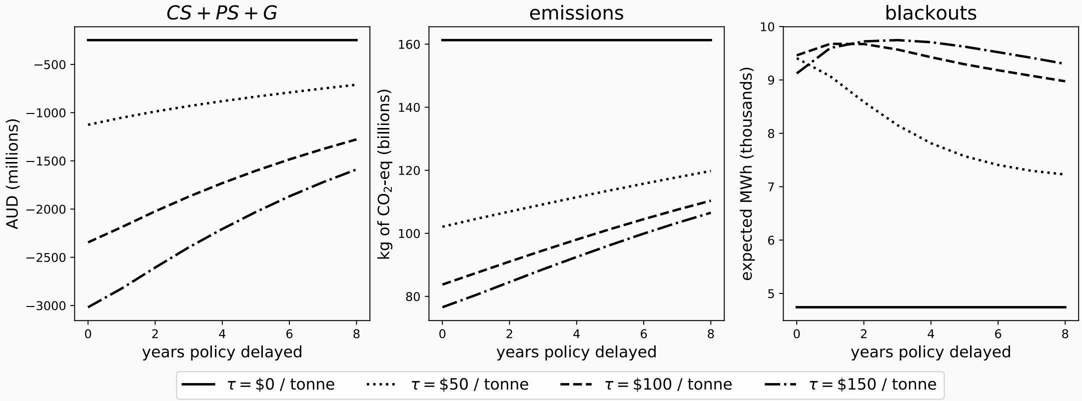
Policy Timing: Welfare



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