The Role of Dynamic Electricity Pricing in Decarbonization: Results from a National Model

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Decarbonizing the Electricity Sector

Policy Instruments

- Carbon Pricing
  - Goulder and Schein (2013); Stavins (2022)
- Clean Energy Subsidies
  - Gillingham and Sweeney (2010); Bollinger and Gillingham (2023)
- Clean Energy & Renewable Portfolio Standards
  - Goulder and Stavins (2011)
- Utility Regulation & Rate Reform
  - Borenstein, Bushnell and Wolak (2002); Borenstein and Bushnell (2022)

Lingering Concerns

- Broader Decarbonization Efforts
  - Gillingham, Ovaere and Weber (2021); Davis (2023); Wolak (2011)
- Welfare & Distributional Implications

Variable Pricing

Do customers respond to variable pricing?

- National Academies of Sciences, Medicine et al. (2021); Wolak (2011); Barbose, Goldman and Neenan (2004); Barbose et al. (2005); Jessoe and Rapson (2014); Fabra et al. (2021)

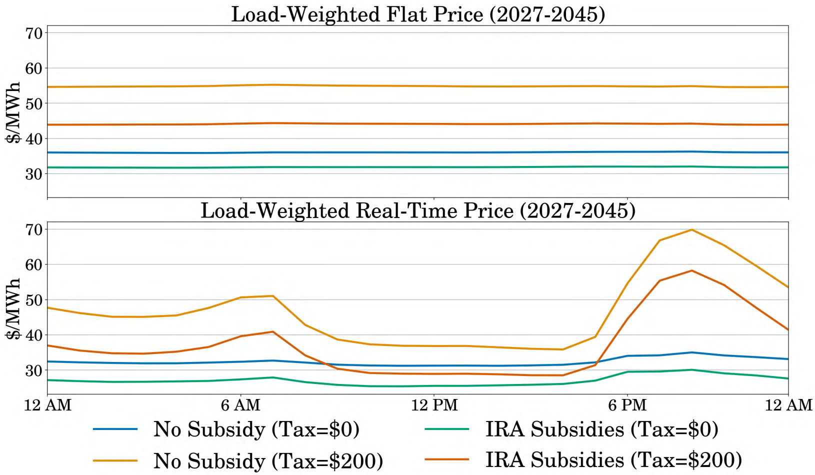
What is the value of variable pricing?

- Borenstein, Jaske and Rosenfeld (2002); Joskow and Tirole (2007)
- Borenstein (2005); Borenstein and Holland (2005); Blonz (2022)

What is the value of variable pricing in a high-renewable system?

- Imelda, Fripp and Roberts (2024)

Decarbonization Policy & Energy Prices



Contributions

Research Questions

1. What are the welfare and emissions benefits of variable pricing (RTP & TOU) relative to the flat pricing alternative?
2. How do benefits from variable pricing interact with existing Inflation Reduction Act (IRA) subsidies and carbon taxes?
3. How do various combinations of policy compare to the first-best solution?

Market Failure & Multiple Policy Instruments

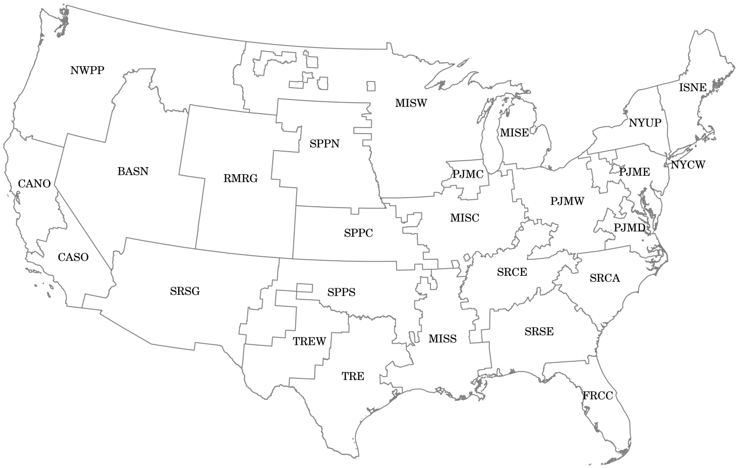
- Newell and Stavins (2003); Jaffe, Newell and Stavins (2005); Bennear and Stavins (2007); Goulder and Parry (2008); Gillingham and Sweeney (2010); Stern and Stiglitz (2021); Stern (2022)

Capacity Expansion Modeling

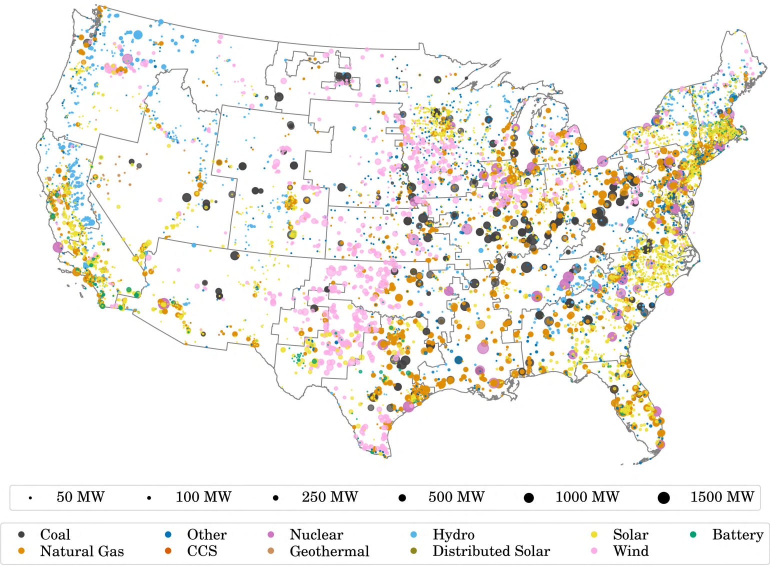
National Implementation of Switch 2.0 (Johnston et al., 2019)

- Model Inputs
  - 26 Zones & 10 Independent Weather Weeks
  - Planning Periods: 2027, 2030, 2035, 2040, 2045
  - PowerGenome: EIA, NETL, NREL, PUDL, & Vibrant Clean Energy
- Model Objective
  - Joint optimization of capital investments for $\sim$ 1,600 sites and 57 interregional transmission corridors and chronological operation in a least-cost fashion.
- Policy Implementation
  - Carbon Taxes: \$0 & \$200
  - IRA Subsidies
    - Assumption: capital intensive projects (nuclear, offshore wind, and batteries) take the ITC and all other qualifying technology takes the PTC.

Switch Zones



Switch Inputs: 2023 Existing Resources (EIA Form 860)



Switch Price-Responsive Demand

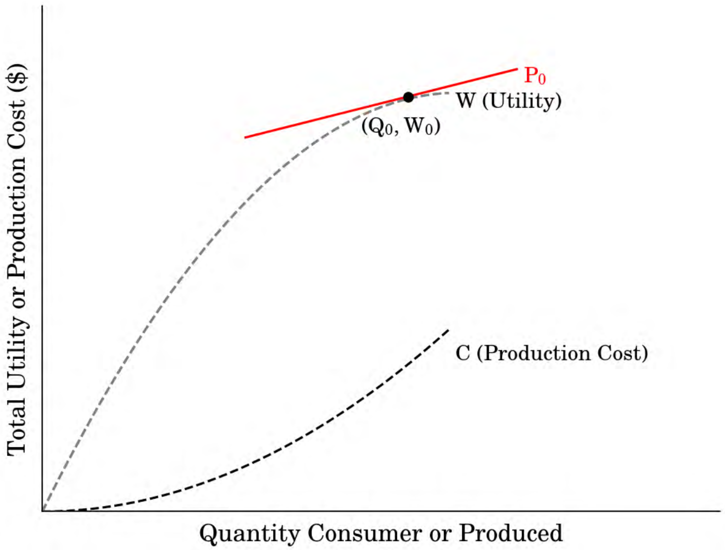
Demand Systems

- Linear & Constant Elasticity of Substitution
  - 30% of all demand is assumed perfectly inelastic
  - Remaining 70% of load utilizes an assumed elasticity of -0.1
    - Hirth, Khanna and Ruhnau (2024): -0.05
    - Deryugina, MacKay and Reif (2020): -0.09→-0.27

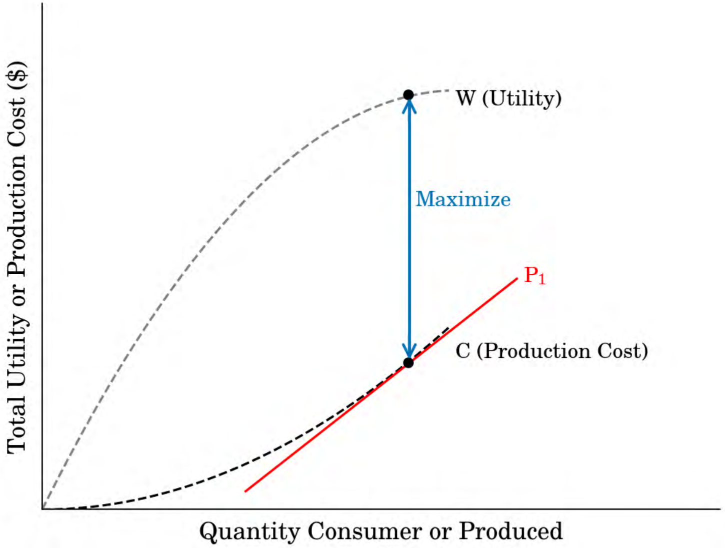
Electricity Tariffs

- Flat Pricing
- Real-Time Pricing
- Time-of-Use Pricing
  - Optimized conditional on block and model region
  - 3-Block: 9PM - 9AM, 9AM - 5PM, & 5PM - 9PM

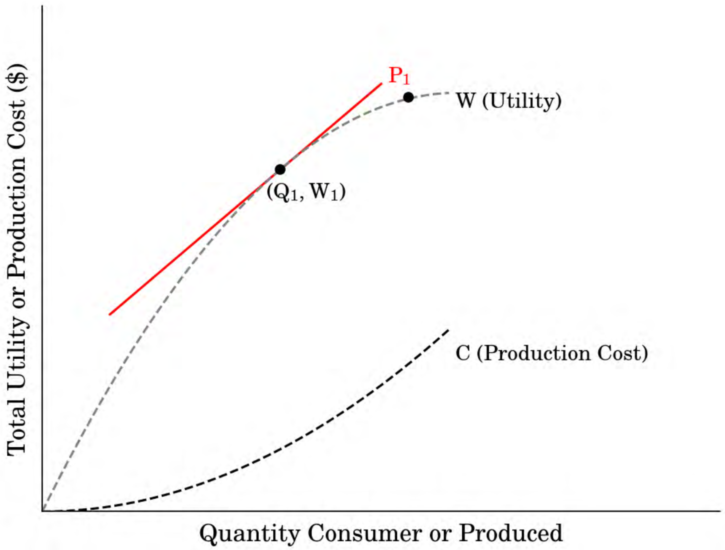
Switch Iterative Demand System



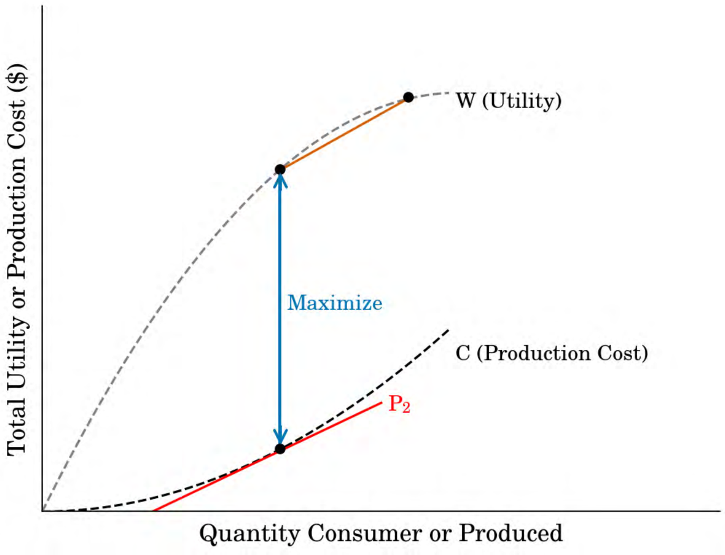
Switch Iterative Demand System



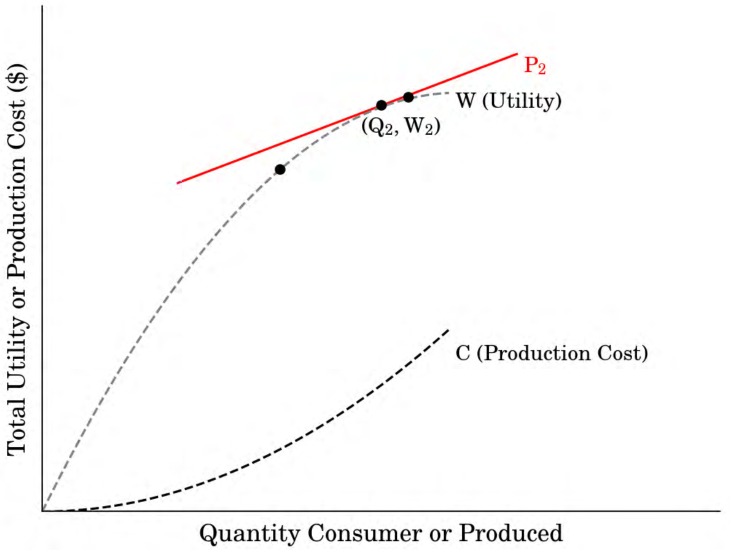
Switch Iterative Demand System



Switch Iterative Demand System



Switch Iterative Demand System



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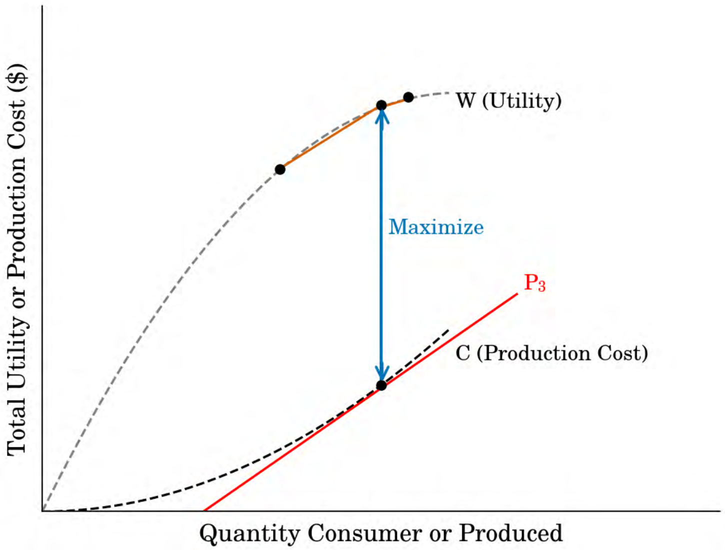

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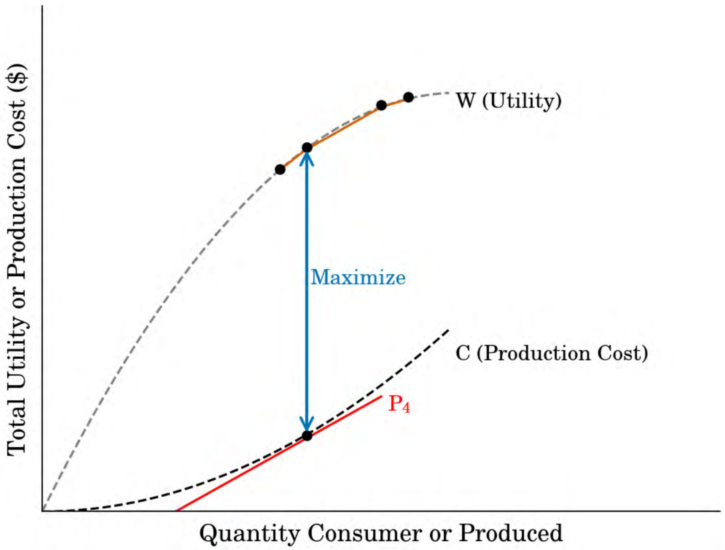
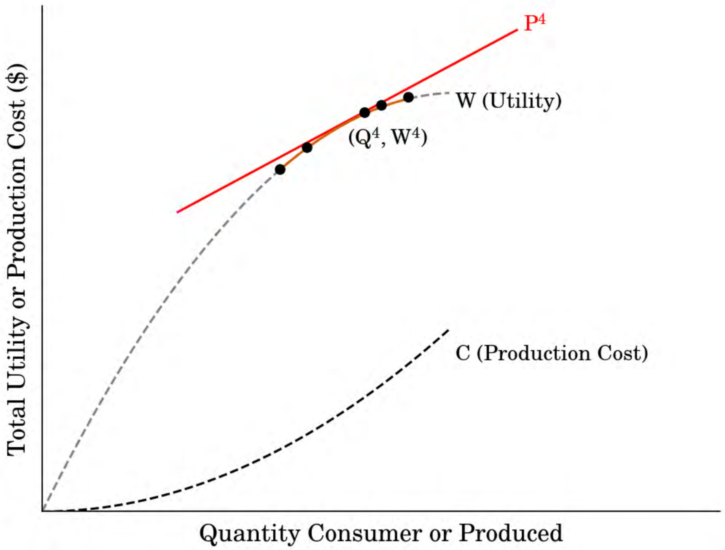
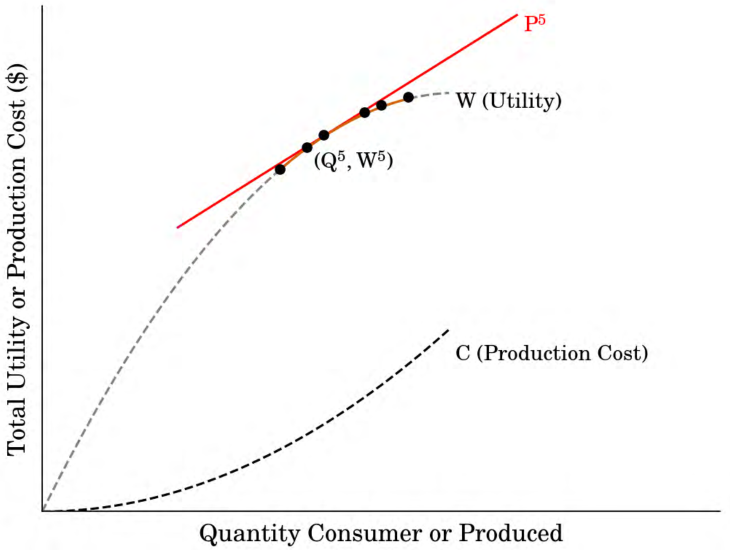


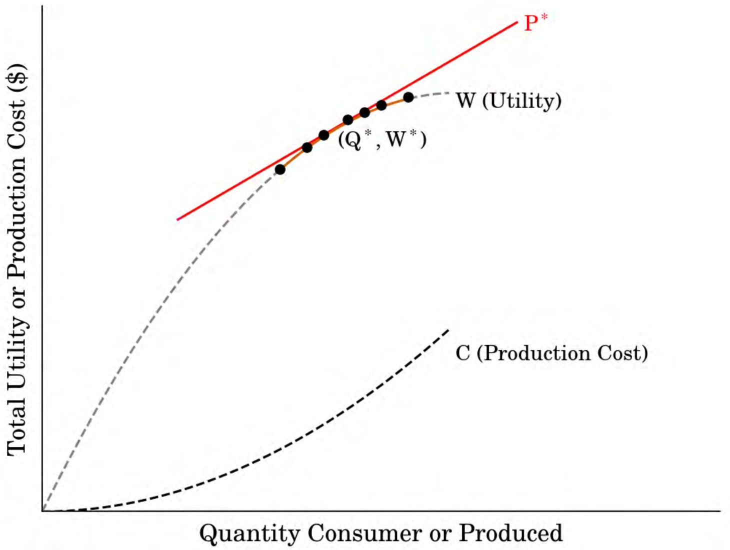
Switch Iterative Demand System



Switch Iterative Demand System



Switch Iterative Demand System



Scenarios

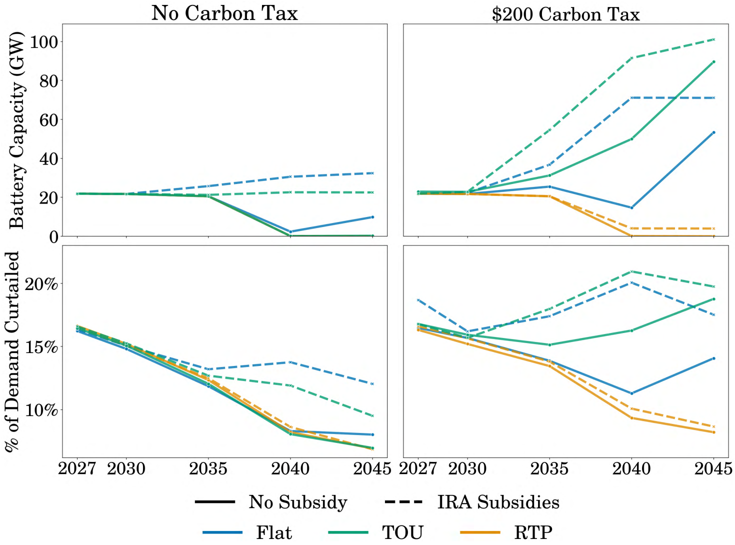
1. No IRA Subsidies & No Carbon Tax
2. No IRA Subsidies & \$200 Carbon Tax per tonne of CO_2
3. IRA Subsidies & No Carbon Tax
4. IRA Subsidies & \$200 Carbon Tax per tonne of CO_2

Results: System Cost

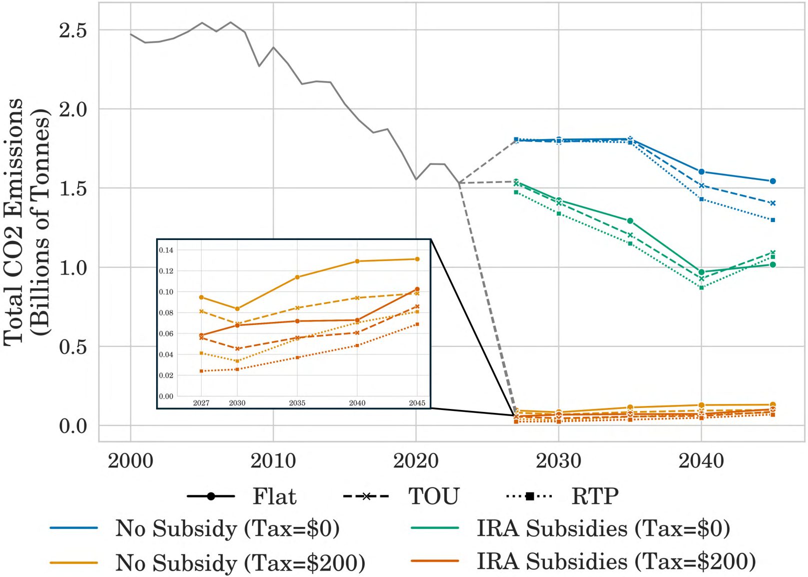
	System Cost ($/MWh)			Decrease (%)	
	Flat	TOU	RTP	TOU	RTP
No Subsidy (Tax=$0)	35.96	34.35	31.66	4.48	11.97
IRA Subsidies (Tax=$0)	31.80	30.15	27.10	5.18	14.78
No Subsidy (Tax=$200)	54.64	51.50	46.70	5.74	14.53
IRA Subsidies (Tax=$200)	43.27	41.08	37.21	5.06	13.99

Note: Load-weighted marginal costs by tariff and policy scenario. Relative decreases in cost represent the percentage decrease in total system cost attributable to a variable pricing tariff, relative to the flat pricing baseline.

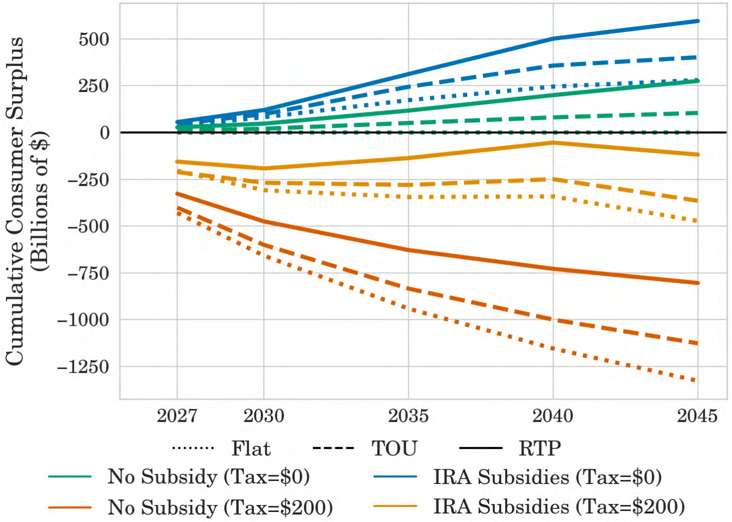
Battery Installation & Energy Curtailment



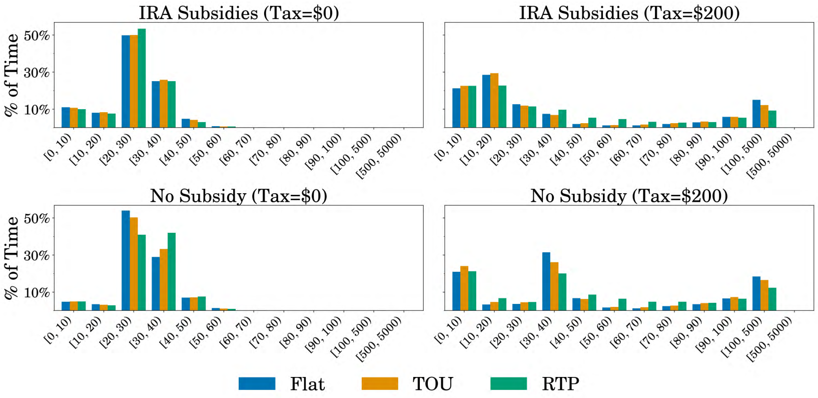
Carbon Emissions Abatement by Scenario



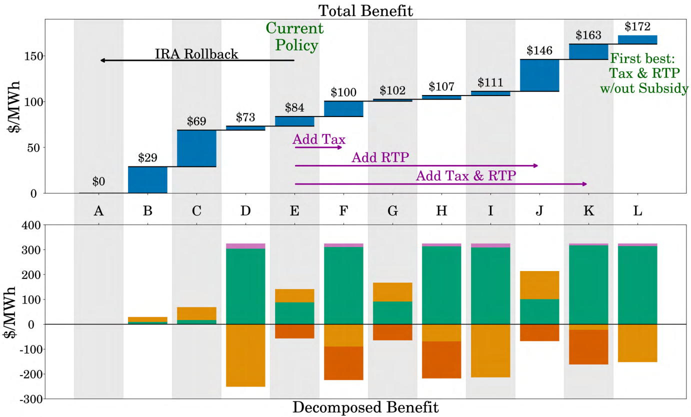
Change in Consumer Surplus: No Policy & Flat Pricing Baseline



Customer Exposure to Severe Pricing Events



Total Benefits by Policy Combination



Scenarios

A - No Subsidy (Tax=$0): Flat
B - No Subsidy (Tax=$0): TOU
C - No Subsidy (Tax=$0): RTP
D - No Subsidy (Tax=$200): Flat
E - IRA Subsidies (Tax=$0): Flat
F - IRA Subsidies (Tax=$200): Flat
G - IRA Subsidies (Tax=$0): TOU
H - IRA Subsidies (Tax=$200): TOU
I - No Subsidy (Tax=$200): TOU
J - IRA Subsidies (Tax=$0): RTP
K - IRA Subsidies (Tax=$200): RTP
L - No Subsidy (Tax=$200): RTP

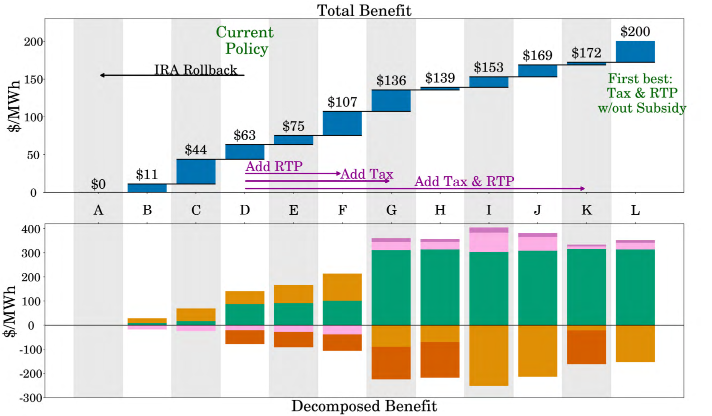
Components

Δ CO2 Pollution ($200/Tonne)
Δ Consumer Surplus
Δ IRA Costs (ITC & PTC)
Δ Gov't Revenue

Conclusion

1. RTP alone captures 95% of the benefits of the optimal carbon tax of \$200 per tonne with flat pricing.
   - An optimized TOU tariff captures approximately one third of the benefits of RTP.
2. The first best scenario (\$200 carbon tax & RTP) provides a 104% relative increase in net benefits over existing policy (IRA Subsidies & flat pricing).
   - 90% of these benefits are attainable with the addition of RTP to existing policy (IRA subsidies).
3. RTP insulates consumers from welfare losses resulting from decarbonization.
   - On average, consumers see welfare benefits of \$350B from 2027 to 2045.
   - Adding RTP to existing policy reduces the negative impact of a \$200 carbon tax by 85%.
4. Independent of policy, RTP unanimously improves environmental outcomes when compared to flat and TOU tariffs.
   - Additionally, energy is cheaper (13.8% reduction in LWMC) with less overall waste.

Total Benefits Expanded



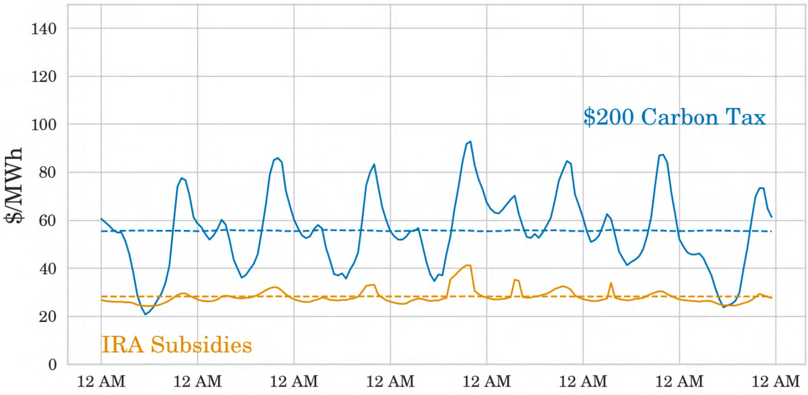
Scenarios

A - No Subsidy (Tax=$0): Flat
B - No Subsidy (Tax=$0): TOU
C - No Subsidy (Tax=$0): RTP
D - IRA Subsidies (Tax=$0): Flat
E - IRA Subsidies (Tax=$0): TOU
F - IRA Subsidies (Tax=$0): RTP
G - IRA Subsidies (Tax=$200): Flat
H - IRA Subsidies (Tax=$200): TOU
I - No Subsidy (Tax=$200): Flat
J - No Subsidy (Tax=$200): TOU
K - IRA Subsidies (Tax=$200): RTP
L - No Subsidy (Tax=$200): RTP

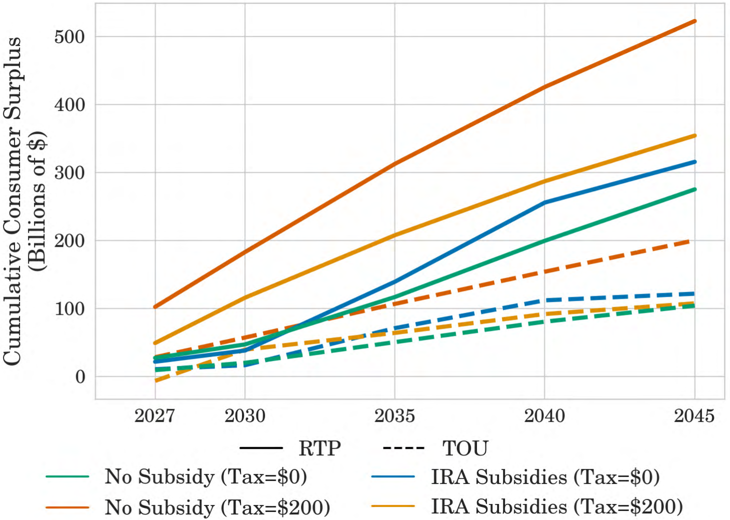
Components

- Δ CO2 Pollution ($200/Tonne)
- Δ Consumer Surplus
- Δ Producer Surplus
- Δ IRA Costs (ITC & PTC)
- Δ Gov't Revenue

Price Variability by Tariff



Change in Consumer Surplus: Within Policy & Flat Pricing Baseline



Variable Pricing & Consumer Surplus

		Billions of USD	Change in CS Relative to Baseline			
	Period	Baseline Expenditure	TOU (%)	TOU ($B)	RTP (%)	RTP ($B)
No Subsidy (Tax=$0)	2027	384.83	2.52	9.7	7.19	27.7
	2030	293.87	3.66	10.8	6.75	19.8
	2035	560.28	5.43	30.4	12.45	69.8
	2040	495.41	6.08	30.1	16.68	82.6
	2045	431.00	5.45	23.5	17.53	75.6
IRA Subsidies (Tax=$0)	2027	350.75	3.16	11.1	6.30	22.1
	2030	246.38	2.39	5.9	6.68	16.5
	2035	468.94	11.62	54.5	21.57	101.2
	2040	422.90	9.67	40.9	27.52	116.4
	2045	396.43	2.45	9.7	15.09	59.8
No Subsidy (Tax=$200)	2027	814.50	3.53	28.8	12.60	102.6
	2030	522.47	5.53	28.9	15.43	80.6
	2035	843.12	5.87	49.5	15.38	129.7
	2040	708.48	6.69	47.4	15.95	113.0
	2045	603.66	7.62	46.0	16.07	97.0
IRA Subsidies (Tax=$200)	2027	590.06	-1.02	-6.0	8.39	49.5
	2030	353.69	0.77	2.7	6.66	23.6
	2035	596.72	4.13	24.6	15.39	91.8
	2040	492.14	5.63	27.7	16.12	79.3
	2045	562.03	2.79	15.7	11.93	67.1

Note: Change in consumer surplus (CS) relative to the baseline expenditure required to serve all bids of the demand system in each planning period. Each variable pricing tariff is compared with the flat pricing alternative at the same level of policy and taxes to compute the relative difference in expenditure required to serve all demand within that scenario.

Price Distribution

	Price						Marginal Cost					
Flat Pricing	10th	Mean	90th	99th	Max	# Hours > $1000	10th	Mean	90th	99th	Max	# Hours > $1000
No Subsidy (Tax = $0)	27.58	34.27	42.75	54.87	55.37	0	20.60	31.44	39.01	52.54	5000.00	852
No Subsidy (Tax = $200)	42.78	53.02	67.51	87.81	88.39	0	0.00	49.67	106.55	128.60	5000.00	152
IRA Subsidies (Tax = $0)	22.90	30.05	37.06	51.38	51.48	0	9.72	27.87	36.10	50.15	5000.00	874
IRA Subsidies (Tax = $200)	31.47	41.33	54.83	74.28	78.51	0	0.00	38.15	104.34	117.69	5000.00	49
2-Block Time-of-Use Pricing	10th	Mean	90th	99th	Max	# Hours > $1000	10th	Mean	90th	99th	Max	# Hours > $1000
No Subsidy (Tax = $0)	26.43	31.39	37.74	42.22	46.10	0	21.28	31.25	39.37	52.06	5000.00	923
No Subsidy (Tax = $200)	40.03	50.60	64.66	76.46	86.12	0	0.00	49.92	106.43	125.97	5000.00	86
IRA Subsidies (Tax = $0)	21.17	28.04	35.27	40.17	43.32	0	9.77	27.83	35.92	50.96	5000.00	643
IRA Subsidies (Tax = $200)	28.54	39.66	52.79	66.51	74.04	0	0.00	38.76	104.20	119.90	5000.00	68
3-Block Time-of-Use Pricing	10th	Mean	90th	99th	Max	# Hours > $1000	10th	Mean	90th	99th	Max	# Hours > $1000
No Subsidy (Tax = $0)	26.06	31.16	37.79	43.05	46.04	0	21.18	30.91	38.86	51.79	5000.00	652
No Subsidy (Tax = $200)	39.40	49.39	64.13	82.79	90.38	0	0.00	47.80	105.55	122.61	5000.00	244
IRA Subsidies (Tax = $0)	21.17	27.34	34.64	40.68	45.20	0	9.77	27.02	35.47	49.74	5000.00	560
IRA Subsidies (Tax = $200)	29.03	38.53	50.37	67.22	82.25	0	0.00	37.15	102.40	117.52	5000.00	145
Real-Time Pricing	10th	Mean	90th	99th	Max	# Hours > $1000	10th	Mean	90th	99th	Max	# Hours > $1000
No Subsidy (Tax = $0)	21.86	29.97	39.55	53.25	1503.73	1	21.86	29.97	39.55	53.25	1503.73	1
No Subsidy (Tax = $200)	0.00	47.07	102.64	117.23	461.09	0	0.00	47.07	102.64	117.23	461.09	0
IRA Subsidies (Tax = $0)	9.95	25.63	34.94	49.03	719.05	0	9.95	25.63	34.94	49.03	719.05	0
IRA Subsidies (Tax = $200)	0.00	36.89	98.58	114.44	530.33	0	0.00	36.89	98.58	114.44	530.33	0

Notes: This table outlines the distribution of load-weighted final prices and marginal costs throughout the full modeling period (2027-2045). Costs are weighted across all 26 zones by the final quantity demand in each region at each hour—weighted from the 10 weeks of hourly input data to a representative year based on weights assigned in the weather clustering process.

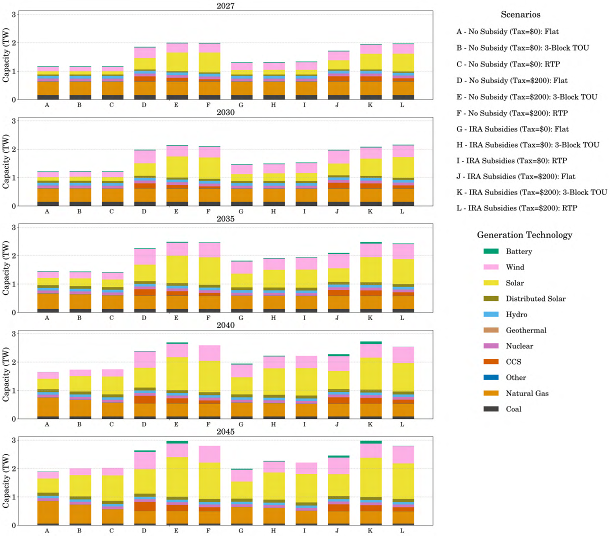
Transmission Expansion

		Capacity per km (GW)				Annual Cost (Billions of $)			
		Flat	2-Block TOU	3-Block TOU	RTP	Flat	2-Block TOU	3-Block TOU	RTP
No Subsidy (Tax=$0)	2027	252.94	254.01	244.91	220.70	8.07	8.08	8.03	7.90
	2030	286.08	277.38	269.77	245.74	8.25	8.23	8.16	8.01
	2035	307.45	309.82	308.24	245.74	8.52	8.56	8.37	8.01
	2040	329.42	328.43	320.51	248.30	9.32	8.99	8.72	8.05
	2045	352.62	348.85	344.28	253.31	9.78	9.41	9.23	8.13
IRA Subsidies (Tax=$0)	2027	220.86	219.51	213.16	208.28	8.36	8.30	8.16	8.02
	2030	238.01	232.92	228.68	223.24	8.72	8.68	8.59	8.38
	2035	337.59	350.64	335.57	261.68	10.42	10.43	10.03	9.05
	2040	401.84	419.11	405.58	279.39	12.04	12.19	11.41	9.52
	2045	429.80	452.81	430.35	294.07	12.58	12.65	11.88	9.88
No Subsidy (Tax=$200)	2027	430.99	430.97	431.97	421.24	12.39	12.23	12.10	11.48
	2030	485.08	490.11	487.19	451.10	13.52	13.27	12.94	12.00
	2035	620.69	614.64	632.19	598.36	16.97	16.60	15.97	14.23
	2040	686.13	667.96	689.89	662.44	18.26	17.68	17.12	15.61
	2045	764.15	725.21	747.68	742.02	19.95	19.08	18.70	16.96
IRA Subsidies (Tax=$200)	2027	394.74	439.96	430.22	390.02	11.59	12.14	12.01	11.66
	2030	417.71	467.61	459.44	396.26	12.09	12.71	12.61	11.76
	2035	529.29	594.69	600.46	502.61	14.69	15.71	15.03	13.04
	2040	580.23	672.68	646.02	536.33	15.73	17.12	15.93	14.17
	2045	648.62	730.60	715.14	620.96	17.66	19.23	18.41	16.11

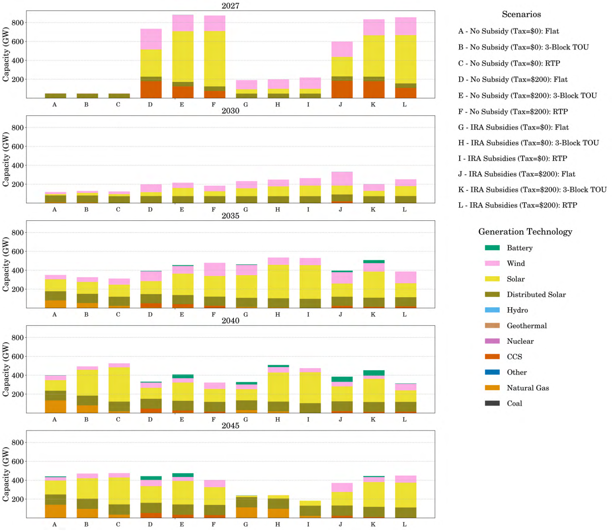
Note: Optimal interregional transmission expansion by scenario and planning period.

Pollution Abatement Relative to Flat Pricing Baseline

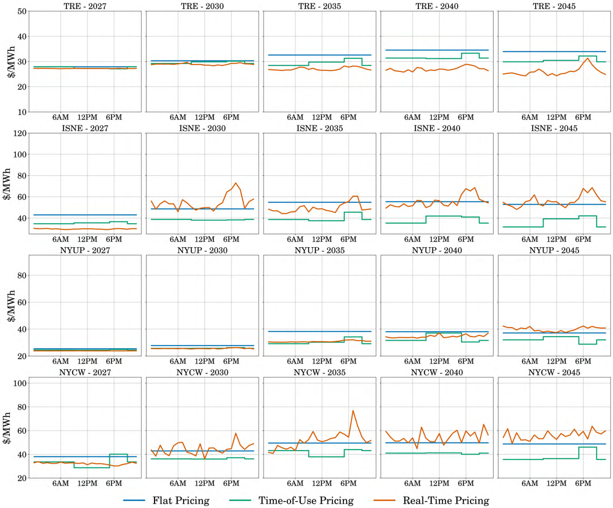
Generation Mix



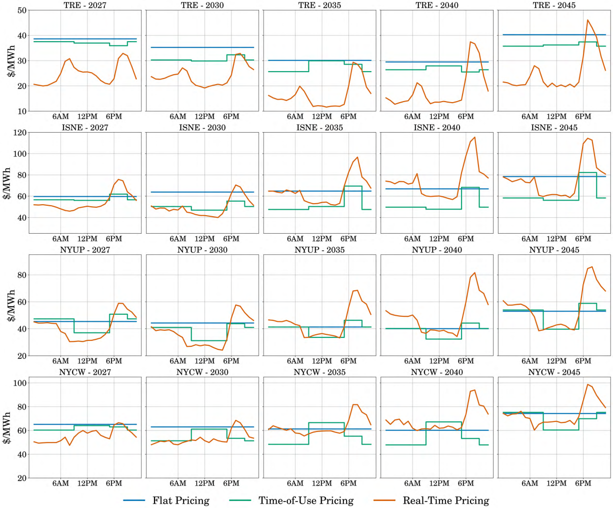
New Generation Capacity



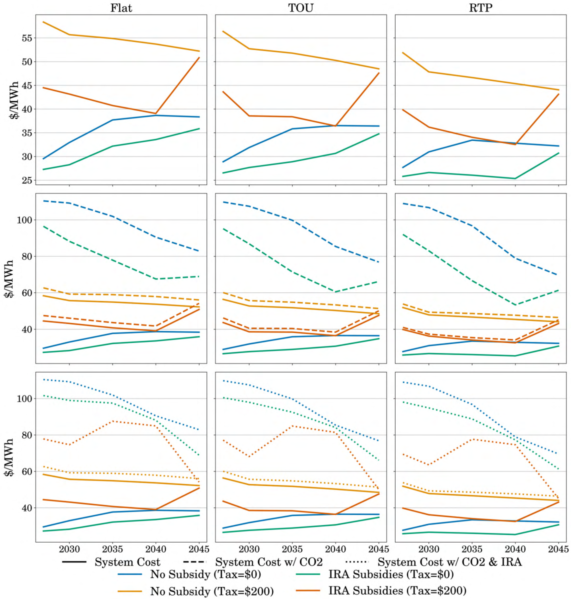
Optimal Tariffs: No Subsidy & No Tax



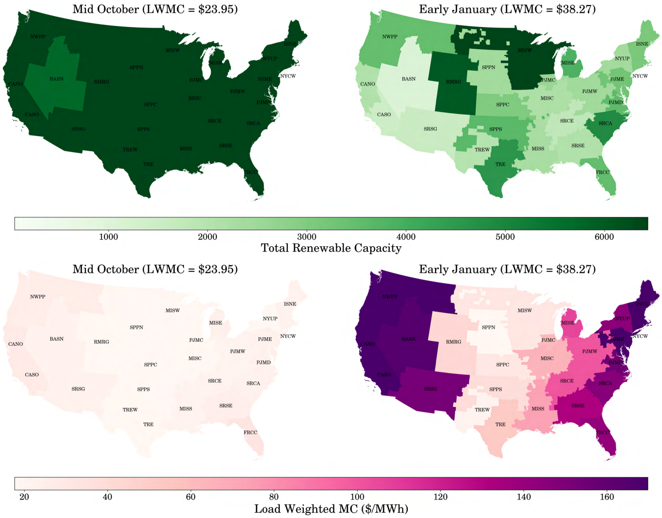
Optimal Tariffs: IRA Subsidies & $200 Tax



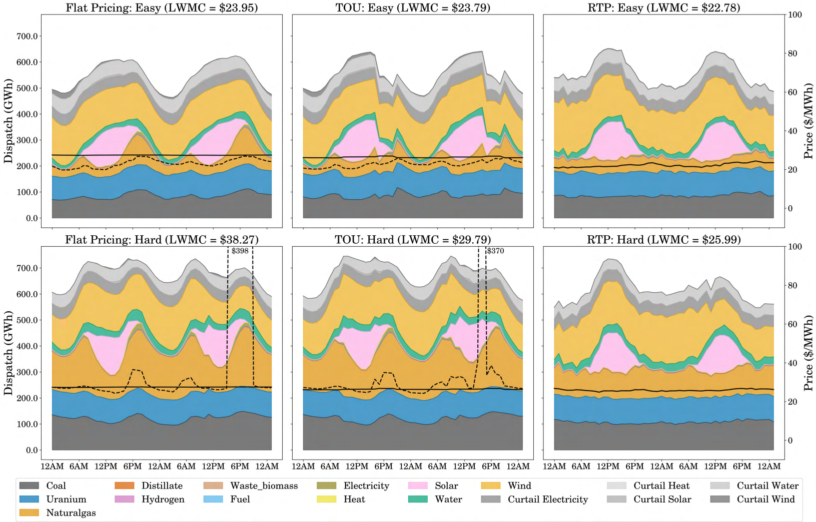
System Costs by Period



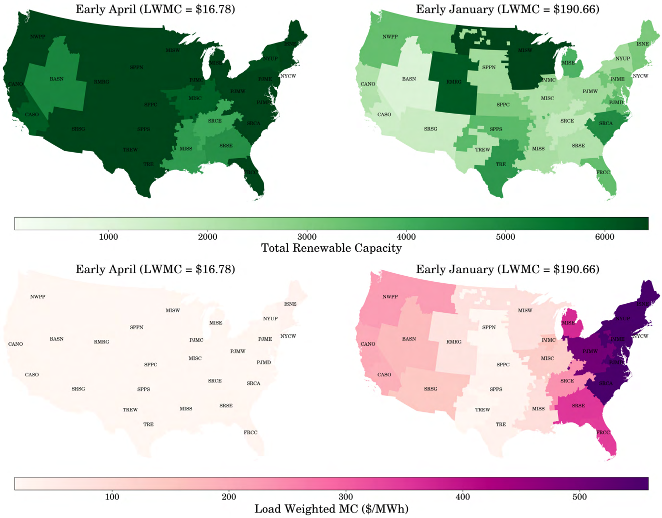
Hardest to Serve Week: 2027



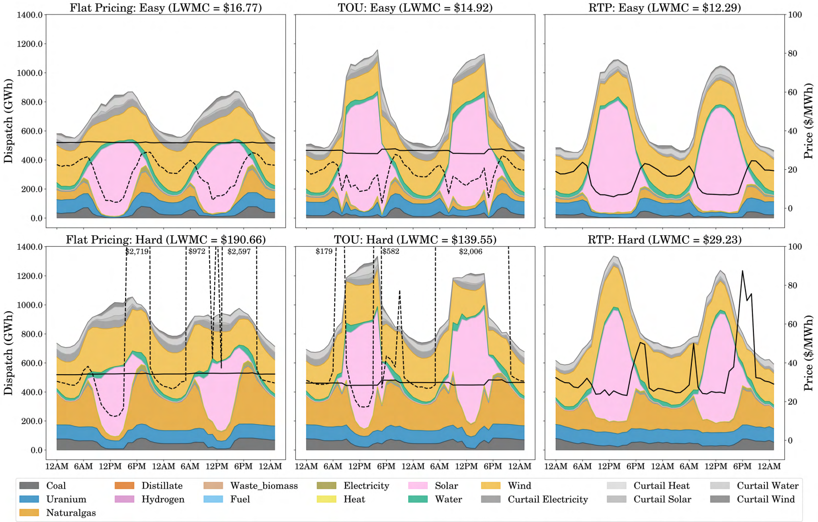
System Dispatch: 2027



Hardest to Serve Week: 2040



System Dispatch: 2040



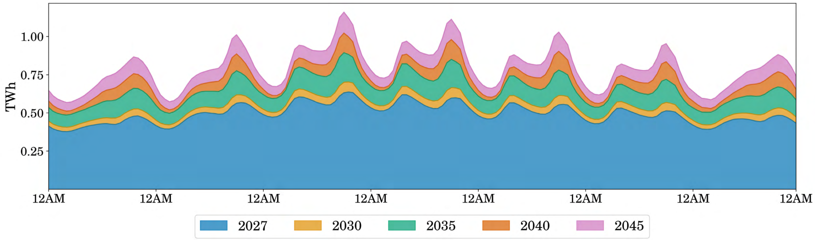
Optimal Grid by Demand System

	Flat		TOU		RTP	
	Lin	CES	Lin	CES	Lin	CES
System Cost ($/MWh)	35.96	36.46	34.35	34.94	31.66	32.02
Total Demand (TWh)	27.94	29.07	28.00	29.33	28.00	29.44
CO2 Emissions (Billions of Tonnes)	8.56	8.87	8.32	8.66	8.13	8.46

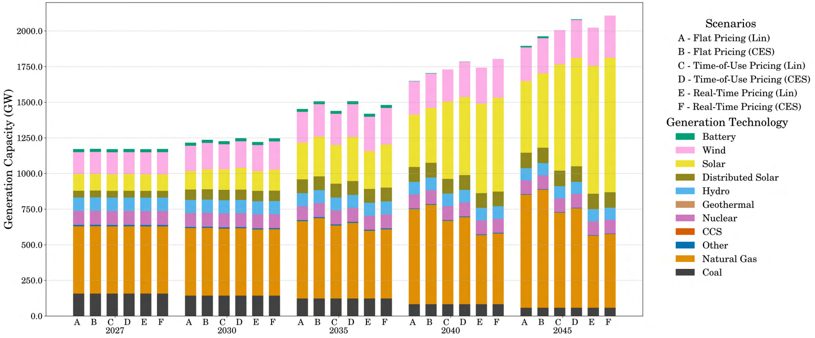
Note: This table compares total system (2027-2045) system cost, quantity demanded, and resulting carbon emissions across linear and constant elasticity of substitution (CES) demands.

Load Growth

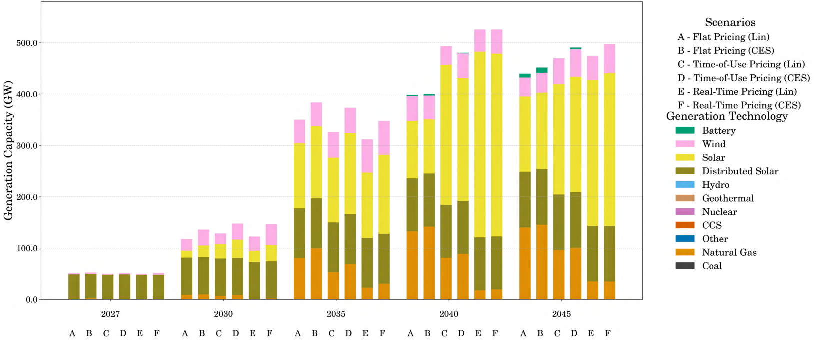
f



Generation Mix by Demand (No Subsidy & No Tax)



New Generation Capacity by Demand (No Subsidy & No Tax)



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