Decarbonization and Electrification in the Long Run

Stephen Holland (University of North Carolina at Greensboro)

Erin Mansur (Dartmouth College)

Andy Yates (University of North Carolina at Chapel Hill)

Addressing climate change requires substantial transformations of the economy

- Decarbonization of the grid
- Electrification (increasing demand) may or *may not* make this more difficult
- The electricity sector of the future may look nothing like today
- We develop a long run model to explore these issues
  - Theoretical possibilities
  - Simulations shows relevance of theoretical results and provides additional insights into decarbonization and electrification policies

Long-run competitive equilibrium

- Build on model from Borenstein (2005)
- Representative year with many time periods (hours)
- Time-varying electricity demand with non-zero elasticity
- Generation (wind, solar, nuclear, baseload natural gas, peaker)
  - Choice of capacity and hourly output
  - Intermittency of renewables
- Storage
  - Choice of capacity
  - Dynamic optimization of storage

Planner's problem (no elasticity, no storage)

$$\max_{q_{it}, K_i} - \sum_t \left[\sum_i c_i q_{it} \right] - \sum_i r_i K_i$$

- Endogenous choice of
  - q_{it} generation by technology *i* in hour t
  - K_i capacity for technology *i*

- System balance
  - $Q_t = \sum_i q_{it}$ in hour t

- Technology i has:
  - c_i constant marginal cost (can include carbon)
  - r_i unit capital cost
  - f_{it} hourly capacity factor, $f_{it} \in [0,1]$
  - Generation constraint: $q_{it} \leq f_{it} K_i$

Planner's problem (no storage)

$$\max_{Q_t, q_{it}, K_i} \sum_t \left[U_t(Q_t) - \sum_i c_i q_{it} \right] - \sum_i r_i K_i$$

- Endogenous choice of
  - q_{it} generation by technology *i* in hour *t*
  - K_i capacity for technology *i*
  - Q_t consumption in hour *t*
- System balance
  - $Q_t = \sum_i q_{it}$ in hour t
- Technology i has:
  - c_i constant marginal cost (can include carbon)
  - r_i unit capital cost
  - f_{it} hourly capacity factor, $f_{it} \in [0,1]$
  - Generation constraint: $q_{it} \leq f_{it} K_i$

- Consumer benefit is $U_t(Q_t)$ so demand D_t is defined s.t. $U_t'(D_t(p)) \equiv p$

Planner's problem

$$\max_{Q_t, q_{it}, b_t, K_i, \bar{S}} \sum_t \left[U_t(Q_t) - \sum_i c_i q_{it} \right] - \sum_i r_i K_i - r_s \bar{S}$$

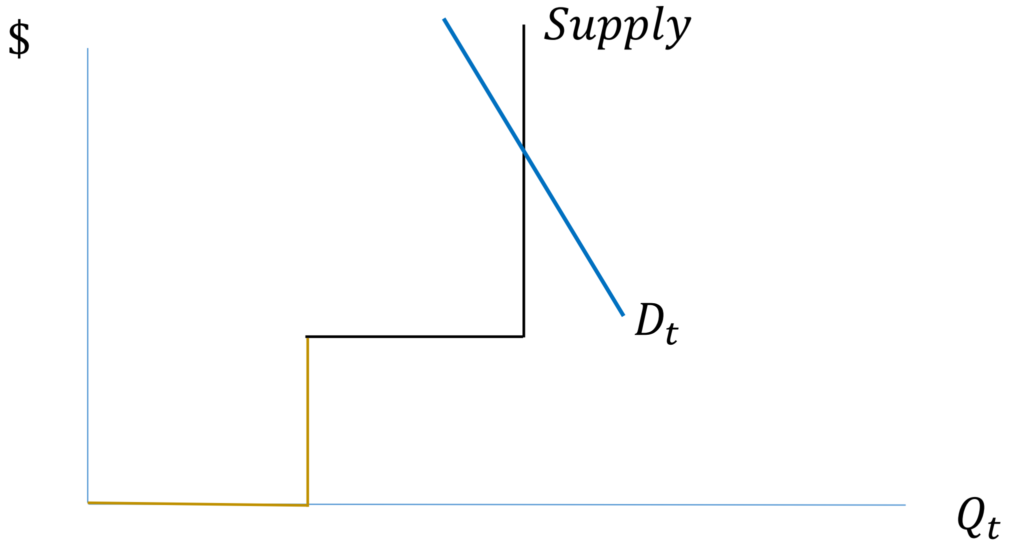
- Additional endogenous choice of
  - q_{it} generation by technology *i* in hour *t*
  - K_i capacity for technology *i*
  - Q_t consumption in hour *t*
  - b_t battery (dis)charging in hour *t*
  - $\bar{S}$ battery capacity
- System balance
  - $Q_t + b_t = \sum_i q_{it}$ in hour *t*
- Technology i has:
  - c_i constant marginal cost (can include carbon)
  - r_i unit capital cost
  - f_{it} hourly capacity factor, $f_{it} \in [0,1]$
  - Generation constraint: $q_{it} \leq f_{it} K_i$
- Battery has:
  - r_s unit capital cost
  - S_t battery charge state
  - $S_t = S_{t-1} + b_t$ battery evolution
  - $0 \leq S_t \leq \bar{S}$ battery state bounds

Note: Perfect foresight and no losses from charging/discharging or storing.

Economic Interpretation of Solution

Short-run equilibrium

- Supply step of $f_{it}\ K_i$
- Demand time varying



Long-run equilibrium

- Entry/exit zero profit condition:

$$\sum_t \max\{p_t - c_i, 0\} f_{it} = r_i$$

- Battery zero profit condition:

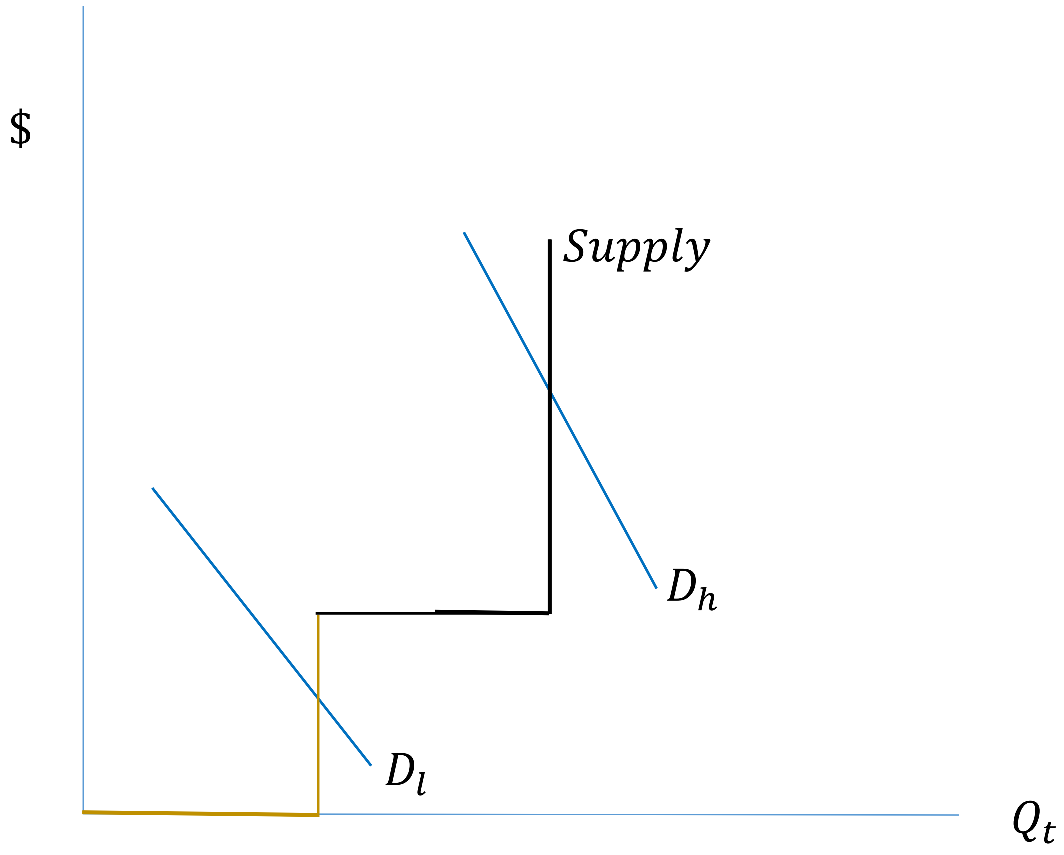
$$\sum_t p_t \frac{-b_t}{\bar{S}} = r_s$$

Theory results

- Long run may differ from short run intuition
  - Carbon tax may increase electricity consumption
  - Cheaper storage may decrease renewable capacity
  - Renewable subsidies may increase emissions
  - *Electricity demand growth may decrease emissions*

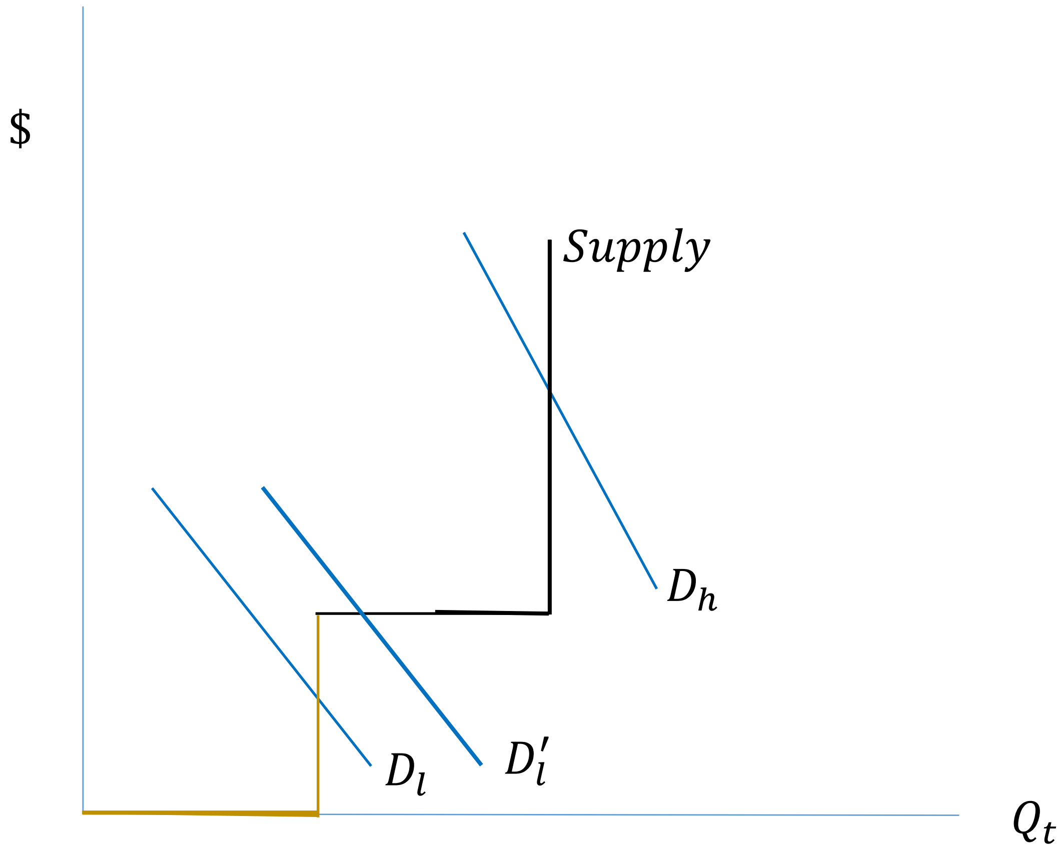
Demand growth may ↓ emissions

- Initial Equilibrium
  - Low marginal cost renewable produces in both periods
  - High marginal cost fossil produces in the high period



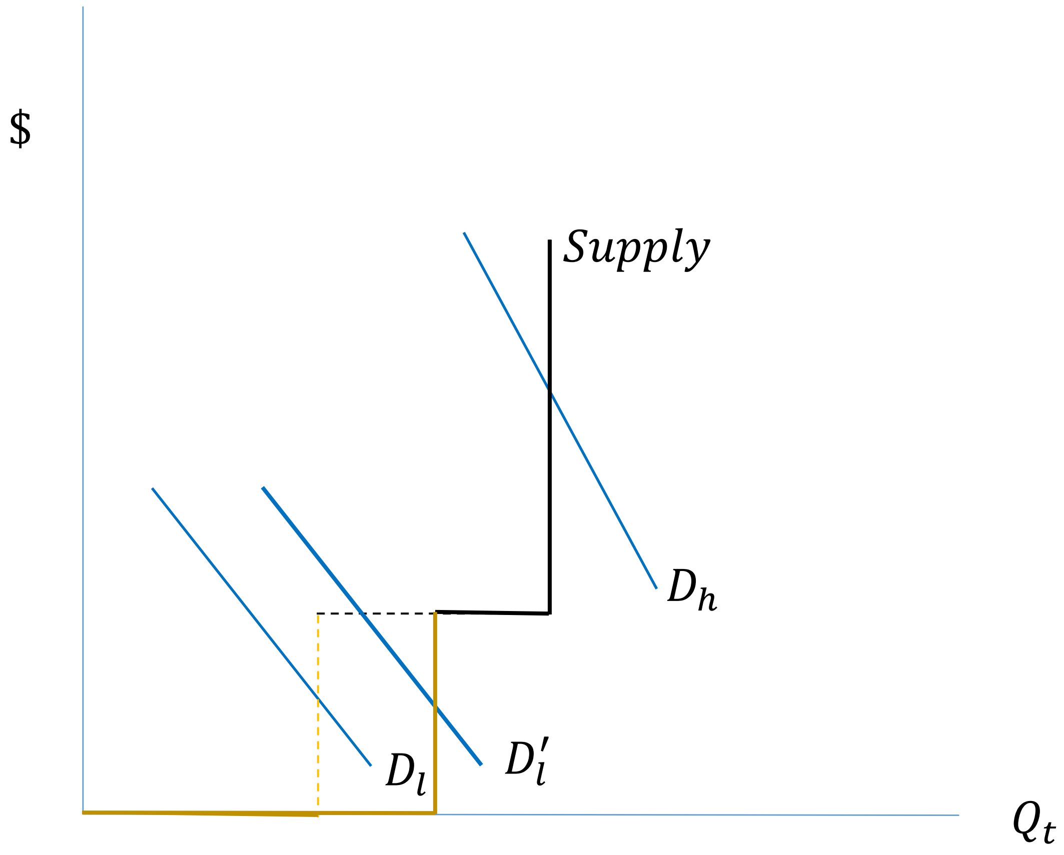
Demand growth may ↓ emissions

- Suppose new EVs charge in low period
  - Low period price p_l increases
  - Induces entry of renewables



Demand growth may ↓ emissions

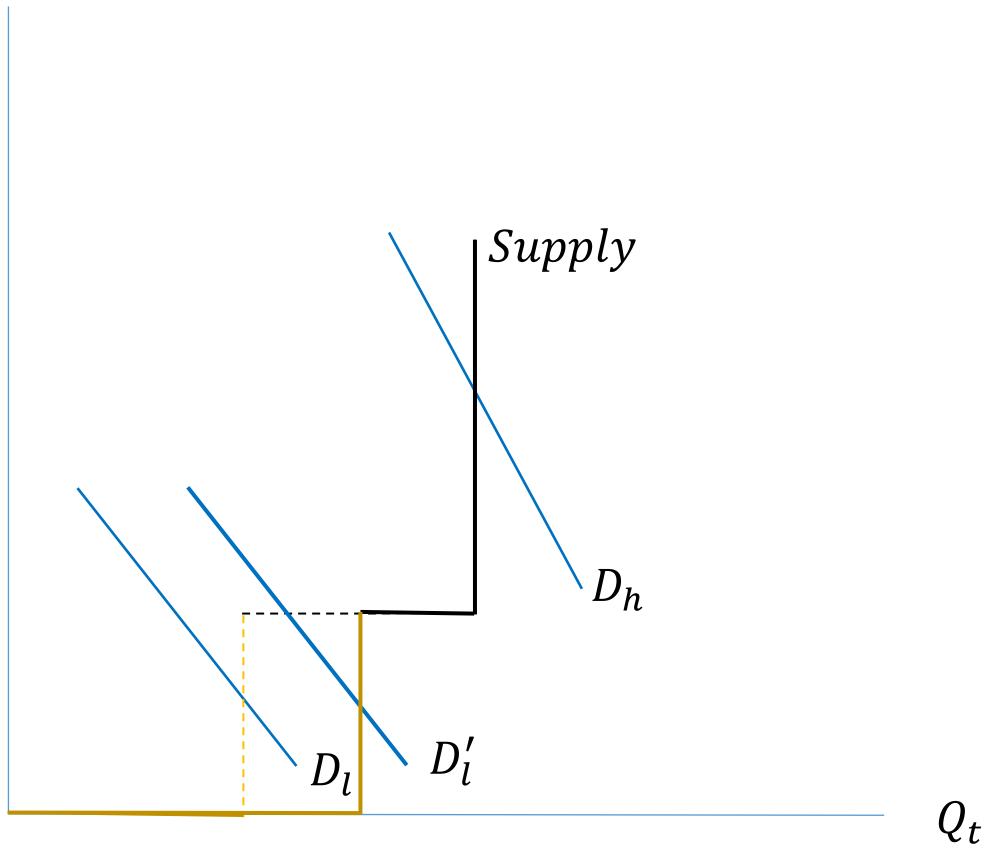
- Suppose new EVs charge in low period
  - Low period price p_l increases
  - Induces entry of renewables
  - Renewable capacity displaces fossil capacity 1:1
  - Fossil generation (and emissions) *decrease*



Demand growth may ↓ emissions

- Suppose new EVs charge in low period
  - Low period price p_l increases
  - Induces entry of renewables
  - Renewable capacity displaces fossil capacity 1:1
  - Fossil generation (and emissions) *decrease*

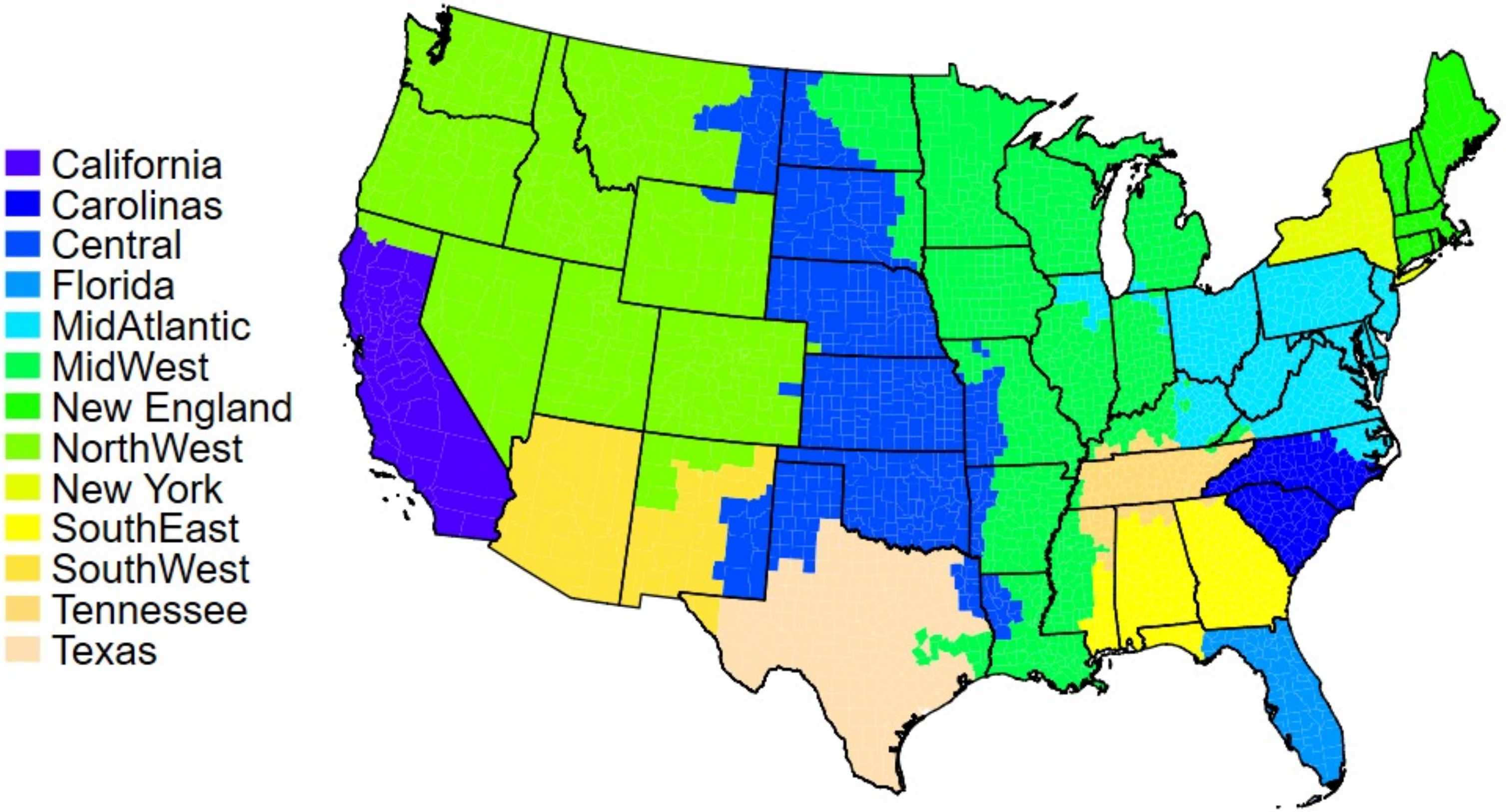
- Incremental emissions can range from *negative* to the fossil emissions rate
  (or even higher if 3[+] periods)
  - If charging in period h, then incremental emissions are fossil
  - If charging in period l, then incremental emissions are negative
  - If charging in both periods, then incremental emissions are in between



Simulation Data

- US electricity sector in 2019 for 13 EIA regions
  - Hourly consumption, solar & wind generation (EIA 930); hourly prices (ISOs & FERC)
- Hourly demand functions
  - Elasticity ≈ -.15
- Construct hourly capacity factors for wind & solar

  (EIA 860)
- Transmission
  - No constraints within region
  - Separate regions vs. combined



Capital & Marginal Costs for Different Technologies

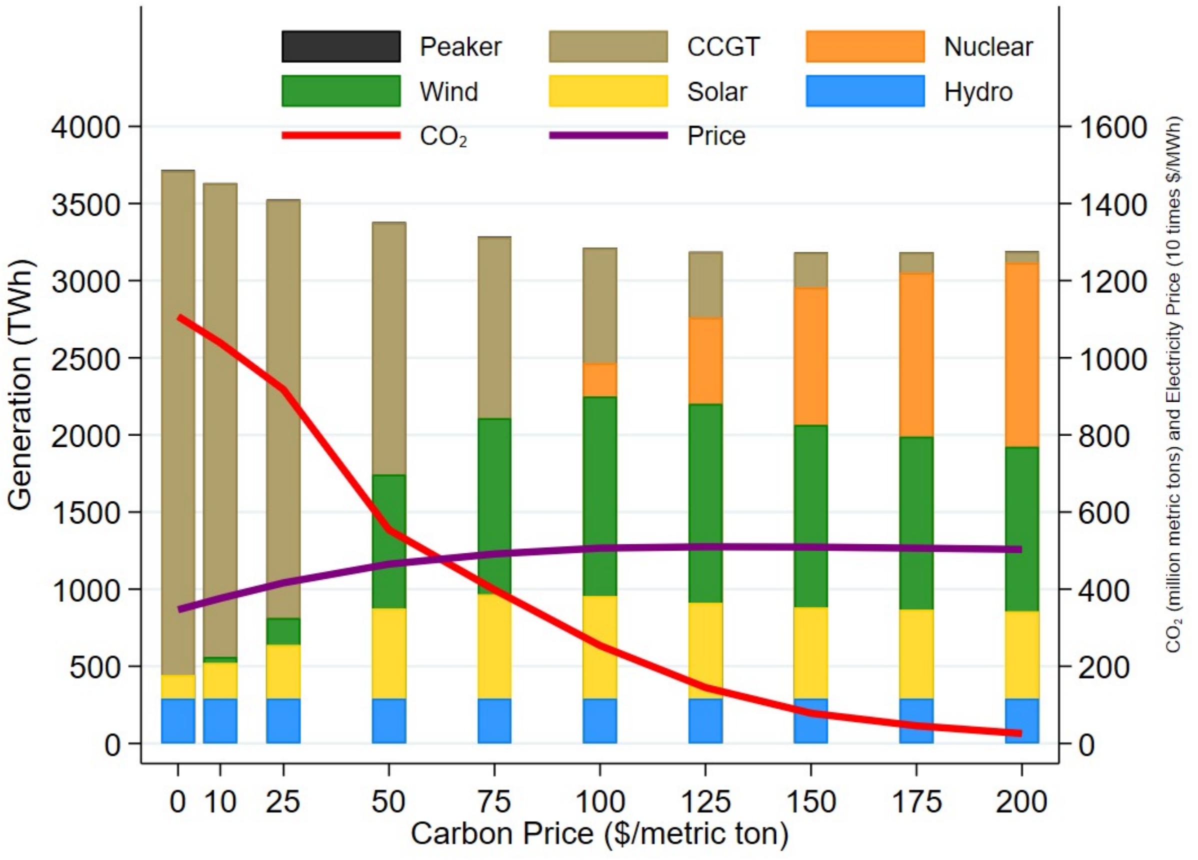
	Annual Capital Cost \$ per MW	Marginal Cost \$ per MWh	Carbon Emissions tons/MWh
Gas Combustion Turbine	54,741	44.13	0.526
Gas Combined Cycle	79,489	26.68	0.338
Advanced Nuclear	528,307	2.38	0
Wind (onshore)	132,602	0	0
Solar PV	83,274	0	0
Battery Storage	18,935	0	0

Notes: EIA Annual Energy Outlook, 2021 (online in 2026). Annual capital cost, r_i, includes fixed O&M and transmission costs. Battery cost r_s is per MWh storage capability

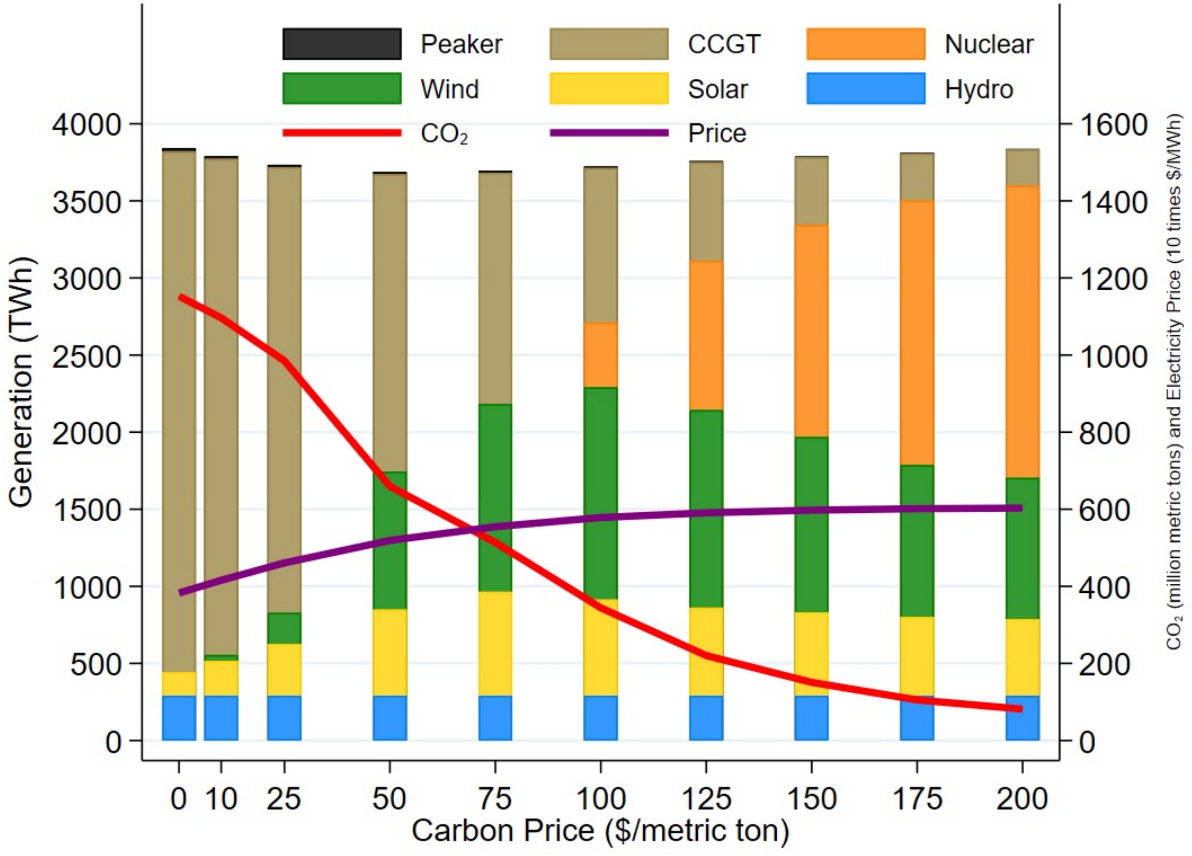
Solution algorithms

- Direct solution of planner's problem
  - Feasible when benefit U_t is quadratic and regions are separate
  - Hourly data: 60,000 variables and 120,000 constraints
- Gradient search algorithm
  - Often slower, but applicable in more cases
  - Profits are the gradient of the planner's objective
  - Given capacities, find prices and profits and iterate
  - Imbedded dynamic programming algorithm for battery

Carbon pricing (all regions aggregated)



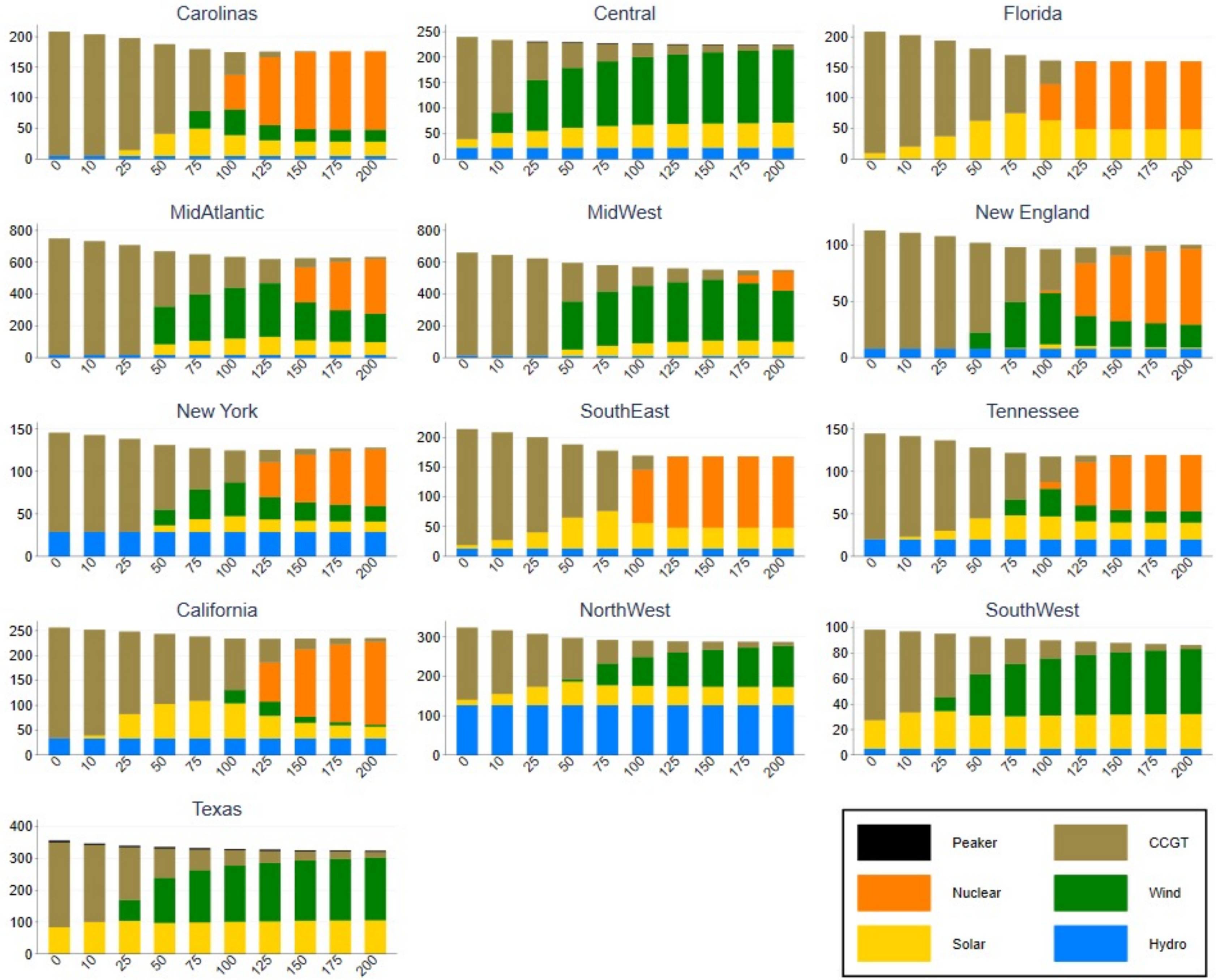
With linear demand



With iso-elastic demand

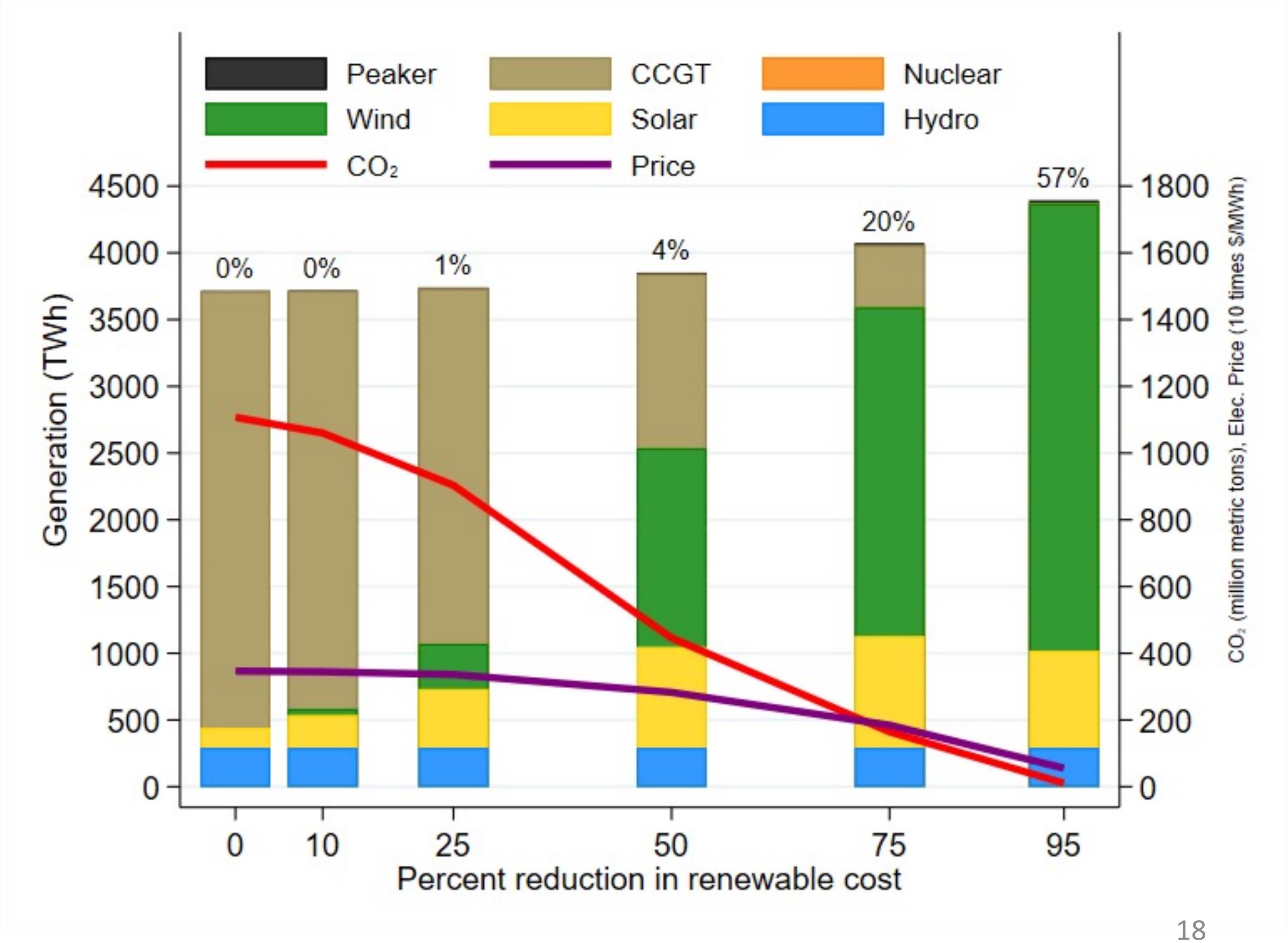
Carbon pricing for each region

- Carbon prices above $150 per metric ton reduce emissions
- Solar prevalent in most regions
- Regions without wind capability see nuclear entry
- Peaker gas plants rarely cost effective in model



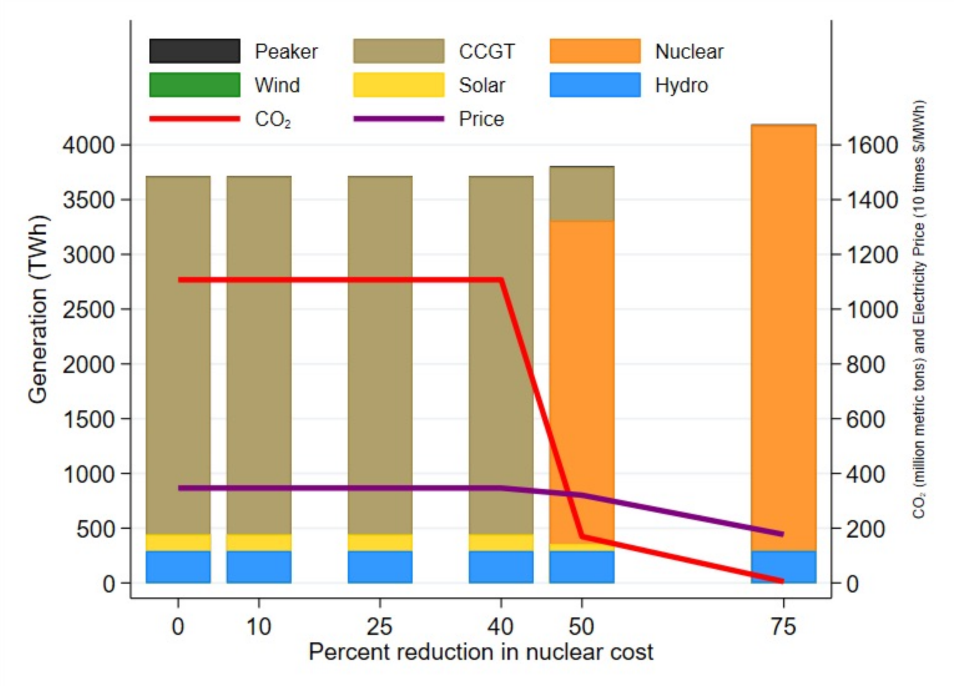
Reduction in renewable capital costs

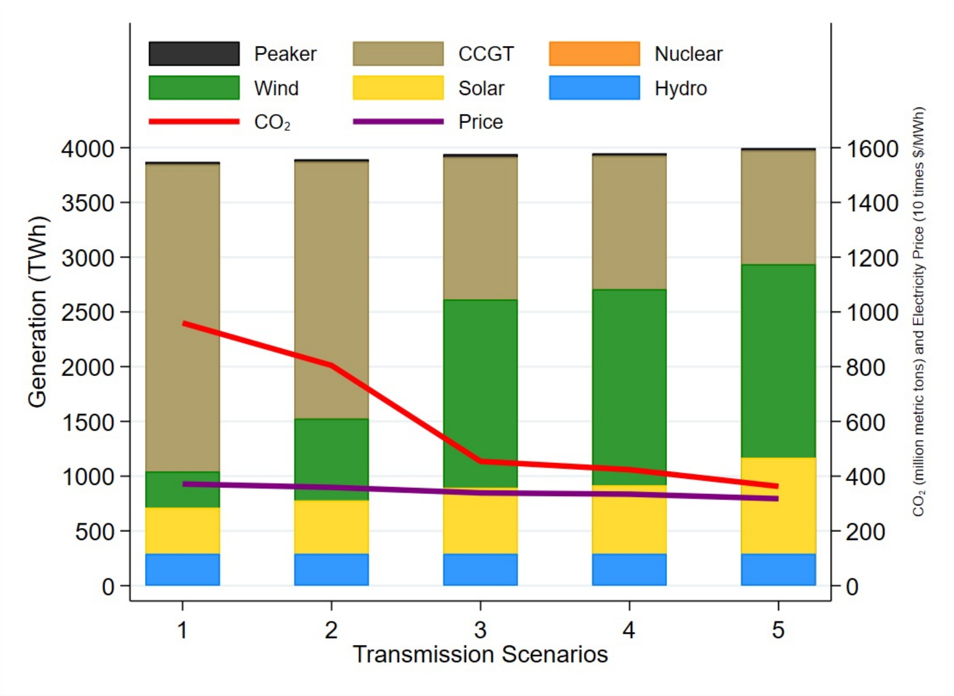
- Large reduction in emissions from 50% drop in costs
- More wind than solar added
- Percent of renewable generation curtailed shown above bar charts

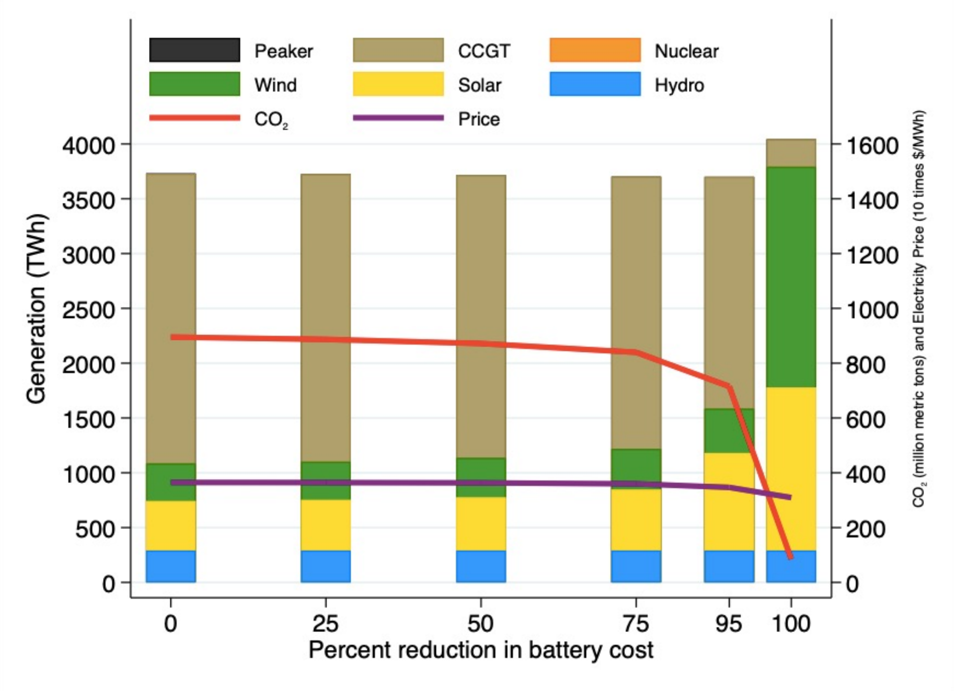


Other cases

- If nuclear costs fall 50%, then decarbonizes
- Transmission (integrate markets) matters if Midwest wind serves Eastern load
- Batteries do little even if costs down 95%







Second-best policies (single policy)

Policy	Annual Welfare Gains ($ billions) for SCC of $50	$100	$150	$200
Panel A: First best				
Pigouvian Carbon Tax	11.91	48.11	97.55	151.90
Panel B: Second-best subsidy				
Renewable	6.21	36.85	70.37	103.88
	[25]	[50]	[50]	[50]
Solar	3.45	17.53	33.31	54.31
	[25]	[50]	[50]	[75]
Wind	3.26	26.61	53.83	81.06
	[25]	[50]	[50]	[50]
Nuclear	0.00	13.33	60.73	108.13
	[0]	[50]	[50]	[50]
Battery	0.05	0.19	0.33	0.47
	[25]	[25]	[25]	[25]

[% subsidy]

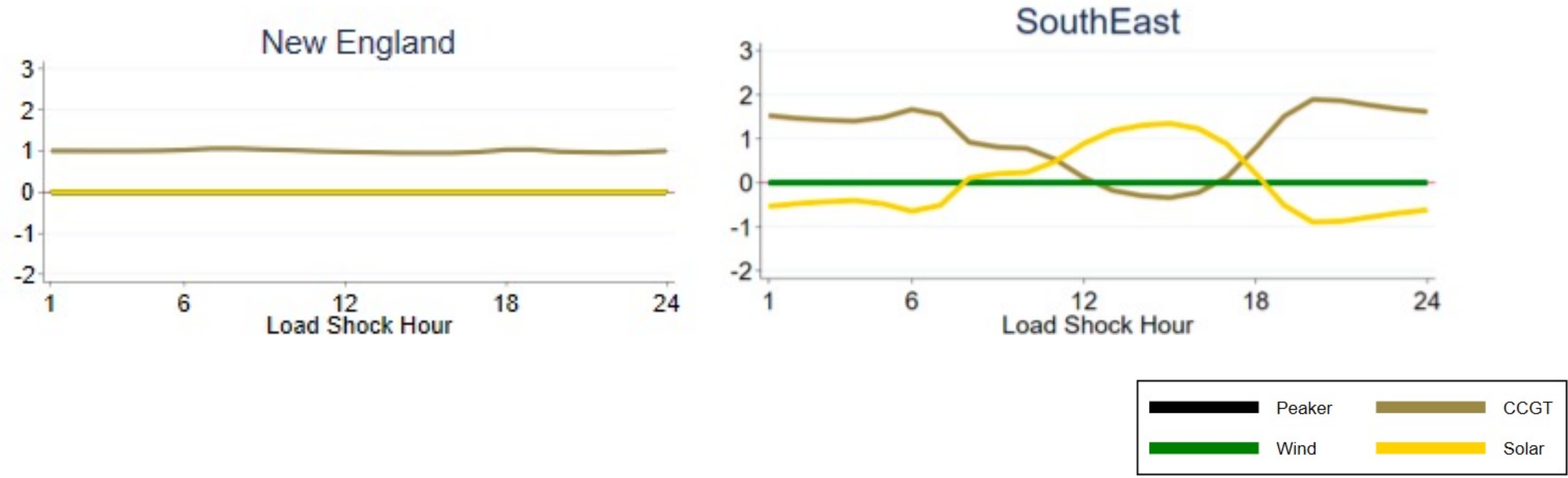
Second-best policies (complementarities)

	Annual Welfare Gains ($ billions) for SCC of			
Policy	$50	$100	$150	$200
Panel C: Relative gains of second-best subsidy combination				
Battery and Renewable	0.15	0.50	2.08	5.12
	[25,25]	[25,50]	[50,50]	[75,50]
Battery and Solar	0.10	0.43	2.44	7.27
	[25,25]	[25,50]	[50,50]	[50,75]
Battery and Wind	0.08	0.14	0.52	0.94
	[25,25]	[25,50]	[25,50]	[50,50]
Battery and Nuclear	0.00	0.38	1.46	3.17
	[25,0]	[25,50]	[50,50]	[50,50]
Renewable and Nuclear	0.00	0.14	5.30	6.22
	[25,0]	[50,50]	[50,50]	[50,50]
Solar and Wind	2.76	10.24	16.53	22.82
	[25,25]	[50,50]	[50,50]	[50,50]

[% subsidy]

Electrification

- Electrification changes which plants are build
- Incremental generation by technology
  - Hour-of-day load shocks (w/ renewable cost ↓ 25%)



Effects of electric vehicle adoption

Charging Profile	EV Share	Electricity Price ($/MWh)	CO_2 (mmt)	Incremental Emissions (mt/MWh)	Incremental Generation (MWh/MWh)	Incremental Renewables (MWh/MWh)
	0%	36.51	903	.	.	.
Convenience	100%	35.98	1,148	0.36	0.98	-0.08
Carbon Minimizing	100%	30.57	842	-0.09	1.02	1.32

- EV charging..
  - may reduce emissions from the grid in total
  - may crowd out renewables, thereby increasing the emissions intensity

Welfare Gains of 100% EV Adoption

Charging Profile	Electricity Price ($/MWh)	CO_2 (mmt)	Annual Welfare Gains ($ billions) for SCC of $0	$50	$100	$150	$200
Convenience	35.98	1,148	60.4	88.9	117.3	145.8	174.2
Carbon Minimizing	30.57	842	36.0	79.8	123.5	167.3	211.0
Social Profile	35.71	946	55.9	94.4	133.0	171.6	210.1

Accounts for the consumer surplus from electricity and driving, the cost of electricity and gasoline, the capital costs of gasoline and electric vehicles, and the carbon externality from electricity and driving gasoline vehicles

Social profile assumes SCC of $100

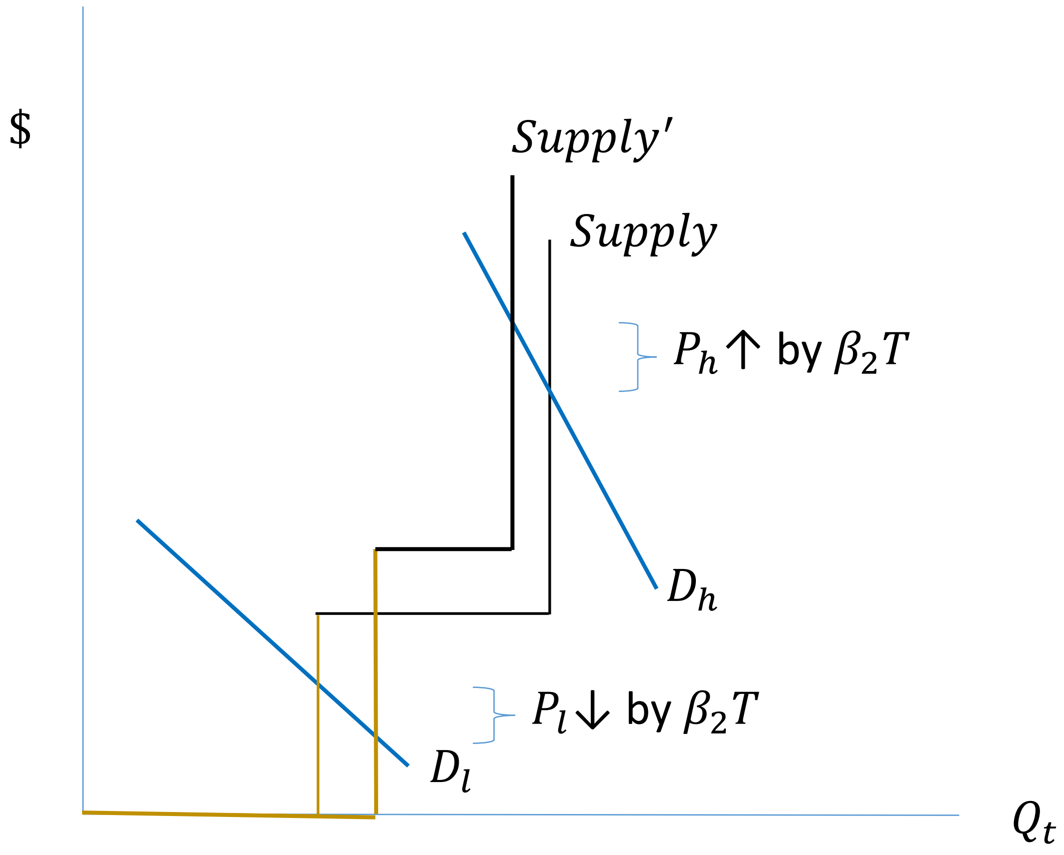
Conclusions

- We analyze a tractable long run model
- Long run effects are often different from short run intuition
- Electrification may facilitate decarbonization
- Timing of EV charging matters, so infrastructure matters
- Value of batteries deserves more study

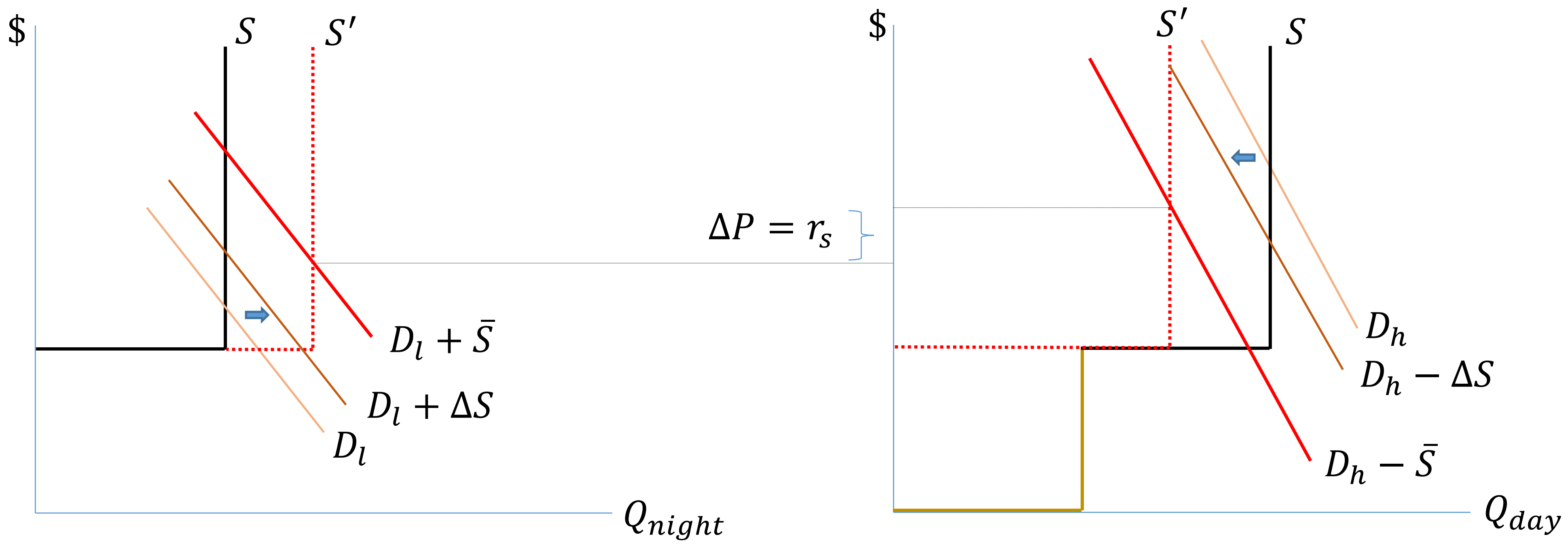
extras

Result 1: Carbon tax may ↑ electricity use

- Carbon tax (T) causes polluting technology *i*'s c_i to rise by $\beta_i T$
- Prices increase in hours when fossil plants are marginal
  - Some fossil plants exit
  - Renewables enter (more fossil exit)
- Prices *decrease* in hours when renewables are marginal
- Net effect on consumption depends on the slopes of the demand curves
  - If renewable hours flat (elastic) then electricity use increase



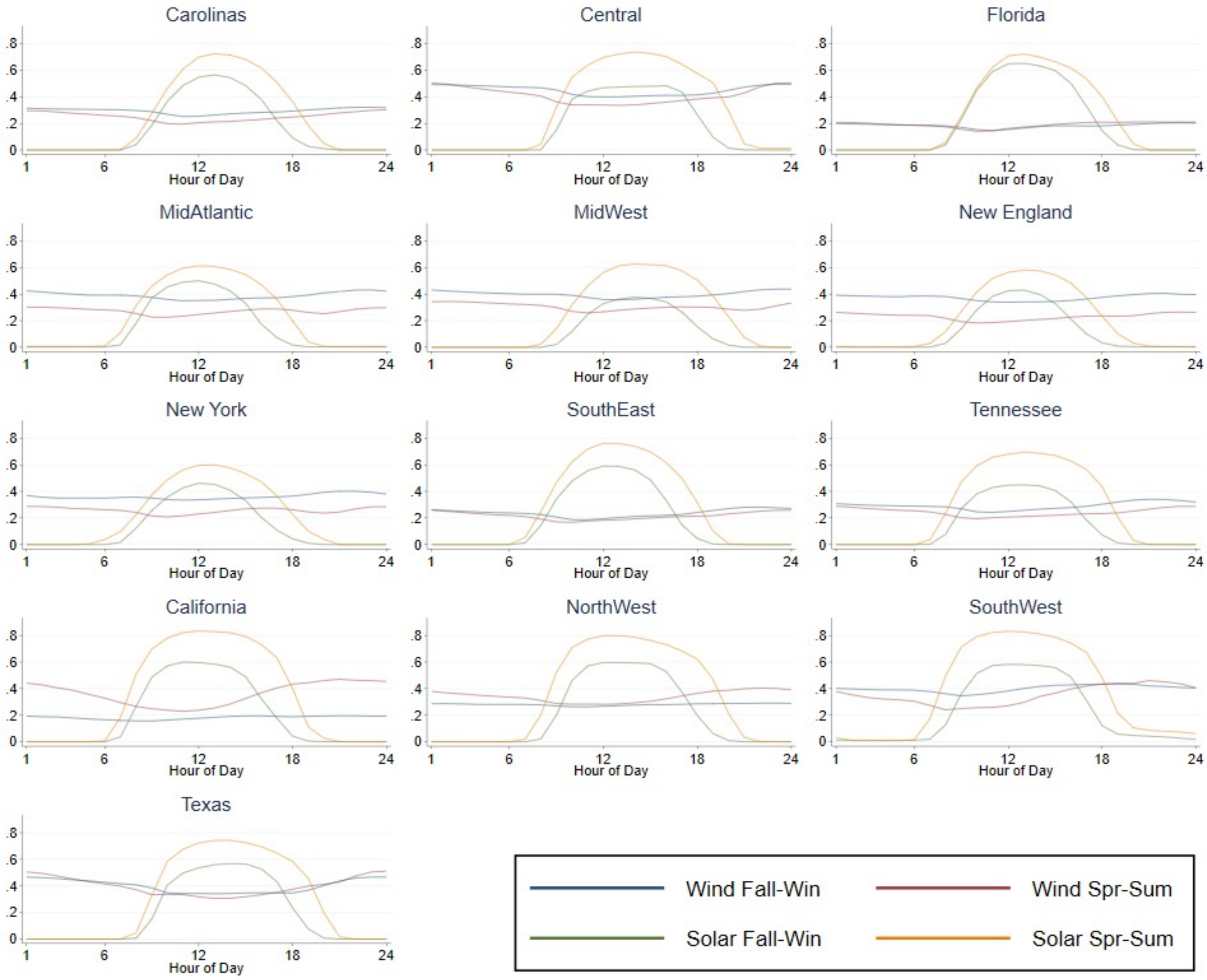
Result 2: Cheaper storage may ↓ renewables



- With solar producing only in period h, storage completely drives out solar
  - Storage crowds out technologies that produce primarily at high prices
- Define levelized cost of energy (LCOE) as $c_i + \frac{r_i}{\sum_t f_{it}}$
- As $r_s \to 0$, storage favors the technology with the lowest LCOE
  - In regions where renewables are not very productive, storage favors fossil generation

Mean hourly computed capacity factors by season and hour of day

- Calibrate capacity factors by using data on monthly generation (EIA 923) and capacity (EIA 860)
- Distribute generation within a month using hourly 930 data
- No wind generation data in some markets
  - Use hourly wind speed data
  - Nonlinear transformation



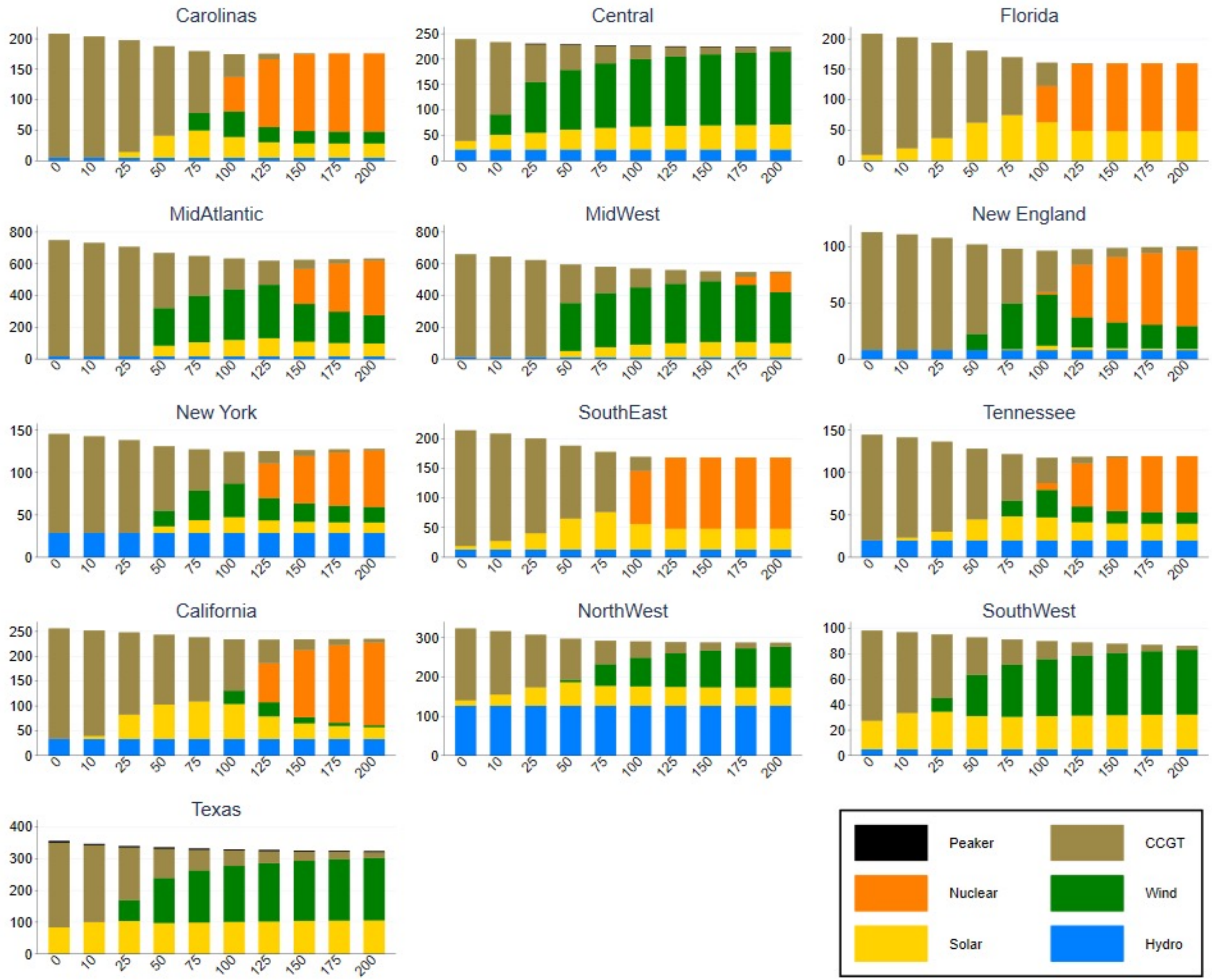
Calibration

- Demand functions
  - Model as having customers facing dynamic pricing
  - Assume an elasticity of -0.15 and examine linear and iso-elastic forms
  - Pin demand curve at observed hourly consumption and market price
    - Prices from ISOs or FERC 714 “system lambda” for regions under regulation

- Generation
  - Five endogenous technologies: solar, wind, nuclear, peaker natural gas, CCGT (baseload natural gas)
    - Coal is dominated by CCGT at current fuel prices and is not in the model
  - Hydroelectric power is modeled as exogenous

Carbon pricing for each region

- Carbon prices above $150 per metric ton reduce emissions
- Solar prevalent in most regions
- Regions without wind capability see nuclear entry
- Peaker gas plants rarely cost effective in model

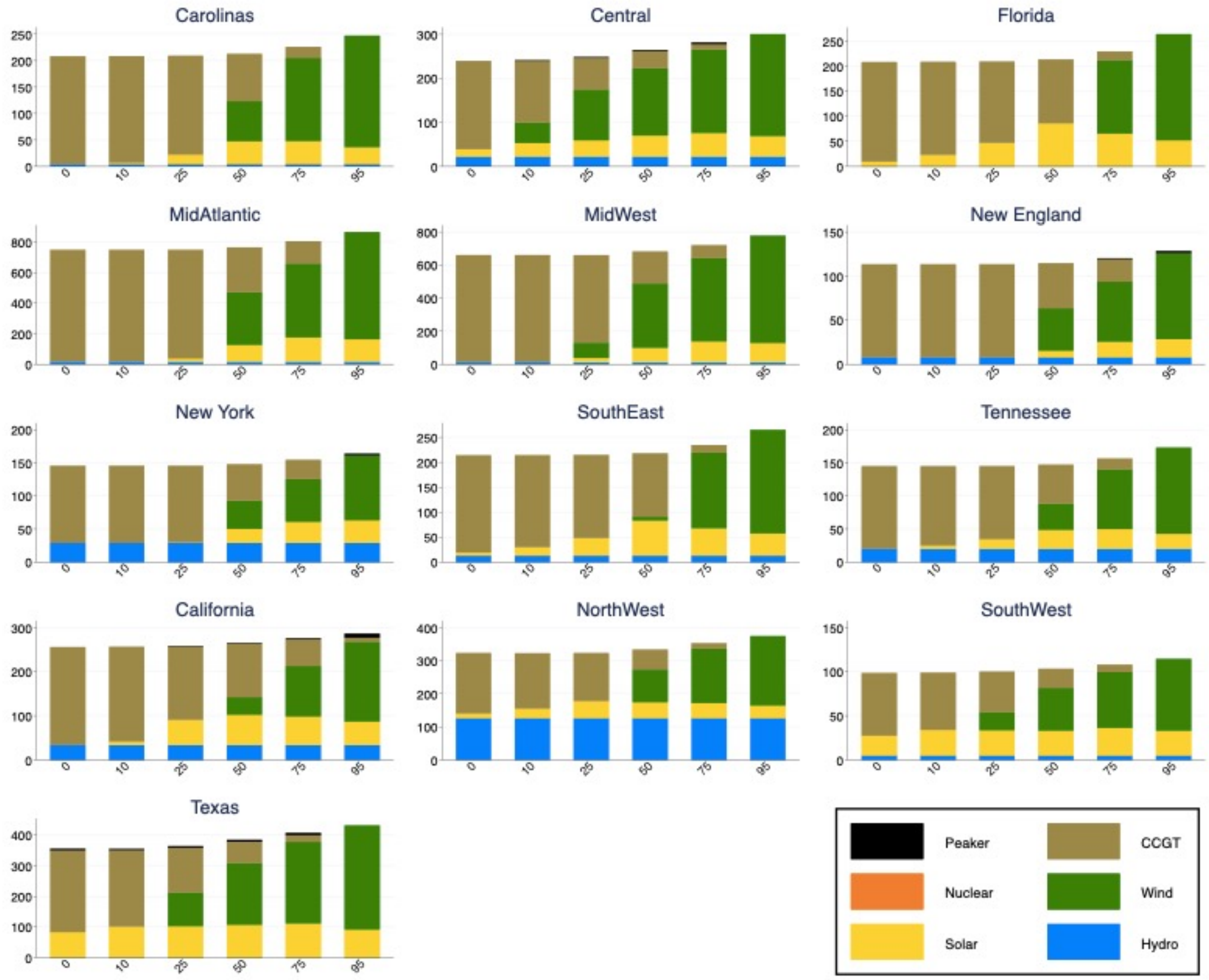


Benefits of carbon pricing

Carbon Price ($/ton)	Electricity Price ($/MWh)	Carbon (mmt)	Annual Welfare Gains ($ billions) for SCC of $0	$50	$100	$150	$200
0	37.65	1,107	**0.0**	0.0	0.0	0.0	0.0
50	50.92	554	-16.1	**11.6**	39.3	66.9	94.6
100	55.92	254	-38.6	4.1	**46.7**	89.4	132.0
150	56.52	78	-59.7	-8.2	43.2	**94.7**	146.1
200	56.04	26	-68.7	-14.6	39.5	93.6	**147.6**

- High taxes when damages are low is costly
- No carbon price when damages are high much more costly

Renewable subsidies for each region

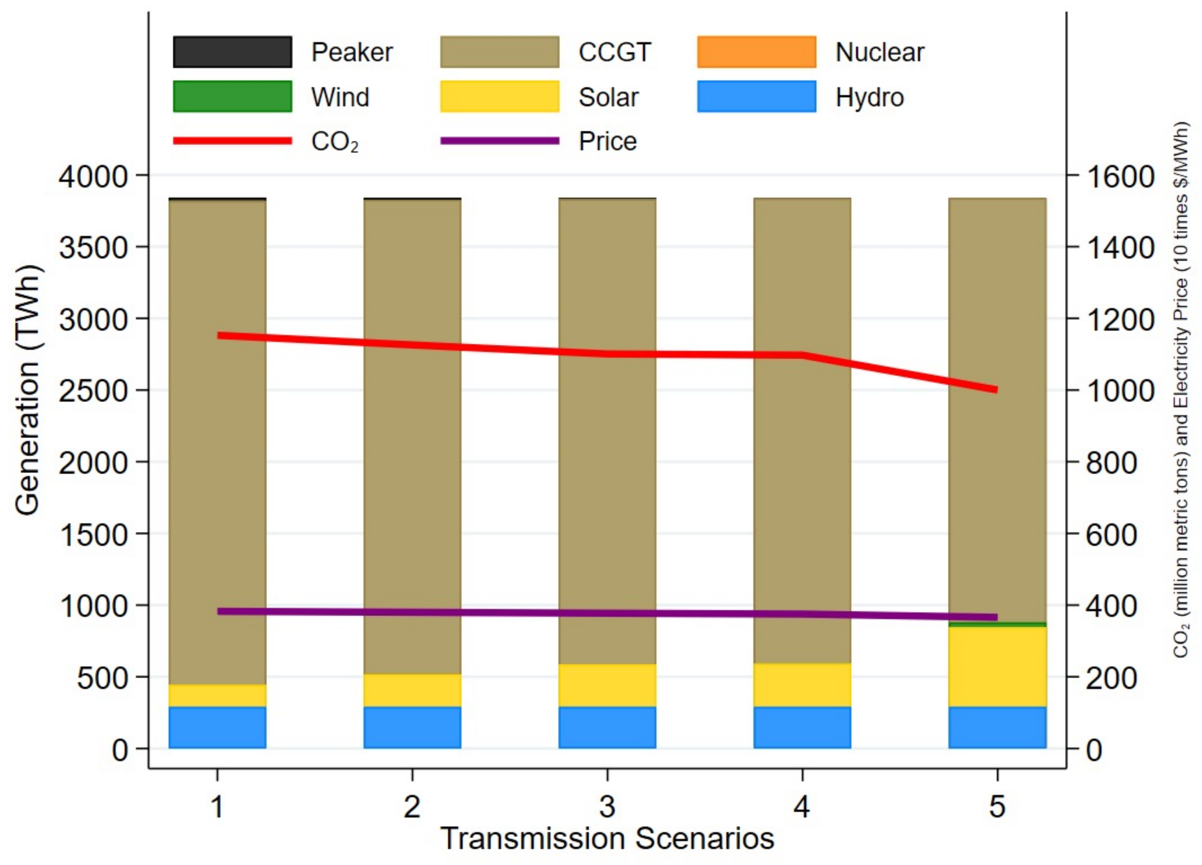


Benefits of reducing renewable capital costs

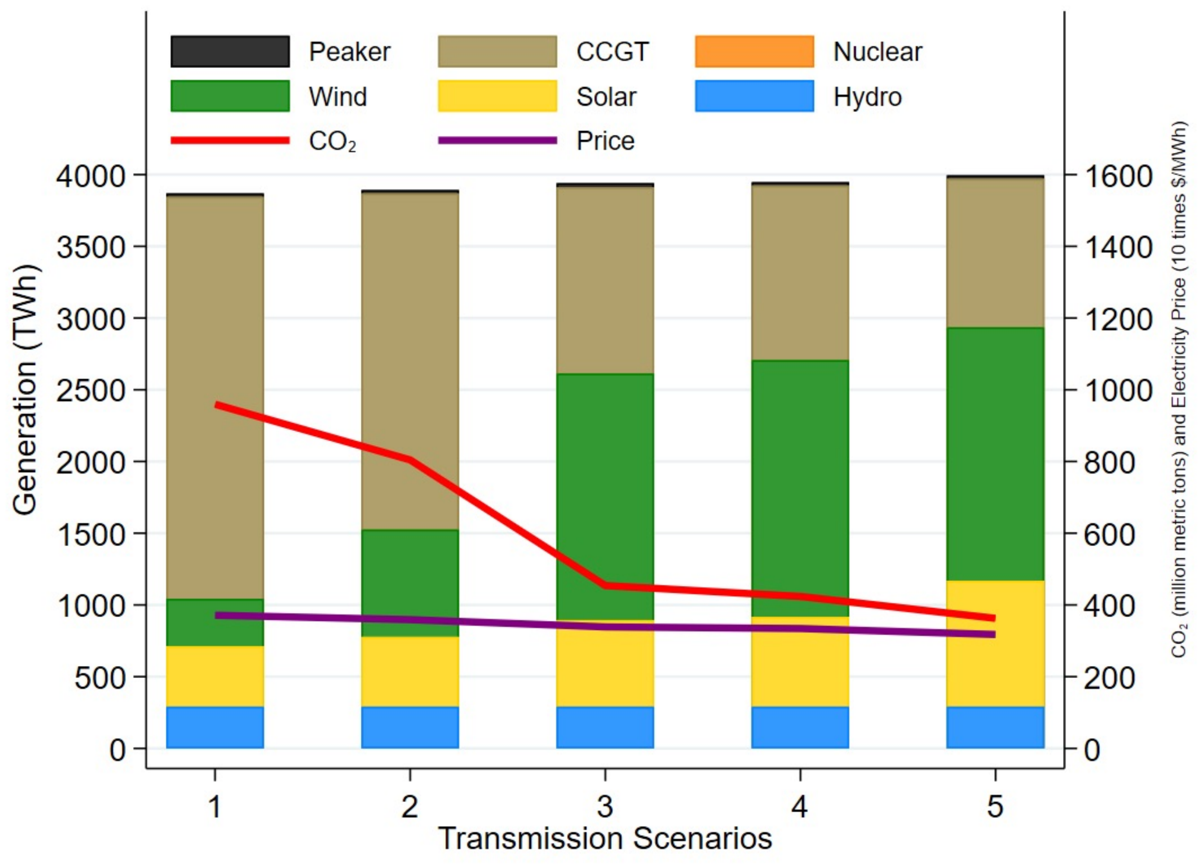
Cost Reduction (%)	Electricity Price ($/MWh)	Carbon (mmt)	Annual Surplus Gains ($ billions) for SCC of					Subsidy Cost $ bill
			$0	$50	$100	$150	$200	
0	37.65	1,107	0.0	0.0	0.0	0.0	0.0	0.0
25	36.51	903	3.6	13.8	24.0	34.2	44.4	7.7
50	30.69	446	21.4	54.5	87.6	120.6	153.7	51.5
75	20.07	165	57.3	104.5	151.6	198.7	245.9	146.4
95	6.14	10	113.8	168.6	223.5	278.3	333.2	424.4

Transmission (market integration)

Scenario 1: 13 transmission regions
Scenario 2: 5 regions (NE, SE, MW, Texas, & West)
Scenario 3: 3 regions (East, Texas, & West)
Scenario 4: 2 regions (East plus Texas, & West)
Scenario 5: 1 unified region



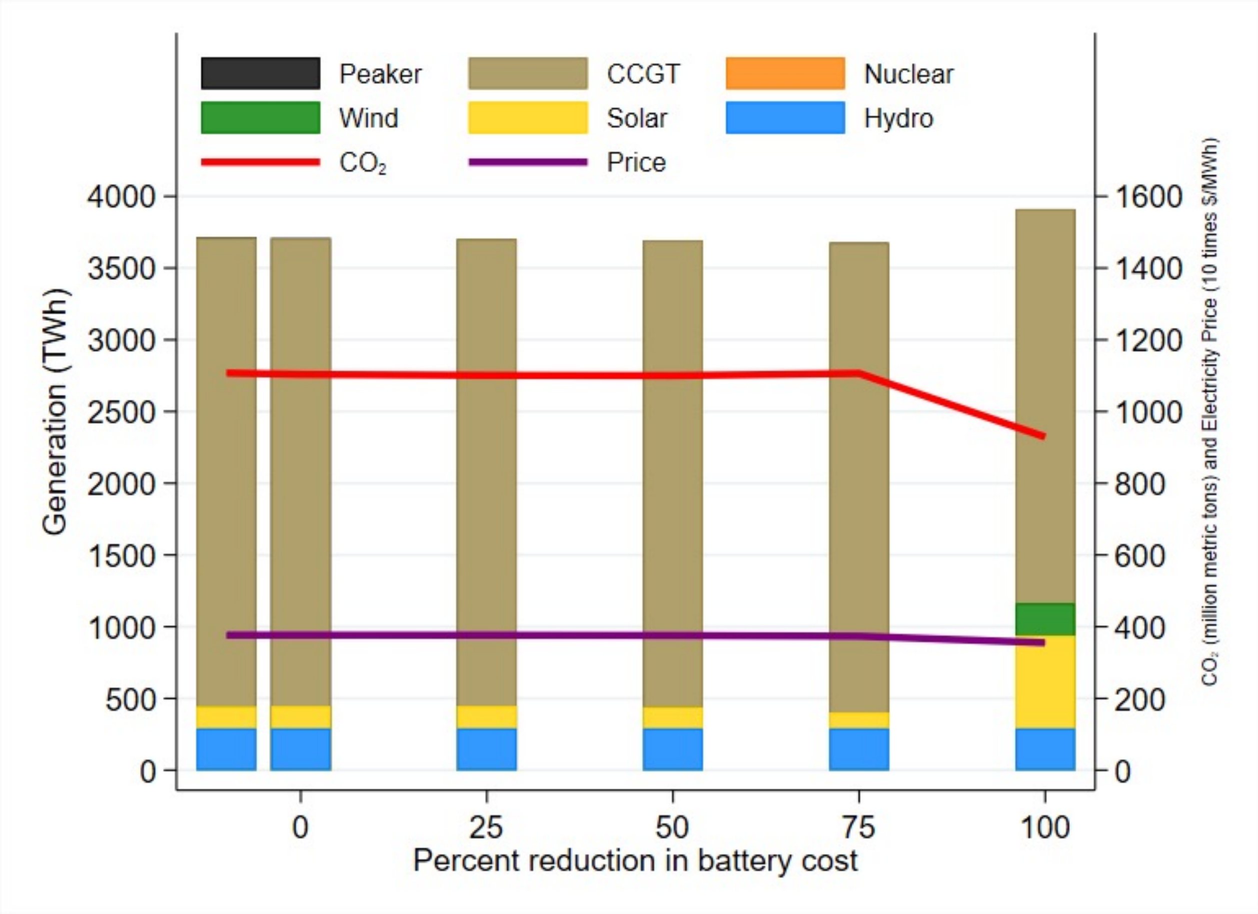
With baseline renewables costs



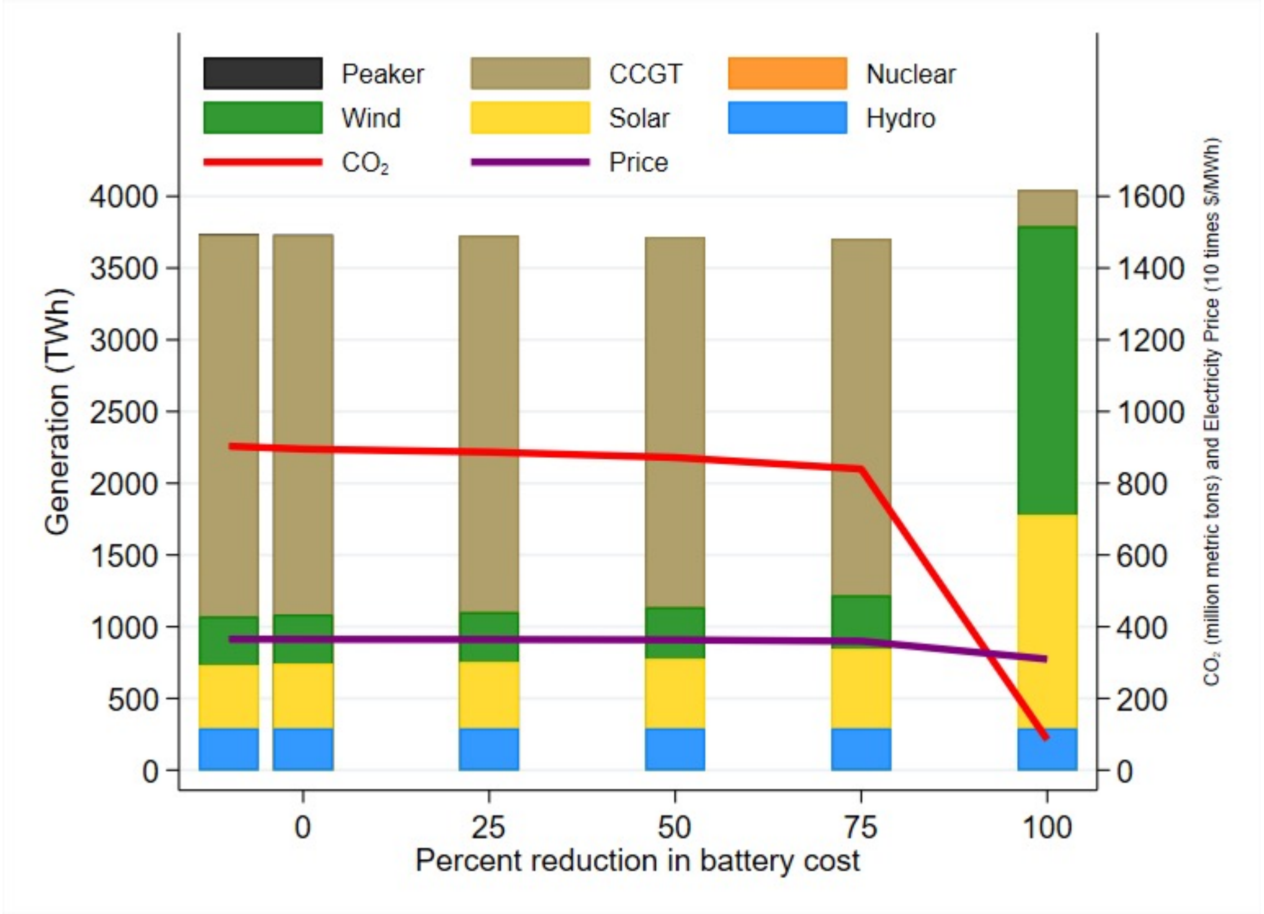
With 25% drop in renewables costs

Transmission Scenario	Electricity Price ($/MWh)	Carbon (mmt)	Annual Surplus Gains ($ billions) for SCC of $0	$50	$100	$150	$200	Subsidy Cost $ bill
Panel A: Baseline renewable capital costs								
Baseline	38.26	1,153	0.0	0.0	0.0	0.0	0.0	N.A.
Scenario 2	38.00	1,126	1.4	2.7	4.1	5.4	6.8	N.A.
Scenario 3	37.74	1,101	2.6	5.2	7.8	10.4	13.0	N.A.
Scenario 4	37.50	1,097	3.7	6.5	9.2	12.0	14.8	N.A.
Scenario 5	36.59	1,000	7.4	15.0	22.7	30.3	37.9	N.A.
Panel B: 25% reduction in renewable capital costs								
Scenario 1	37.12	960	3.6	13.2	22.9	32.5	42.2	7.4
Scenario 2	35.90	804	7.9	25.3	42.7	60.1	77.5	11.5
Scenario 3	33.88	454	15.0	49.9	84.9	119.8	154.8	21.1
Scenario 4	33.43	424	16.8	53.2	89.7	126.1	162.6	22.0
Scenario 5	31.76	363	22.3	61.8	101.4	140.9	180.4	22.8

Reduction in battery capital costs



With baseline renewables costs



With 25% drop in renewables costs

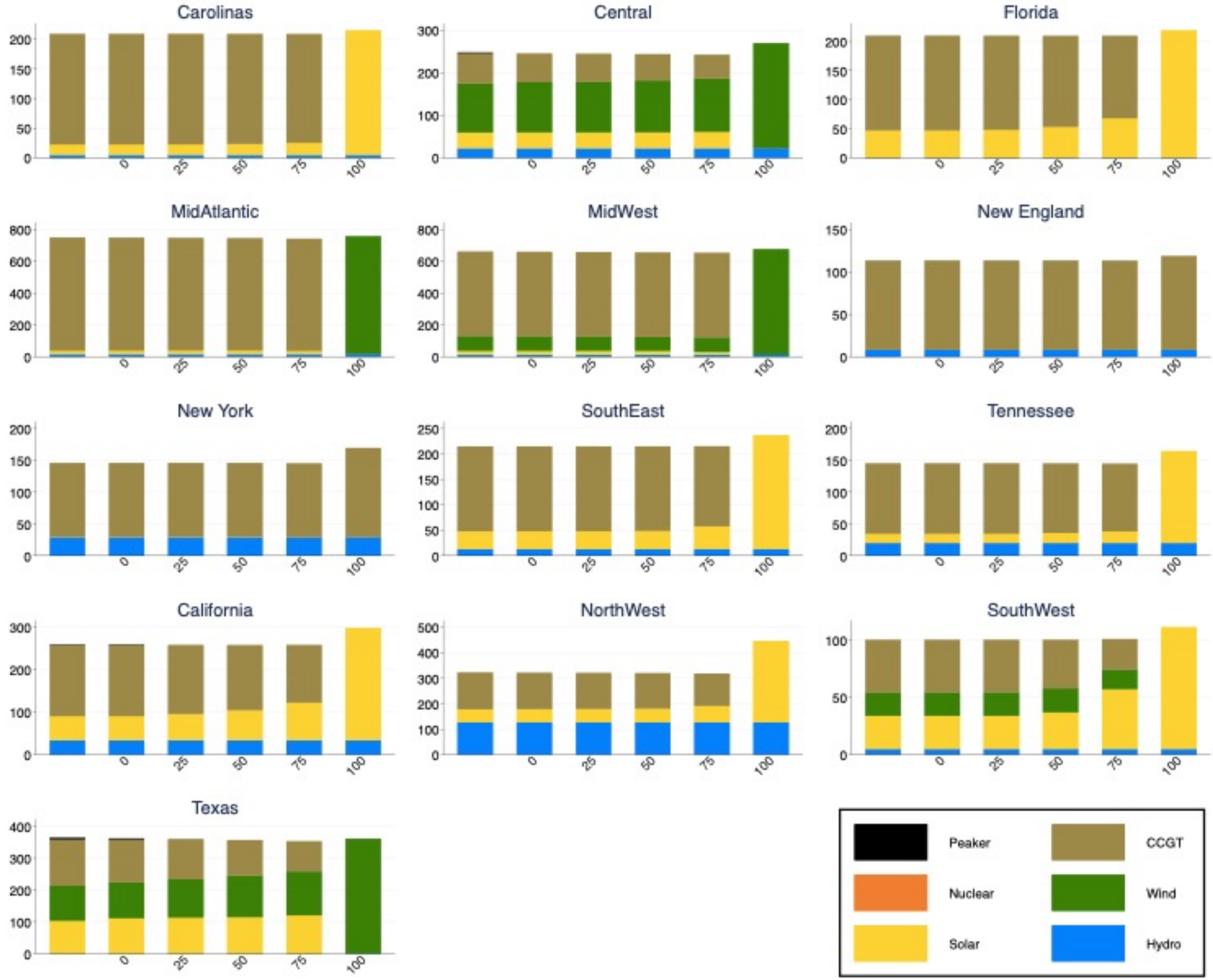
Levelized cost and capacities with costless battery capacity

- At current renewable costs, CCGT cheapest in all but 4 markets
- Central (SPP) has cheaper wind
- West has cheaper solar

Region	Solar	Wind	CCGT
East			
Carolinas	$ 45.93	$ 55.37	**$ 35.75**
Central	$ 39.94	**$ 35.16**	$ 35.75
Florida	$ 41.97	$ 81.00	**$ 35.75**
MidAtlantic	$ 50.29	$ 45.72	**$ 35.75**
MidWest	$ 54.07	$ 43.05	**$ 35.75**
New England	$ 59.22	$ 50.06	**$ 35.75**
New York	$ 53.62	$ 49.05	**$ 35.75**
SouthEast	$ 41.83	$ 66.81	**$ 35.75**
Tennessee	$ 45.19	$ 56.56	**$ 35.75**
West			
California	**$ 35.25**	$ 55.52	$ 35.75
NorthWest	**$ 35.20**	$ 48.62	$ 35.75
SouthWest	**$ 32.61**	$ 40.23	$ 35.75
Texas			
Texas	$ 38.86	$ 37.84	**$ 35.75**

Battery subsidies for each region

25% renewable capital cost ↓



Benefits of reducing battery capital costs

- Depend on reduction in renewables costs
  - At current renewable costs, emissions same even if subsidize batteries by 75%
- Only if batteries are free and renewables costs are halved does full decarbonization occur
  - Cost of these subsidies $9.5 trillion annually

Cost Reduction (%)	Electricity Price ($/MWh)	Carbon (mmt)	Annual Surplus Gains ($ billions) for SCC of $0	$50	$100	$150	$200	Subsidy Cost $ bill Battery	Renew
Panel A: Baseline renewable capital costs									
Baseline	37.65	1,107	0.0	0.0	0.0	0.0	0.0	N.A.	N.A.
0	37.65	1,104	0.1	0.3	0.5	0.7	0.9	0.0	N.A.
25	37.63	1,101	0.3	0.6	1.0	1.3	1.6	0.3	N.A.
50	37.56	1,100	0.8	1.2	1.5	1.9	2.2	1.4	N.A.
75	37.35	1,106	2.1	2.2	2.2	2.3	2.3	6.8	N.A.
100	35.53	929	30.4	39.4	48.3	57.2	66.1	4,548.4	N.A.
Panel B: 25% reduction in renewable capital costs									
No Storage	36.51	903	3.6	13.8	24.0	34.2	44.4	N.A.	7.7
0	36.49	895	3.8	14.4	25.0	35.6	46.2	0.0	7.9
25	36.44	887	4.1	15.1	26.1	37.2	48.2	0.4	8.0
50	36.33	872	4.8	16.5	28.3	40.1	51.8	1.9	8.3
75	35.97	840	6.4	19.8	33.2	46.6	59.9	8.2	9.1
100	30.95	85	46.7	97.8	148.9	200.1	251.2	8,284.2	84.8
Panel C: 50% reduction in renewable capital costs									
No Storage	30.69	446	21.4	54.5	87.6	120.6	153.7	N.A.	51.5
0	30.62	433	21.8	55.5	89.2	122.9	156.6	0.0	51.9
25	30.52	420	22.4	56.7	91.1	125.4	159.8	0.7	52.5
50	30.26	395	23.5	59.1	94.8	130.4	166.0	3.5	53.7
75	29.30	292	27.1	67.8	108.5	149.3	190.0	20.3	59.9
100	20.71	0	86.8	142.2	197.6	252.9	308.3	9,309.4	185.9
Panel D: 75% reduction in renewable capital costs									
No Storage	20.07	165	57.3	104.5	151.6	198.7	245.9	N.A.	146.4
0	19.92	147	58.0	106.0	154.0	202.0	250.0	0.0	147.0
25	19.72	134	58.8	107.4	156.1	204.8	253.4	1.1	147.7
50	19.29	110	60.5	110.4	160.3	210.1	260.0	5.4	148.5
75	17.90	52	66.1	118.9	171.7	224.4	277.2	30.8	146.9
100	10.36	0	130.4	185.8	241.1	296.5	351.9	9,921.2	303.4

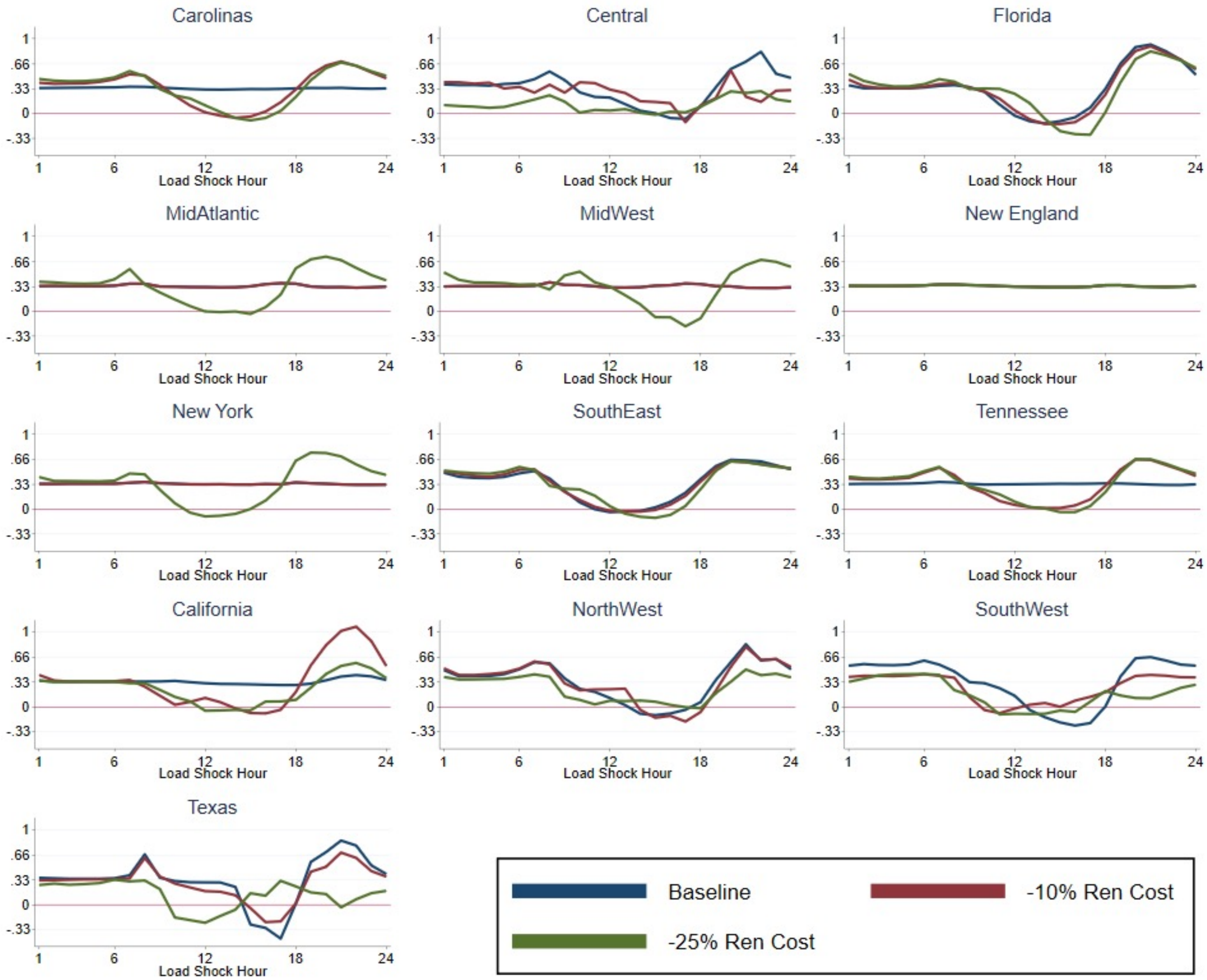
Outline

- Introduction
- Model
- Calibration
- Results on decarbonization policies
  - Pricing policies
  - Arbitrage policies
  - Policy interactions and the second best
- Results on electrification policies
- Discussion and conclusion

Welfare gains of carbon tax & renewable subsidy interactions

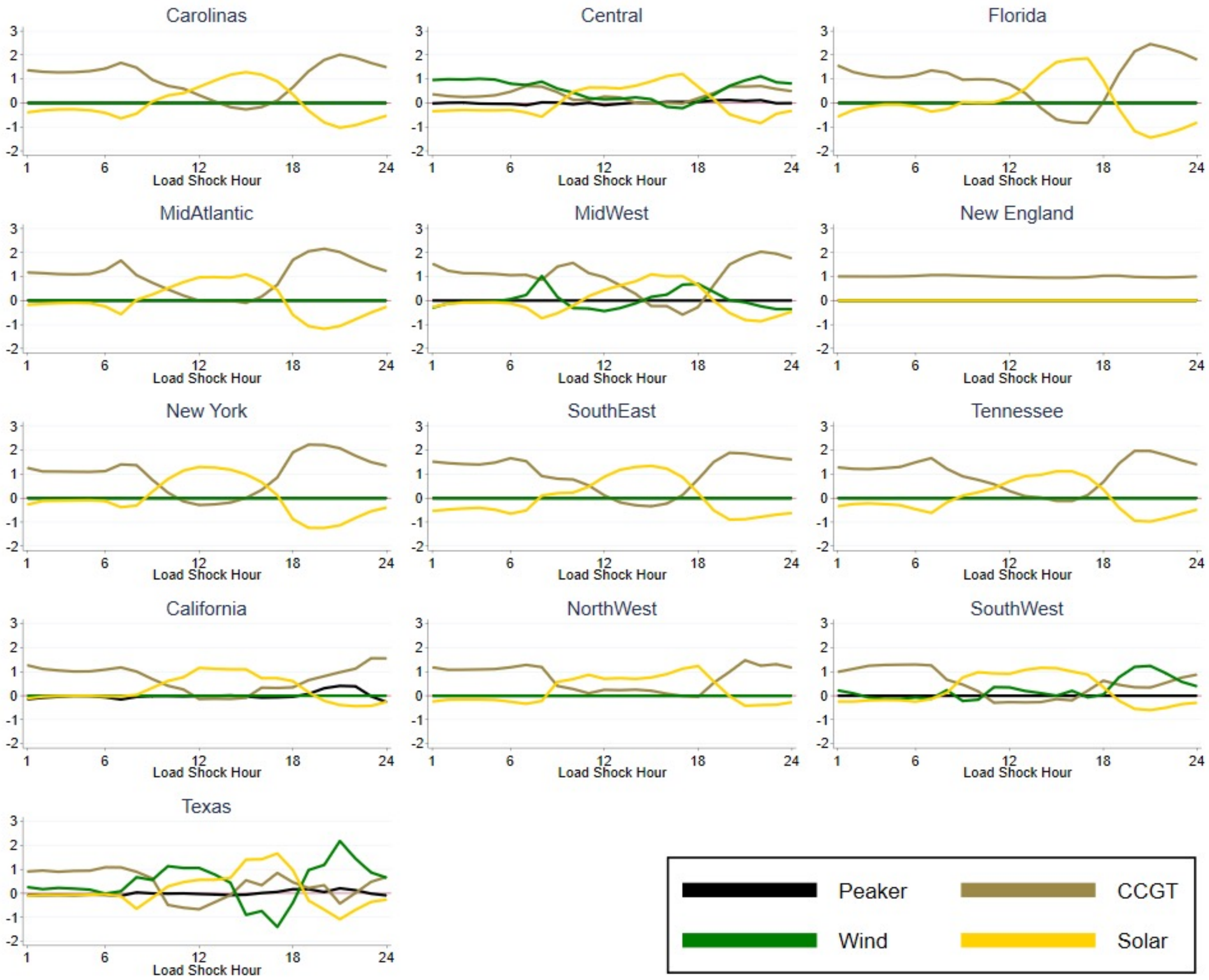
Carbon Tax	Renewable Subsidy					
	0	0.1	0.25	0.5	0.75	0.95
0	0.0	4.4	16.2	36.1	5.2	-200.9
→ 10	6.5	12.1	31.2	37.0	1.2	-203.0
25	16.5	28.4	39.5	37.0	-4.4	-205.9
50	39.3	42.7	44.1	33.3	-12.0	-210.0
75	45.3	46.0	44.2	29.0	-18.4	-212.7
100	46.7	46.0	42.7	24.9	-23.4	-214.9
125	45.6	44.8	39.8	21.4	-27.2	-216.9
150	43.2	43.0	37.2	18.4	-30.0	-218.9
175	41.2	40.9	34.9	15.7	-32.3	-220.6
200	39.5	39.2	32.8	13.5	-34.0	-222.3

Incremental emissions by hour-of-day load shocks



Incremental generation by technology for hour-of-day load shocks

25% renewable capital cost ↓



Electricity sector costs of 100% EV adoption

- **Flat profile**: equal charging in all hours
- **Solar profile**: charging proportional to the average solar capacity factor for that hour in that region
- **Wind profile**: charging proportional to the average wind capacity factor for that hour in that region
- **Private profile**: charges EVs to optimize surplus assuming no carbon damages
- **Social profile**: charges EVs to optimize surplus assuming the SCC is $100

Charging Profile	Electricity Price ($/MWh)	Carbon (mmt)	Annual Welfare Gains ($ billions) for SCC of $0	$50	$100	$150	$200
Panel A: Baseline renewable capital costs							
Convenience	37.07	1,361	68.2	96.2	124.2	152.2	180.2
Carbon Minimizing	31.58	1,183	45.4	82.3	119.2	156.1	193.0
Flat	37.65	1,340	68.5	97.6	126.7	155.7	184.8
Solar Profile	37.00	1,254	64.4	97.7	131.1	164.5	197.8
Wind Profile	37.64	1,344	68.4	97.3	126.2	155.1	183.9
Private Profile	37.30	1,339	71.1	100.2	129.3	158.4	187.5
Social Profile	36.81	1,243	66.5	100.4	134.4	168.3	202.2
Panel B: 25% reduction in renewable capital costs							
Convenience	35.98	1,148	60.4	88.9	117.3	145.8	174.2
Carbon Minimizing	30.57	842	36.0	79.8	123.5	167.3	211.0
Flat	36.52	1,103	60.2	90.9	121.6	152.3	183.0
Solar Profile	36.02	964	55.1	92.7	130.4	168.1	205.8
Wind Profile	36.51	1,111	60.2	90.6	120.9	151.2	181.6
Private Profile	36.09	1,066	62.5	95.0	127.6	160.2	192.7
Social Profile	35.71	946	55.9	94.4	133.0	171.6	210.1