Inframarginal Investments with Clean Energy Subsidies

Evidence from the U.S. Inflation Reduction Act

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EPRI Energy Systems and Climate Analysis

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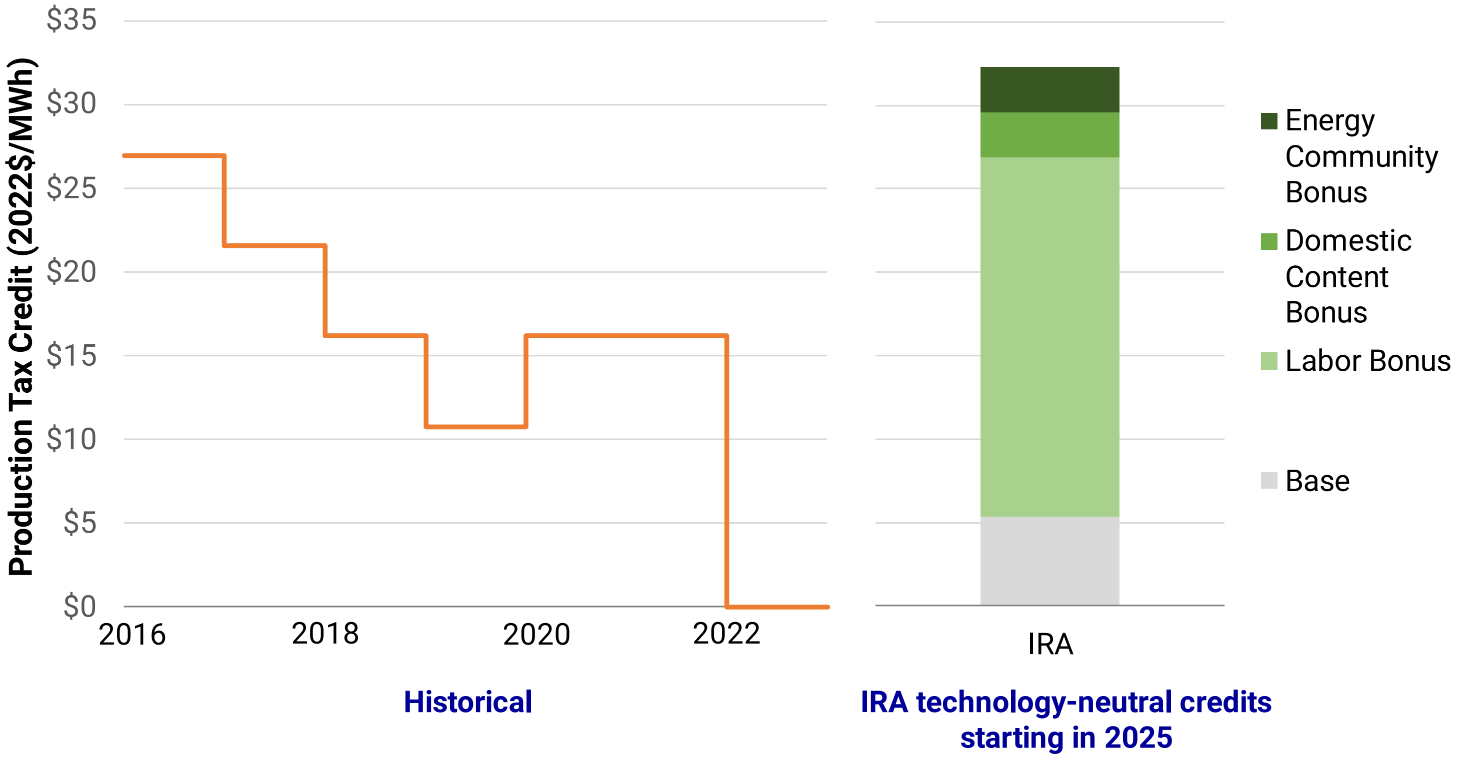
Context: Inflation Reduction Act of 2022

E&E NEWS | CLIMATEWIRE

How the Senate climate bill could slash emissions 40%

By Scott Waldman, Benjamin Storrow | 07/28/2022 06:55 AM EDT

Sen. Joe Manchin (D-W.Va.) struck a deal with Senate Majority Leader Chuck Schumer (D-N.Y.) on major climate and energy legislation yesterday. Francis

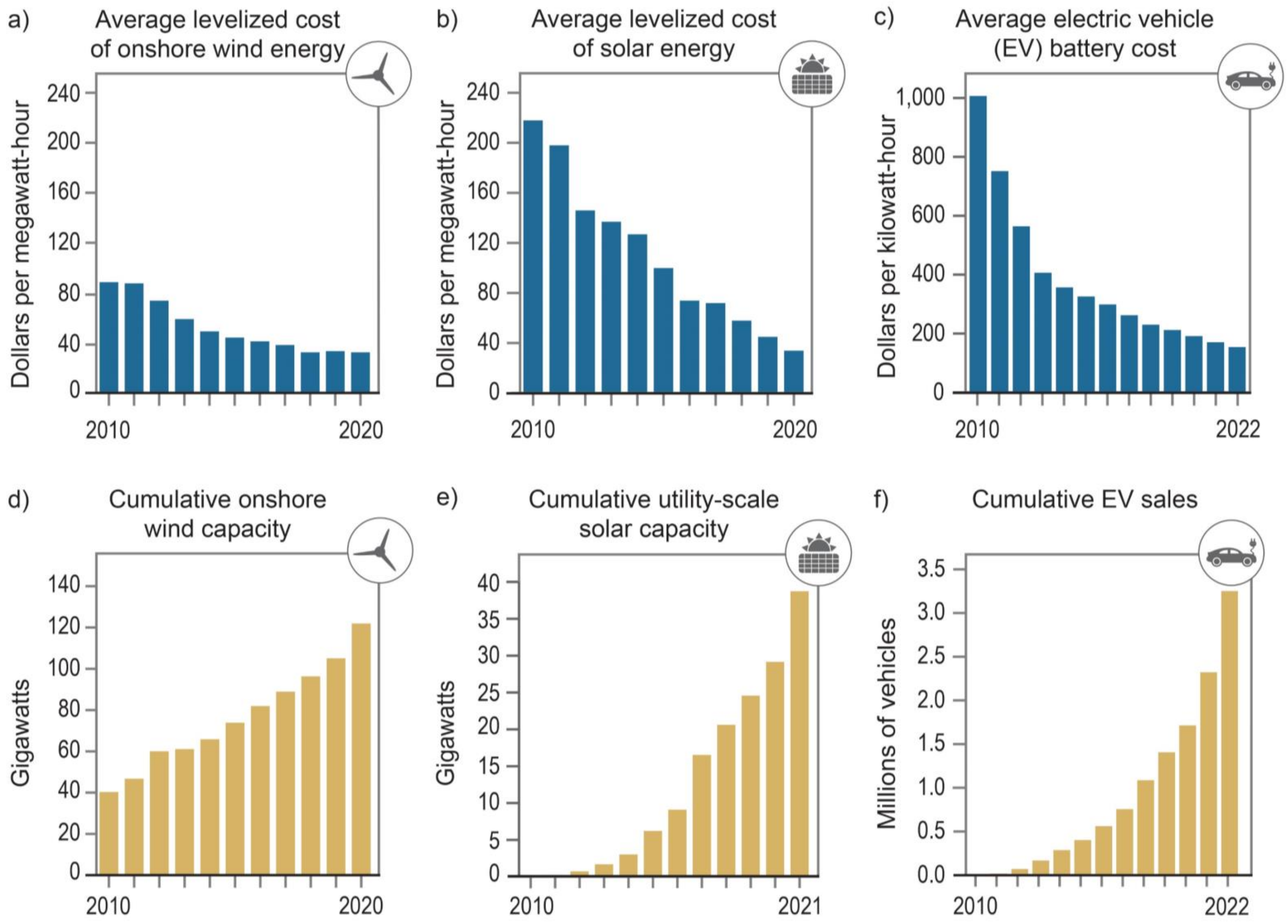


Historical

IRA technology-neutral credits starting in 2025

Questions about potential impacts of subsidy-based climate policy approaches

Inframarginal Investment Concerns



- Concerns that subsidies are wasted on inframarginal firms and households
  - **Inframarginal** = would adopt in the absence of policy
  - Esp. in settings with increasing clean energy deployment (left)
- Expected that incentives will induce additional responses, but degree of inframarginal investments is unclear
- Inframarginal share has implications for emissions, fiscal costs, political economy

Source: Davis, et al. (2023), U.S. Fifth National Climate Assessment (link)

Motivating Questions

- What is the extent of inframarginal investments for power sector tax credits under the U.S. Inflation Reduction Act?
  - Variation by technology and credit type?
  - Which factors could alter inframarginal shares?
- How cost-effective are tax credits? How does analysis that accounts for inframarginal investments alter these assessments?

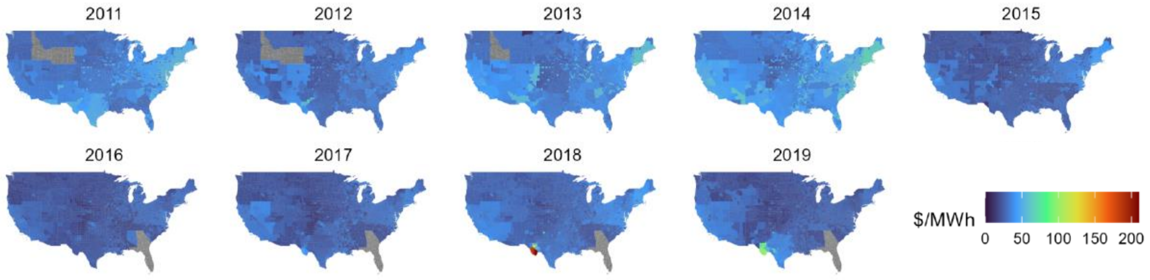
Two Approaches: Empirical and Numerical Modeling

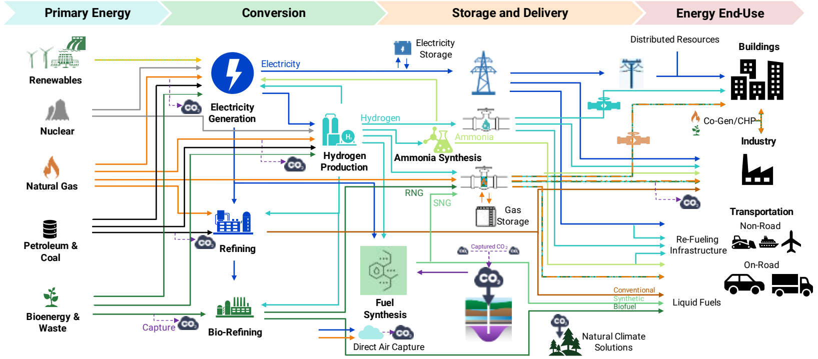
Empirical

- Can estimate historic sensitivity of firms and consumers to all-else-equal changes in cost and revenue
  - We look at effects of electricity price changes on U.S. wind/solar deployment
  - Can use to estimate effects of subsidies *with assumptions*
- Challenges: External validity—applications to future energy markets with non-marginal technological change and local conditions

Numerical/Dynamic Structural Models

- Can explore dimensions of energy demand and supply system that reduced-form methods cannot
  - Fully interconnected system identifies which fossil plants are turned off
  - Examines adoption with and without subsidies to quantify inframarginal shares
  - Can separate effects of policies, technology cost declines, other drivers
- Challenges: Accounting for structural and parametric uncertainties





Empirical Analysis: Wind and Solar Tax Credits

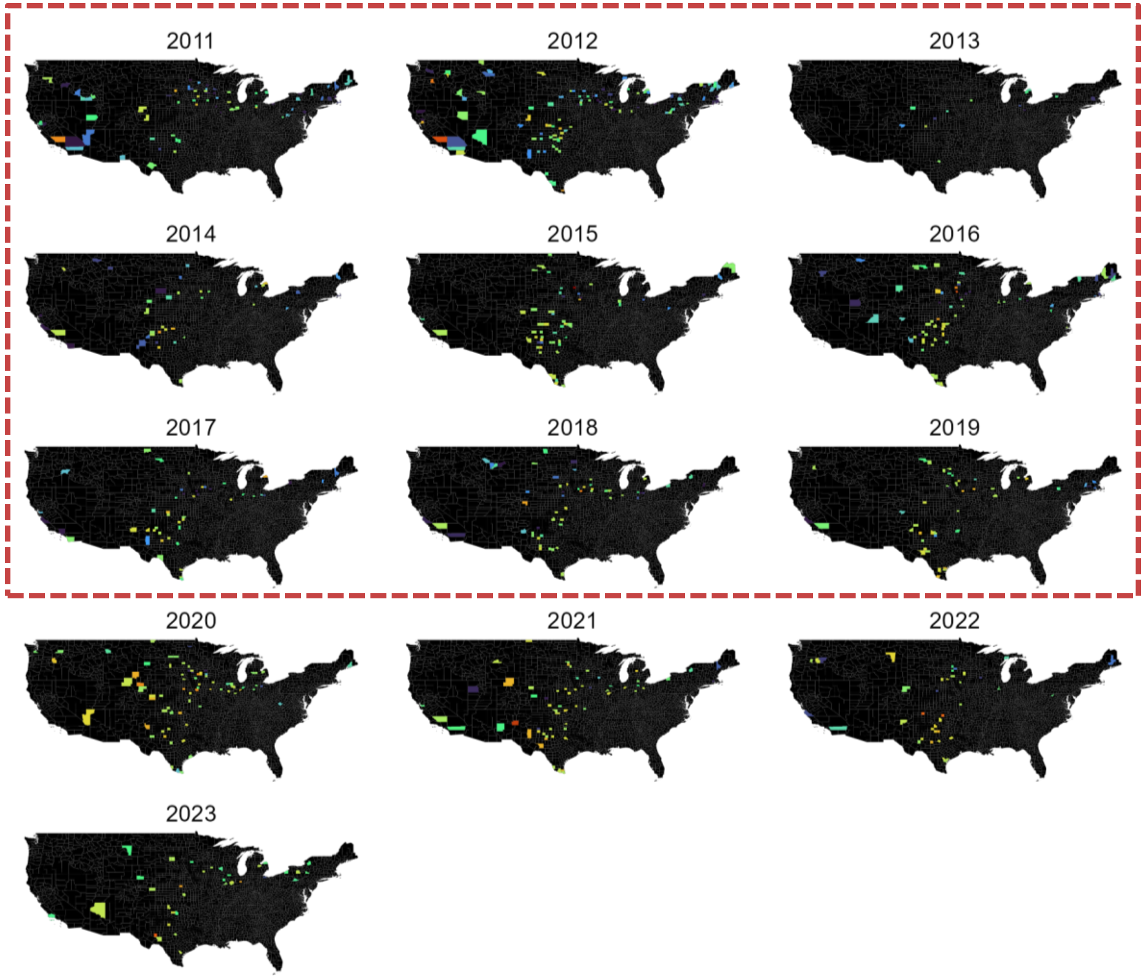
Approach

- Goal: Estimate effect of **production tax credit (PTC) for wind and solar**
  - Focus on contiguous U.S.
  - Insufficient spatial and temporal variation in historical PTC data
- Solution: Use electricity **locational marginal price (LMP)** shocks
  - Assume expectations are random walk with (fixed) drift
  - Implies price shocks change future revenue expectations one-to-one
  - **Limit study period to 2010-2019** when this assumption is plausible
- Roads not taken
  - IRA bonuses for energy communities: Concerns with business stealing, limited geography, and insufficient time in data
  - Event study using time-series variation in renewable subsidies: Concerns with large shifts in macroeconomy, accounting for policy expectations, and relatively small changes in subsidy magnitudes

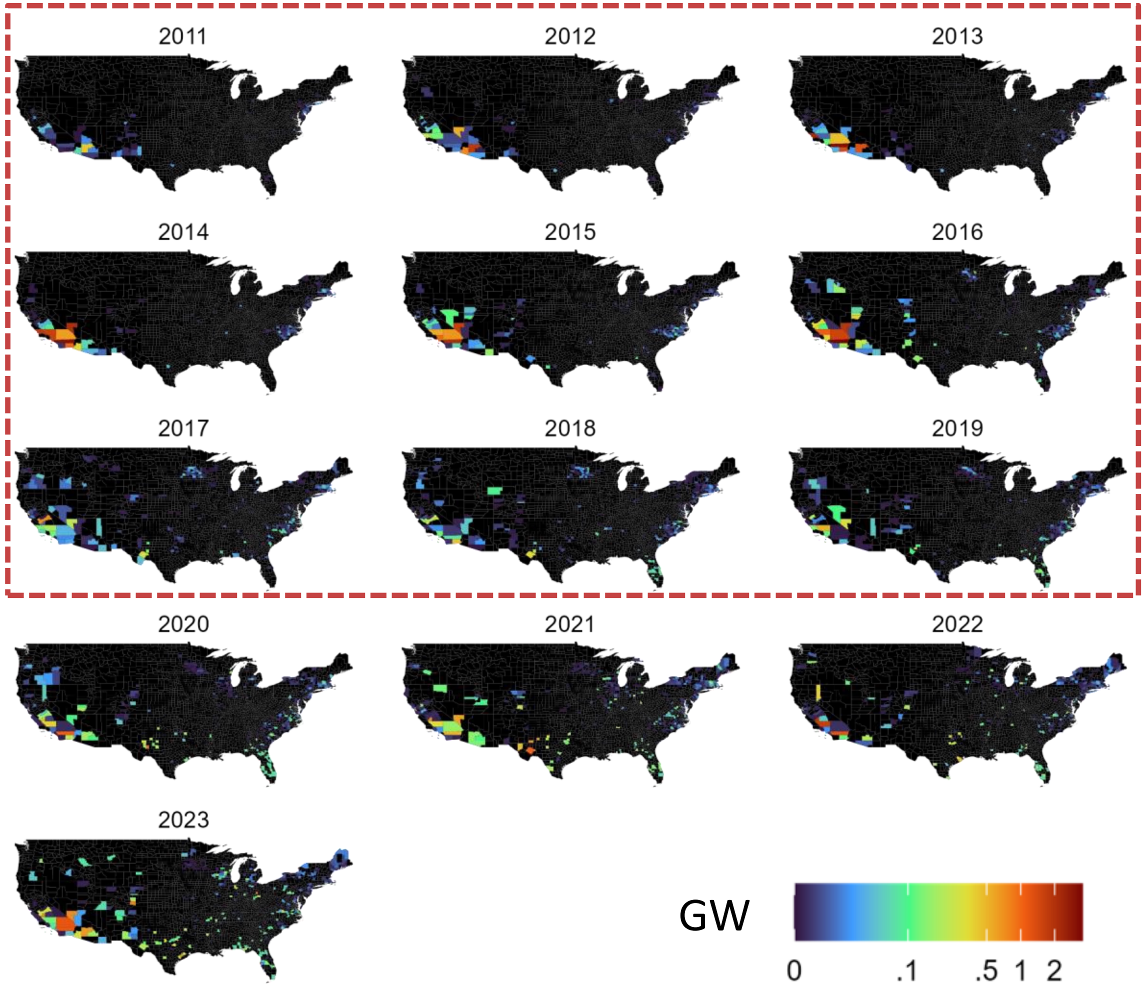
Data for Capacity Additions by County

Land-Based Wind Additions

Study Period

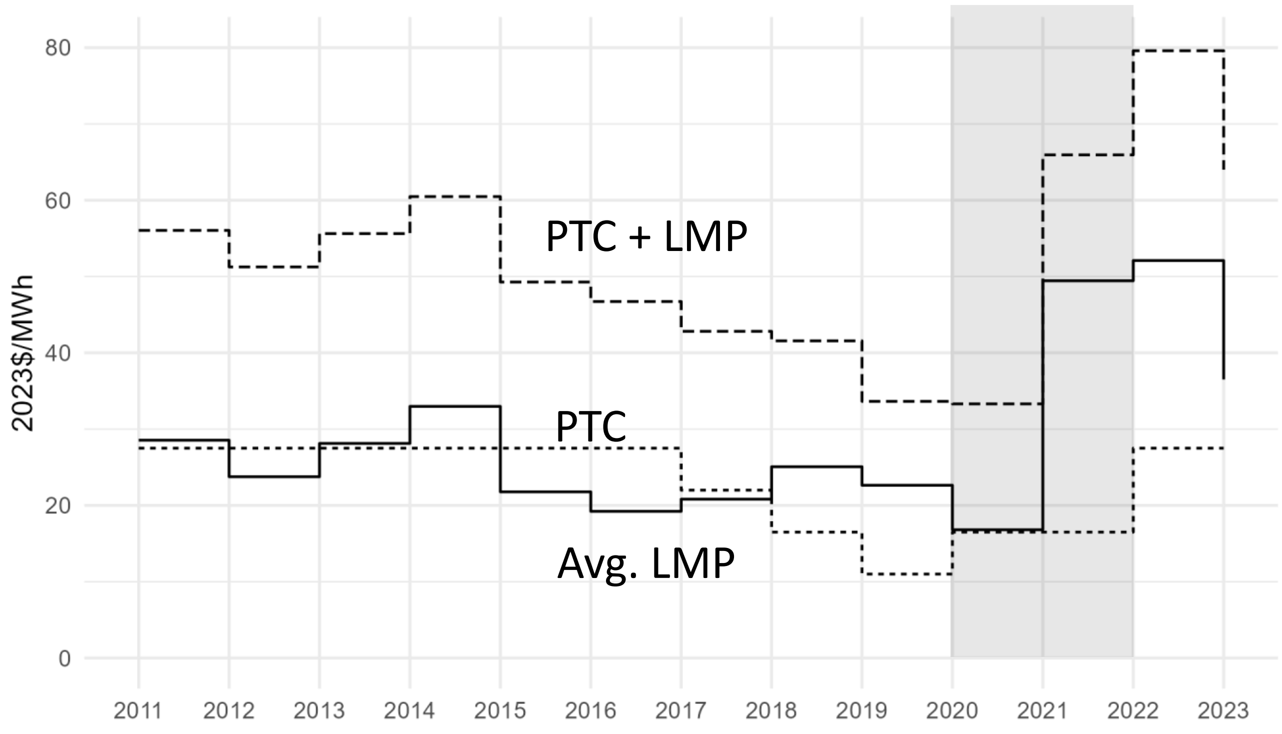


Utility-Scale Solar PV Additions



Wind and solar capacity additions from U.S. Energy Information Administration (EIA) Form 860

PTC Roughly Doubles Revenues in Study Period



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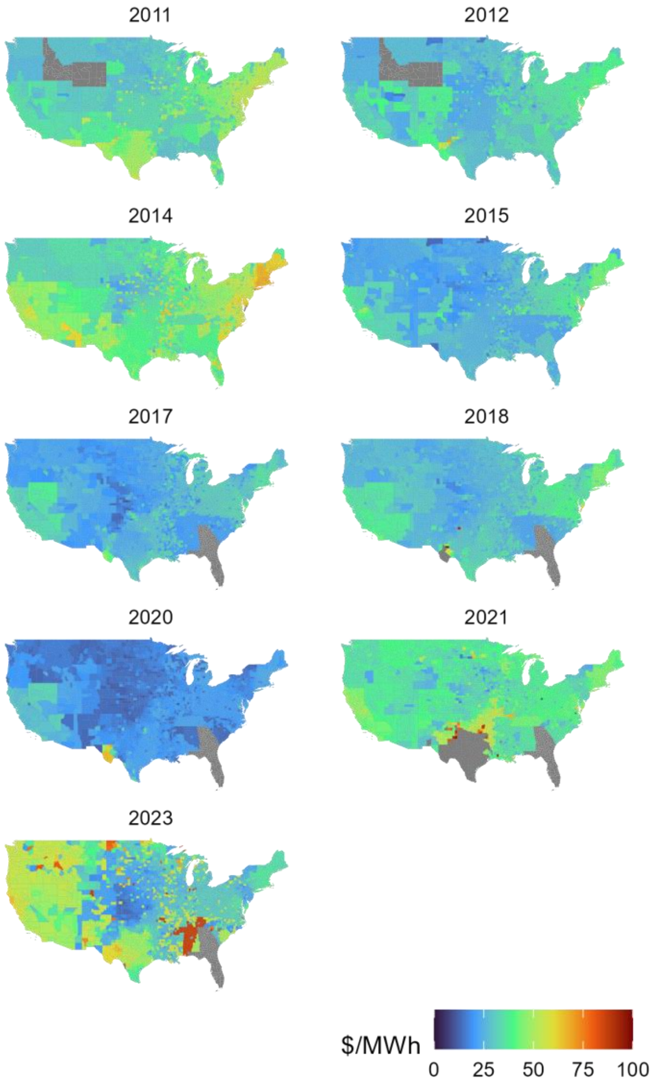
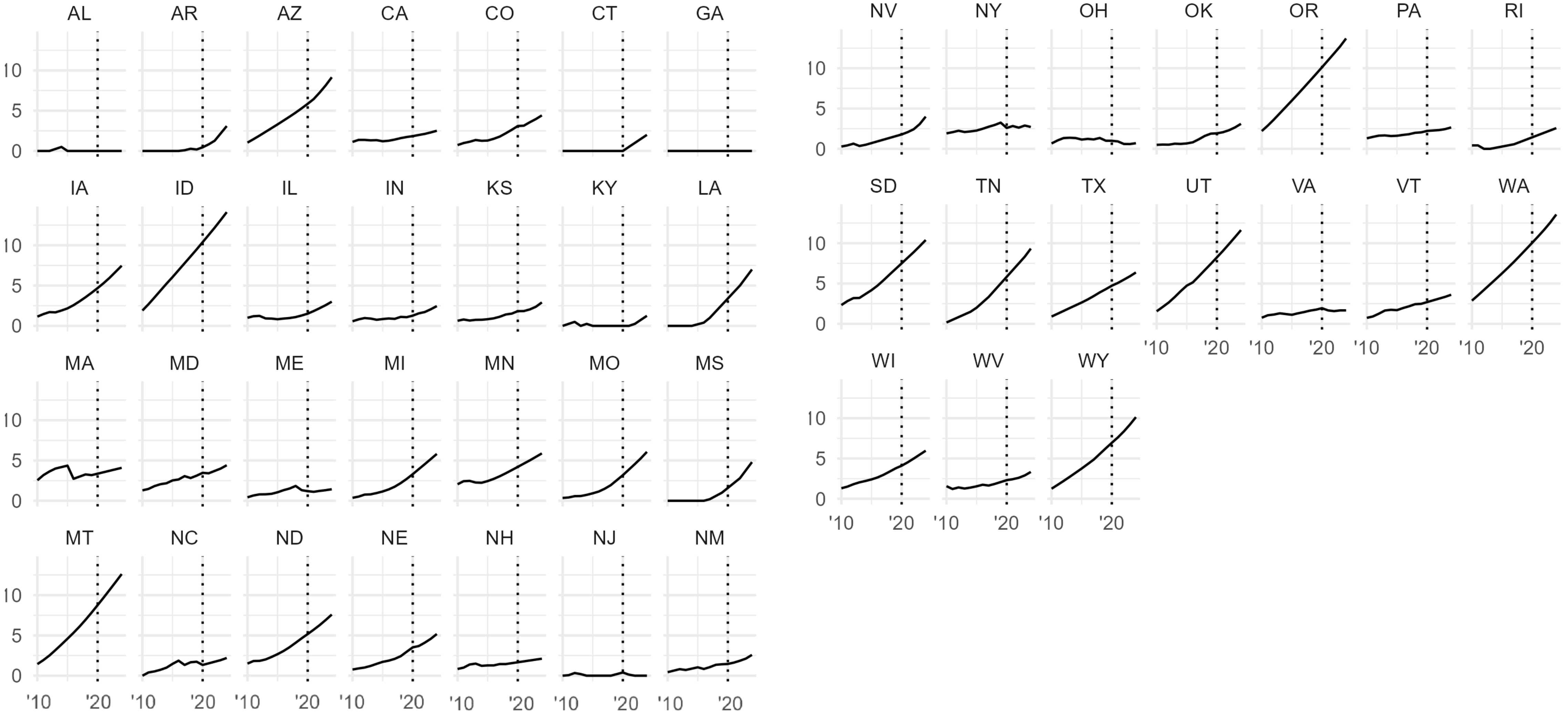


Large wholesale price increases in post-study period

Based on locational marginal price data from LBNL's ReWEP tool (link)

Interconnection Queue Trends Are Heterogeneous

Average Years in Queue for Wind



Average time in queue has been increasing over time but with considerable variation across states

Based on interconnection queue data from LBNL (link)

Identification Strategy

$$\mathbf{E}\left[\mathrm{MW}_{jt}\right] = \exp\left(\beta_1 p_{j,t-1} + \beta_2 t + \beta_3 \hat{e}_{j,t-1} + \mathbf{X}_{j,t-1}\gamma\right)\alpha_{1_j}$$

j = county; *t* = year

- Exponential conditional mean model estimated with Poisson quasi-MLE
  - Non-negative dependent variable
  - Intuitive interpretation of average partial effect
  - Fully robust
- Prices (*p)* are LMPs, lagged one year to avoid simultaneity: Likely a better match to final investment decision
- X are a set of controls for time-varying idiosyncratic errors
  - By state: Average time in queue for wind and solar, total capacity in queue for wind and solar
  - By county: Lagged capacity additions for wind and solar

Results for States Without Binding RPS*

Wind (MW Additions)

	(1)	(2)	(3)	(4)
	Poisson FE	+ market controls	+ state trends	+ control function
lag elec. price + PTC	0.095*	0.080**	0.075**	0.095*
	(0.039)	(0.027)	(0.023)	(0.040)
first stage resid.				-0.055
				(0.083)
year	0.439***	0.597+	-0.452	-0.475
	(0.094)	(0.313)	(0.939)	(0.912)
N	802	802	802	802
first stage F-stat				59.2
PTC avg. partial eff.	261%	220%	205%	261%
county FE	X	X	X	X
year×state			X	X

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Solar (MW_{AC} Additions)

	(1)	(2)	(3)	(4)
	Poisson FE	+ market controls	+ state trends	+ control function
lag elec. price	-0.001	0.013	0.028*	0.030*
	(0.024)	(0.015)	(0.013)	(0.013)
first stage resid.				0.034
				(0.021)
year	0.306***	1.142***	1.631**	1.566**
	(0.052)	(0.238)	(0.601)	(0.602)
N	1124	1099	1099	1048
first stage F-stat				6.8
PTC avg. partial eff.	-2%	36%	77%	82%
county FE	X	X	X	X
year×state			X	X

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Notes: Market controls include lagged variables for both wind and solar: avg. time in queue, capacity in queue, capacity additions. First-stage residual using Henry Hub natural gas price as IV. *Non-binding RPS defined as standards <25% in 2023.

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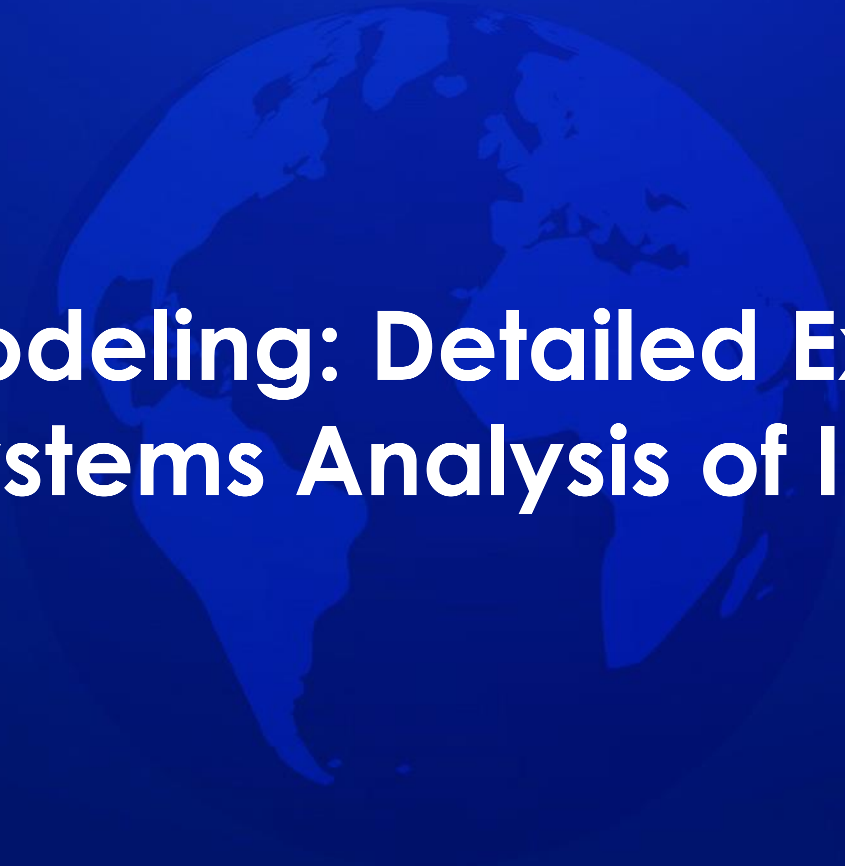
- For wind, coefficients imply 205-261% avg. partial effect
  - Inframarginal share of one-third for preferred specification
  - Coefficient is statistically significant across all specifications
- For solar, PTC increases solar capacity by 77%
  - Inframarginal share over 56% for preferred specification
  - For solar and wind in binding RPS states, no significant relationship between LMP and additions



Numerical Modeling: Detailed Ex-Ante Energy Systems Analysis of IRA

Numerical/Dynamic Structural Models of IRA Impacts

Economy

- EPS-EI (Energy Innovation)
- GCAM-CGS (University of Maryland, Center for Global Sustainability)
- MARKAL-NETL (National Energy Technology Laboratory)
- NEMS-RHG (Rhodium)
- REGEN-EPRI (EPRI)
- RIO-REPEAT (Princeton, Evolved Energy Research)

Electric Only

- E4ST-RFF (Resources for the Future)
- Haiku-RFF (Resources for the Future)
- IPM-EPA (U.S. Environmental Protection Agency)
- IPM-NRDC (Natural Resources Defense Council)
- ReEDS-NREL (National Renewable Energy Laboratory)

11 independent models from IRA model intercomparison in *Science*

Scenarios for the IRA Model Intercomparison

To evaluate impacts on emissions and energy systems, IRA scenarios are compared to their counterfactual reference scenarios without IRA.

Reference (Ref)

- Counterfactual scenario with other federal and state policies/incentives.
- On-the-books policies through early 2022, including IIJA, federal tax credits with phase outs, state emissions policies and standards.

Inflation Reduction Act (IRA)

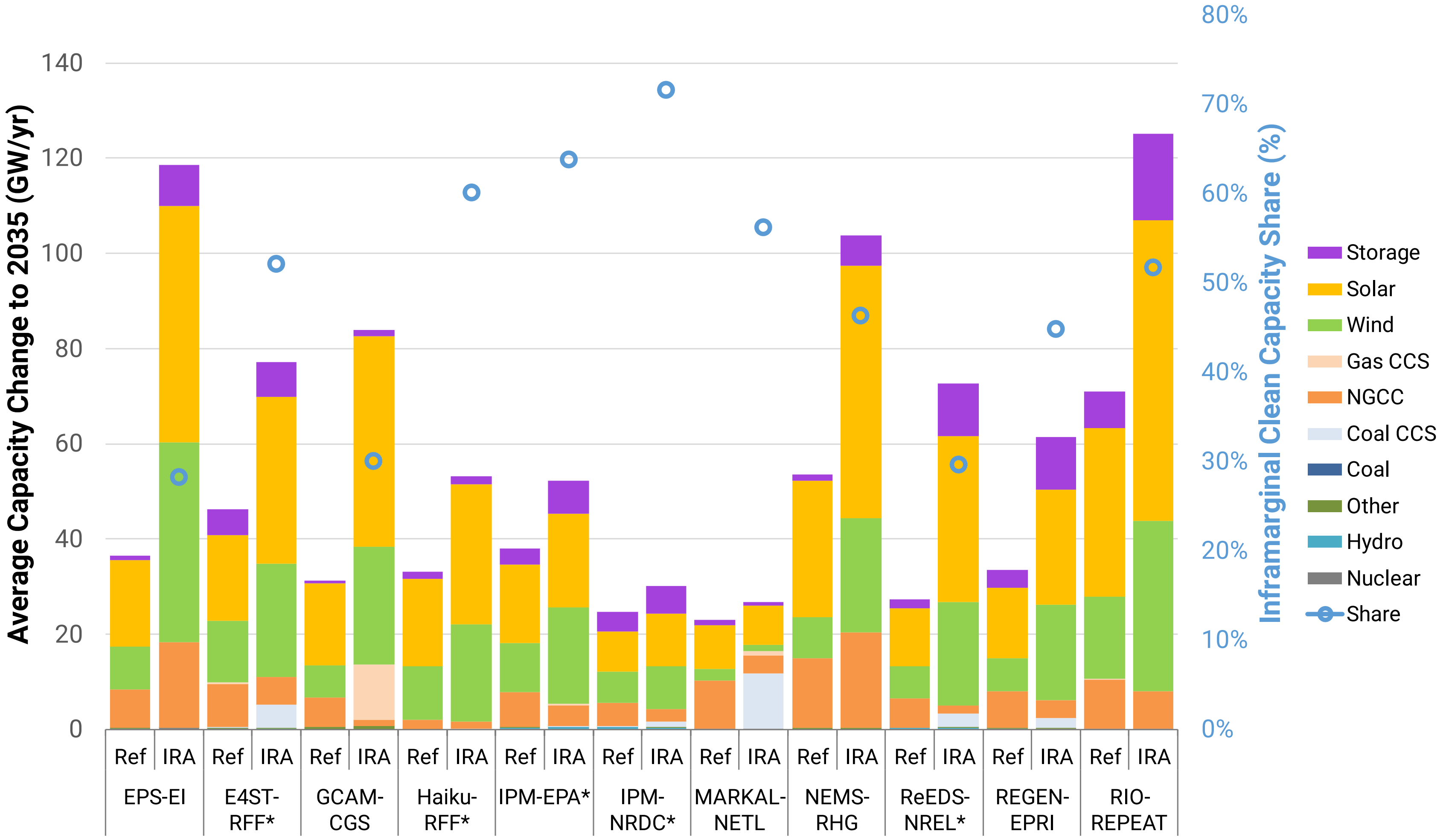
- Central estimates of core climate and energy provisions.
- Coverage and implementation vary by model.

Unharmonized Assumptions

- Input assumptions about technological cost and performance and fuel prices (though figures compare inputs across models).
- IRA implementation varies based on model structure and interpretation of IRA provisions.

For more detail, see Bistline, et al. (2023), Emissions and Energy Impacts of the Inflation Reduction Act, *Science*

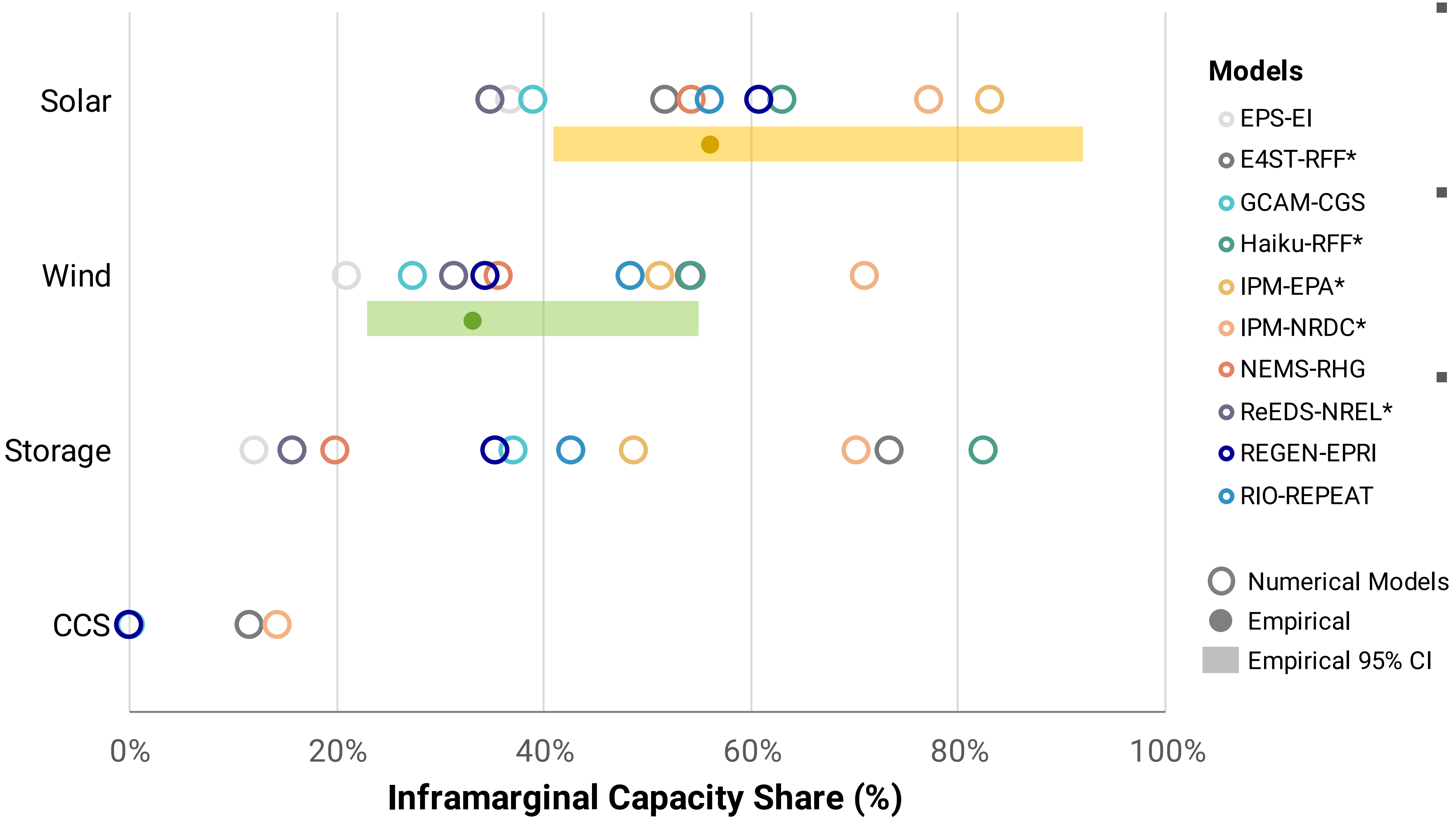
Power Sector Capacity Investments without/with IRA



- Cross-model variation in the extent of clean investment
  - Includes renewables, CCS-equipped capacity, and nuclear
  - 23-117 GW/yr low-CO_2 with IRA (13-61 GW/yr without IRA)
  - Solar/wind are largest investments
- Inframarginal share of clean electricity ranges from 28-72%
  - Generally lower (i.e., more additional capacity with IRA) for models with greater IRA-induced solar capacity
  - NB: In capacity terms rather than investment $ terms

* Electric sector only modeling

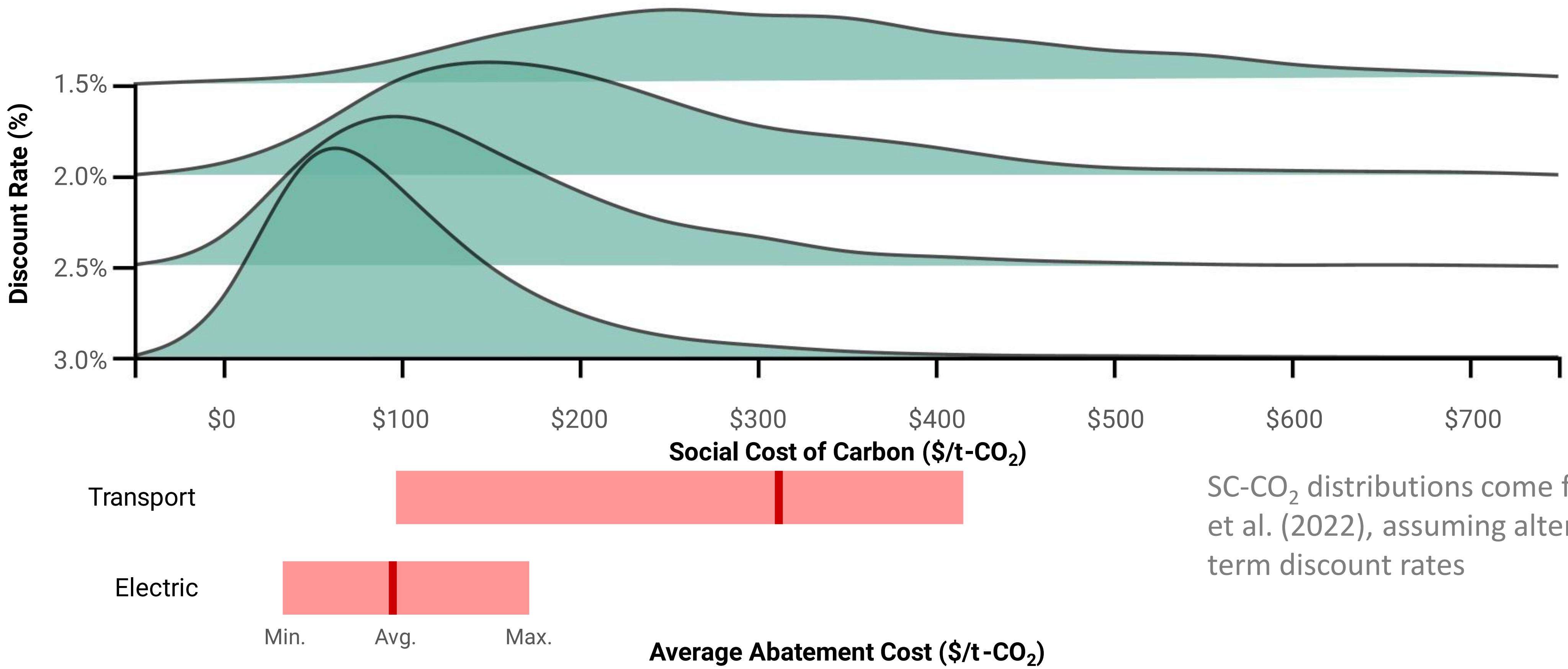
Technology-Specific Inframarginal Shares



- Solar has higher inframarginal shares than wind, with large cross-model variation for both
- CCS is largely additional with IRA incentives, which reflects lower adoption without IRA
- Empirical and numerical estimates are consistent
  - Empirical shares limited to states without binding RPS constraints
  - If binding RPS states were also included, empirical values would be higher and align more closely with numerical modeling

* Electric sector only modeling

Comparison of Abatement Costs and Climate Benefits



SC-CO_2 distributions come from Rennert, et al. (2022), assuming alternate near-term discount rates

- Power sector abatement costs are generally less than social cost of carbon estimates
  - Avg. cost ($96/t-$CO_2$) and range across models ($34-170/t-$CO_2$)
  - Means for SC-CO_2 distributions range from $100-360/t-$CO_2$
- Costs of electric vehicle credits are higher
  - Range from $98-420/t-$CO_2$
  - Higher costs of credits is partially due to higher inframarginal shares

Summary of Key Takeaways

Large shares of inframarginal recipients and non-additional investments with power sector tax credits

- Empirical: Third of wind capacity additions and half of solar are inframarginal in states without binding RPS (all subsidies are inframarginal for states with mandates)
- Numerical: 28-72% of investments over next decade may occur without credits

Analysis that treats all recipients as additional would underestimate fiscal costs of tax credits and overestimate emissions reductions

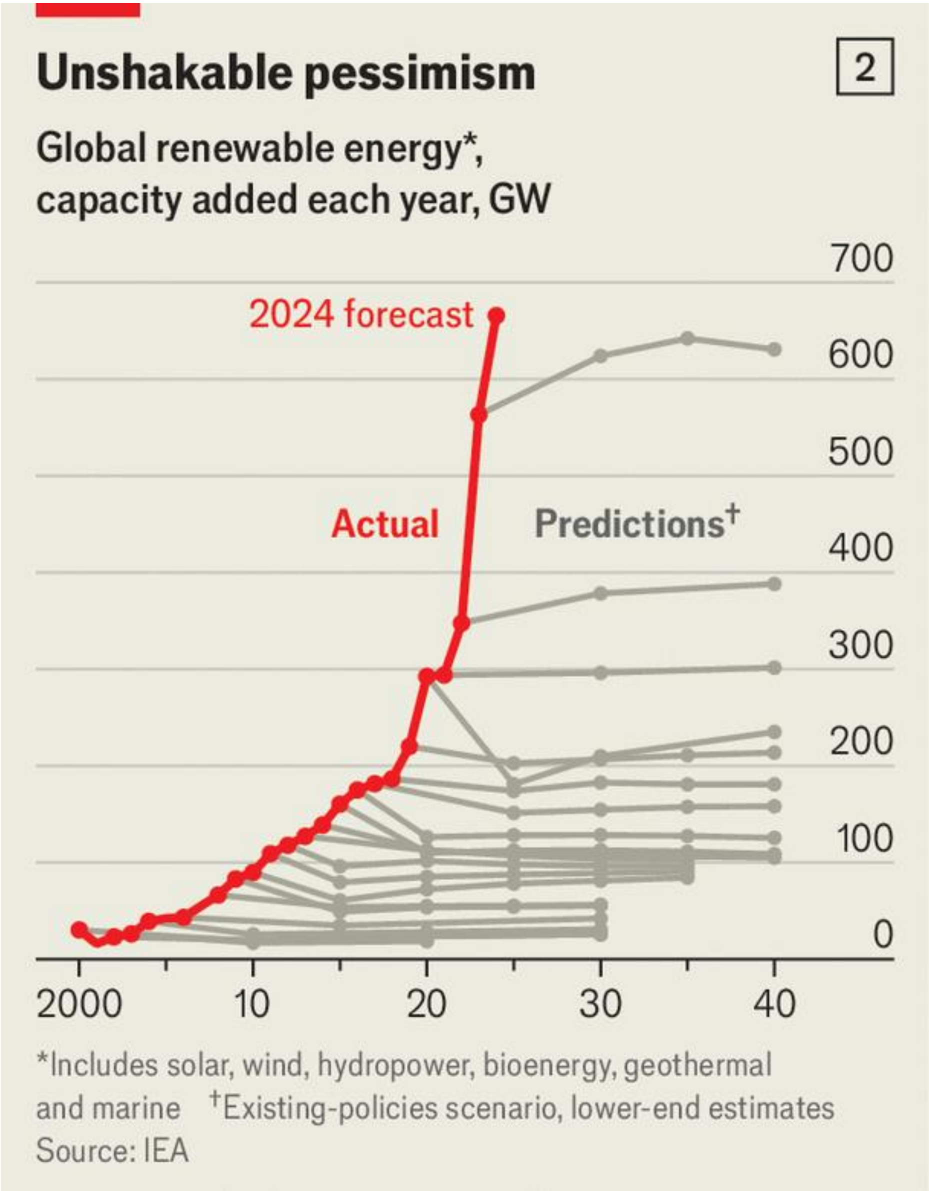
- Costs are two times higher for power sector credits and three times for vehicle credits
- Higher inframarginal shares for EVs due to cost-effectiveness before subsidies

Abatement costs of power sector tax credits are cost-effective, even once inframarginal investments are taken into account

- Average abatement costs of IRA's power sector credits (\$96/t-CO_2) are generally lower than recent social cost of carbon estimates (\$100-360/t-CO_2)
- Differences across models in ex-ante assessments of renewables deployment

Future Analysis

- Refine empirical analysis
  - Include ITC and PTC choice
  - Calculate inframarginal generation
  - Compare IRA magnitude with interest rates and interconnection queue impacts
- Conduct additional numerical modeling
  - Explore cross-model variation
  - Conduct sensitivities in single model setting to isolate impacts of interest rates, etc.
  - Incorporate insights from empirical analysis into numerical models



*Includes solar, wind, hydropower, bioenergy, geothermal and marine †Existing-policies scenario, lower-end estimates

Source: IEA

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Results for States with Binding RPS

WIND

	(1)	(2)	(3)	(4)
	Poisson FE	+ market controls	+ state trends	+ control function
lag elec. price + PTC	-0.144*	-0.028	-0.009	-0.004
	(0.065)	(0.058)	(0.083)	(0.087)
first stage resid.				-0.031
				(0.249)
year	-0.369*	-0.408	-1.150***	-1.149***
	(0.175)	(0.328)	(0.228)	(0.233)
N	133	133	133	133
first stage F-stat				31.6
PTC avg. partial eff.	-396%	-77%	-25%	-10%
county FE	X	X	X	X
year×state			X	X

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

SOLAR

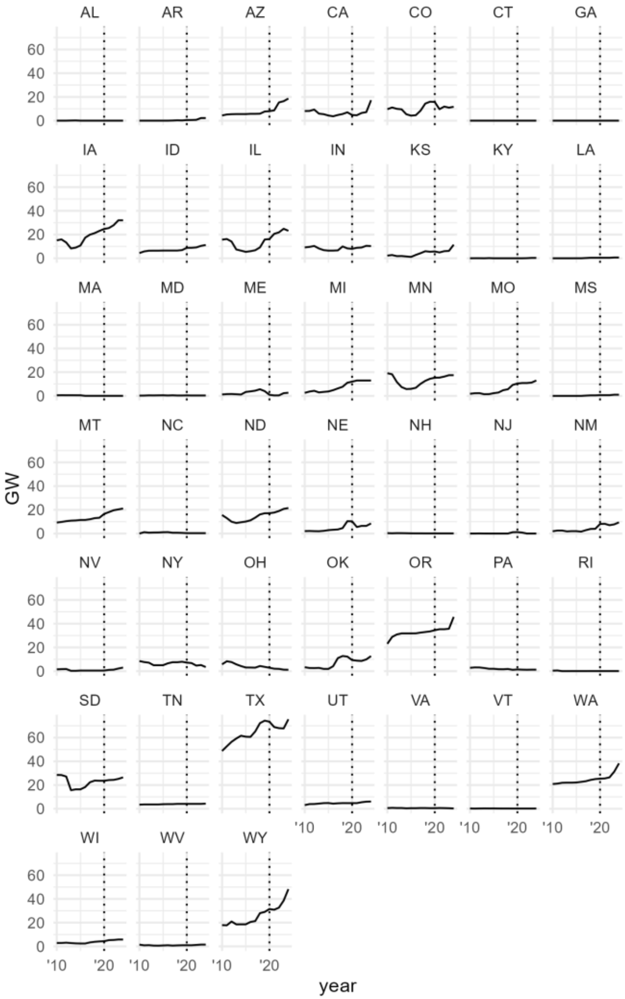
	(1)	(2)	(3)	(4)
	Poisson FE	+ market controls	+ state trends	+ control function
lag elec. price	-0.085	-0.038	0.012	0.008
	(0.054)	(0.050)	(0.052)	(0.058)
first stage resid.				-0.047
				(0.033)
year	0.528***	1.050**	0.854***	0.863***
	(0.084)	(0.332)	(0.222)	(0.185)
N	437	437	437	437
first stage F-stat				31.6
PTC avg. partial eff.	-235%	-105%	33%	22%
county FE	X	X	X	X
year×state			X	X

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

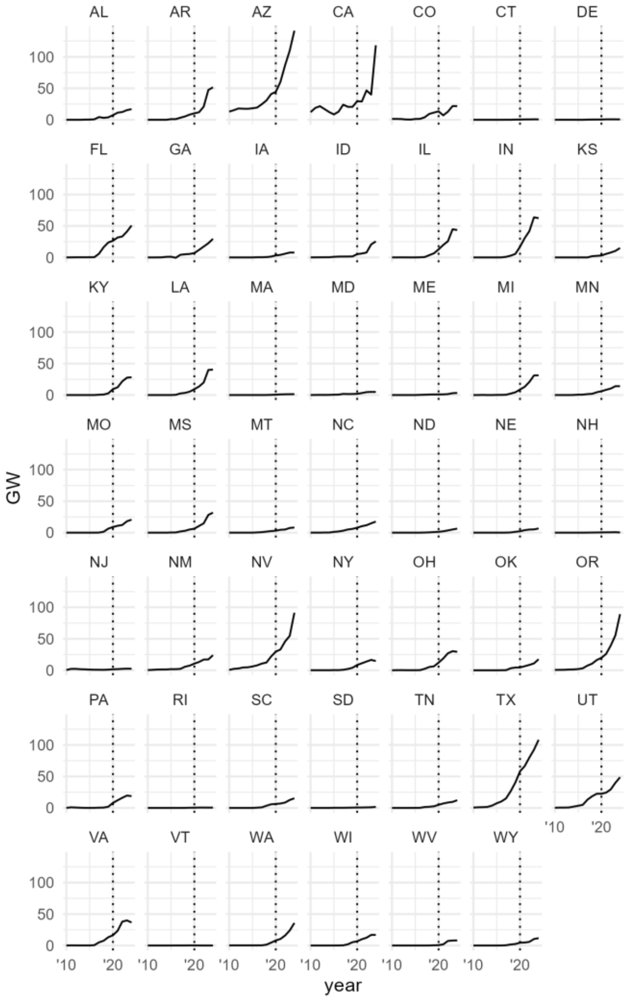
Note: Market controls include lagged variables for both wind and solar: avg. time in queue, capacity in queue, capacity additions. First-stage residual using Henry Hub natural gas price as IV. *Non-binding RPS defined as long-run standards <25%.

Queue Capacity of Wind and Solar

Wind



Solar



Control Function Approach

- IV-like approach to test and correct for endogeneity (Lin and Wooldridge, 2019)
- Linear first stage:

$$p_{jt} = \delta_1 \text{HH spot}_t + \mathbf{X}\rho + \alpha_{2_j} + e_{jt}$$

HH = Henry Hub Spot price used as IV

- Second stage includes first stage residuals

$$\mathbf{E}\left[\text{MW}_{jt}\right] = \exp\Big(\beta_1 p_{j,t-1} + \beta_2 t + \beta_3 \hat{e}_{j,t-1} + \mathbf{X}_{j,t-1}\gamma\Big)\alpha_{1_j}$$

- A significant coef. on the first-stage residual indicates endogeneity

Summary of Sub-Samples

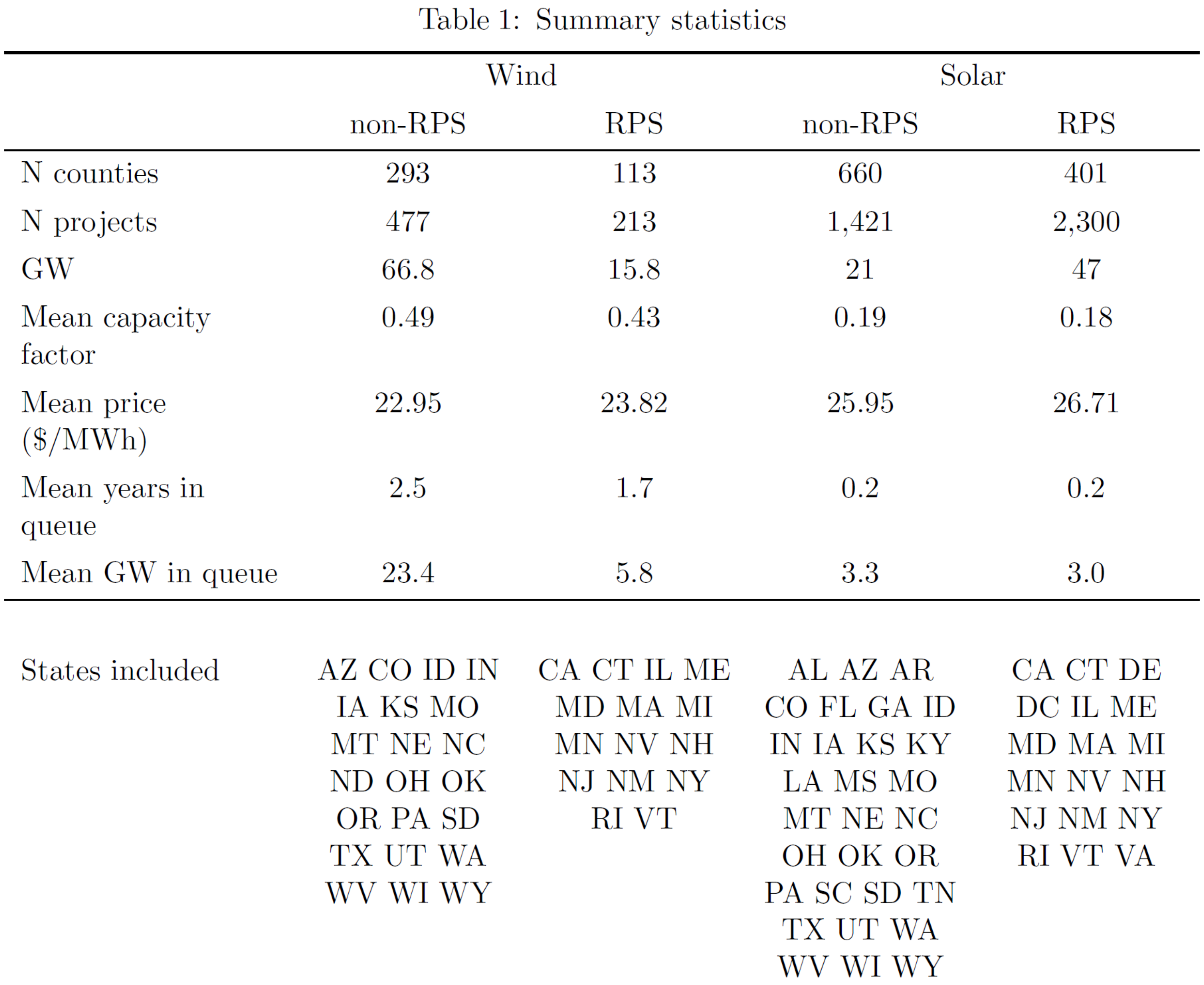


Table 1: Summary statistics

	Wind		Solar	
	non-RPS	RPS	non-RPS	RPS
N counties	293	113	660	401
N projects	477	213	1,421	2,300
GW	66.8	15.8	21	47
Mean capacity factor	0.49	0.43	0.19	0.18
Mean price ($/MWh)	22.95	23.82	25.95	26.71
Mean years in queue	2.5	1.7	0.2	0.2
Mean GW in queue	23.4	5.8	3.3	3.0
States included	AZ CO ID IN IA KS MO MT NE NC ND OH OK OR PA SD TX UT WA WV WI WY	CA CT IL ME MD MA MI MN NV NH NJ NM NY RI VT	AL AZ AR CO FL GA ID IN IA KS KY LA MS MO MT NE NC OH OK OR PA SC SD TN TX UT WA WV WI WY	CA CT DE DC IL ME MD MA MI MN NV NH NJ NM NY RI VT VA

IRA Incentives Modeled

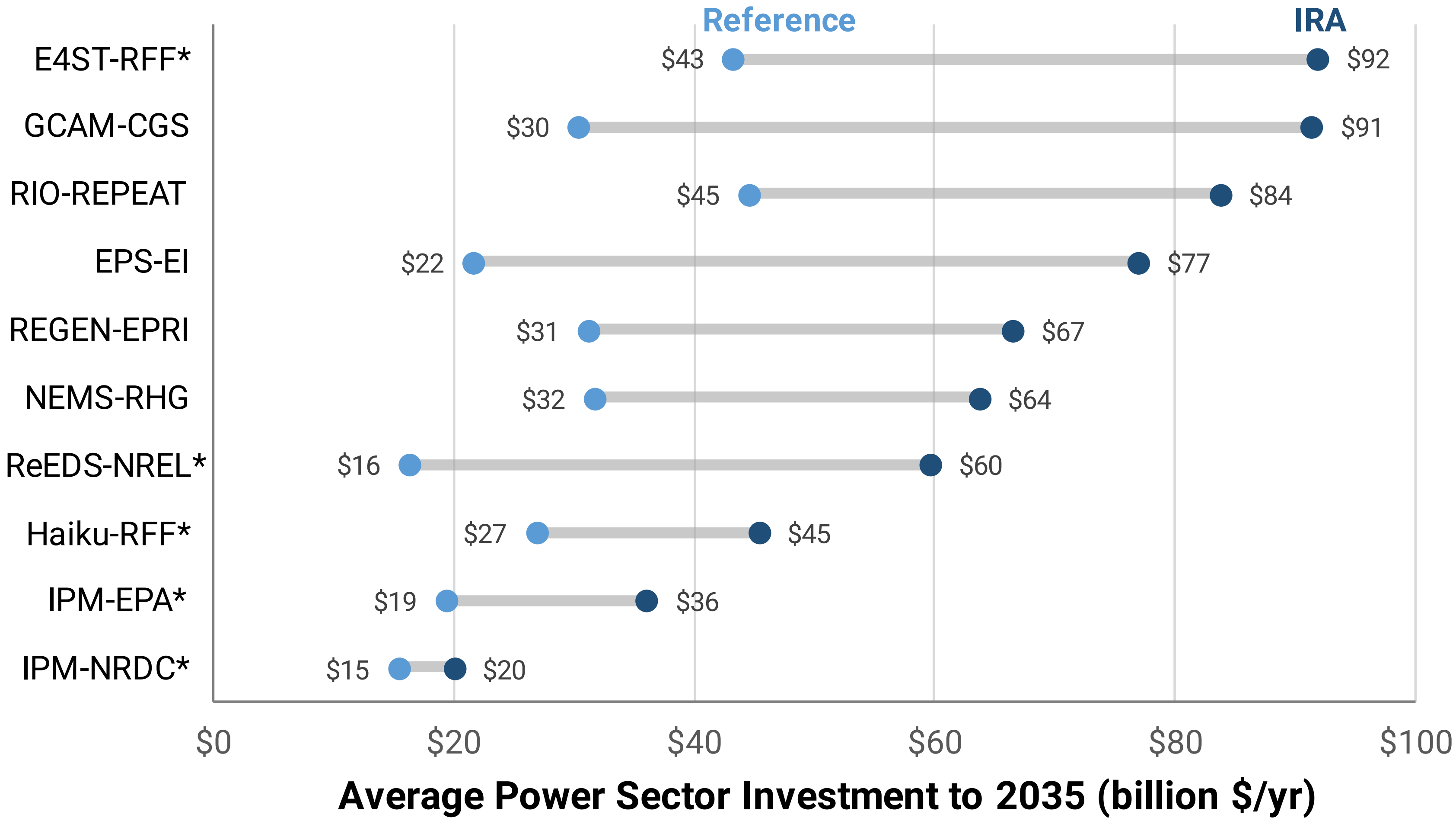
Sector	Program (Section)	EPS-EI	E4ST-RFF	GCAM-CGS	Haiku-RFF*	IPM-EPA*	IPM-NRDC*	MARKAL-NETL	NEMS-RHG	ReEDS-NREL*	REGEN-EPRI	RIO-REPEAT
Electricity	Production tax credit (PTC) extension (13101)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Investment tax credit (ITC) extension (13102)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Solar in low-income communities (13103/13702)	🟩	🟨	🟨	⬜	🟨	🟨	⬜	🟨	🟩	🟩	🟩
	PTC for existing nuclear (13015)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	New clean electricity PTC (45Y, 13701) and ITC (48E, 13702)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Accelerated depreciation (13703)	⬜	🟨	🟨	⬜	🟩	⬜	⬜	🟨	🟩	🟩	🟨
	Funds for rural coops (22004)	🟩	🟨	🟨	⬜	⬜	⬜	⬜	🟩	🟨	🟨	🟩
	Transmission financing (50151)	🟩	🟨	🟨	⬜	⬜	⬜	🟩	🟨	🟨	🟩	🟩
Multi-Sector	45Q: Extension of credits for captured CO2 (13104)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	45V: Production credits for clean hydrogen (13204)	🟩	🟨	🟩	⬜	🟩	⬜	🟩	🟩	🟨	🟩	🟩
	Loan authority for energy infrastructure (50144)	🟩	🟨	🟩	⬜	⬜	⬜	🟩	⬜	🟨	🟨	🟩
Transport	Extension of incentives for biofuels (13201/13202)	🟨	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	⬜	🟩
	Sustainable aviation credit (13203)	🟨	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	⬜	🟩
	Clean vehicle credit (13401)	🟩	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	🟩	🟩
	Credit for previously owned clean vehicles (13402)	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩
	Commercial clean vehicle credit (13403)	🟩	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	🟩	🟩
	Alternative refueling property credit (13404)	🟩	⬜	🟩	⬜	⬜	⬜	🟩	⬜	⬜	🟩	🟩
	Clean fuel PTC (13704)	🟨	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	⬜	🟩
Buildings	Residential clean energy credit (13302)	🟩	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	🟩	🟩
	Energy efficient commercial building deduction (13303)	🟩	⬜	🟩	⬜	⬜	⬜	⬜	🟩	⬜	🟩	🟩
	Energy efficient home credit (13304)	🟩	⬜	🟩	⬜	⬜	⬜	⬜	🟩	⬜	🟩	🟩
	Home energy efficiency credit (50121)	🟩	⬜	🟩	⬜	⬜	⬜	⬜	🟩	⬜	🟩	🟩
	High efficiency home rebate program (50122)	🟩	⬜	🟩	⬜	⬜	⬜	⬜	🟩	⬜	🟩	🟩
Industry and Other	Extension of advanced energy project credit (13501)	🟩	⬜	🟨	⬜	⬜	⬜	⬜	🟨	⬜	🟨	🟩
	Advanced manufacturing production credit (13502)	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟨
	Vehicle manufacturing loans/grants (50142/50143)	⬜	🟨	⬜	⬜	⬜	⬜	🟩	⬜	⬜	⬜	🟨
	Advanced industrial facilities (50161)	🟩	🟨	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟩
	Low-carbon materials (60503/60504/60506)	🟩	🟨	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟨
	Biodiesel, Advanced Biofuels, SAF	🟨	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	⬜	🟩
	Greenhouse Gas Reduction Fund	🟩	⬜	🟨	⬜	⬜	⬜	⬜	🟨	⬜	🟨	🟩
	Oil and gas lease sales	🟩	⬜	🟨	⬜	⬜	⬜	⬜	🟩	⬜	⬜	🟨
	Methane Emissions Reduction Program	🟩	⬜	🟩	⬜	⬜	⬜	🟩	🟩	⬜	⬜	🟩
	Agriculture and forestry provisions	🟩	⬜	🟩	⬜	⬜	⬜	⬜	🟩	⬜	⬜	🟩

🟩 Included
🟨 Not Included
⬜ Not Applicable

Caveats

- Not all climate/energy provisions listed
- Implementation of modeled provisions varies across groups, given differences in model structure and coverage
- Focus on central estimate (with low/high IRA implementation scenarios for some models)

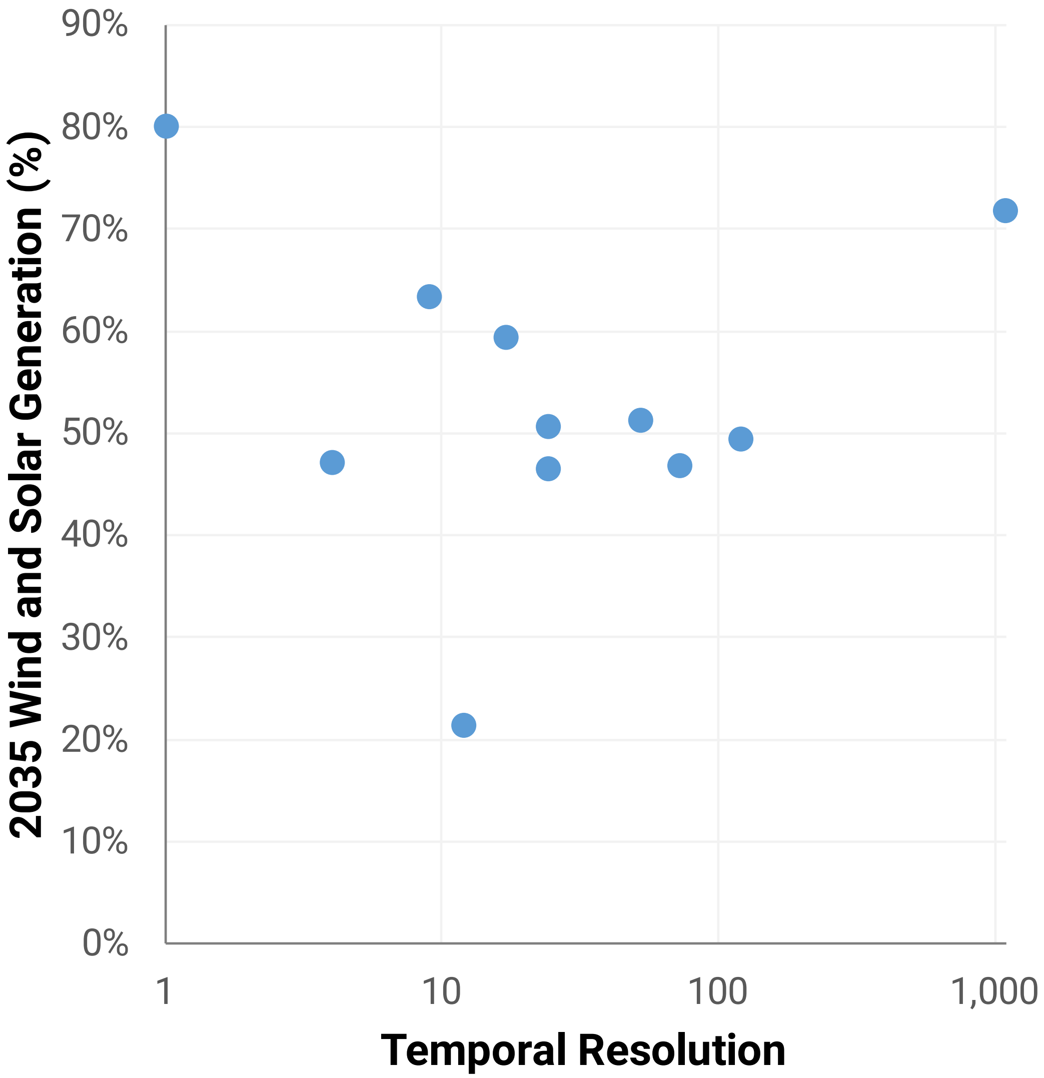
Power Sector Investments without/with IRA

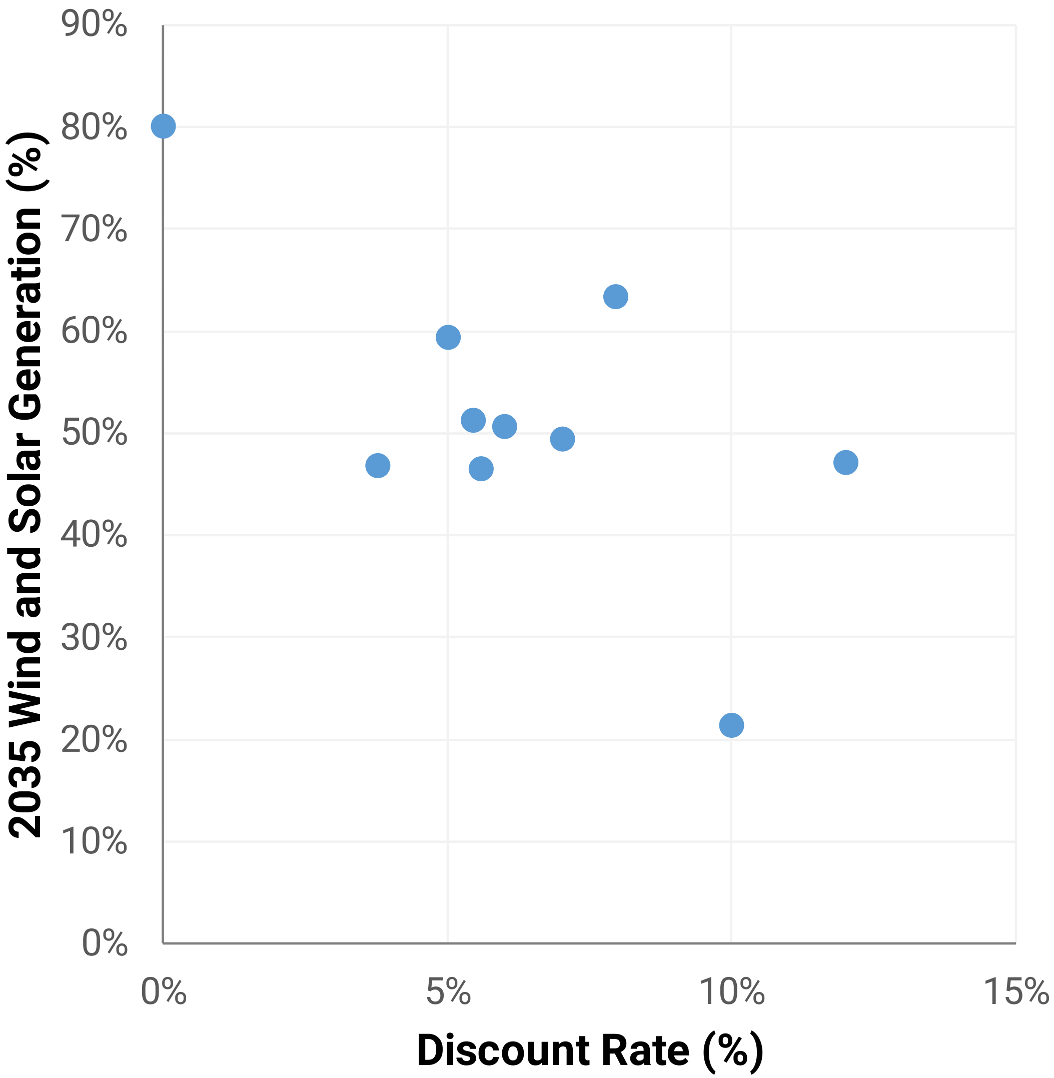


- Inframarginal shares in investment dollar terms track capacity shares (27-77%)
- Electric vehicle credits have higher inframarginal shares
  - Our analysis: 67-93% for IRA credits using numerical modeling
  - Allcott, et al. (2024): 67-77% using ex-post analysis of IRA credits

* Electric sector only modeling

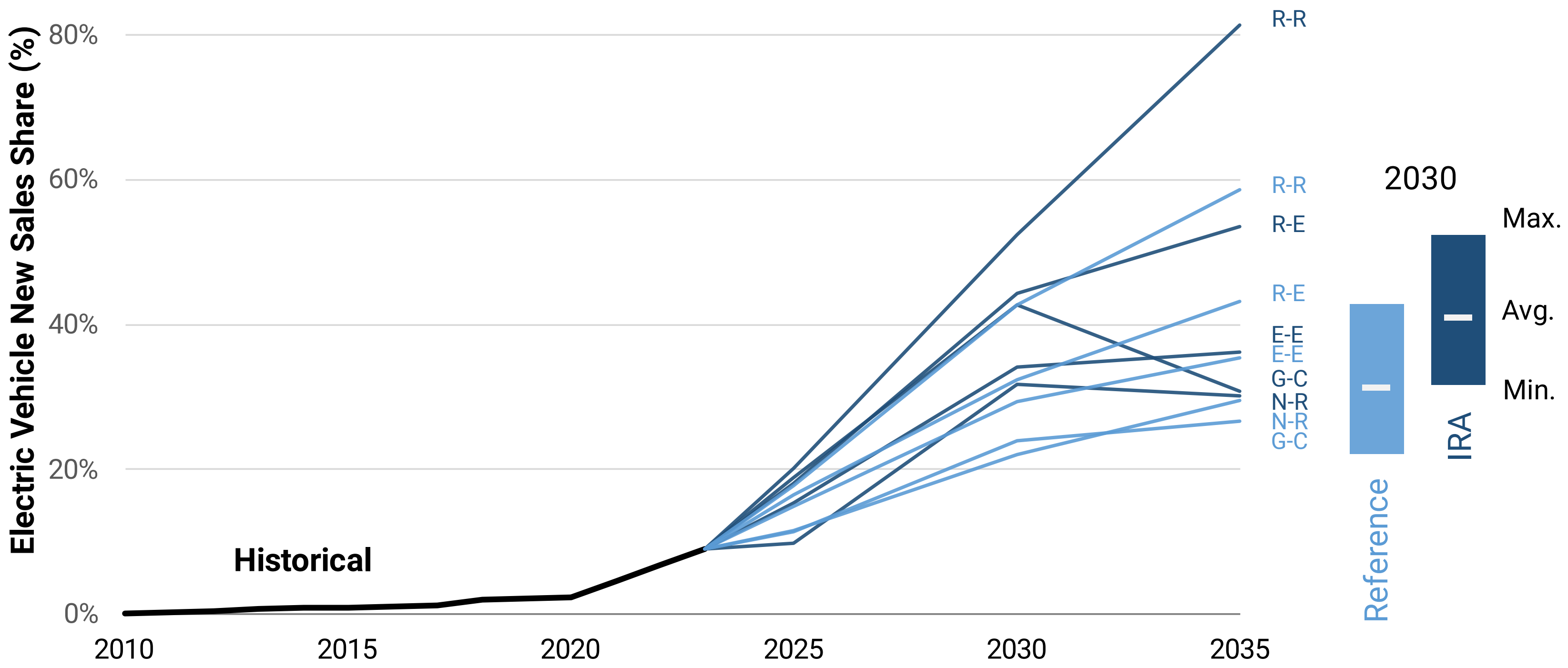
Impact of Model Choices on Wind/Solar Deployment





Source: Bistline, et al. (2024), "Power Sector Impacts of the Inflation Reduction Act of 2022" (link)

Electric Vehicle Adoption with IRA Incentives



- New sales share of light-duty EVs, including BEVs and PHEVs
- IRA modestly increases EV sales shares
  - By 2030, electric vehicles are 32-52% of new sales with IRA (22-43% under reference)
  - Even with IRA tax credits, 2030 sales are below 50% target
- Inframarginal investment shares span 67-93%
- For IRA scenarios, models generally increase at slower rate between 2030 and 2035 after subsidies expire

Numerical Modeling Summary Table

Metric/Sector	Min.	Avg.	Max.
Inframarginal Share[1] (%), Power Sector Capacity	28%	49%	72%
Inframarginal Share[1] (%), Transport Electric Vehicle Sales	67%	81%	93%
Avg. Abatement Cost[2] ($/t-$CO_2$), Power Sector	$34	$96	$170
Avg. Abatement Cost[2] ($/t-$CO_2$), Transport	$98	$310	$420
Cumulative Fiscal Costs[3] (billion $ to 2035), Power Sector	$180	$450	$820
Cumulative Fiscal Costs[3] (billion $ to 2035), Transport	$120	$420	$750

- Transport subsidies have higher inframarginal shares and abatement costs
- Analysis that treats all recipients as additional underestimates fiscal costs
  - Power sector: Subsidies per unit output are twice as large
  - Transport: Per-vehicle subsidies are nearly three times as large when non-additional purchasers are accounted for

[1] Inframarginal share is ratio of investment without IRA to investment with IRA (cumulative $ terms through 2035)

[2] Average abatement costs are the change in discounted resource costs over the change in undiscounted emissions relative non-IRA counterfactual through 2035

[3] Cumulative fiscal costs through 2035 are shown in real 2020 dollar terms