Does Natural Gas Generation Buildout Cause Carbon Lock-In?

A Social Planner's Perspective for Grid Optimization Using PJM Data

Thomas Lee
thomlee@wharton.upenn.edu

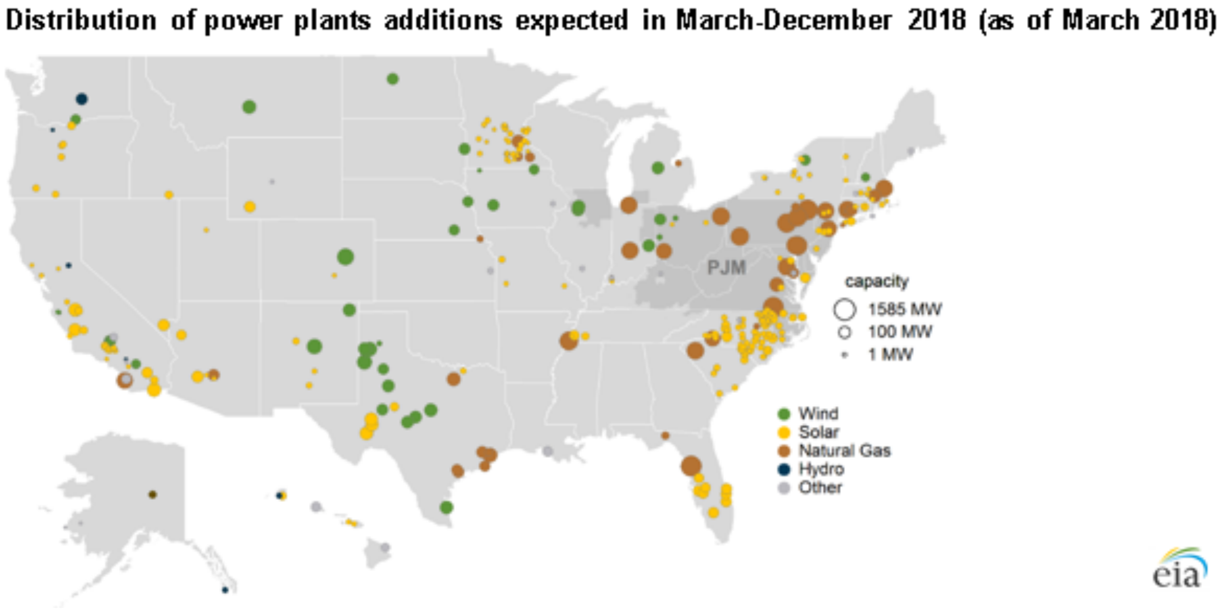
May 9, 2018
Energy Economics and Finance Seminar
Kleinman Center, University of Pennsylvania

Based on Senior Capstone Submitted December 10, 2017
Advisors: Monique Guignard-Spielberg, Andrew Huemmler

Motivation

- Social cost of carbon is not fully included.
    - RGGI: **$3.79 / short ton** (2018 March 14 auction)
    - What is priced in?

- Natural gas combined-cycle generation buildout
    - ~**15 GW** constructed for 2017-18
    - Another ~**22 GW** under development
    - PJM total installed capacity ~200 GW



Question: Does new gas generation capacity "lock out" or "crowd out" new renewables investment, even if/when a fuller carbon price is introduced later?

Dumoulin-Smith, Julien, Jerimiah Booream, Mark Piorkowski. 2017. "US Electric Utilities & IPPs: Where's All The Gas Build Coming From?" UBS Global Research. February 3, 2017. https://neo.ubs.com/shared/d1QlBB5rMNXCdOf/.
The Regional Greenhouse Gas Initiative. "Auction Results." Accessed May 4, 2018. https://www.rggi.org/auctions/auction-results
https://www.eia.gov/todayinenergy/detail.php?id=36092#tab2

Outline

- **Main conclusion**: New natural gas capacity investment in PJM is consistent with a $50 / ton carbon price. For the current grid system with existing capacities, the potential for carbon lock-in based purely on sunk costs is minimal.

- Prior work
- Limits of carbon lock-in potential
  - LCOE: carbon price range
  - Load intermittency
  - Renewables intermittency
- Numerical results
  - Greenfield
  - Existing capacities

Summary of Average PJM Emissions by Scenario (kg CO2 equivalent / MWh)		
No carbon price	Delayed carbon price	Full pricing now
396 (119% higher)	**181** (0.2% higher)	**181**

Prior work

- Arthur 1989: path dependence from increasing returns, network effects
    - E.g. QWERTY, 29.97 frames per second
- Liebowitz & Margolis 1995: “third-degree” path dependence – “ex ante path inefficient”
- Unruh 2000: “carbon lock-in”
- Erickson et al. 2015: carbon price where new renewable energy source is competitive with existing conventional source
- Mignone et al. 2017: natural gas combined cycle investments are robust to rising carbon prices

Arthur, W. Brian. 1989. “Competing Technologies, Increasing Returns, and Lock-In by Historical Events.” *The Economic Journal* 99 (March): 116-131. Royal Economic Society.

Dixit, Avinash. 1989. “Entry and Exit Decisions under Uncertainty.” *Journal of Political Economy* 97 (June): 620-638. The University of Chicago Press.

Liebowitz, Stan J., Stephen E. Margolis. 1995. “Path Dependence, Lock-In, and History.” Journal of Law, Economics and Organization 11 (1995): 205-226. SSRN.

Unruh, Gregory C. 2000. "Understanding carbon lock-in." Energy policy 28, no. 12 (October): 817-830.

Erickson, Peter, Sivan Kartha, Michael Lazarus, Kevin Tempest. 2015. “Assessing carbon lock-in.” Environmental Research Letters 10, no. 8 (August): 1-7.

Mignone, Bryan K., Sharon Showalter, Frances Wood, Haewon McJeon, Daniel Steinberg. 2017. “Sensitivity of natural gas deployment in the US power sector to future carbon policy expectations.” Energy Policy 110 (November): 518-524.

Regret function: carbon lock-in

- Some vector of pre-existing capacities x^0

- A full carbon price C
  - Optimal capacities → $x^{*full} = opt\left(x^0, C^{full}\right)$

- A delayed carbon price trajectory: first 0, then C
  - Initial "optimal" capacities → $x^{*myopic} = opt(x^0, 0)$
  - After carbon price included → $x^{*delay} = opt\left(x^{*myopic}, C\right)$

- Regret = $emissions\left(x^{*delay}\right) - emissions\left(x^{*full}\right)$

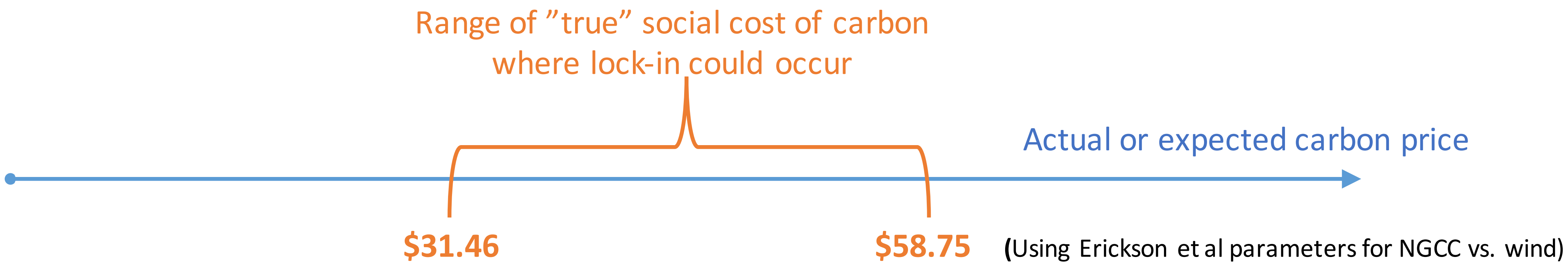
Impact of delaying a carbon price vs. cap

Externality Policy	Carbon Price	Carbon Cap
Initial period without full policy	• **Higher emissions** • Possibly overbuild capacity that will be unnecessary later	• **Higher emissions** • Possibly overbuild capacity that will be unnecessary later
After full policy is included	• **Higher emissions locked-in**	• **No carbon lock-in by construction** • Need higher carbon price vs. no delay

- Dual problems (equivalent carbon price is optimal dual variable for carbon cap constraint)
- Focus on carbon price as benchmark

Sunk cost lock-in occurs over carbon price *range*

- For lock-in to exist, carbon price:
  - Can't be too high → otherwise alternatives are competitive (Erickson et al.)
  - Can't be too low → otherwise counterfactual would not have any alternatives



$$\left[\frac{K_{new}\cdot a_{new}+F_{new}}{h\cdot P_{new}}-\left(\frac{\boldsymbol{K_{old}\cdot a_{old}}+F_{old}}{h\cdot P_{old}}+V_{old}\right)\right]/E_{old}<\boldsymbol{C}<\left[\frac{K_{new}\cdot a_{new}+F_{new}}{h\cdot P_{new}}-\left(\frac{F_{old}}{h\cdot P_{old}}+V_{old}\right)\right]/E_{old}$$

Definitions of LCOE formula variables listed in appendix.

Load intermittency reduces lock-in potential

- Assume load duration curve, 2 perfectly dispatchable resources
- How much capacity of each type is optimal?
  - FOC → higher variable cost resource should run for hours

$$\boldsymbol{h}^* = \frac{\boldsymbol{k_2} - \boldsymbol{k_1} \quad (\$/\mathrm{MW})}{\boldsymbol{v_1} - \boldsymbol{v_2} \quad (\$/\mathrm{MWh})}$$

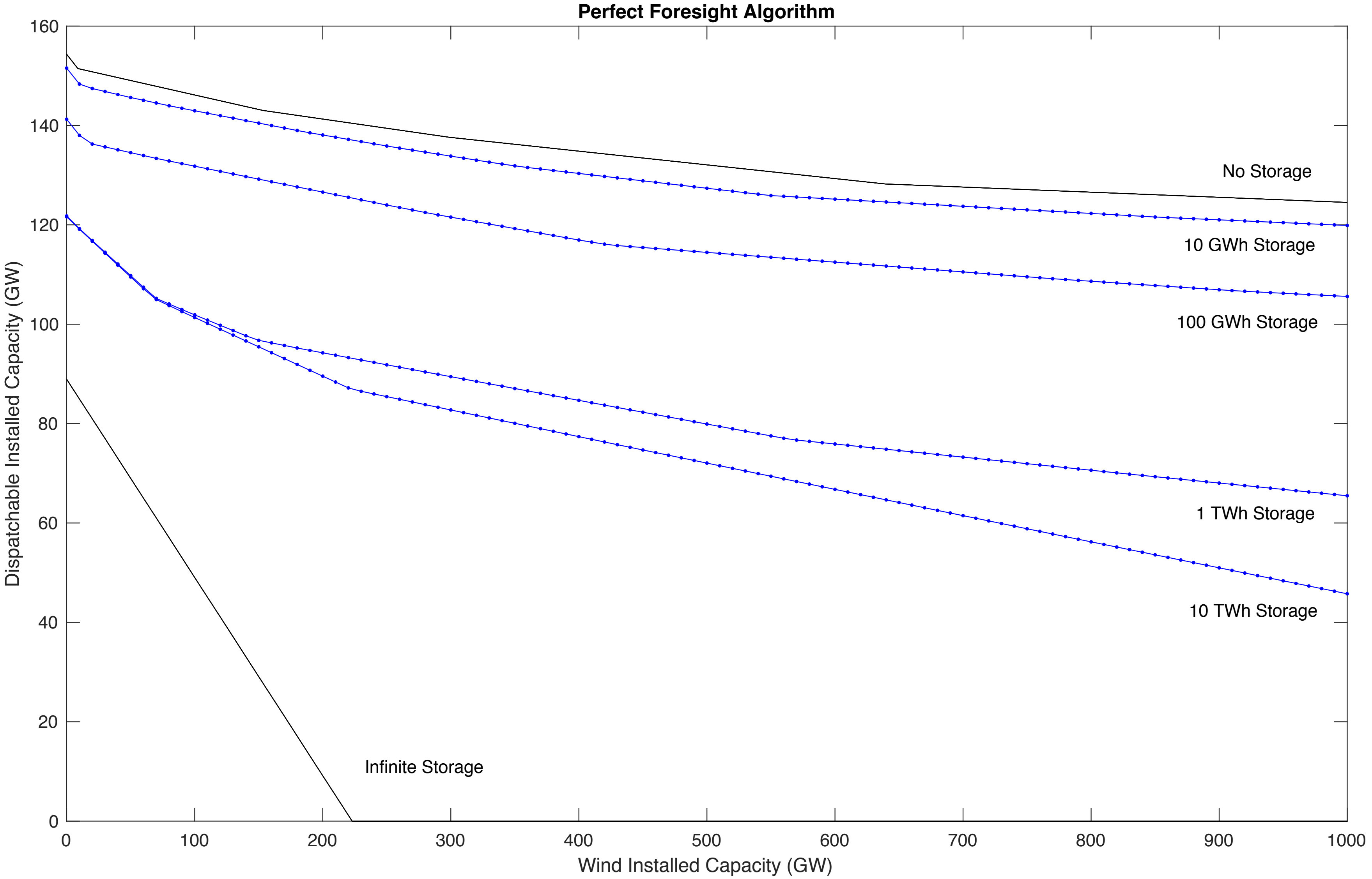
  - If "a lot" of higher variable cost resource already built

$$\boldsymbol{h}^{*\boldsymbol{path}} = \frac{\boldsymbol{k_2} \quad (\$/\mathrm{MW})}{\boldsymbol{v_1} - \boldsymbol{v_2} \quad (\$/\mathrm{MWh})} > \boldsymbol{x}^*$$

- For lock-in to exist, need to build more than the optimal amount under the all-in-price scenario

$\boldsymbol{k}$ is capital cost and $\boldsymbol{v}$ is variable cost. Assume resource type 1 is higher variable cost. Full derivation in appendix.

Renewables intermittency reduces lock-in potential



Numerical results

LP: Capacity Expansion Optimization

minimize	$C_{cap} + C_{fin} + C_{ext}$	(Objective function)
subject to	$\forall i{:}\ X_i = \mathbf{X_{old,i}} + X_{new,i}$	
	$C_{cap} = \sum_i A_{r,n_i} k_i X_{new,i}$	(Capital costs)
	$C_{fin} = \sum_i \left(f_i X_i + \frac{1}{N} v_i \sum_t P_{i,t} \right)$	(Operating monetary costs)
	$C_{ext} = \sum_i \left(\frac{1}{N} s_i \sum_t P_{i,t} \right)$	(Operating externality costs)
	$\forall t{:}\ \sum_{i=1}^{n} P_{i,t} - P_{stor,t}^{+} + P_{stor,t}^{-} \geq L_t$	(Hourly load balance)
	$\forall i,t{:}\ P_{i,t} \leq X_i a_{i,t}$	(Generation resource adequacy)
	$\forall i,t{:}\ -r_i X_i \leq P_{i,t} - P_{i,t-1} \leq r_i X_i$	(Ramping constraint)
	$Q_0 = 0$	(Zero initial storage charge)
	$0 \leq P_{stor,t}^{-} \leq \gamma Q_{t-1}$	(Energy available to be discharged)
	$0 \leq P_{stor,t}^{+} \leq \sum_{i=1}^{n} P_{i,t}$	(Energy available to be stored)
	$0 \leq Q_t \leq Q_{max}$	(Finite, positive energy capacity)
	$Q_t = \gamma Q_{t-1} + P_{stor,t}^{+} - P_{stor,t}^{-}$	(Conservation of energy)

Indices

i	Resource type: coal, gas (CT and CC), wind, solar, nuclear, hydro
t	Time hour of the year (Size 8760 * N years)

Decision Variables

$X_{new}(i)$	New power capacity to be constructed, in MW
$P(i,t)$	Dispatch of each resource type for each hour, in MWh

Cost Parameters

$k(i)$	Capital cost for power capacity, in \$ / kW
$f(i)$	Annual fixed operating and maintenance cost, in \$ / kW
$v(i)$	Variable fuel costs for energy generation, in \$ / MWh
$s(i)$	Variable externality costs for energy generation, in \$ / MWh

$X_{old}(i)$	Existing power nameplate capacity at start of period, in MW
$r(i)$	Ramp rate, in MWh output that can be adjusted up or down in 1 hour per MW capacity (%)
$l(t)$	Load demand (RTO-level metered load) in given hour, in MWh
$a(i,t)$	Physically available capacity value of resource, in dimensionless % (Assumed to be always 1 for resources that are not wind or solar.)

Starting from 0 existing capacities

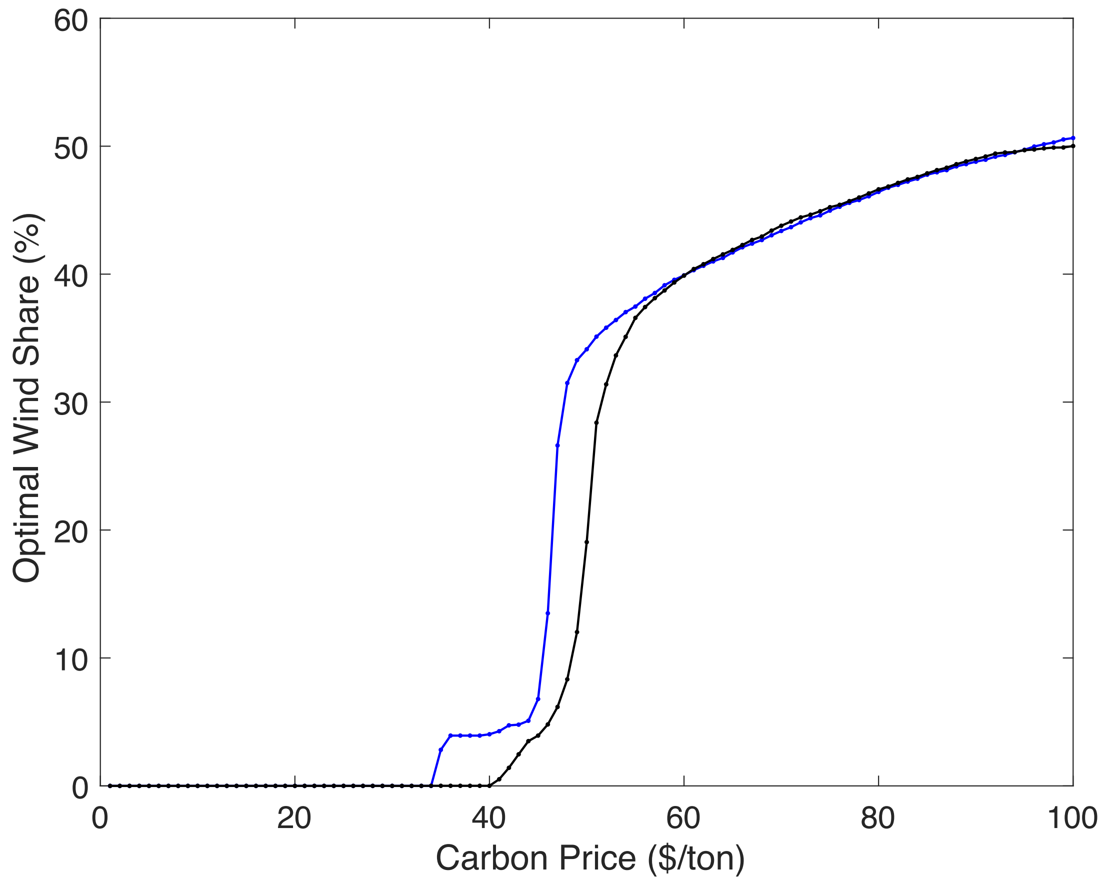
CO_2 Price ($ / ton)	Capacity (GW) Always 0	Capacity (GW) First 0, Then 50	Capacity (GW) Always 50	Energy Share (%) Always 0	Energy Share (%) First 0, Then 50	Energy Share (%) Always 50
CT	57.63	**51.87**	**52.01**	3.92	**1.77**	**2.38**
CC	98.53	**98.53**	**81.36**	96.08	**72.63**	**56.71**
Wind	0	**57.74**	**79.02**	0	**25.60**	**35.00**
Solar	0	**0**	**22.56**	0	**0**	**5.90**
Average CO2 equivalent (kg / MWh)				449.41	**331.61**	**265.71**

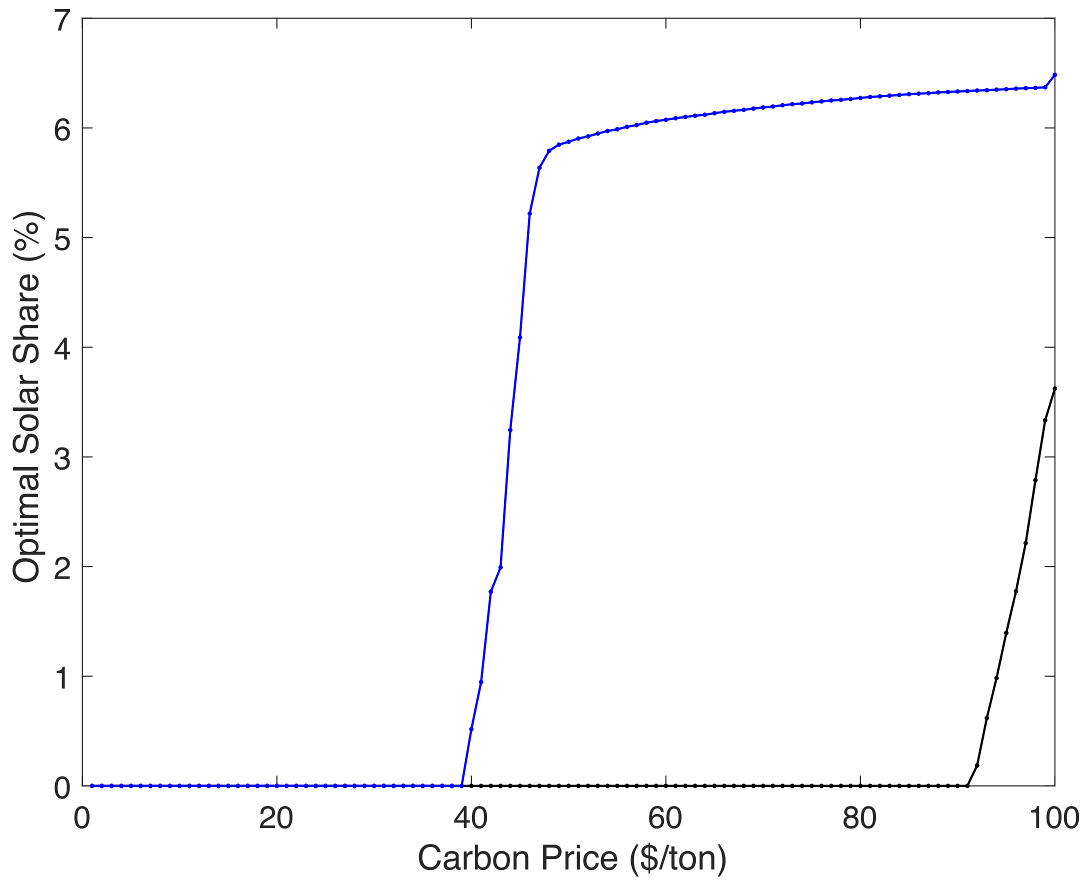
➔ Lock-out of wind: 21.3 GW, 9.4% generation

➔ Lock-out of solar: 22.56 GW, 5.9% generation

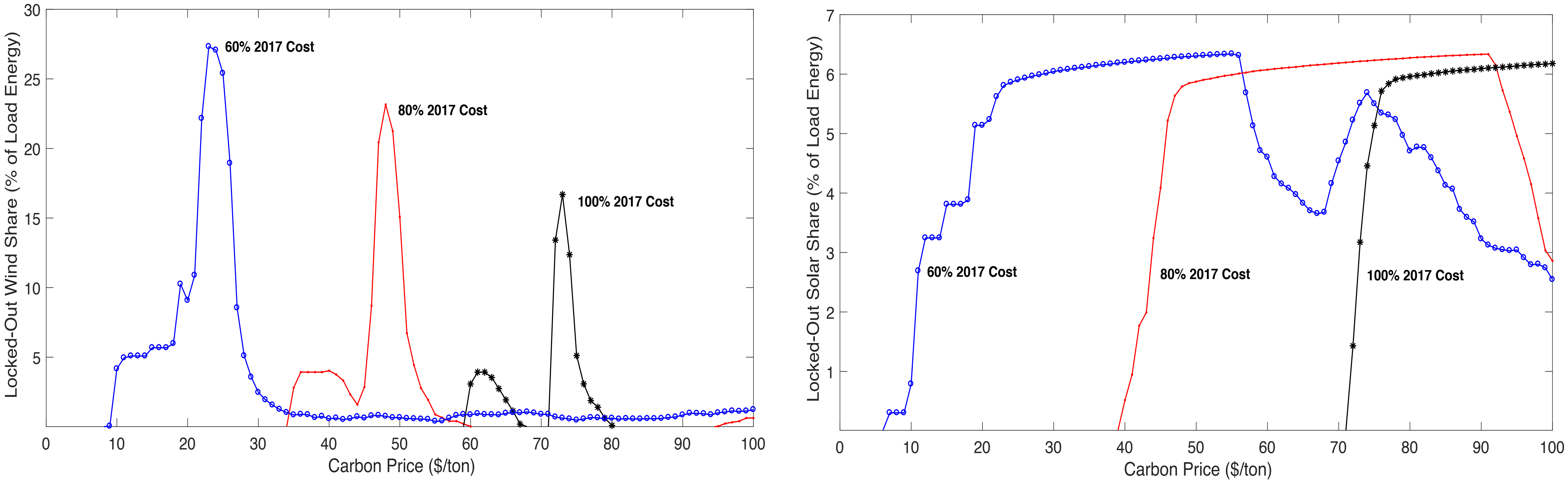
➔ **Carbon lock-in: 65.9 kg CO2 equivalent / MWh** (~25% total)

What happens at different “true” carbon prices?





What happens at different carbon prices?



Starting from existing capacities

Start with existing – Assume some exogenous retirements of both coal and nuclear

CO_2 Price ($ / ton)	Capacity (GW)				Energy Share (%)			
	Existing	Always 0	First 0, Then 50	Always 50	Always 0	First 0, Then 50	Always 50	**Δ from Delay**
CC	41.05	48.12	48.12	46.68	29.36	33.16	32.47	**+0.69%**
Wind	7.92	7.92	56.61	57.63	3.36	24.01	24.44	**-0.43%**
Solar	0.88	0.88	5.07	5.01	0.22	1.28	1.26	**+0.02%**
Coal	47.62	47.62	31.14	32.57	29.10	3.56	3.86	**-0.30%**
Nuclear	25.27	25.27	25.27	25.27	27.07	27.07	27.01	**+0.06%**
Hydro	9.91	9.91	9.91	9.91	10.62	10.53	10.51	**+0.02%**
CT	25.25	25.25	25.25	25.25	0.27	0.40	0.39	**+0.10%**
Average CO2 equivalent (kg / MWh)					395.83	181.02	180.65	**+0.37 kg/MWh**

➔Very minimal lock-out effect (~0.2% of emissions)

➔First order effect from including carbon price – even if delayed

Existing capacities assuming higher NGCC

Optimal Capacity Expansion and Generation Shares for Coal and Renewables, Under Increasing Levels of Initial Gas Combined-Cycle Capacity

	Starting CC (GW)	**48**	**55**	**60**	**70**	**90**	**100**
Δ Capacity (GW)	Coal	–16.48	**–23.16**	–23.39	–35.58	–47.62	–47.62
	Solar	4.19	3.95	**0**	0	0	0
	Wind	48.69	47.80	47.23	47.23	**19.64**	0
Energy Share (%)	Coal	3.56	**2.30**	1.84	0.74	0	0
	Solar	1.28	1.22	**0.22**	0.22	0.22	0.22
	Wind	24.01	23.63	23.39	23.39	**11.70**	3.36
Average Emissions (kg CO2 equivalent / MWh)		**180.15**	**176.16**	**179.46**	**174.29**	**222.24**	**258.94**

- New gas displaces old coal immediately
- Solar starts to get displaced – but optimal share was small to start
- Wind gets displaced only after 90 GW – 49 GW existing = ~49GW new gas CC

Model limitations / extensions

<u>Factors that affect optimal renewables share:</u>

- Transmission system, power flow
- Scale effects: siting, reserve requirements, etc.
- Inter-annual uncertainty (using 2012 meteorological year)
- Heterogeneity: offtake customers, etc.

<u>Factors that affect lock-in mechanism:</u>

- Optionality, capital structure: right now discount rate can represent r_{WACC}, but treated as fixed income annuity
- Strategic investment behavior: not social planner
- Endogenous fuel prices
- Improving alternative technologies in between periods
- Infrastructure network effects (Unruh)

Takeaway: Don't need to worry about sunk cost lock-in, worry about pricing the externality.

- Theoretical framework diminishes carbon lock-in potential
  - "True" carbon price can't be too low or high versus actual or expected
  - Lock-in can only exist after sunk costs exceed "always full price" optimal
  - Intermittent renewables need capacity backup
- Numerical analysis using LP optimization suggests minimal carbon lock-in in PJM due to NGCC generation buildout, due to pre-existing resource capacity – consistent with Mignone et al.
- First order effect is including externality pricing, even if delayed

Summary of Average PJM Emissions by Scenario (kg CO2 equivalent / MWh)			
Carbon Price	Zero	Delayed	Full
No Existing Resources	**449** (69% higher)	**332** (25% higher)	**266**
Pre-Existing Resources	**396** (119% higher)	**181** (0.2% higher)	**181**

Appendix

Mignone et al.

Table 1: Natural Gas Generation and Capacity in Optimal Solutions Under Capped and Rising Carbon Regulation Scenarios, from Mignone et al.

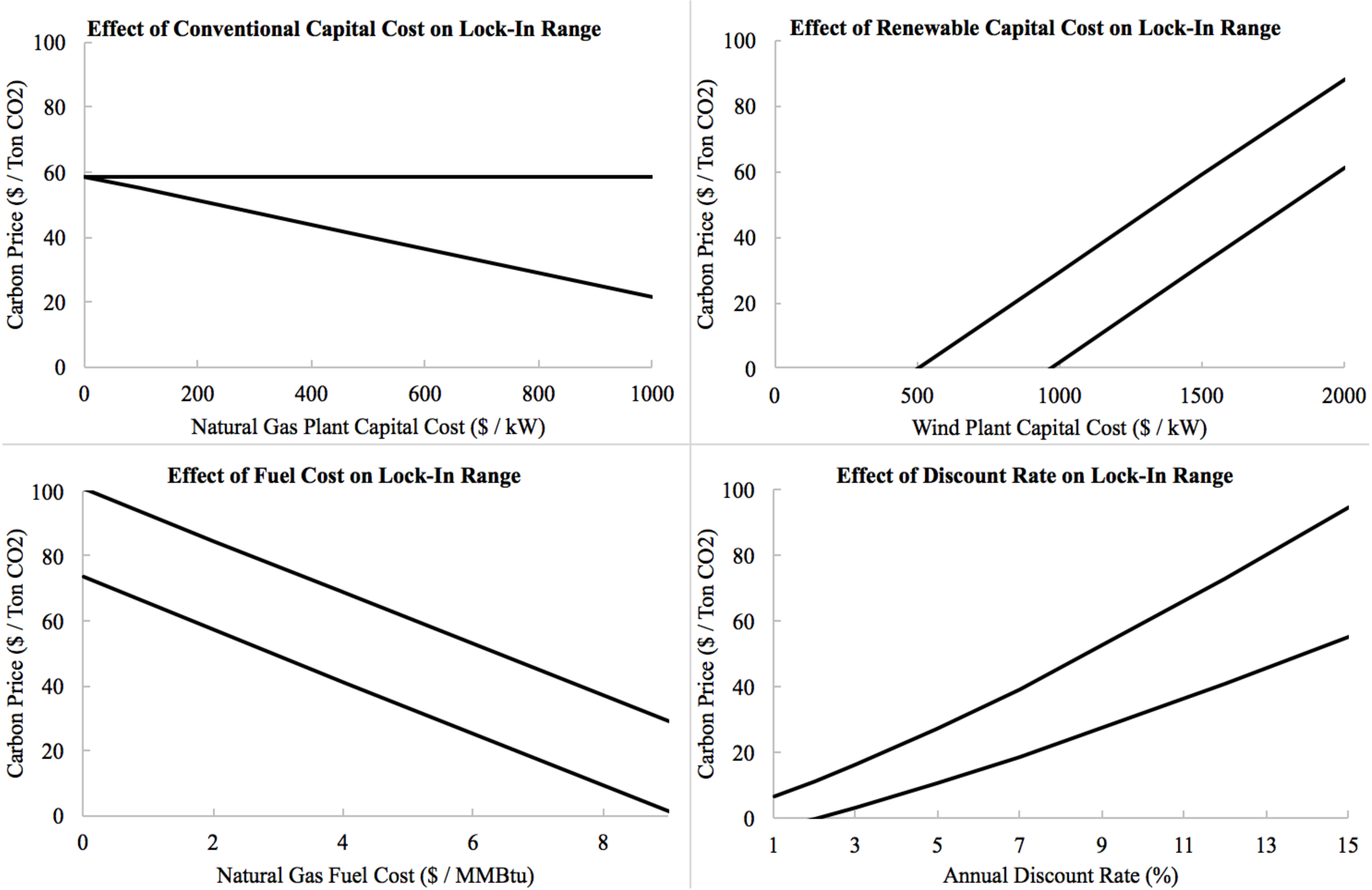
	Generation (TWh)			Capacity (GW)			Capacity Factor		
	2015	2030	2050	2015	2030	2050	2015	2030	2050
Capped Price	1092	1260	1753	226	277	386	55%	52%	52%
Rising Price		1328	1525		299	406		51%	43%

Carbon lock-in range

$$\left[\frac{K_{new} \cdot a_{new} + F_{new}}{h \cdot P_{new}} - \left(\frac{\boldsymbol{K_{old} \cdot a_{old}} + F_{old}}{h \cdot P_{old}} + V_{old}\right)\right] / E_{old} < \boldsymbol{C} < \left[\frac{K_{new} \cdot a_{new} + F_{new}}{h \cdot P_{new}} - \left(\frac{F_{old}}{h \cdot P_{old}} + V_{old}\right)\right] / E_{old}$$

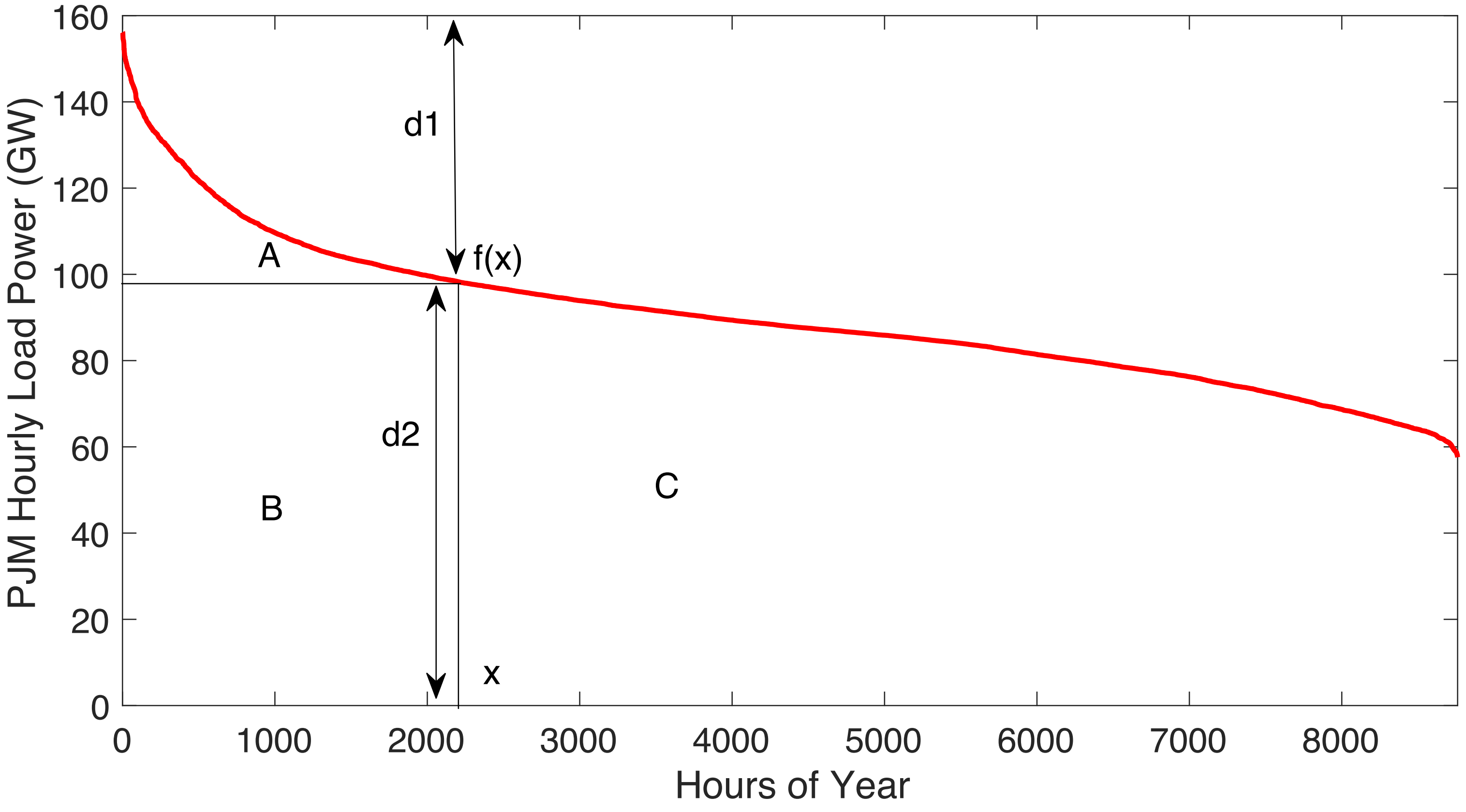
- C = carbon cost ($ / tons)
- E = emission rate (tons / MWh)
- K = capital cost ($ / MW)
- F = fixed costs ($ / MW)
- V = variable costs ($ / MWh)
- P = capacity factor of power generation (%)
- a = annuity factor = $\frac{r}{1-(1+r)^{-n}}$
- h = hours in year = 8760 hours

Conditions for Lock-In (LCOE)



Conditions for Lock-In (Load Duration)

- Load duration curve for PJM
- Inverse CDF



Conditions for Lock-In (Load Duration)

Assume 2 resources. Then total costs:

$$
\begin{aligned}
J &= k_1 d1 + k_2 d_2 + v_1 A + v_2 (B + C) \\
&= k_1[f(0) - f(x)] + k_2 f(x) + v_1 \left[\int_0^x f(s)ds - xf(x)\right] + v_2 \left[\int_x^{x_{max}} f(s)ds + xf(x)\right]
\end{aligned}
$$

FOC:

$$
\begin{aligned}
\frac{\partial J}{\partial x} &= -k_1 \frac{\partial f(x)}{\partial x} + k_2 \frac{\partial f(x)}{\partial x} + v_1 \left[f(x) - f(x) - x\frac{\partial f(x)}{\partial x}\right] + v_2 \left[-f(x) + f(x) + x\frac{\partial f(x)}{\partial x}\right] \\
&= (k_2 - k_1)\frac{\partial f(x)}{\partial x} + (v_2 - v_1)x^* \frac{\partial f(x)}{\partial x} = 0
\end{aligned}
$$

$$
\boldsymbol{x^* = \frac{k_2 - k_1}{v_1 - v_2}}
$$

Conditions for Lock-In (Load Duration)

- What if we have **a little** existing amounts of resource 1, that does **not exceed** the "greenfield" optimal?
- $\theta_1 < f(0) - f(x^*)$

$$J_{pre} = k_1[f(0) - f(x) - \boldsymbol{\theta_1}] + k_2 f(x) + v_1[\dots] + v_2[\dots]$$

- The derivative does not change.
- **NO LOCK-IN**

Conditions for Lock-In (Load Duration)

- What if we have **lots of** existing amounts of resource 1, that **does exceed** the "greenfield" optimal?
- $\theta_1 >> f(0) - f(x^*)$
- No capital cost incurred for resource 1

$$J_{pre} = k_2 f(x) + v_1[\dots] + v_2[\dots]$$

- New optimal

$$x^{*(1)} = \frac{k_2}{v_1 - v_2} > x^*$$

$$\boxed{\boldsymbol{d_2^{*(1)} = f\left(x^{*(1)}\right) < f(x^*)}}$$

LOCK-IN

Capacity Value of Renewables

- 1. Zero storage
- Level of wind capacity exactly determines necessary gas capacity

$$P_{var,t} = X_{var} A_t$$

$$P_{disp,t} = NL_t = \max\left\{0, L_t - P_{var,t}\right\}$$

$$X_{disp} = \max_{\mathrm{t}}\{NL_t\} \quad (1)$$

Capacity Value of Renewables

- 2. Finite storage capacity
- Only charge storage if excess renewables

Let $S_0 = 0$

For time $t = 1 \dots T$:

$$P^{+}_{stor,t} = \min\{S_{max} - \gamma S_{t-1},\ \max\{0, P_{var,t} - L_t\}\} \qquad \text{(Store into battery)}$$

$$P^{-}_{stor,t} = \min\{\gamma S_{t-1},\ \max\{0,\ L_t - P_{var,t}\}\} \qquad \text{(Discharge from battery)}$$

$$S_t = \gamma S_{t-1} + P^{+}_{stor,t} - P^{-}_{stor,t}$$

$$NL_t = L_t - P_{var,t} - P^{-}_{stor,t} + P^{+}_{stor,t}$$

Capacity Value of Renewables

- 3. Finite storage capacity
- Optimize charge – this might end up using more energy

minimize X_{disp}

such that $S_0 = 0$	(Zero initial charge)
$0 \leq P^{-}_{stor,t} \leq \gamma S_{t-1}$	(Amount of energy available to be discharged)
$0 \leq P^{+}_{stor,t} \leq P_{var,t} + X_{disp}$	(Amount of energy available to be stored)
$0 \leq S_t \leq S_{max}$	(Finite energy capacity)
$S_t = \gamma S_{t-1} + P^{+}_{stor,t} - P^{-}_{stor,t}$	(Conservation of energy across time)
$P_{var,t} + X_{disp} - P^{+}_{stor,t} + P^{-}_{stor,t} \geq L_t$	(Resource adequacy to cover load)

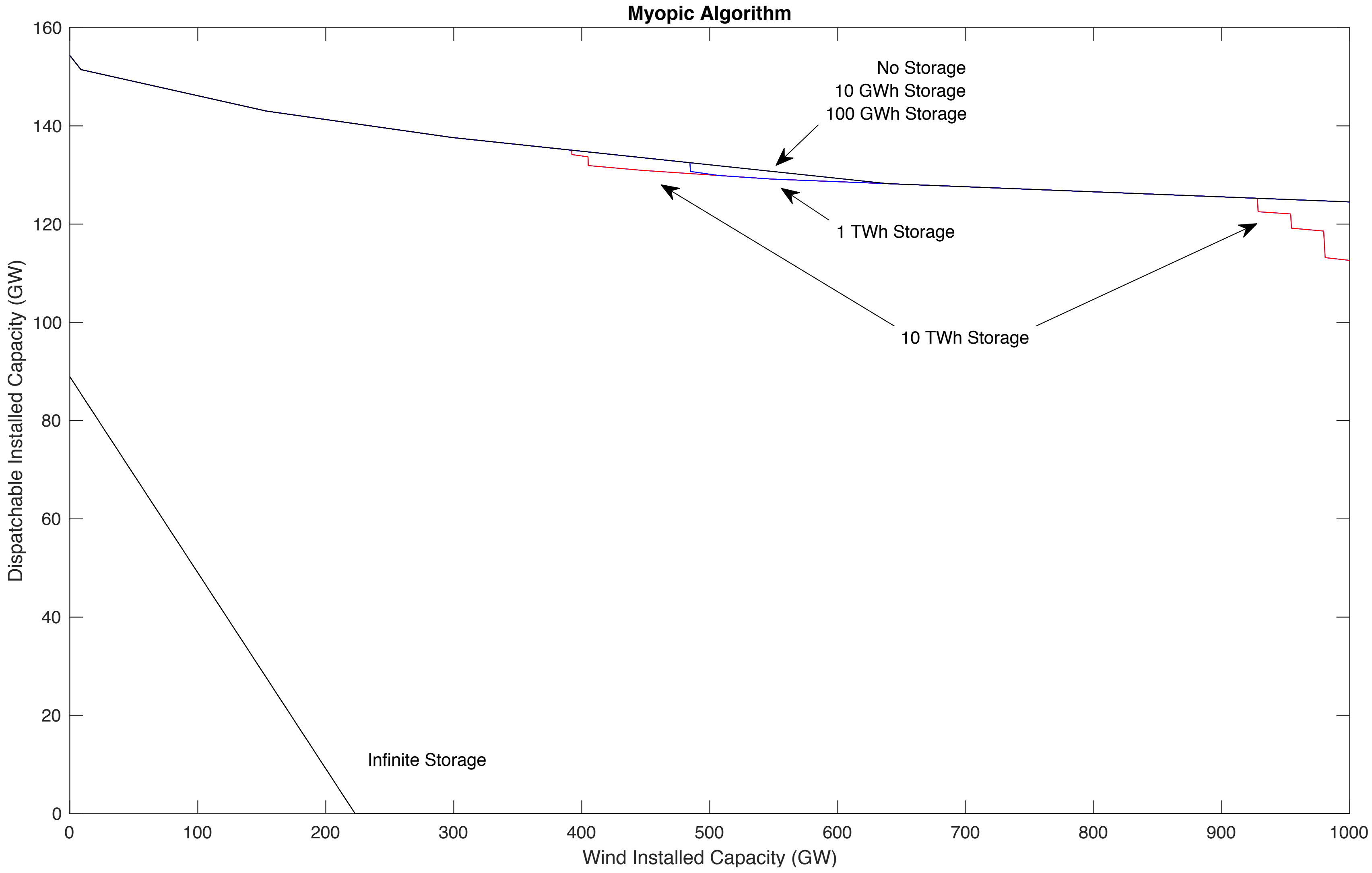
Capacity Value of Renewables

- 4. Infinite storage capacity
- Stored energy can "time travel" with no decay

$$X_{disp} = \frac{1}{T}\sum_{t}\left(L_t - P_{var,t}\right)$$

** This is equivalent to the LCOE-only analysis*

Capacity Value of Renewables



Cost Parameters for Numerical Analysis

Table 7: Natural Gas and Coal Variable Cost Assumptions by Chemical Energy Content

Fuel Type	Natural Gas	Coal
Fuel Price ($ / MMBtu)	4	2
Combustion Emission Rate (kg CO_2 / MMBtu)	53.07	93.35
Natural Gas Energy Density (kg CH_4 / MMBtu)	$(1 / 53.4)10^3 = 18.73$	NA
Natural Gas Fugitive Emission Rate	1%	
Global Warming Potential Multiplier of CH_4 vs. CO_2	86	

Table 8: Cost Assumptions by Resource Types

Resource Type	Units	Gas CC	Onshore Wind	Solar PV	Gas CT	Coal	Nuclear	Hydro
Overnight Capital	$/kW	1283	2271	2524	Assume no new buildout			
Assumed Lifetime	years	20	20	30				
Capital Annuity	$/kW/year	121.11	171.51	162.70				
Fixed O&M	$/kW/year	9.94	46.71	21.66	6.76	70	100	15
Fixed Cost	$/kW/year	131	209	180	6.76	70	166	15
Variable O&M	$/MWh	1.99	0	0	10.63	7.06	2.29	2.66
Heat Rate	MMBtu/MWh	6.3	0	0	9.8	9.75	0	0
Variable Fin. Cost	$/MWh	27	0	0	50	27	0	0
Variable Carbon Cost	$/MWh	21.79	0	0	33.91	43.58	0	0
Total Variable Cost	$/MWh	58	0	0	97	88	2.3	2.7

Including Energy Storage

Table 12: Effect of Exogenous Inclusion of Energy Storage Capacity on Lock-In Effect

	Storage Capacity	**10 GWh**			**262 GWh**	
	Carbon Price ($/ton)	**0**	**FZTF**	**50**	**0**	**50**
Δ Capacity (GW)	Gas CC	4.27	0	0	0	0
	Wind	0	50.64	53.92	0	62.58
	Solar	0	0	0	0	0
Energy Share (%)	Gas CC	28.44	32.58	30.16	27.03	28.68
	Wind	3.36	24.83	26.22	3.36	29.77
	Solar	0.22	0.22	0.22	0.22	0.22

No Exogenous Nuclear Retirements

Table 13: Effect of nuclear retirements.
Start with existing – Assume exogenous retirements of only coal, but not nuclear

	Capacity (GW)			**Energy Share (%)**	
Carbon Price ($ / ton)	Existing	Always 0	Always 50	Always 0	Always 50
CC	**41.05**	**41.05**	41.05	23.24	25.52
Wind	**7.92**	**7.92**	54.56	3.36	23.13
Solar	**0.88**	**0.88**	4.82	0.22	1.22
Coal	**47.62**	**46.23**	30.29	26.16	3.86
Nuclear	**33.73**	**33.73**	33.73	36.14	36.12
Hydro	**9.91**	**9.91**	9.91	10.62	10.23
CT	**25.25**	**25.25**	25.25	0.27	0.39