The Future of Clean Energy

PREPARED BY

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Brattle

Recap: What we thought a year ago

Large-scale shift to clean energy supply:

- Renewable and battery investments driven by attractive low supply costs, GHG targets, and IRA+state incentives
- Electrification via EVs, heat pumps, H2, and increasing data center growth
- Slow or no gas CC investment
- Continued coal retirements

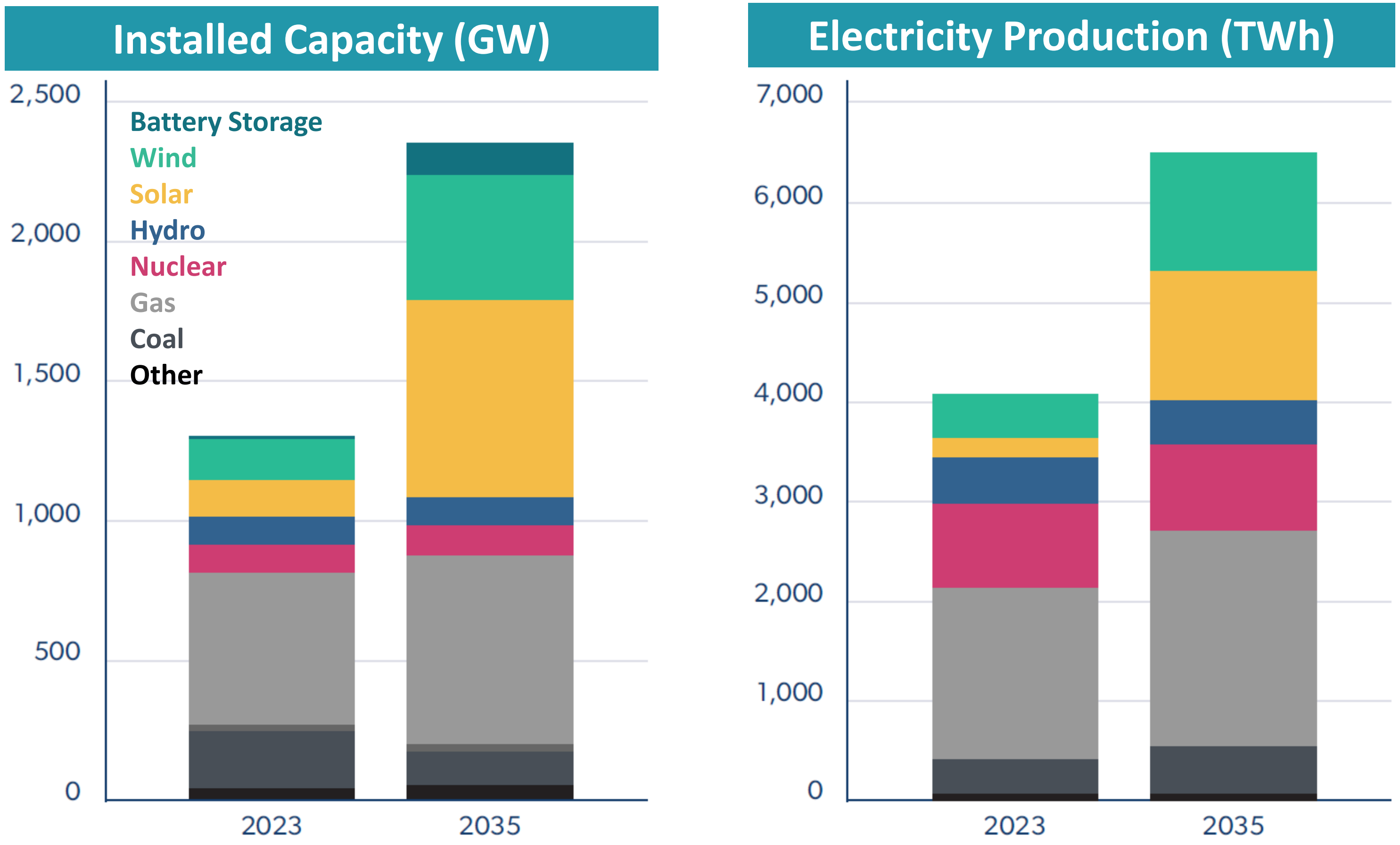
Critical barriers to transition included:

- Supply chain bottlenecks
- Interconnection queue delays
- Permitting barriers

Question Then: How to manage clean transition reliably and affordably?

Question Today: Can we still do it?

Projected Future Energy and Capacity
under 2024 laws and projected market conditions



Source: Brattle simulations of U.S. electricity investment and operations using gridSIM model. From A Wide Array of Resources is Needed to Meet Growing U.S. Energy Demand. The Brattle Group. February 2025.

We already knew we had hard work to ready the grid for transition

Readying the grid for clean energy transition

Involves a massive program of policy and market reforms that can continue to push forward over coming 3-5 years, even if policy-driven clean energy transition is delayed

	Economy-wide Transition Planning	Infrastructure Decisions	Resource Investment Incentives	Efficient Operating Incentives	Reliability	Managing Affordability
Grid Reforms Needed to Enable Transition	• Set enforceable, sector-specific GHG targets • Self-consistent electricity & gas forecasts (electrification, H_2, gas reductions) • Electrification programs, incentives & enabling tariffs	• Gas-electric planning and electrification coordination • H_2 infrastructure • Transmission planning	• Procurement & contracting mechanisms • Market-based incentive programs or utility planning reforms • Enabling customer self-supply	• Join/form RTO markets • Enhanced RTO energy & ancillary market designs • Reflect GHG incentives in operations (market or policy) • Enable third-party & emerging resources	• Resource adequacy accounting & incentives • Grid codes & interconnection requirements • Enhanced ancillary markets • Address emerging threats (flexibility, voltage/weak grid, frequency)	• Customer energy burden, especially for low-income segments • Jobs & GDP impacts • Stranded gas infrastructure cost recovery

Examples: See comprehensive state program study efforts including in New Jersey, Massachusetts, DC, Illinois.

Electrification & Renewables: Where do fundamentals align?

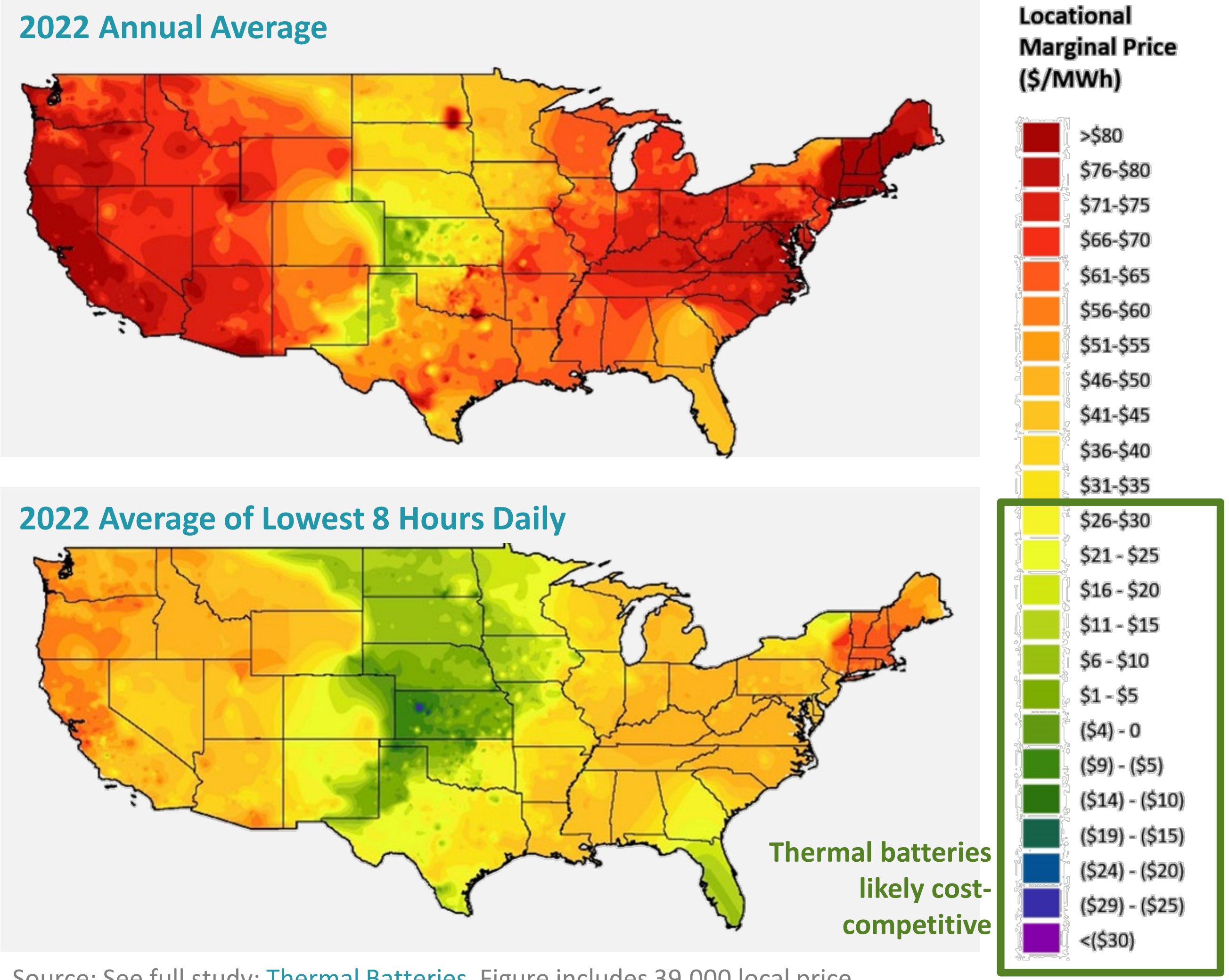
In a study of how thermal batteries can be deployed to electrify industrial heat, reviewed U.S areas with many low and negative prices. Driven by:

- Low-cost, abundant renewable resources
- Limited transmission capability to deliver renewable power to demand centers (cities)
- Renewable policy incentives & REC/contract payments

Same trends illustrate the potential for:

- Regions with high renewable potential to attract/retain investments, jobs & GDP from manufacturing & data centers that value low-cost and low-GHG power
- Transmission expansions needed to deliver low-cost renewables to demand centers

Wholesale Electricity Prices



Source: See full study: Thermal Batteries. Figure includes 39,000 local price nodes for 2022 (prices pulled from Energy Velocity)

Transmission

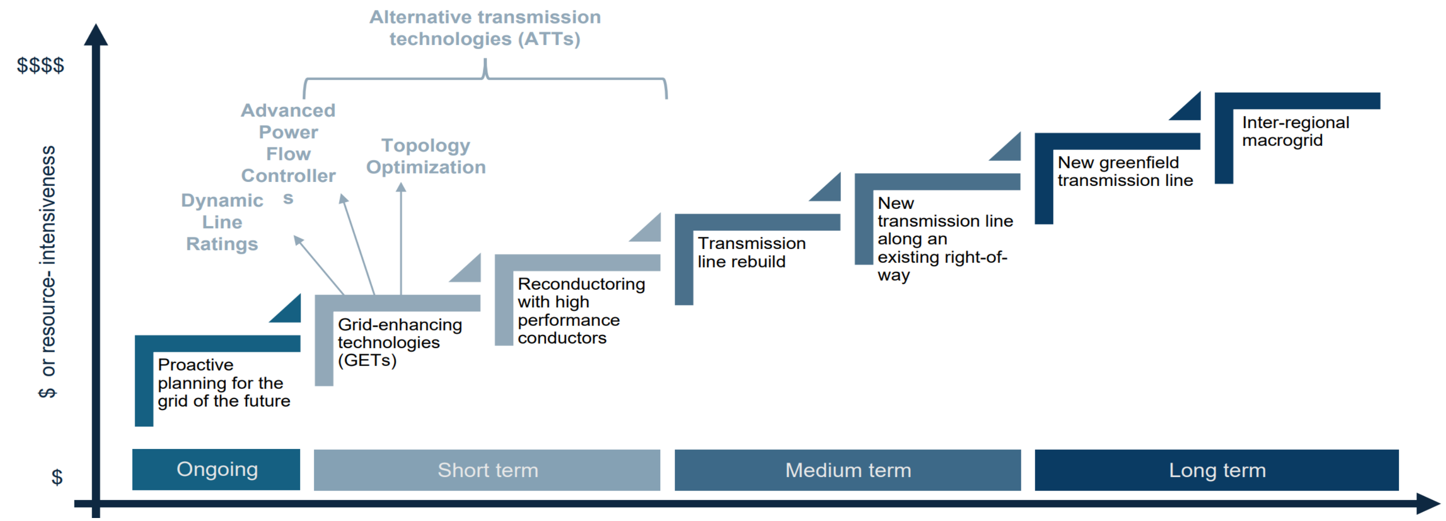
Key bulk transmission system reforms:

- **Advanced Tx Technology**: Can enable the existing grid to deliver much more power with lower congestion costs
- **Regional Planning:** Scenario-based, multi-value planning processes that account for policies
- **Interconnection:** Speet the queue & clear the backlogs. Queue (and permitting delays) have been the greatest barriers to new resource deployments in most places

Each of these programs & reforms have been successfully demonstrated in different jurisdictions, but adoption progress remains slow

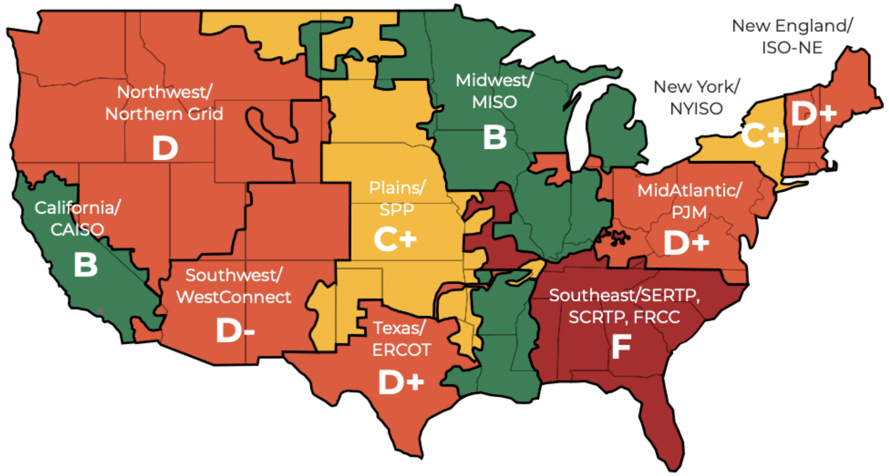
Sources: Optimizing Grid Infrastructure and Proactive Planning to Support Load Growth and Public Policy Goals. The Brattle Group. July 2025; Incorporating GETs and HPCs into Transmission Planning Under FERC Order 1920. The Brattle Group. April 2025; Alternative Transmission Technologies in Order 1920 and PJM. RMI. September 2024. AEI 2024 Generator Interconnection Scorecard. Transmission Planning & Development Regional Report Card.

Advanced Transmission Technologies: Getting More from the Existing Grid



Transmission Performance Scorecards

Planning: Building Out Cost-Effective Transmission Expansion



Interconnection: Getting Resources Online Quickly

CAISO	B
ERCOT	B
ISO-NE	D+
MISO	C-
NYISO	C-
PJM	D-
SPP	C-

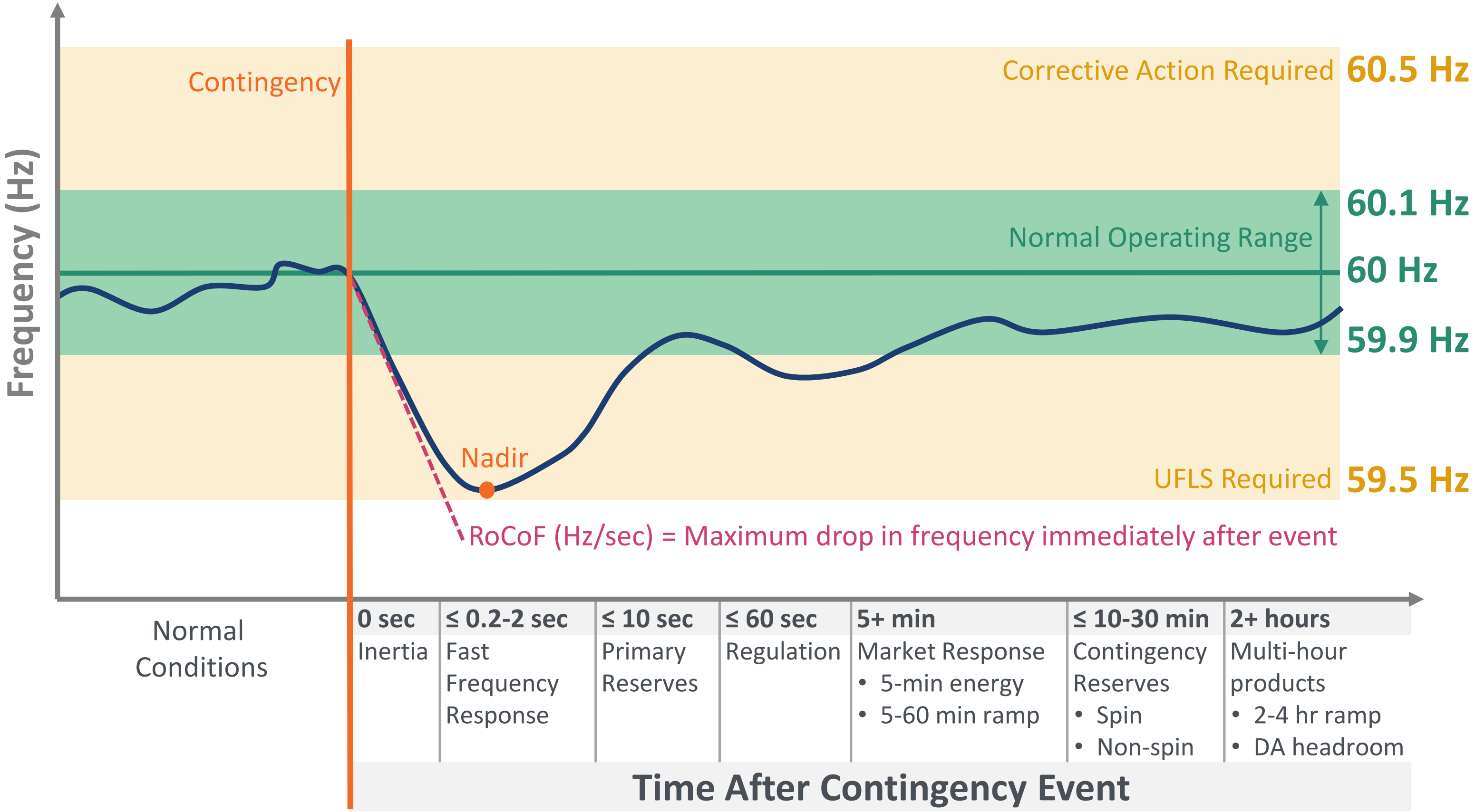
Reliability & Resilience: Grid operators need to proactively manage new reliability threats at every timeframe

Globally, grid operators with high-renewable systems grappling with emerging reliability challenges. Comprehensive reform program needs to include:

- **Advanced grid codes & interconnection** standards for inverter-based resources (so batteries & renewables are "grid forming" rather than "grid following")
- **Operational enhancements:** better forecasting, better system visibility
- **Voltage & system strength:** Boost weak areas of the grid with poor voltage stability (IBR controls, synchronized condensers)
- **Frequency control:** Study & define minimum inertia and max RoCoF levels, introduce fast frequency control products, update and align interconnection requirements (e.g. ride-through, droop settings)
- **Flexibility:** to improve system balancing capabilities (ramping and headroom products at market timescales of 5-30 min, 2-4 hours, day-ahead)
- **Resource Adequacy**: capacity market reforms to improve accreditation, modeling, seasonality, performance

Absent reforms: Grids become susceptible to major events, e.g. [2016 South Australia]; [2025 Iberian Peninsula]

Frequency Control: Timeline After a Major Event



Notes: Illustrative suite of frequency settings for typical US grid systems (settings vary by system size and typically have multiple Hz trigger points). RoCoF settings and inertia levels are tracked by some but not all North American systems,but will need to be more carefully managed (as in EU and Australia) by all high-renewable grids. Illustrative suite of products would constitute a relatively complete suite of reliability products, but most US systems currently feature only a subset.

GHG Tracking & Incentives: Granular GHG tracking data and associated policy/contract incentives will do more for less

Global, Top-Down View: GHG Protocol & investor reporting debate focuses on merits of annual vs. 24x7 procurements, emissionality & 3-pillar requirements. Considering impacts for renewable developers and reporting companies

State/RTO Bottom-Up View: Focus of utility, state commissions, and RTOs aims to improve GHG tracking, while aligning cost-effective procurement & operations with on-the-ground realities (nodal dispatch, reliability needs, RTO settlements)

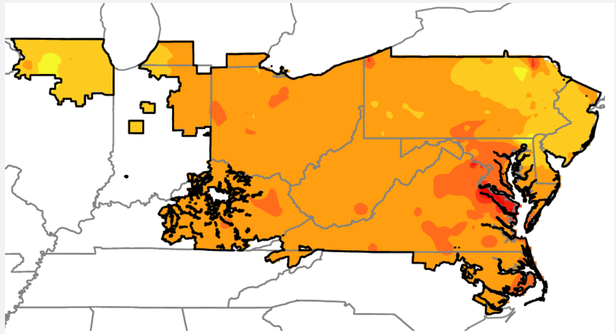
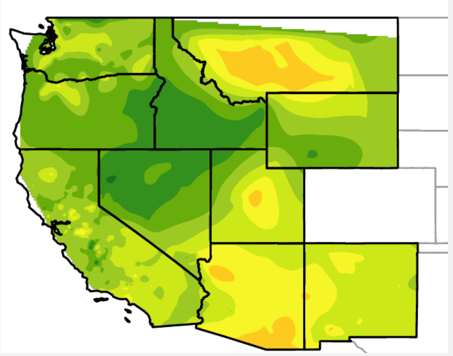
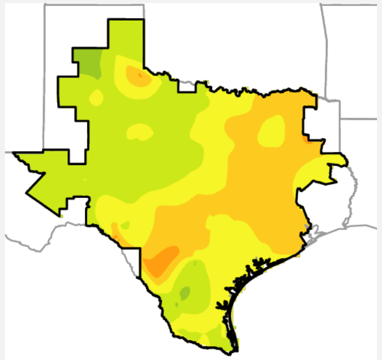
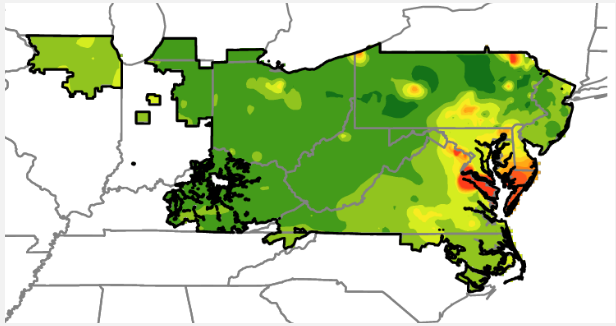
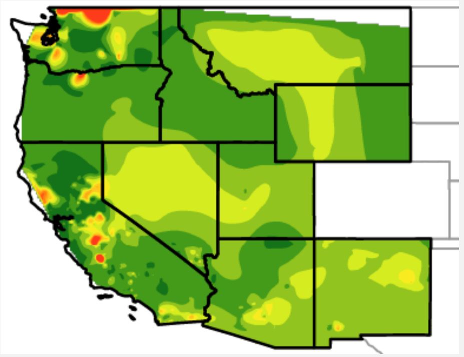
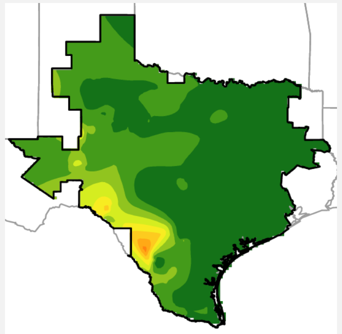
	PJM	West	ERCOT
Where to locate renewables? **Profile**: Flat production (can be renewable-profile adjusted)			
Where to locate batteries? **Profile:** Charge in lowest 4 LME hours daily (discharge in highest 4 LME hours)			

Figure Notes: *Hourly LME data not modified to account for renewable output profiles. Data from REsurety LME data product, year 2022 data.

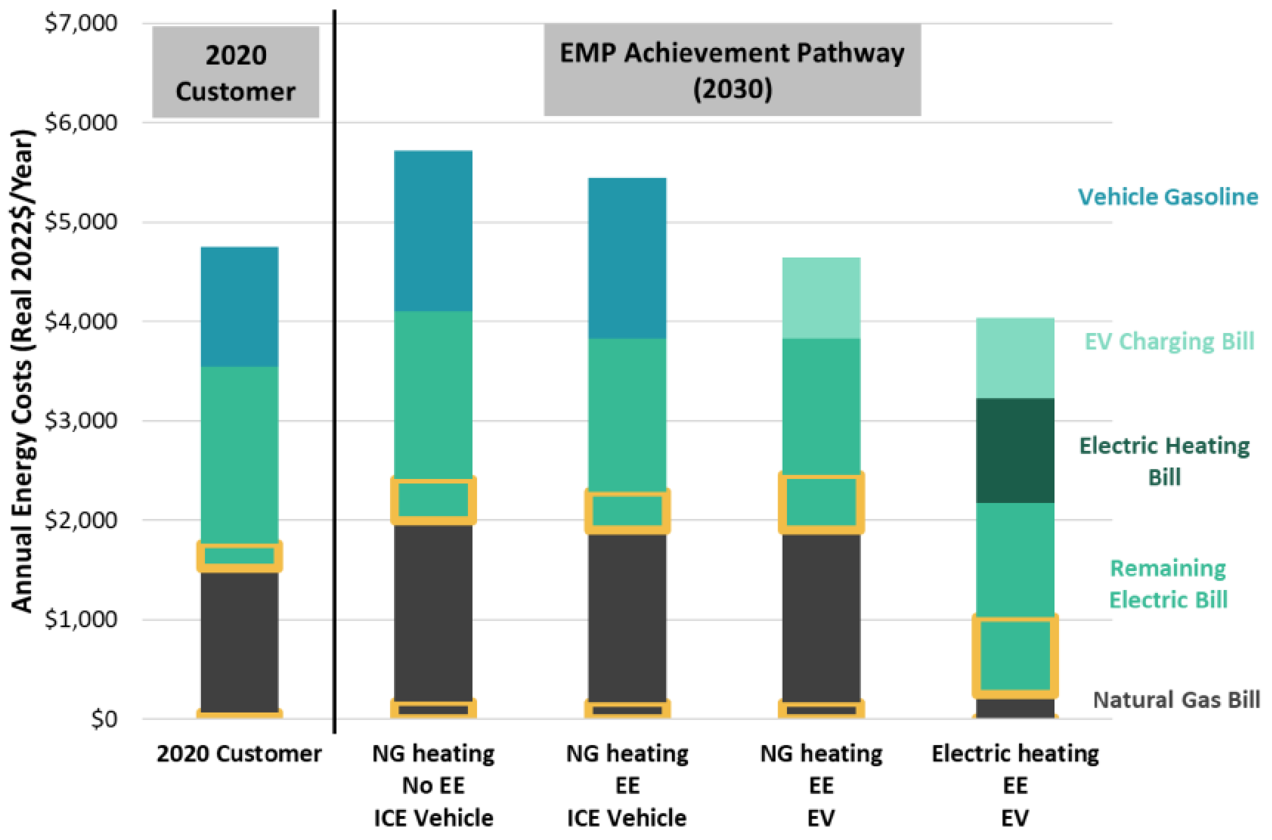
Affordability: States aiming to contain total energy burden

Components needed to manage affordability and total energy burden:

- **Do it cheap:** Many inefficiencies associated with traditional approaches to planning, incentives & contracts that fail to align with underlying policy goals, or leverage competitive market signals and innovative technologies/providers
- **Gas systems:** Systems aiming to greatly reduce gas uses need a new approaches to joint gas/electrification planning, limit future spending (within safety limits), recover embedded stranded asset costs, and mitigate rates on remaining gas customers
- **Limits on cost increases:** Clarifies the "willingness to pay" enabling accelerated achievement when costs are low (and deferrals when costs are high)
- **Customer affordability**: Review total energy burden by customer class, establish reasonable total energy burden targets (measured as sum of transport, heating/gas, electric), to inform customer segments for targeted EE/electrification investments and rate assistance

Example: NJ Customer Impact Analysis

Projection of 2030 Annual Energy Costs for Differently-Situated Customers



Source: New Jersey Energy Master Plan Customer Impact Analysis

And now: It’s even harder

(Viewpoint from past year in PJM.)

Now we face: Massive increases in AI/data center load growth, combined with supply restrictions & policy instability

Demand Growth: By 2035, compared to today:

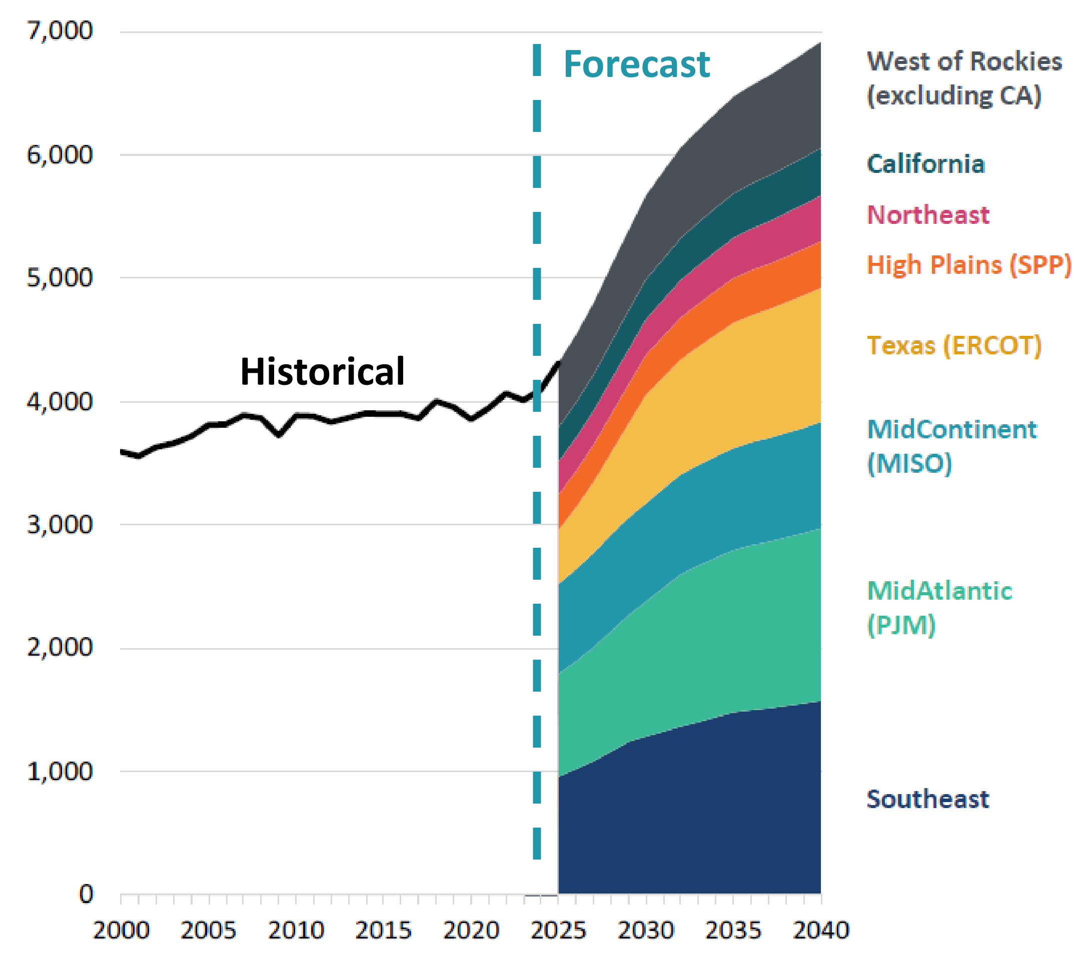
- Total annual electricity demand in the United States projected to **grow by 50%**
- Peak demand in the U.S. projected to **grow by 30%** (5x the growth rate of the past decade)

Supply Restrictions: New supply insufficient to meet rapid demand growth:

- Permitting and queue barriers/delays
- Turbines and component manufacturing have limited capacity to fill global demand (e.g. gas turbine orders quote 3-7+ year timelines, pricing quotes up to ~2.5x from recent years)

Policy Instability: Rollback of IRA incentives with OBBBA, import tariff-driven cost escalation, OSW projects at risk from federal permits/leases

US ANNUAL ELECTRICITY CONSUMPTION (TWH)



Sources: Optimizing Grid Infrastructure and Proactive Planning to Support Load Growth and Public Policy Goals. A Wide Array of Resources is Needed to Meet Growing U.S. Energy Demand. The Brattle Group. February 2025; Sources : Electricity Demand Growth and Forecasting in a Time of Change. The Brattle Group. May 2024. US gas-fired turbine wait times as much as seven years; costs up sharply. S&P Global. May 2025; Turbocharged vs turbo lag: the new landscape for gas-fired power. Wood Mackenzie. May 2025.

PJM Example: How the quadrennial review process has been affected by acute tight supply conditions and policy instability

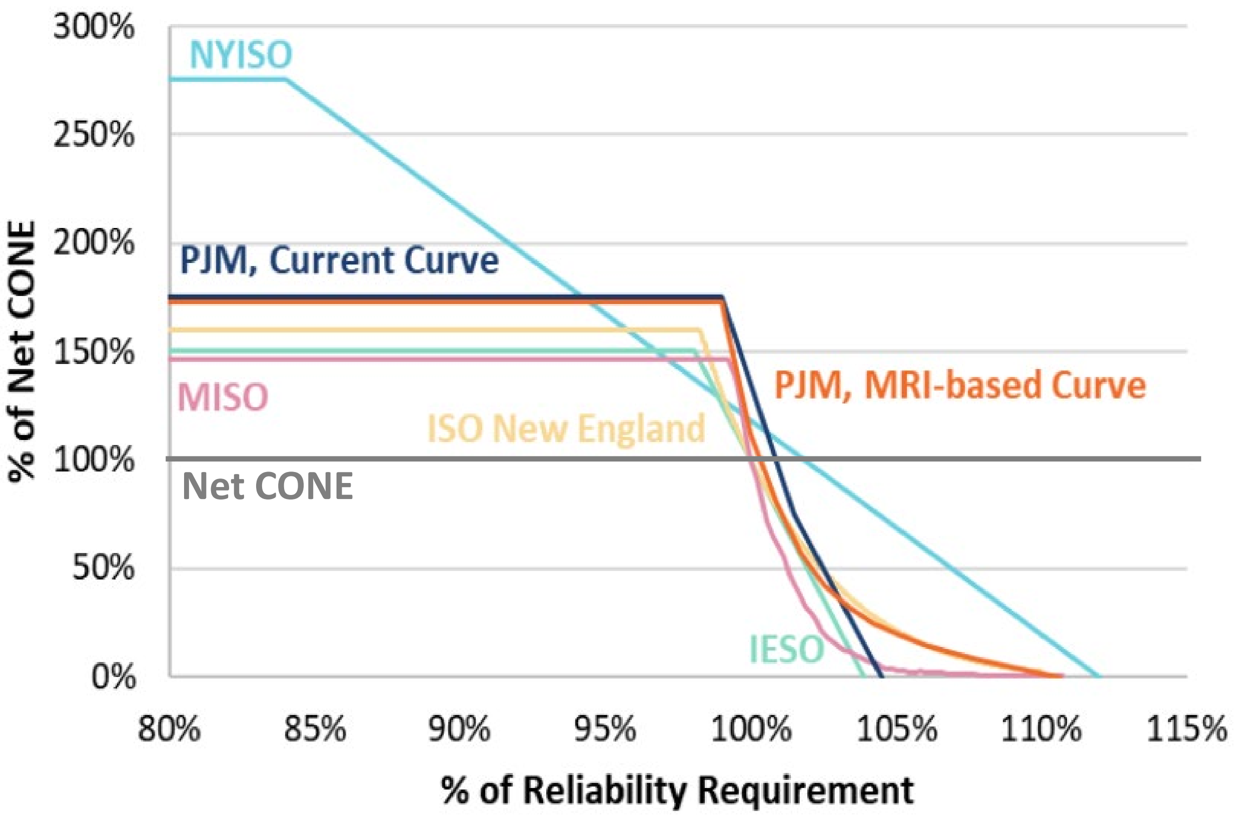
PJM Quadrennial Review Process: Every 4 years, an independent consultant (Brattle) recommends updates to capacity market parameters:

- Demand curve shape
- Price cap
- Net Cost of new entry (CONE), including gross CONE and energy & ancillary market offset

Present Review: Spans Fall 2024-Q4 2025. Conducted in challenging conditions:

- Surprise rapid load growth increases
- Rule changes that further tightened supply-demand balance (surprising the market with a sudden price increase in 2025/26 & 2026/27)
- Policy instability driving large uncertainties in resource costs (i.e. Net CONE)
- Parallel efforts to address interacting issues affecting supply demand balance (Large load interconnection reforms, reliability resource initiative to accelerate supply)
- State and governor pressure for rule changes to mitigate customer costs and unlock more supply

PJM Capacity Demand Curve vs. Other Markets



Source: Brattle independent quadrennial review of PJM VRR Curve parameters..

- PJM Rule/Process
- Federal Process/Action
- Market Event
- VRR/CONE Revisions

PJM Example: Timeline of events affecting the quadrennial review

September 27, 2024 —
PJM MIC Quadrennial Review Kickoff
First special MIC session for 2024/25 VRR parameter review.
Gross CONE: $566/MW-day CC; $452/MW-day CT; $730/MW-day BESS 4-hour

October 24, 2024
PJM MIC Quadrennial Review Meeting
Stakeholder session; parameters and methods discussion.

November 26, 2024
PJM MIC Quadrennial Review Meeting
Preliminary Brattle estimates of CONE increase. Supply chain tightness and equipment costs are largest contributing factors.
Gross CONE: $701/MW-day CC; $544/MW-day CT; $803/MW-day BESS 4-hour

December 17, 2024
PJM MIC Quadrennial Review Meeting
Brattle VRR curve review highlights capital costs, policy and tariff uncertainty, and accelerating demand growth as key factors reshaping PJM's market landscape.

December 30, 2024
PA Governor's Office Files FERC Complaint (Section 206)
Complaint seeks to lower PJM capacity price cap to 1.5× CT CONE due to rate concerns

January 24, 2025
PJM Load Forecast Update
New forecast shows large peak demand growth (70 GW), driven largely by data centers.

February 11, 2025
FERC Approves RRI
Allows acceleration of resource interconnection for 94 projects (26.6 GW).

February 2025 - March 2025
PJM MIC Quadrennial Review Meetings
Ongoing stakeholder work on VRR parameters/CONE methods. Elevated technology risk and material input inflation are key considerations highlighted

February 20, 2025
PJM Tariff Temporary Revisions
PJM submits proposed Tariff revisions to FERC to establish a 2-year temporary price cap and price floor for all RPM auctions

April 11, 2025
PJM MIC Quadrennial Review Meeting
Brattle presents final VRR curve parameter recommendations.
Gross CONE: $813/MW-day CC; $663/MW-day CT; $652/MW-day BESS 4-hour

April 21, 2025
FERC Approves Temporary $325 Cap / $175 Floor
In response to state pressure amid ratepayer concerns

January-September 2025
New Tariffs on Generator Components and Materials
Tariff actions on solar, battery, copper, and wind components increased capital cost assumptions for nearly every new-entry resource

May 19, 2025
PJM MIC Quadrennial Review Meeting
The IMM argues that the primary drivers of PJM's tight capacity market pricing are large data-center load additions, not purely traditional generation shortfalls.

June 16, 2025
PJM MIC Quadrennial Review Meeting
PJM presents its formal proposal which recommends using a CC as the reference technology in most zones
Gross CONE: $813/MW-day CC

July 4, 2025
Bonus Depreciation is Reinstated by OBBA
Restores 100% bonus depreciation, lowering Gross CONE

July 21, 2025
PJM MIC Quadrennial Review Meeting
Stakeholders received an updated matrix of potential changes and alternate proposals (including views from the independent monitor and developer groups)

July 22, 2025
PJM 2026/27 BRA Clears at Price Cap
Auction clears at $329.17/MW-day, reflecting tight supply

August 22, 2025
PJM MIC Quadrennial Review Meeting
Brattle updates CONE estimates for 100% Bonus Depreciation.
Gross CONE: $757/MW-day CC; $590/MW-day CT; $640/MW-day BESS 4-hour

August-September 2025
PJM Large Load Integration (LLI) Proposal
Proposes rules to limit interconnection of large data center loads unless self-supplied or curtailable,

December 2025
PJM 2027/28 BRA Scheduled

PJM Example: State concerns about PJM capacity price impacts on customers

Capacity price increases:

- Capacity prices were low for several years, followed by substantial & unexpected increases
- Prices very sensitive to supply-demand conditions (impacts observed much sooner than energy price impacts)
- Customers in retail choice states highly exposed to capacity price changes
- Recent price increases mostly driven by tight supply, accreditation changes, retirements. Upcoming years will be more greatly affected by AI/data center load growth

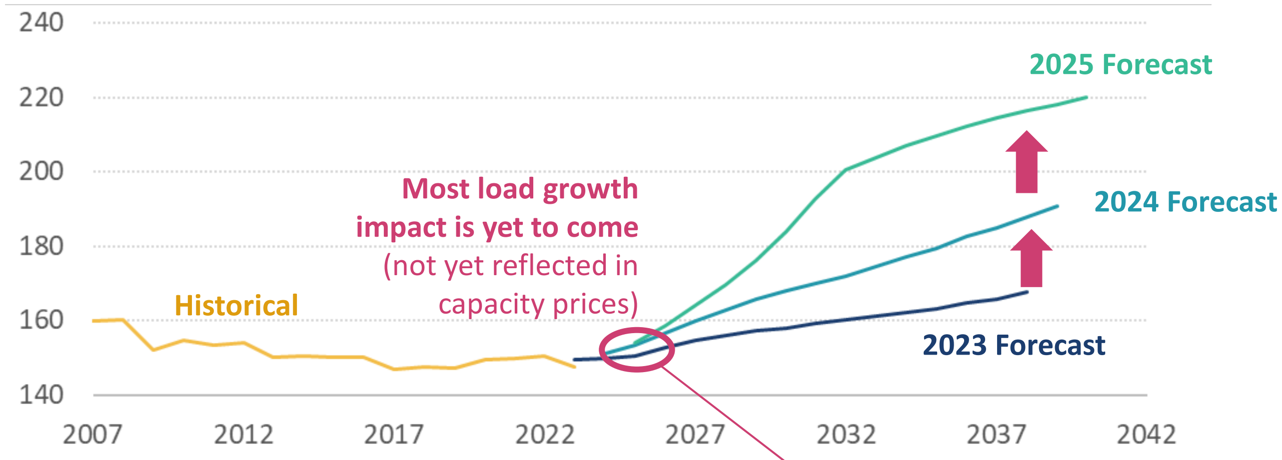
Price Cap:

- PA Gov. Shapiro filed 206 complaint arguing for a lower price cap, and reached an agreement with PJM to implement a temporary 2-year price cap and floor (containing prices to ~$175-325/MW-day* for 2 years, expires after 1 more auction)
- Starting 2028/19: Price cap proposed to increase to $500+/MW-day in RTO (higher in sub-regions)

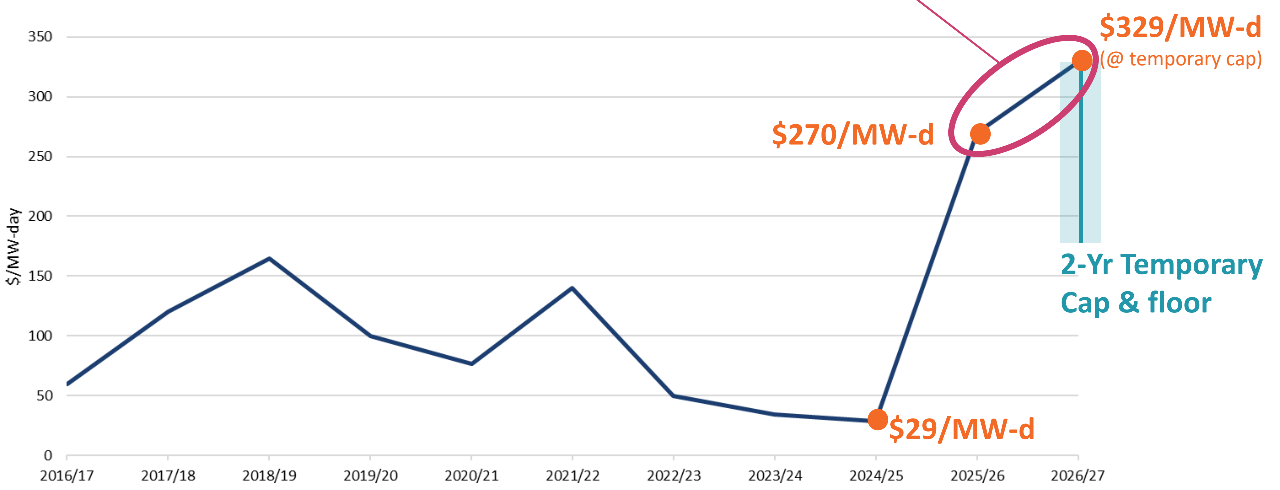
Governors launched a PJM Governors Collaborative, initial convening focused on capacity prices, affordability, governance, and state alternatives

*Price cap and floor range approximate due to changes in resource accreditation.

PJM Peak Summer Load Forecast (GW)



PJM Capacity Auction Clearing Prices ($/MW-day)



Source: PJM, 2026/2027 Base Residual Auction Report, Figure 1. PJM load forecasts.

What’s next?

Outlook for managing challenges & clean energy transition

Now — Navigate transient barriers & regulatory risk with

- High price conditions make all clean and brown power projects more economic (creates both risks & opportunities)
- Instability in pricing increases risk of baking in inefficient higher-cost or higher-GHG resource choices over the long-term (critical to distinguish movements in price associated with policy instability vs. long-term fundamentals)

Mid Term — Continue hard work of building resilient grid for the long term

Reforms for future-proof grid:

- Address barriers to entry (permitting, queue, enabling emerging resources)
- RTO reforms for transmission planning, interconnection, reliability, support GHG data
- State program, contracting, rate, and incentive reforms to enhance competition, manage cost, and improve investment efficiencies

Long Term — Economic fundamentals will (eventually) prevail

- Governments and companies will continue GHG reductions
- AI & data center load growth overwhelming other driving forces until supply & demand realign. Will redirect a portion of investments to retain existing supply and new CCs
- Cost tolerance is limited. Pace of change focus where clean energy and electrification are at/near grid parity

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Dr. Kathleen Spees is a Principal at The Brattle Group with expertise in wholesale electricity markets design and carbon policies.

Her expertise focuses on environmental policy and wholesale electricity market design, economic analysis, and modeling. For RTO market operators she supports implementation and development of wholesale markets including energy, ancillary services, capacity, FTRs, clean energy attribute markets, and integration of emerging technologies. She supports regulators, NGOs, and utilities to develop GHG reduction policy alternatives, conduct power sector and economy-wide modeling of GHG abatement pathways, and assess benefits/costs in the context of policy reforms for clean energy transition. For energy-intensive companies pursuing net zero commitments, Dr. Spees offers economic advice for designing internal GHG pricing and abatement incentive programs, estimating fleet-wide GHG abatement cost curves, identifying least-cost pathways to net zero, designing internal GHG pricing and incentive programs, and conducting due diligence analysis of GHG-abatement investments.

Dr. Spees earned her PhD in Engineering and Public Policy within the Carnegie Mellon Electricity Industry Center and her MS in Electrical and Computer Engineering from Carnegie Mellon University. She earned her BS in Physics and Mechanical Engineering from Iowa State University.