

Overview of Nuclear in Electricity Markets

Insights and Perspectives from EPRI's REGEN Model

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Energy Systems and Climate Analysis

July 19, 2021

National Academies Meeting

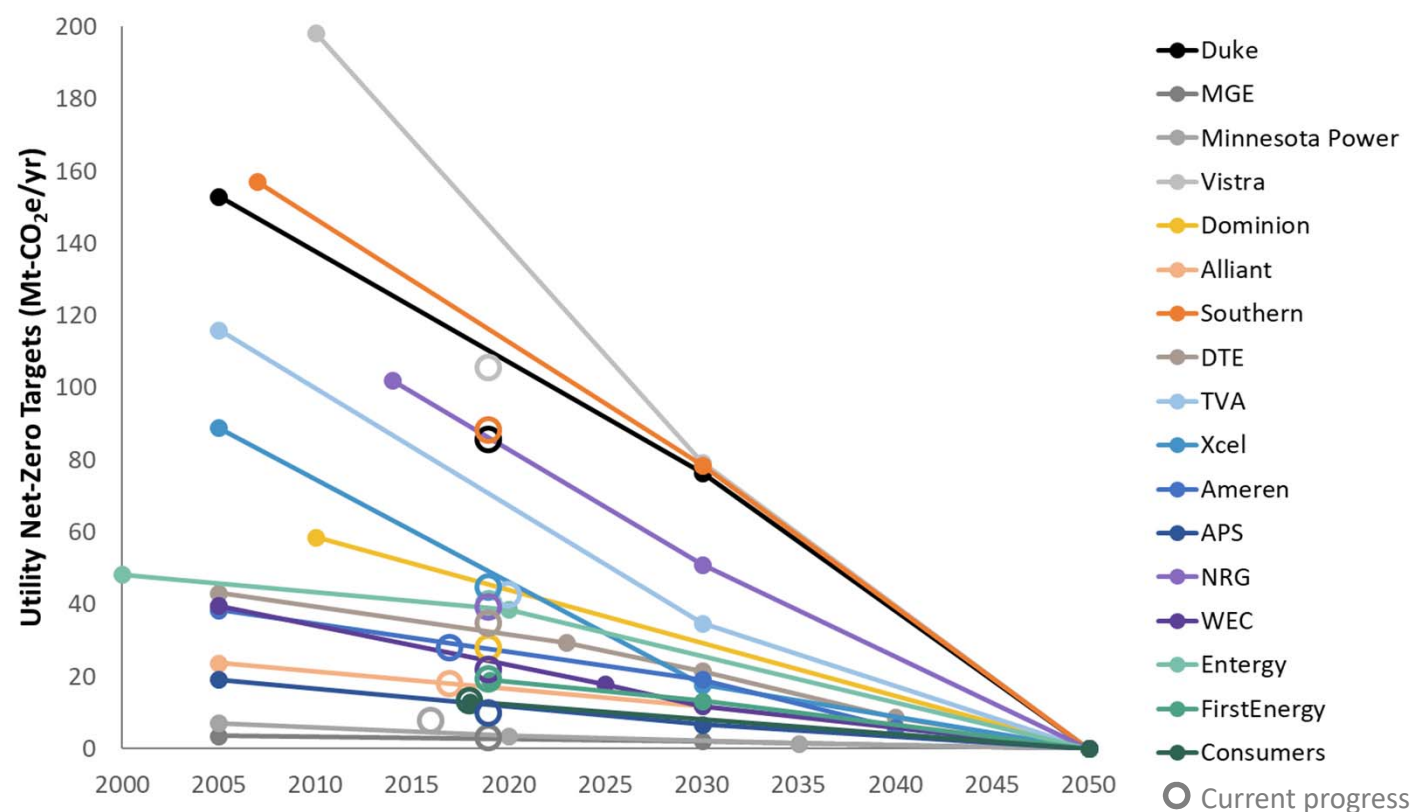
  
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Drivers of Decarbonization in the Electric Sector

- Federal policy
 - CO₂ (e.g., clean electricity standards, tax credits)
 - Air quality (e.g., NAAQS, Regional Haze, CSAPR, CAA regulations)
- State policy
 - Renewable and clean electricity standards (key differences)
 - GHG/CO₂ reductions
- Company pledges (right) and shareholder interest
- Customer demand



Data sources: Company filings; EPRI 201-B database (ID #3002019004)

Questions about timing, strategies, and sector interactions for reaching deep decarbonization targets; this is the evolving landscape where nuclear and other technologies could play roles

Roles for Nuclear and Other Options in Electricity Markets



Low-/Zero-Carbon Electricity: Energy

- Primarily competing with renewables and carbon-capture-equipped generation
- Market size based on drivers of deep decarbonization and policy design



Low-/Zero-Carbon Electricity: Diurnal Capacity

- Competing with short-duration storage, fossil-fired + offsets/carbon removal (CDR, “negative emissions”), demand response
- Market size could be substantial at higher renewable penetrations



Low-/Zero-Carbon Electricity: Longer-Duration Capacity

- Competing with dispatchable renewables (hydro, geothermal), long-duration storage, power-gas-power, gas-fired + offsets/CDR
- Market size depends on depth of variable renewables penetration and decarbonization



Low-/Zero-Carbon Flexibility/Reliability/Ancillary Services

- Competition varies by service but can include energy storage, fossil units with low capacity factors, and others
- Market size depends on renewables level, decarbonization policies (and retirements of existing capacity), other emissions policies



Low-/Zero-Carbon Direct-to-Customer Energy (Co-Production)

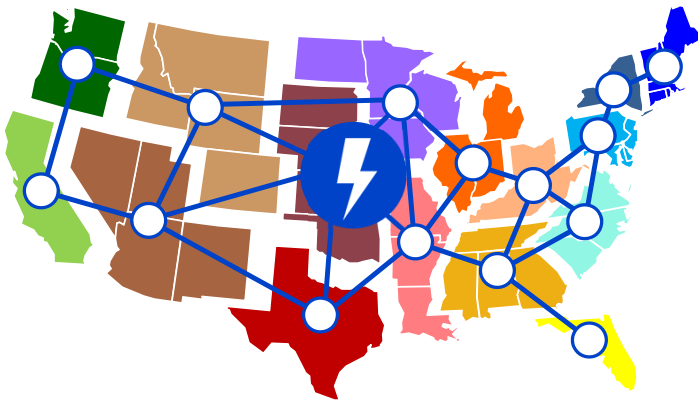
- Competition with renewables, etc.
- Market potential unknown; would be based on establishing clear efficiencies from co-production

Cost and value are key drivers for technology choices in each market

US-REGEN

Regional Economy, GHG, and Energy

Electric Generation



Detailed representation of:

- Energy and capacity requirements
- Renewable integration, transmission, storage
- State-level policies and constraints

Synchronized



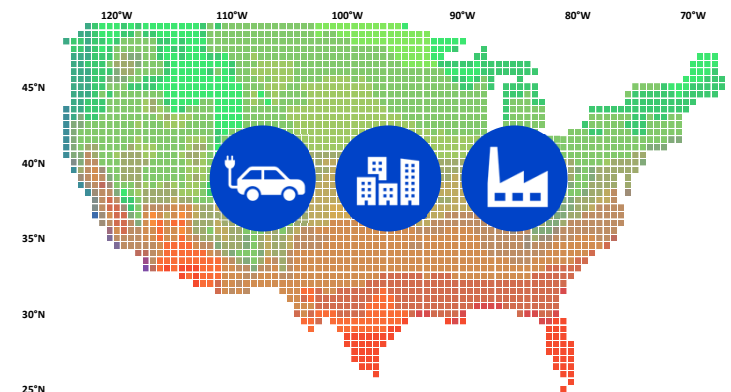
Hourly Load,
Renewables,
and Prices

Model Outputs:

Economic equilibrium
for generation, capacity,
and end-use mix

Emissions, air quality,
and water

Energy Use

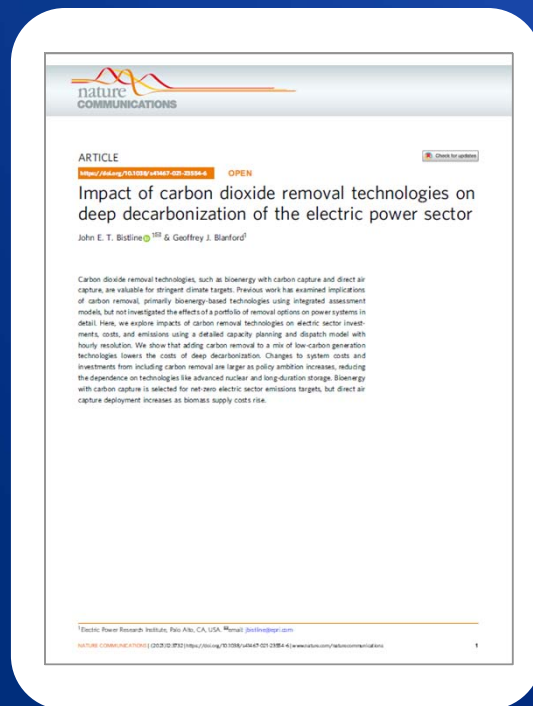


Detailed representation of:

- Customer heterogeneity across end-use sectors
- End-use technology trade-offs
- Electrification and efficiency opportunities

Documentation, articles, and reports available at <https://esca.epri.com>

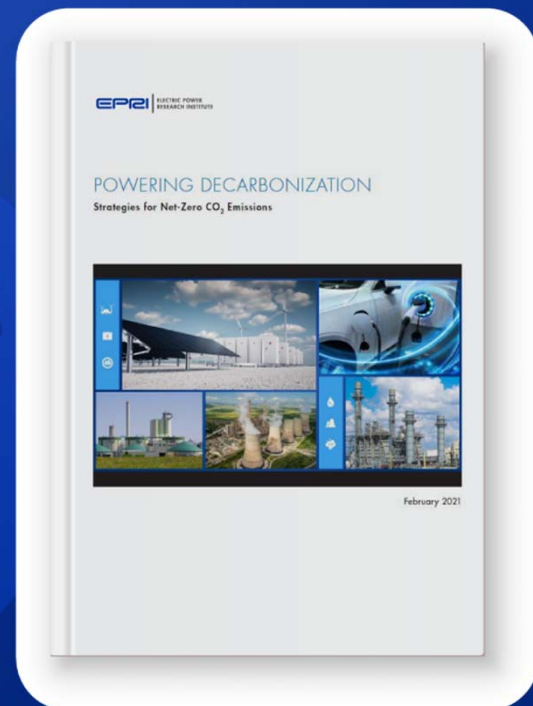
New Research on Power Sector Decarbonization



Impact of Carbon Removal Technologies on Deep Decarbonization

Published in *Nature Communications* in June 2021

[Free to download](#)



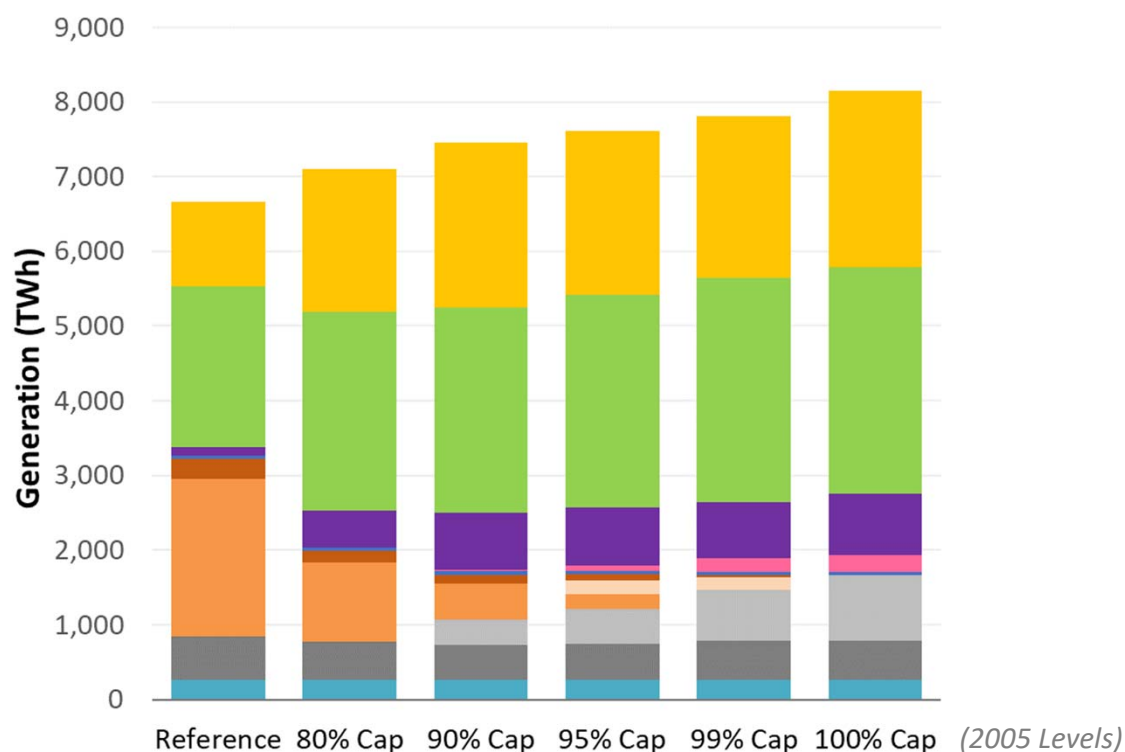
Powering Decarbonization: Strategies for Net-Zero CO₂ Emissions

White Paper Published in February 2021

[EPRI Report #3002020700](#)

Nuclear's Value Increases with Deeper Decarbonization

Scenarios without Carbon Removal

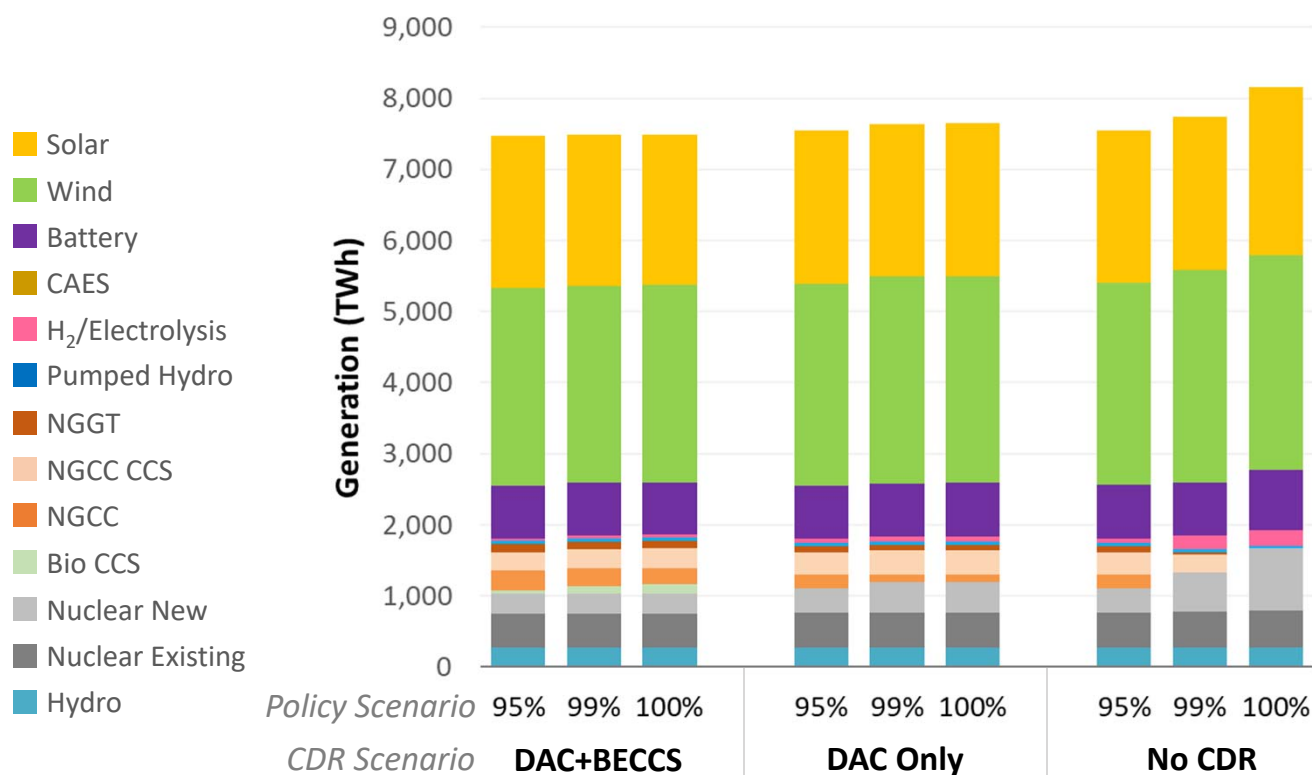


Least-cost path to zero-carbon electricity entails a mix of technologies and resources

- Declining marginal value and increasing system costs of very high variable renewables
- Increasing value of capacity and flexible technologies
- High costs of long-duration (seasonal) energy storage
- Regional differences

Abatement options near 100% entail different technologies (e.g., new nuclear, H₂) and are sensitive to assumptions about the cost/performance technologies

Carbon Removal a Key Determinant of Nuclear Value



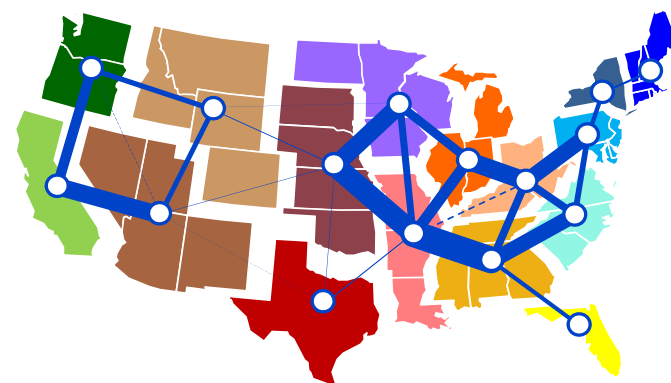
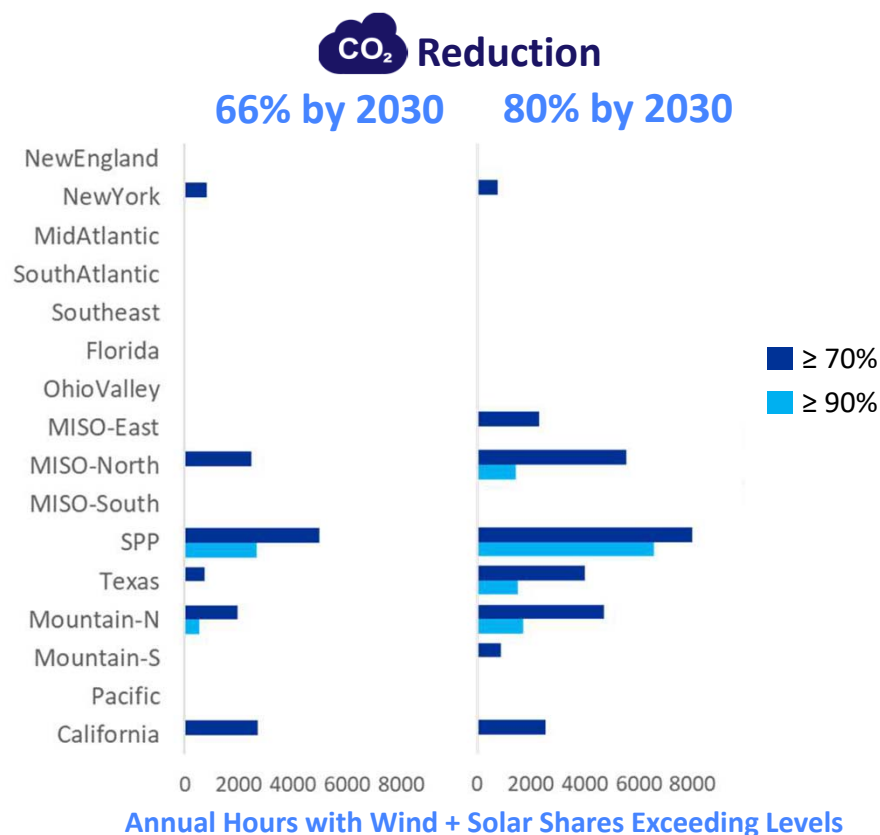
Observations

- CDR impacts depend on policy stringency (only impacts solutions when caps >90%)
- CDR availability:
 - Increases gas capacity/generation by offsetting CO₂ emissions (BECCS negative emissions enable larger shares of low-cost gas)
 - Decreases nuclear, renewables, and long-duration energy storage (gas provides cheaper firm power)

Source: Bistline and Blanford (2021),
Impact of Carbon Removal Technologies...

Policy design and technology assumptions alter electric sector costs and investment pathways

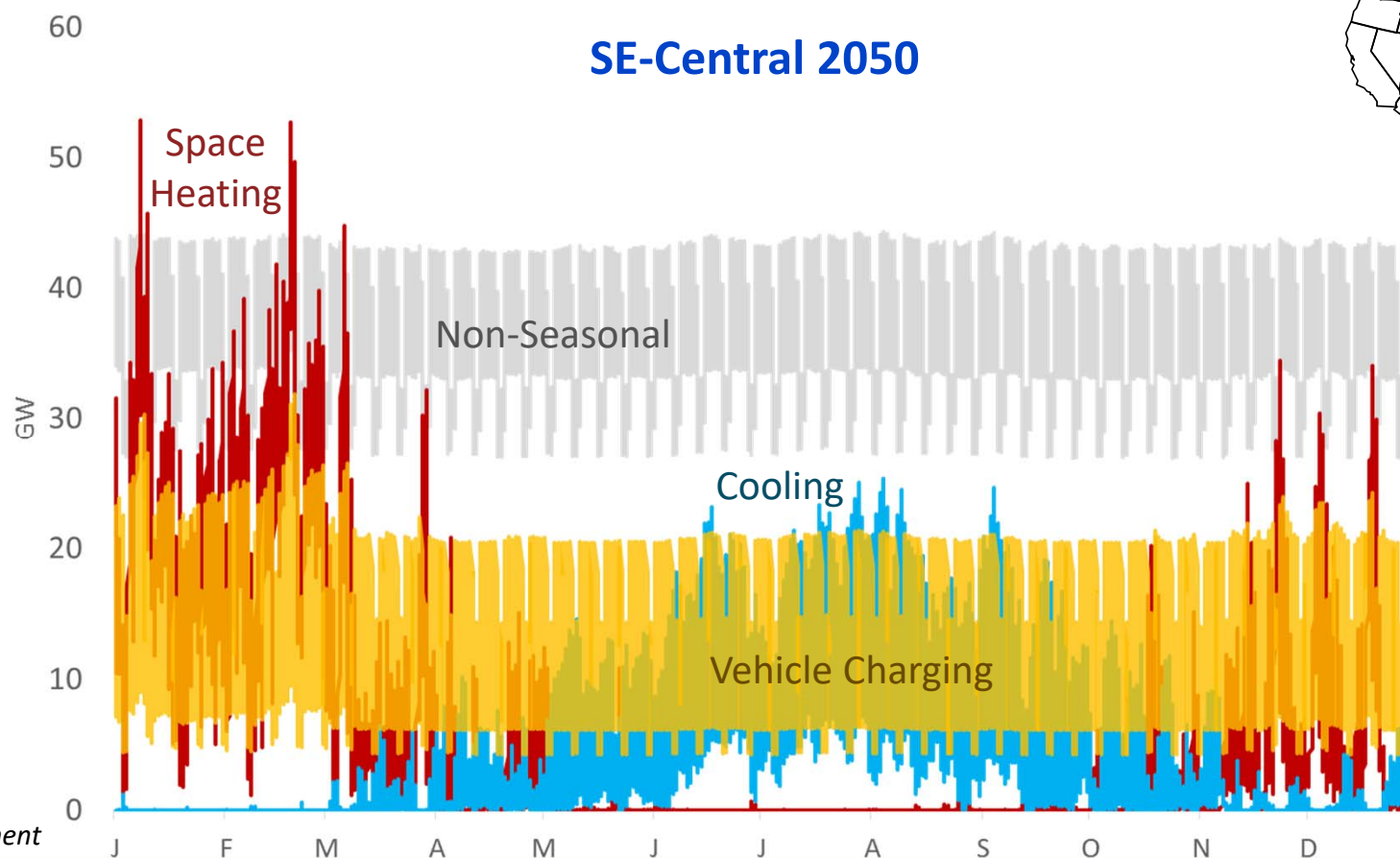
Changing Mix Raises Reliability Questions



- Renewable deployment is concentrated in high-quality-resource regions
- Flexible and dispatchable low-carbon technologies are of high value
- Based on scenarios in Blanford, et al. (2021), “Powering Decarbonization”

Changing resource mixes (including high penetrations of solar, wind, and storage) raise questions about reliability/resiliency, ancillary services, market design

Electrification Alters Load Shapes and Variability

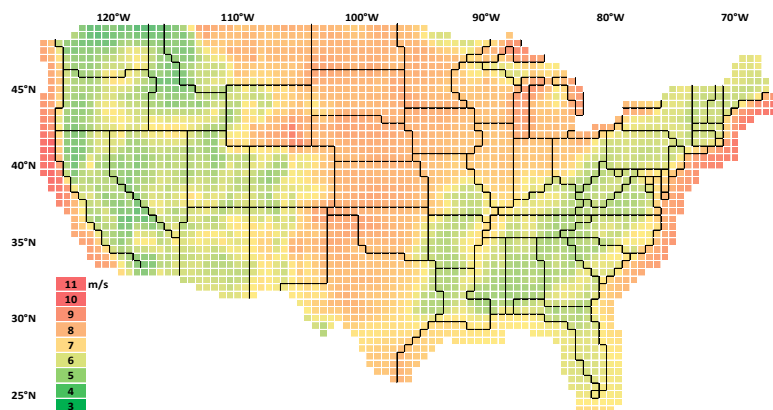


Source: EPRI (2018),
U.S. National
Electrification Assessment

Hourly load shapes will change over time, raising questions about supply and demand flexibility

Future Work: Understanding the Role of Nuclear in Low-Carbon Energy Systems

1. Increasing spatial and temporal granularity for utility-level analysis
2. Linking to operational reliability and production cost models
3. Exploring low-carbon fuel pathways to reach economy-wide net-zero
4. Conducting multi-model comparisons to share best practices and investigate policy and technology scenarios



Average wind speed at 100m (1980–2015) based on NASA's MERRA2 dataset



Venues for model intercomparison studies

Improvements are aimed to help stakeholders understand evolving challenges facing the electric sector

EPRI ESCA Research Summary on Nuclear



EPRI Energy Systems and Climate Analysis Group Research on the Value and Costs of Nuclear Generation

Last Updated: April 2020

This is a summary of all of EPRI's Energy Systems and Climate Analysis (ESCA) Group's research on the economics of nuclear generation, including work in progress. Web links are included where available. Publications marked with an * are available to the public free of charge or are published in academic journals. Other publications are available to EPRI member companies that fund certain program(s), as indicated with a number in brackets preceding the publication title and can be purchased by members of the public who may be interested in doing so, subject to EPRI's product distribution requirements. For a full listing of ESCA research that is free to the public, please visit the ESCA public website at <http://eca.epri.com/research.html>. To receive the ESCA group's quarterly newsletter with research updates, please email your request to eca@epri.com.

ECONOMICS OF EXISTING NUCLEAR

* Bistline, J., M. Brown, S. Siddiqui, and K. Vaillancourt *Electric Sector Impacts of Renewable Policy Coordination: A Multi-Model Study of the North American Energy System* (in review)

* *Impacts of Recent State Renewable Policies in the U.S.*, EPRI Program 201 Back Pocket Insight, December 2019, <https://eca.epri.com/pdf/Back-Pocket-Insights/P201-Back-Pocket-Insight-Recent-State-Policies.pdf>

(201-C, 41.13) *The Economics of Nuclear Plant Modernization in U.S. Markets*, EPRI Report 3002014737, January 2019, <https://www.epri.com/#/pages/product/3002014737>

(103) *Early Retirement Risks for Nuclear in U.S. Markets*, December 2017, <https://membercenter.epri.com/Programs/109396/pages/eventdetails.aspx?eventID=D5E0F8F6-506B-47D0-BBD8-9C3FBD42A3A6>

(103) *Environmental Value of Retaining Existing Nuclear Units*, June 2016, <https://membercenter.epri.com/Programs/109396/pages/eventdetails.aspx?eventID=D5E0F8F6-506B-47D0-BBD8-9C3FBD42A3A6>

ECONOMICS OF ADVANCED NUCLEAR

* Bistline, J.E.T., James, R., and A. Sowder *Technology, Policy, and Market Drivers of (and Barriers to) Advanced Nuclear Reactor Deployment in the United States After 2030*, *Nuclear Technology* 205:1075-1094, 2019, <https://doi.org/10.1080/00295450.2019.1574119>

* *Exploring the Role of Advanced Nuclear in Future Energy Markets: Economic Drivers, Barriers, and Impacts in the U.S.*, EPRI Report 3002011803, March 2018, <https://www.epri.com/#/pages/product/000000003002011803/>

SCENARIO ANALYSES INCLUDING NEW NUCLEAR

(201-C) *Program 201-C Webcast on Technological Options and Uncertainties for Very High CO₂ Reductions*, March 2020, <https://membercenter.epri.com/Programs/109396/pages/eventdetails.aspx?eventID=D8E91360-8B97-4314-82CC-171C1F2CAC64> (webcast recording also available via this link)

* Bistline, J., and G. Blanford *Value of Technology in the U.S. Electric Power Sector: Impacts of Full Portfolios and Technological Change on the Costs of Meeting Decarbonization Goals*, *Energy Economics* 84:104694, February 2020, <https://doi.org/10.1016/j.eneco.2020.104694>

(178-B) *2019 REGEN Scenarios Analysis: Understanding Key Factors That May Impact the Evolution of Electricity Generation in the United States 2015-2050*, EPRI Report 3002016570, December 2019, <https://www.epri.com/#/pages/product/3002016570/>

Public research summary covering:

- Economics of existing nuclear
- Economics of advanced nuclear
- Scenario analysis including nuclear
- Nuclear technology cost and performance estimates

ID 3002018270 ([link](#))

A blue-tinted photograph of four people standing in a row. From left to right: a man with curly hair and glasses in a lab coat; a man with glasses in a lab coat; a woman wearing a hard hat and a lab coat; and a man with glasses in a light blue button-down shirt. They are all smiling and looking towards the right. The background is a solid blue gradient.

Together...Shaping the Future of Energy™

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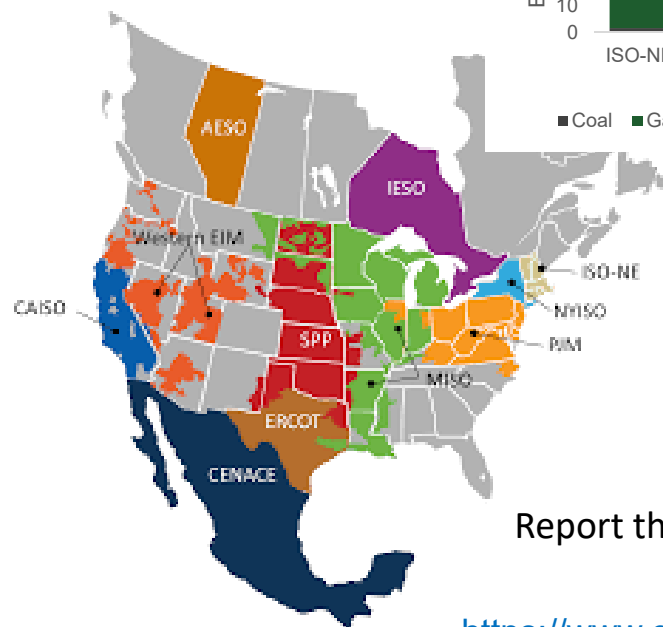
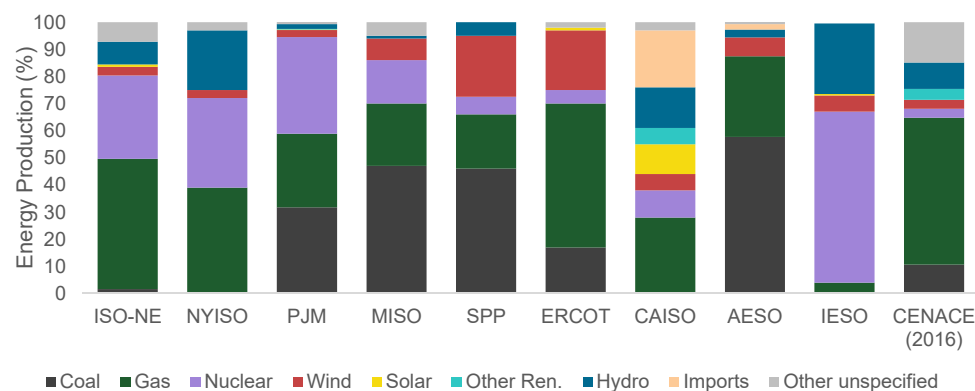
Additional Resources

- Bistline, Blanford (2021), Impact of Carbon Dioxide Removal Technologies on Deep Decarbonization of the Electric Power Sector, *Nature Communications* ([link](#))
- Bistline, Blanford (2020), Value of Technology in the U.S. Electric Sector, *Energy Economics* ([link](#))
- Bistline, James, Sowder, Technology, Policy, and Market Drivers of (and Barriers to) Advanced Nuclear Reactor Deployment in the United States After 2030, *NT* ([link](#))
- Blanford, Wilson, Bistline (2021), Powering Decarbonization: Strategies for Net-Zero CO₂ Emissions, EPRI Report 3002020700 ([link](#))
- EPRI (2018), U.S. National Electrification Assessment, EPRI Report 3002013582 ([link](#))
- Santen, Young, Blanford (2021), Analyzing Federal 100% Clean Energy Standards, EPRI Report 3002020121 ([link](#))
- Young, et al. (2020), US-REGEN Model Documentation, EPRI Report 3002016601 ([link](#))

For more information, see our website at <https://eea.epri.com/>

Organized Electricity Markets in North America

Nine Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) serve 66% of consumers in the U.S. and more than 50% of Canada's population. See the ISO/RTO Council website: www.isorto.org.

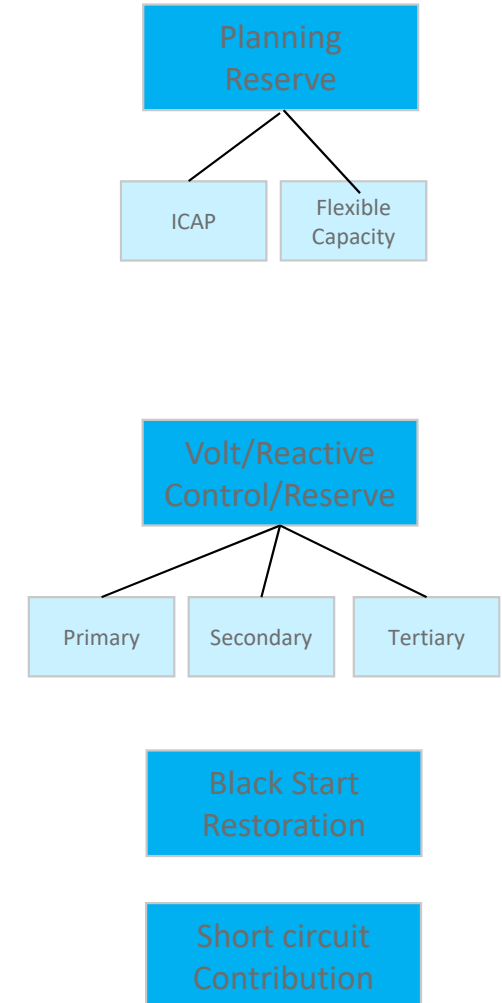
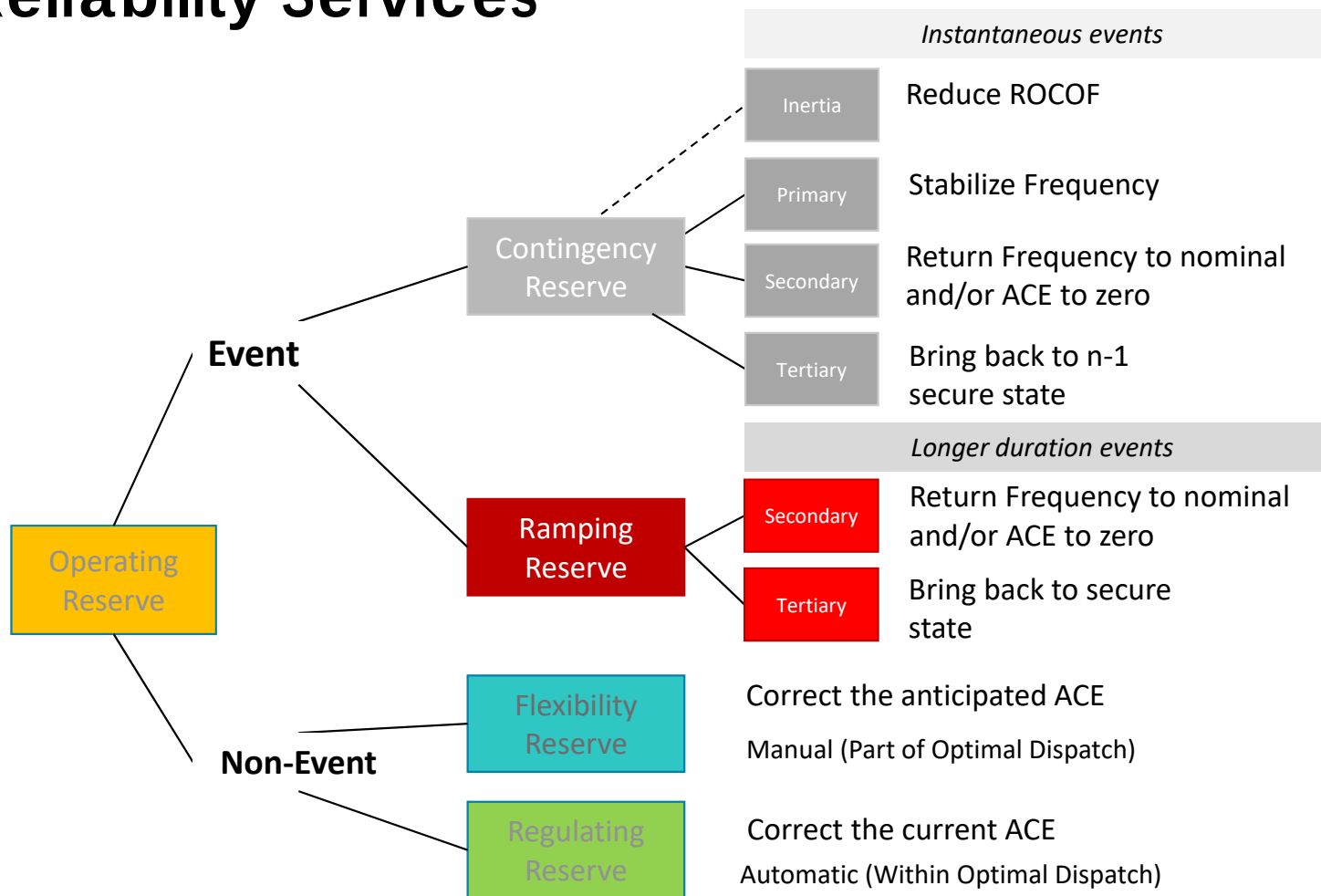


Report that covers all of this!

<https://www.epri.com/#/pages/product/000000003002009273/?lang=en>

	Total Market Volume (\$B)	All-in-Price (\$/MWh)	Energy (\$B)	Ancillary Services Markets (\$M)	Uplift (\$M)	Financial Transmission Rights (\$M)	Capacity Market (\$M)
AESO (CAD\$)	3	25.5	1.8	81	0.23	N/A	N/A
CAISO	9.3	42	8.7	172	108	80	N/A
ERCOT	14	30.15	10	323	0.5	379	N/A
IESO (CAD\$)	17	15.8	2.2	57	146	N/A	N/A
ISO-NE	9.1	76	4.5	128	52	30	2,240
MISO	26.9	31.35	24.7	69	104	252	47
NYISO	8.7	40	5.3	110	38	222	3,000
PJM	40.0	54	23.5	508.1	129	542	8,800
SPP	16.7	24.08	6.3	80	68	308.8	N/A

Reliability Services



ACE: Area Control Error; ROCOF: rate of change of frequency

The logo for REGEN is set against a dark blue background. On the left, a bright, glowing lightning bolt strikes downwards, with a cluster of small, colorful sparks at its base. To the right of the lightning bolt, the word "REGEN" is written in large, bold, white, sans-serif capital letters.

REGEN

Regional Economy, GHG, and Energy

Policy Analysis Technology Insights Energy Use Trends

- A framework for understanding drivers of change in the electric sector and energy system
- Industry-leading representation of end-use load changes, variable renewables, and energy storage
- Supported by EPRI engineering expertise and technology projections

Model Scenarios for *Nature Communications* Analysis

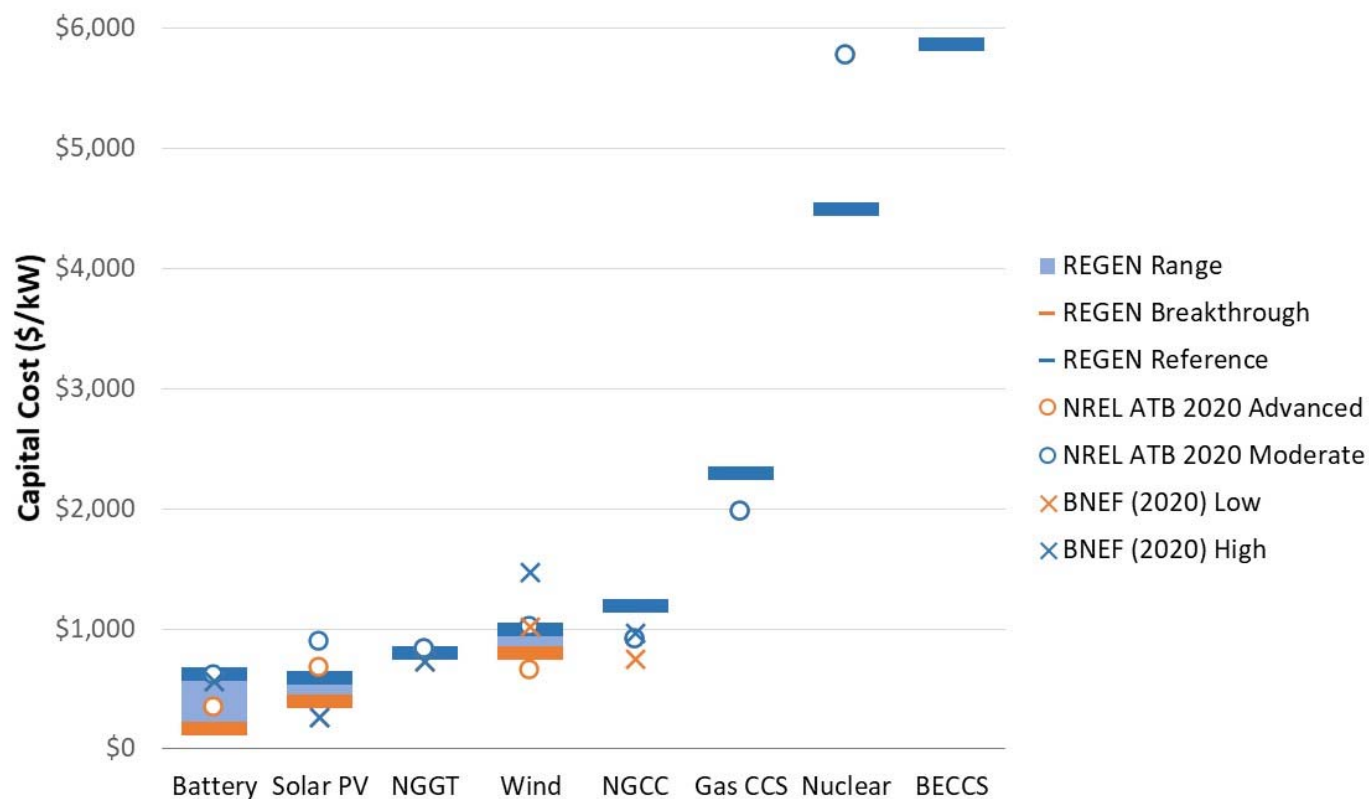
CO ₂ Cap*	RPS Target	Technologies	Gas Prices	CO ₂ Removal
▪ None ▪ 80% ▪ 90% ▪ 95% ▪ 99% ▪ 100%	▪ None ▪ 70–100% ▪ RPS Only	▪ Reference ▪ Breakthrough	▪ Ref (\$4) ▪ \$3/MMBtu	▪ None ▪ DAC Only ▪ All (i.e., DAC and BECCS)

* Caps are on electric sector emissions relative to 2005 levels; no other state/federal policies/incentives included

Including combination sensitivities in each category and one-off sensitivities

Technology Cost Input Assumptions

Nature Communications Study

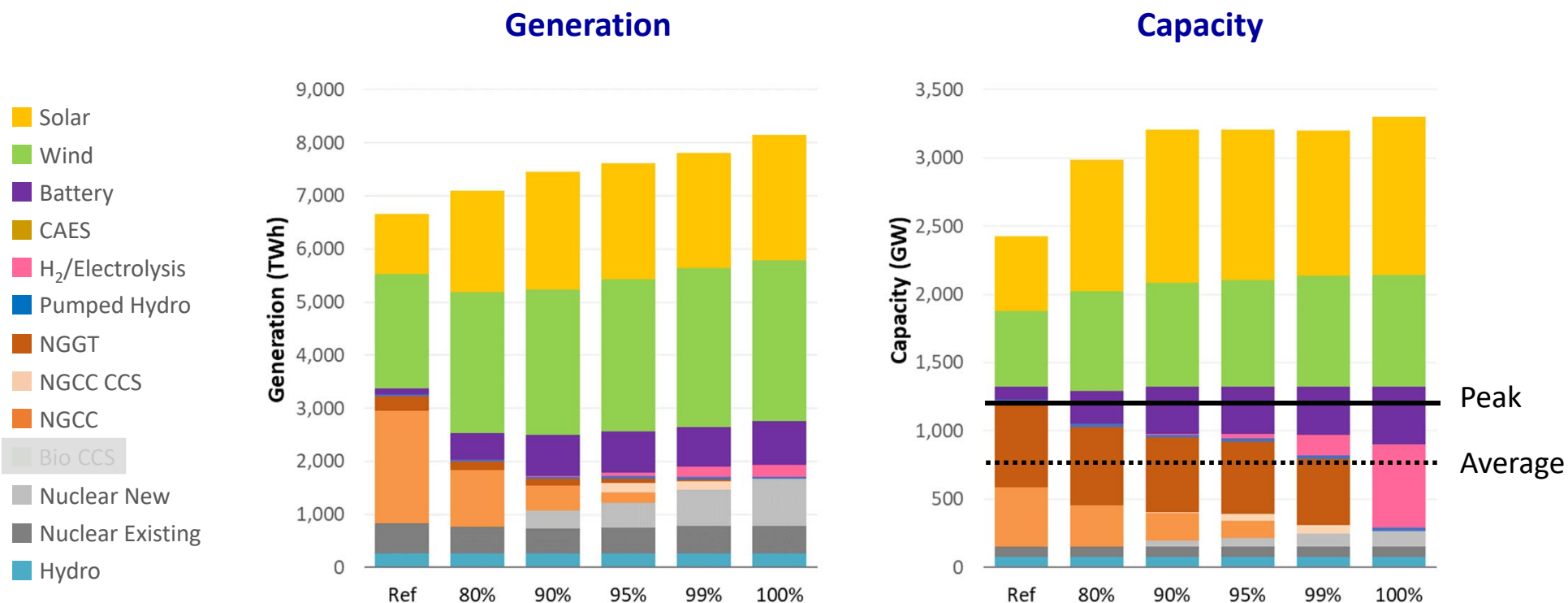


Notes

- Solar PV costs in $\$/kW_{AC}$ terms
- Reference battery storage costs based on four-hour li-ion system (detailed assumptions shown on next slide)
- REGEN range shows capital costs examined in this analysis
 - **Reference** is “best guess” based on anticipated U.S. and global RDD&D
 - **Breakthrough** wind, solar, and storage scenario considers “5% probability” outcome

Capacity Investments Increase with Higher Abatement

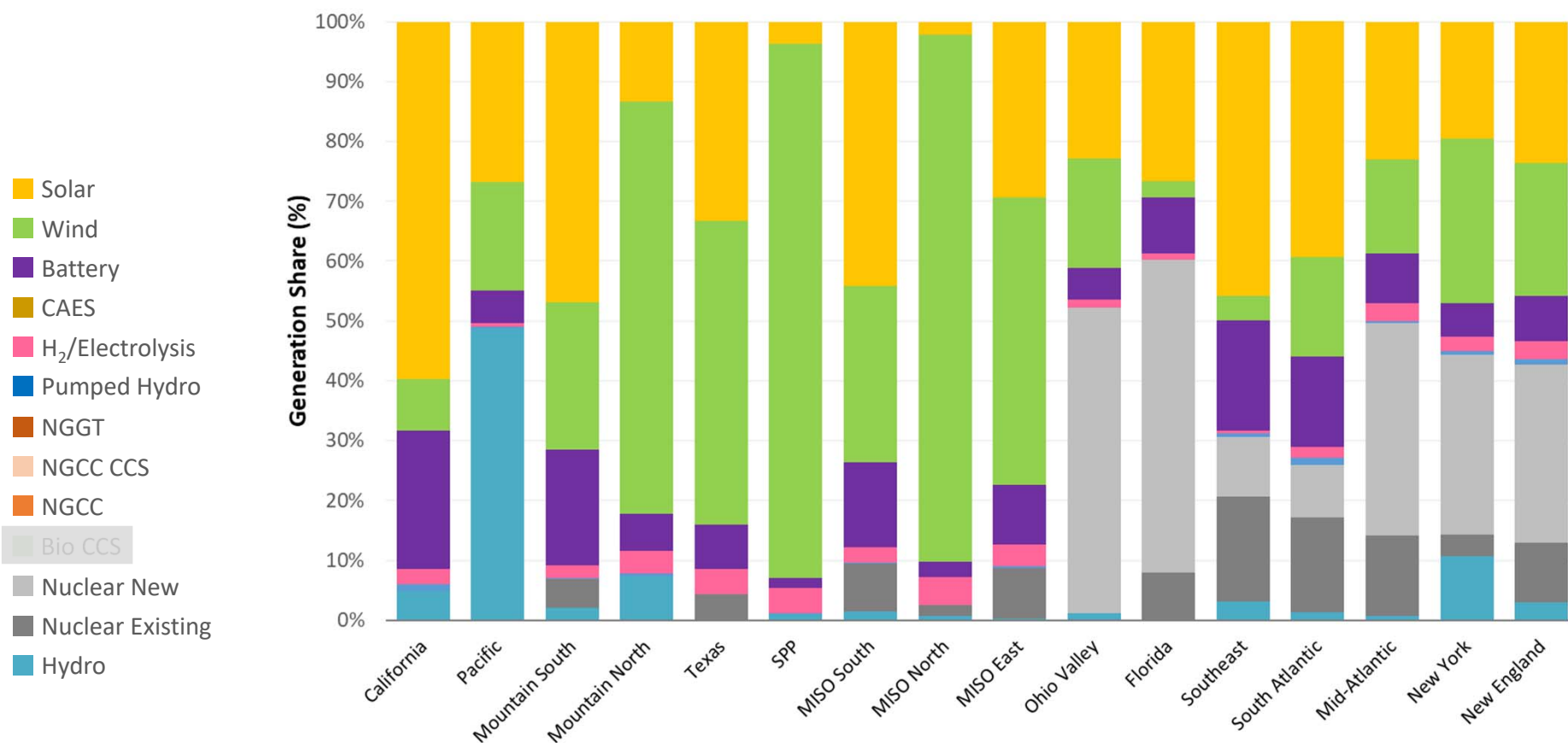
Reference Technology Assumptions, No Carbon Removal



Gas generation falls faster than capacity; many lower utilization options near 100% drives up marginal costs

Regional Generation Shares with 100% CO₂ Cap

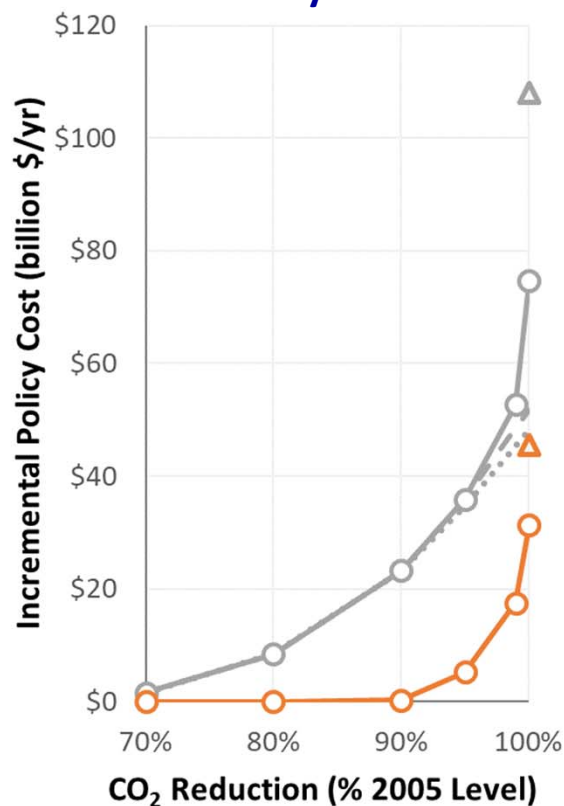
Reference Technology Assumptions, No Carbon Removal



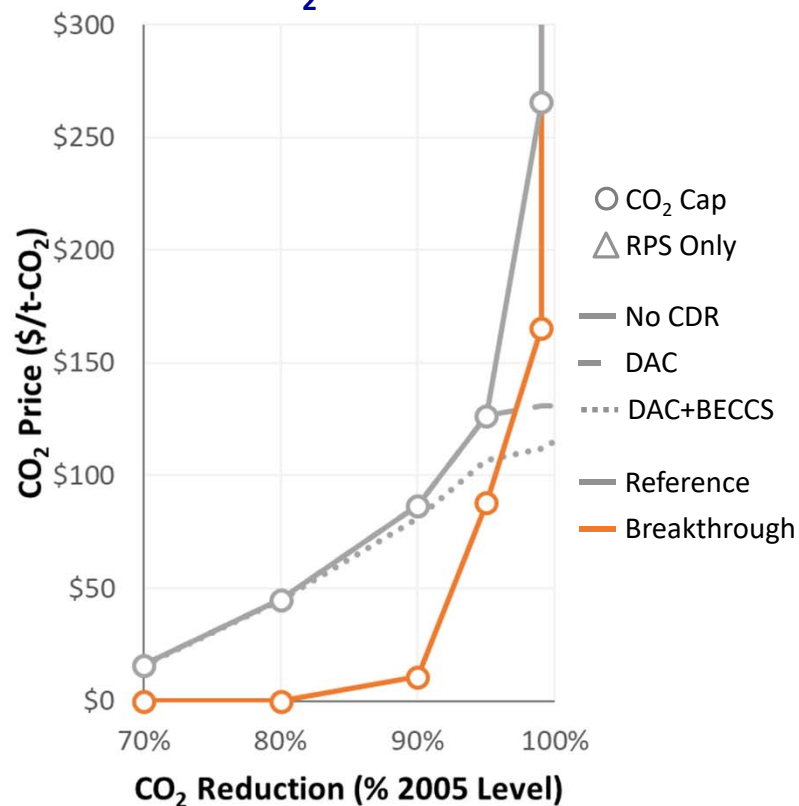
Least-cost decarbonization pathways differ by region and policy stringency

Cost Implications of CDR Availability

Policy Costs



CO₂ Prices



Observations

- CDR lowers cost of achieving policy goals
- CDR places ceiling on marginal abatement costs
- Savings are greater as policy stringency increases
 - 100% cap with DAC only: \$23 billion/yr cost savings
 - 100% cap with BECCS and DAC: \$27 billion/yr cost savings

Source: Bistline and Blanford (2021),
Impact of Carbon Removal Technologies...

For Additional Information



Electric sector policy, technological change, and U.S. emissions reductions goals:
Results from the EMF 32 model intercomparison project

John E. Bistline^{a,*}, Elke Hodson^b, Charles G. Rossmann^c, Jared Creason^d, Brian Murray^e, Alex Barron^f

^a Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, CA 94304, USA

^b U.S. Department of Energy, 1000 Independence Avenue, Washington, DC 20585, USA

^c Southern Company, 600 N. 18th Street, Birmingham, AL 35203, USA

^d U.S. Environmental Protection Agency, 1200 Pennsylvania Avenue, Mail Code 6207J, Washington, DC 20460, USA

^e Duke University, Energy Initiative and Nicholas Institute for Environmental Policy Solutions, Box 90335, Durham, NC 27708, USA

^f Smith College, 44 College Lane, Northampton, MA 01063, USA

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ABSTRACT

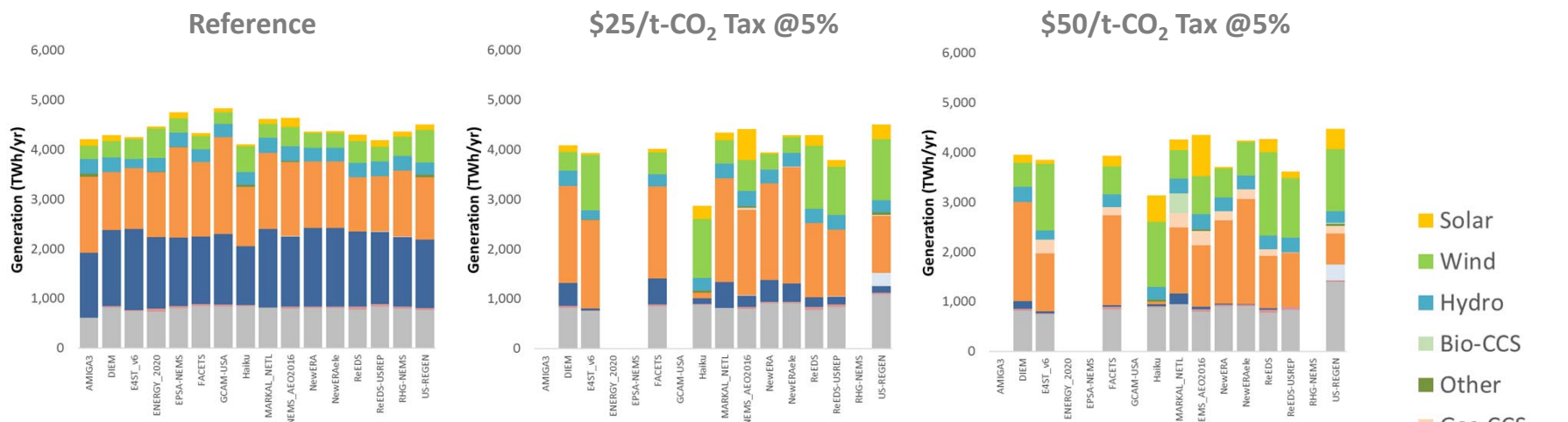
The Energy Modeling Forum (EMF) 32 study compares a range of coordinated scenarios to explore implications of U.S. climate policy options and technological change on the electric power sector. Harmonized policy scenarios (including mass-based emissions limits and various power-sector-only carbon tax trajectories) across 16 models provide comparative assessments of potential impacts on electric sector investment and generation outcomes, emissions reductions, and economic implications. This paper compares results across these policy alternatives, including a variety of technological and natural gas price assumptions, and summarizes robust findings and areas of disagreement across participating models. Under a wide range of policy, technology, and market assumptions, model results suggest that future coal generation will decline relative to current levels while generation from natural gas, wind, and solar will increase, though the pace and extent of these changes vary by policy scenario, technological assumptions, region, and model. Climate policies can amplify trends already under way and make them less susceptible to future market changes. The model results provide useful insights to a range of stakeholders, but future research focused on intersectoral linkages in emission reductions (e.g., the role of electrification), effects of energy storage, and better coverage of bioenergy with carbon capture and storage (BECCS) can improve insights even further.

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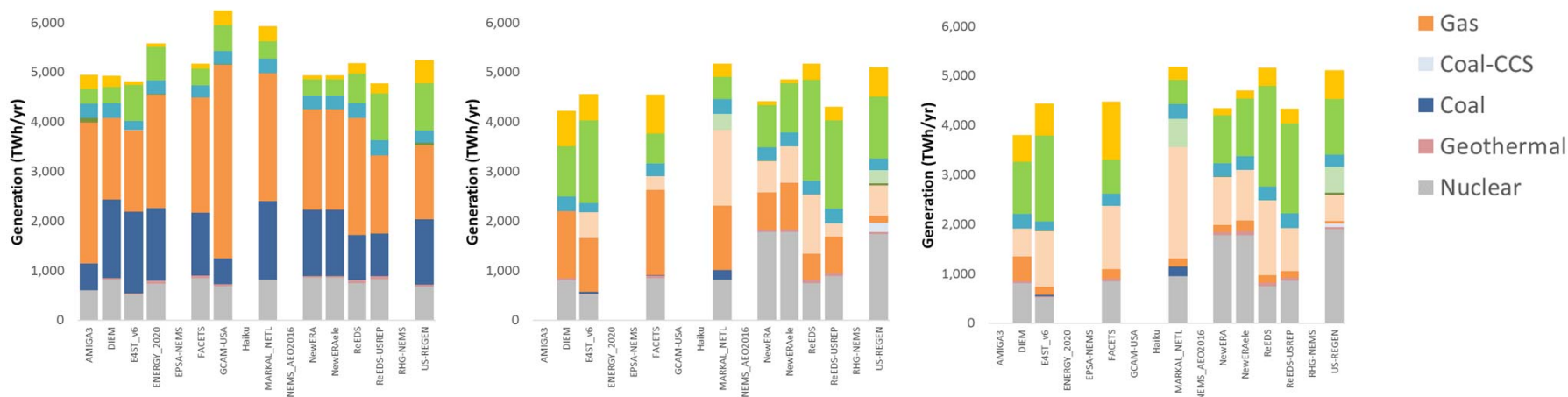
- EMF 32 special issue of *Energy Economics* now available
- Policy synthesis article (left) summarizes results across models and scenarios
 - Available online at:
<https://www.sciencedirect.com/science/article/pii/S0140988318301373>
 - Technology synthesis companion article
- Special issue also contains deep dives by modeling teams
- For other questions about this analysis, contact **John Bistline** (jbistline at epri dot com)

Generation by Technology, Model, and Scenario

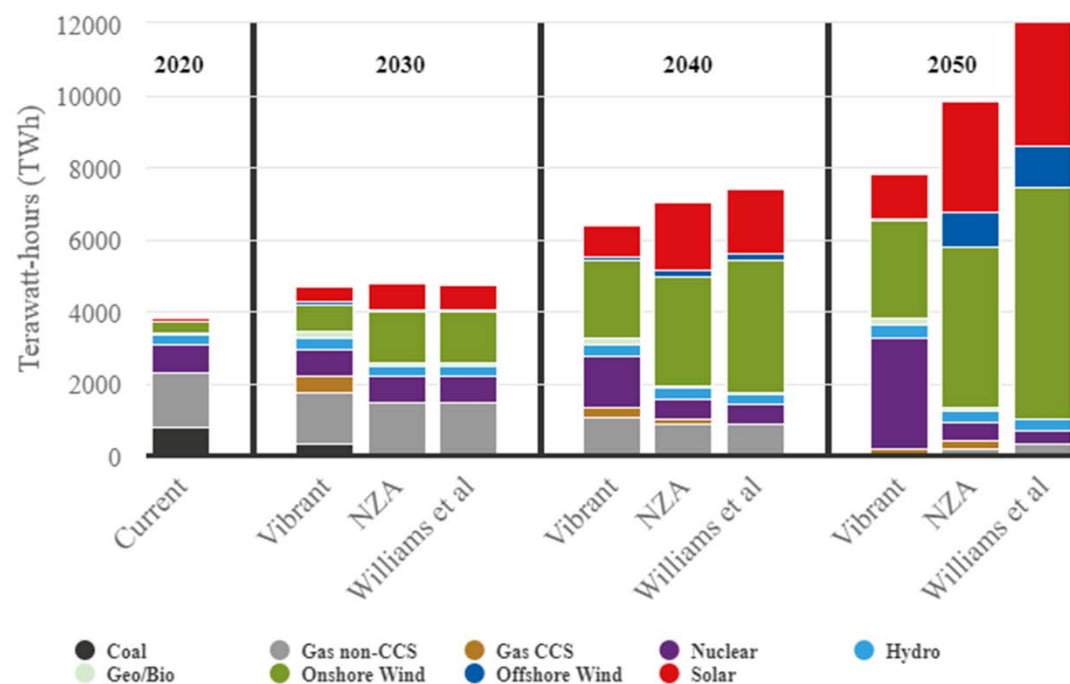
2030



2050



Nuclear in Recent Net-Zero Studies



Source: Breakthrough Institute ([link](#))

Observations

- Total electrification and load shapes to reach net-zero GHG economy-wide differ
- Role for existing and new nuclear varies significantly by model and study
- NZA and Williams, et al. use the same model (RIO)
- Different nuclear technologies
 - Existing
 - New SMR (flexible, load-following)
 - New molten salt reactors (firm, always-on generation)

Caveats: Uses and Limitations of Economic Models

- Models are necessarily numerical abstractions of the complex economic and energy systems they represent. As such, they may contain:
 - Approximation errors
 - Incomplete system dynamics
 - Data quality issues
- When viewing model results, it is important to keep in mind:
 - Analyses are **not intended** to be viewed as predictions or forecasts
 - Insights come by running a variety of cases/sensitivities, comparing the results, and asking “what if” questions
 - Actual dispatch and other model outcomes are dependent on many additional factors, such as policy, uncertainty, and unmodeled factors

“Essentially, **all models are wrong**, but some are useful.”

–George Edward Pelham Box