Fifth Review of the Variable Resource Requirement Curve

PRELIMINARY ASSESSMENT OF THE VRR CURVE SHAPE

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Brattle

Agenda

Overview

Assessment of Over-Procurement

Performance of Current VRR Curve

Alternative Curves

Locational VRR Curves

Discussion

Overview

Current state of VRR review process

Through the quadrennial review process, we are evaluating the ability of the VRR curve to meet reliability needs, including:

- VRR Curve Shape
- Gross CONE
- E&AS Offset

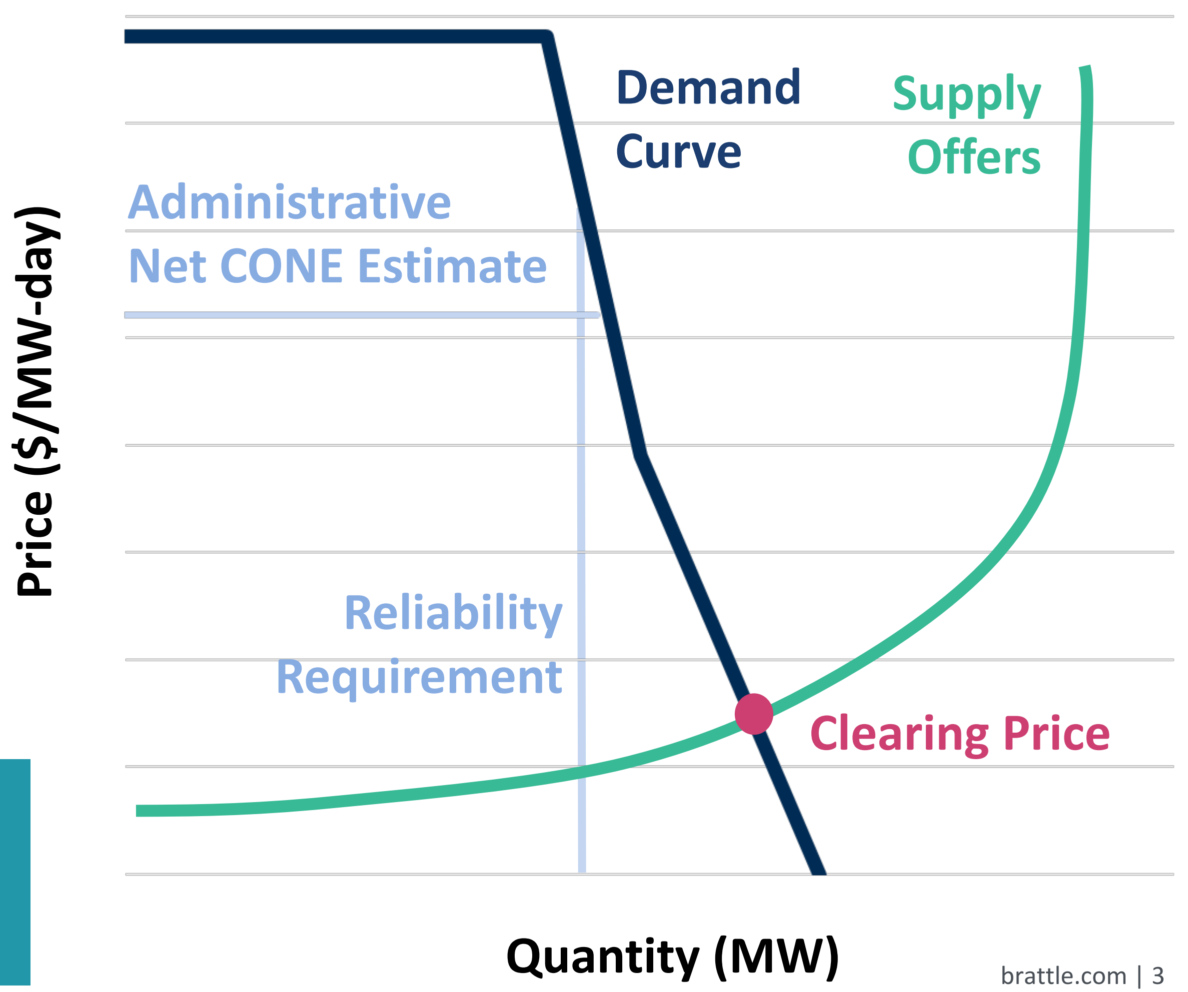
Current stage: initial results and preliminary recommendations

- Initial results and sensitivity analyses aimed at defining workable VRR curve parameter space
- No recommendations are final
- Some numbers (most importantly CONE and Net CONE) are placeholders pending final analyses

Stakeholder Input Requested:

- Feedback on preliminary findings and recommendations
- Additional curve refinements and concepts to be tested

Illustrative Supply and Demand



Demand curve design objectives

Demand Curve Objectives	
Reliability (*based on current PJM rules*)	• Maintain 1-in-10 LOLE system-wide target on a long-term average basis; maintain 1-in-25 conditional LOLE in each locational deliverability area. Reliability as measured immediately prior to the delivery year • Avoid market clearing outcomes that result in insufficient capacity and out-of-market intervention • Maintain reliability across a range of potential market conditions, while mitigating the potential for over-procurement
Prices	• Prices high enough to attract entry when needed for reliability; prices low enough to enable efficient exit and retirements during surplus • Reduce price volatility due to small changes in supply and demand • Mitigate susceptibility to exercise of market power • Allow prices to move sufficiently to reflect changes in market conditions • Few outcomes at the administrative cap
Other	• Strike a balance among competing objectives • Aim for simplicity, stability, transparency, and consensus

Notes: LOLE = Loss of Load Events; IRM = Installed Reserve Margin; CONE = Cost of New Entry

Preliminary/directional recommendations

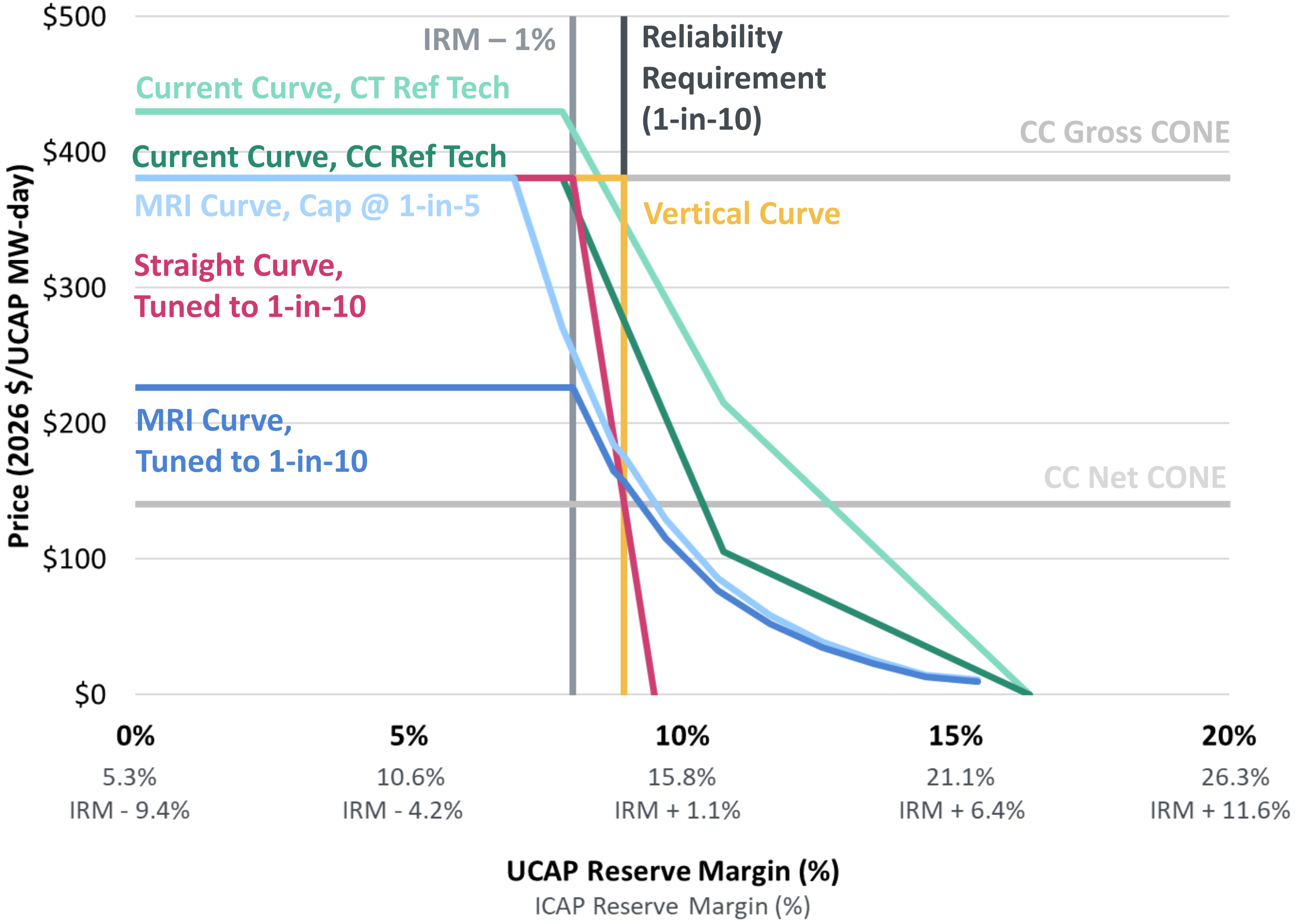
- Eliminate upward bias in the load forecast
- Improve accuracy, transparency, and consistency in capacity supply and demand accounting, particularly in the winter season
- Adopt a gas-fired combined cycle plant as the reference technology, subject to any future evidence that gas CCs cannot be built in some LDAs
- Balance competing objectives through adjustments to the system-wide VRR curve
  - Incorporate a lower Net CONE (consistent with using a gas CC as reference technology)
  - Maintain a price cap that is high enough to account for Net CONE uncertainties and administrative error
  - Consider a steeper curve to mitigate high uncertainty/judgment in Net CONE; shape could be informed by the Marginal Reliability Impact (MRI) curve
- Defer consideration of any additional left-shifting in the BRA VRR curve
- For the LDAs, consider wider or MRI-based demand curves to moderate price volatility and manage reliability needs

Initial range of assessed VRR parameters

We have not yet developed a specific VRR curve recommendation

Directionally, we recommend to adopt a CC-based Net CONE and a steeper VRR curve shape

Illustrative Range of Curves Evaluated

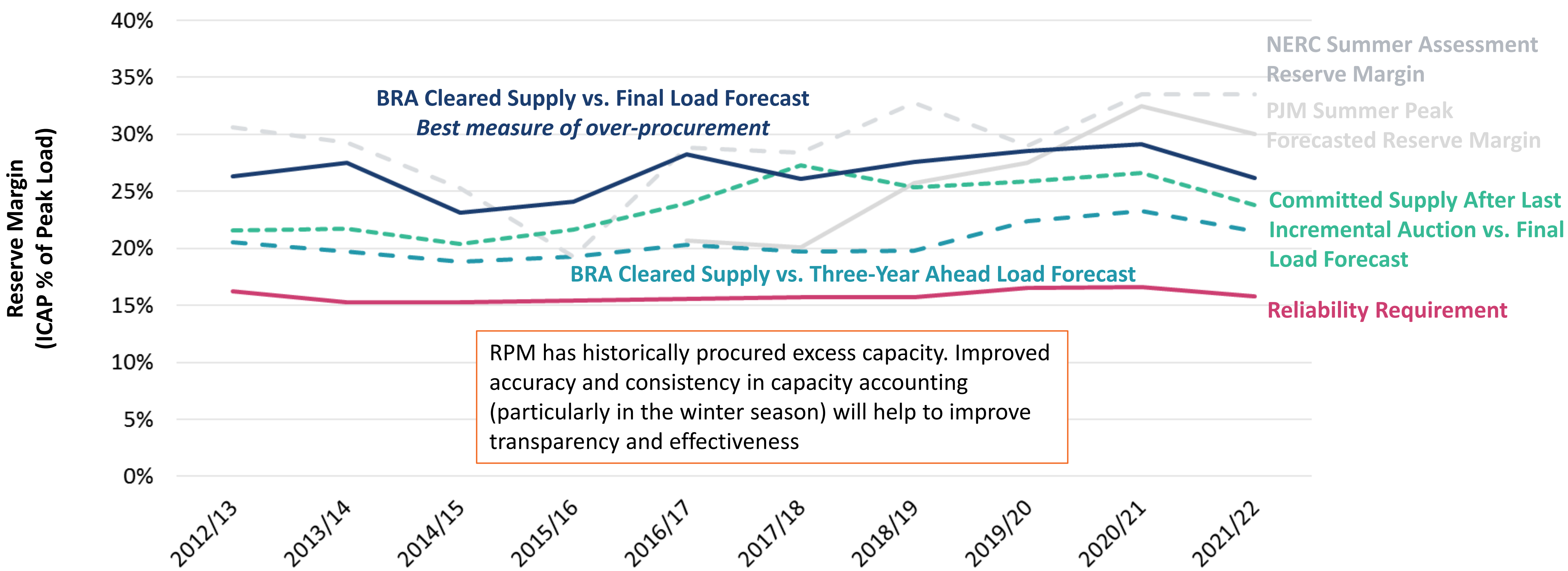


Note: Current Curve, CT has price cap at 1.5 x Net CONE; Current Curve, CC has cap at CC Gross CONE (greater than 1.5 x CC Net CONE); Straight curve, tuned to 1-in-10 BRA LOLE, passes through (Reliability Requirement, CC Net CONE); MRI Curve, tuned to 1-in-10 LOLE is calculated as the avoided expected unserved energy (EUE) per UCAP MW of capacity added, inflated by a $/MWh multiplier to translate into units of capacity price. Multiplier chosen to achieve 1-in-10 BRA LOLE. Gross and Net CONE values are from 2023-2024 BRA Default MOPR, converted to $2026 using a 2.7% inflation rate.

Assessment of Over-procurement

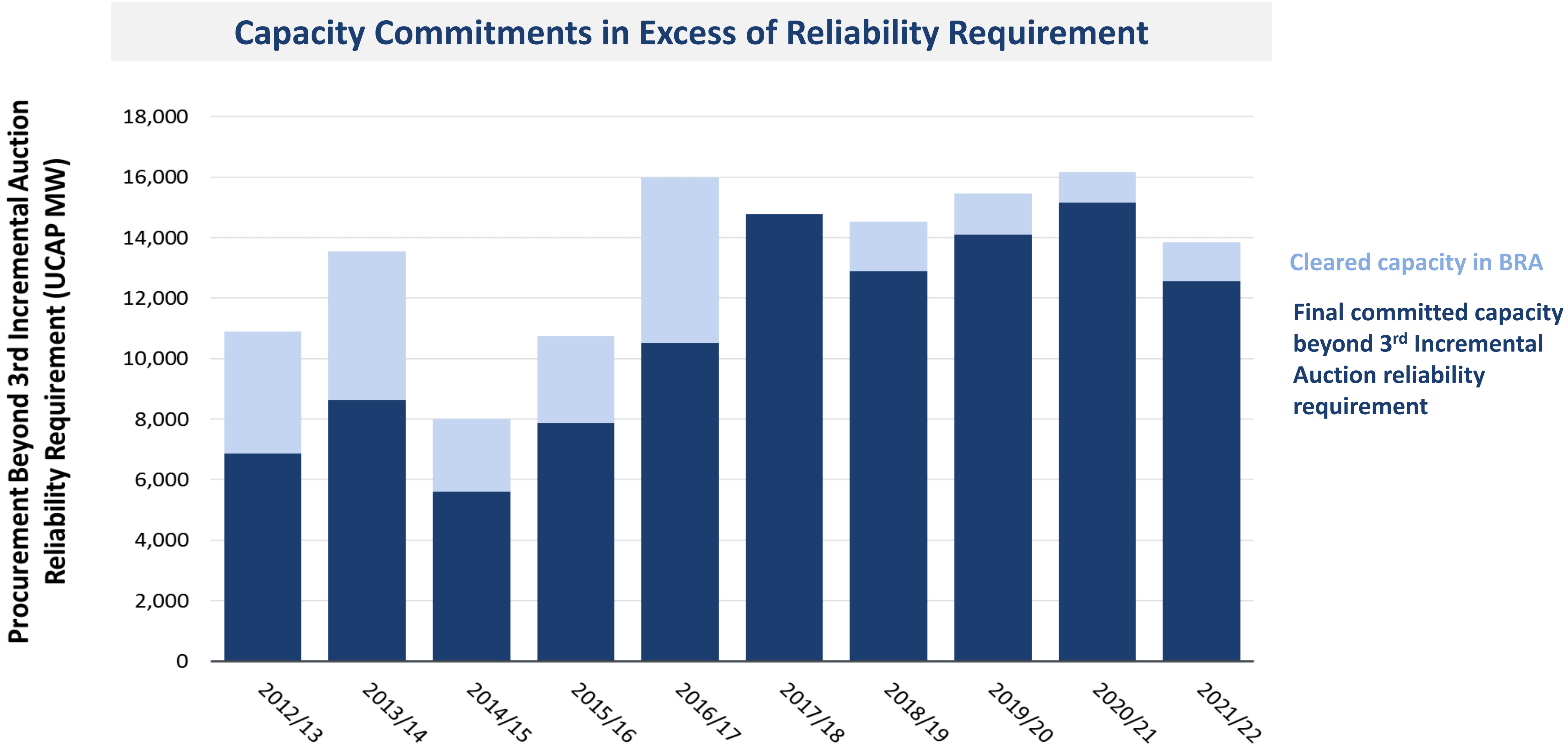
Historical over-procurement in RPM

PJM Installed Reserve Margin



Sources: PJM 2022/2023 RPM Base Residual Auction Results, Table 1; PJM Forecasted Reserve Margin Graphs; NERC Summer Reliability Assessments, BRA Planning Parameters.
Note: Summer Reserve Margins are estimated prior to delivery/ NERC Summer Assessment Reserve Margin includes supply not committed in RPM.
Capacity commitments include EE; reliability requirement is not grossed up for EE.

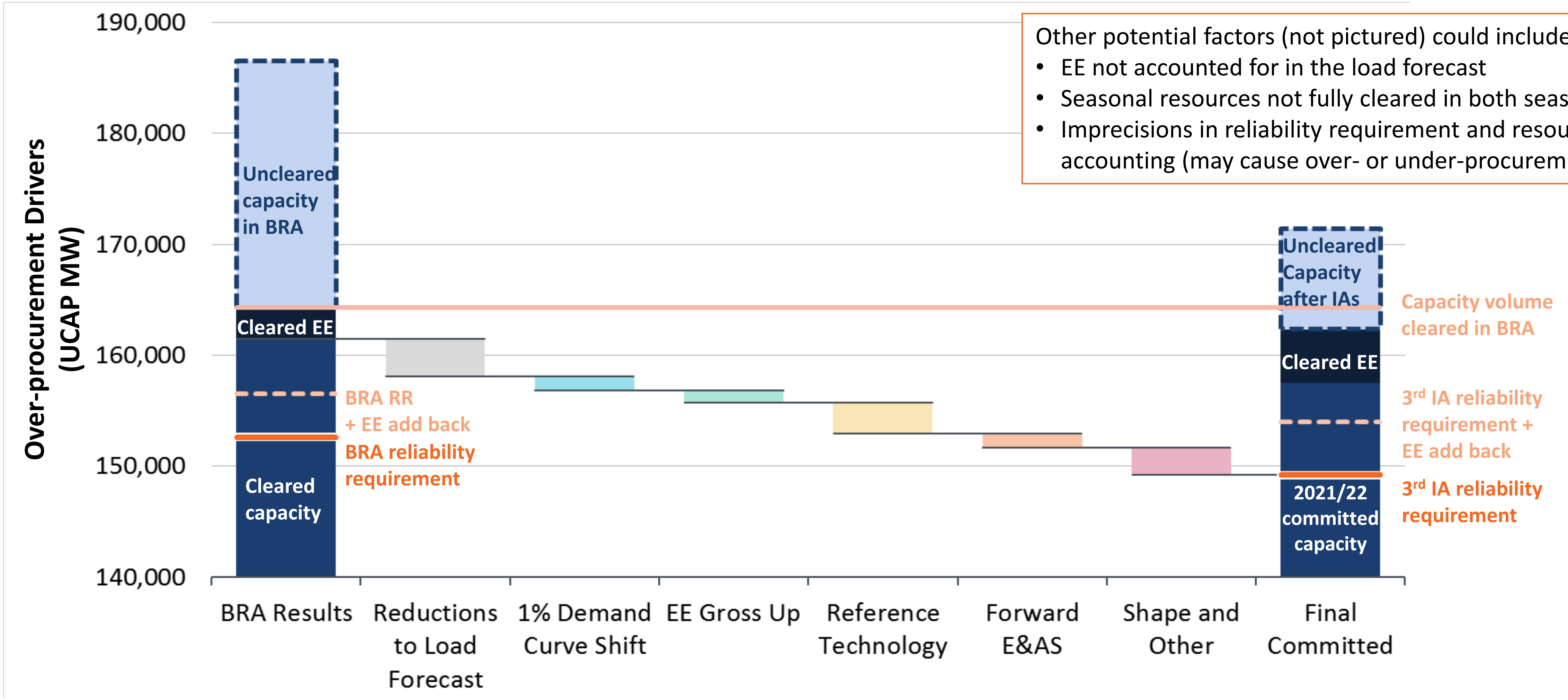
Over-procurement in recent years



Sources: BRA Planning Parameters.
Note: Capacity commitments include EE; reliability requirement is not grossed up for EE.

Factors contributing to over-procurement

Drivers of Over-Procurement in 2021/22 Delivery Year



Other potential factors (not pictured) could include:

- EE not accounted for in the load forecast
- Seasonal resources not fully cleared in both seasons
- Imprecisions in reliability requirement and resource accounting (may cause over- or under-procurement)

Notes: RR = Reliability Requirement; IA = Incremental Auction; BRA = Base Residual Auction; EE = Energy Efficiency

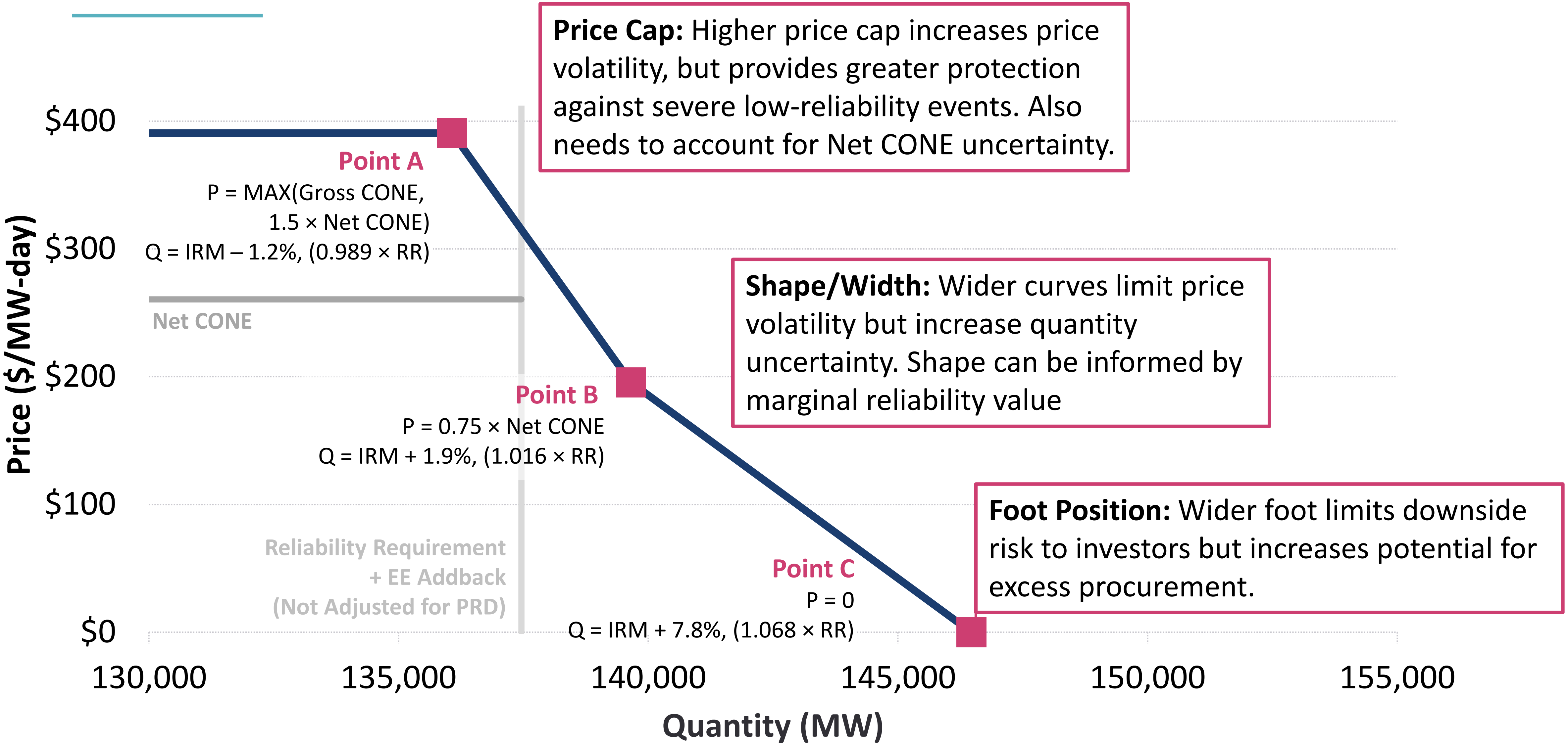
Opportunities to manage over-procurement

Opportunities to Address Over-procurement	
Changes already implemented or being pursued by PJM	• Improve load forecast accuracy and eliminate over-forecast bias • Adopt forward-looking estimate of E&AS revenues • Eliminate 1% left-shift of demand curve • Eliminate discrepancy between EE gross-up and cleared quantities
Areas in scope in the RASTF	• Determine the appropriate level of capacity procurement • Explicitly measure capacity requirements and supply commitments in winter season, and more fully integrate seasonal resources • Improve capacity qualification methods and performance requirements for capacity resources
Other opportunities for improvement	• Change reference technology from CT to CC • Explore possibility of qualifying EE as supply-side resources in the capacity market if suppliers demonstrate that the EE measures are not already accounted for in the load forecast, thereby eliminating the EE addback • Improve accounting consistency and clarity by using UCAP accounting for all purposes in RPM and seasonal reliability assessments; distinguish between supply MW with and without capacity commitments in seasonal assessments

Notes: BRA = Base Residual Auction; EE = Energy Efficiency; E&AS = Energy and Ancillary Services; CT = Simple Cycle Gas Combustion Turbine; CC = Combined Cycle Gas Turbine

Performance of the Current VRR Curve

Conceptual basis for VRR curve parameters



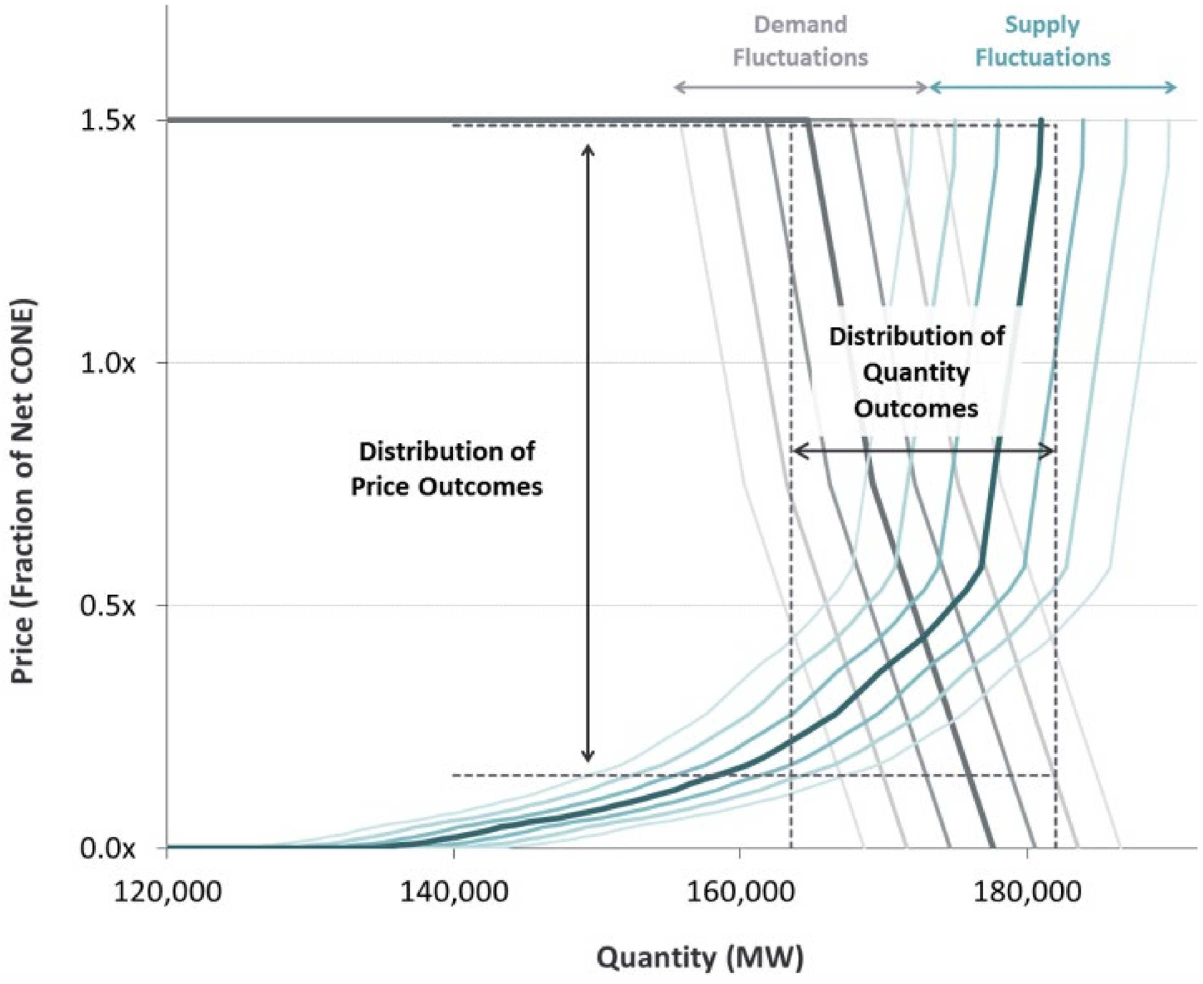
Source: 2022/23 RPM Base Residual Auction Planning Parameters.

Acronyms: P = Price Q = Quantity IRM = Installed Reserve Margin RR = Reliability Requirement PRD = Price Responsive Demand EE = Energy Efficiency

Probabilistic modeling approach

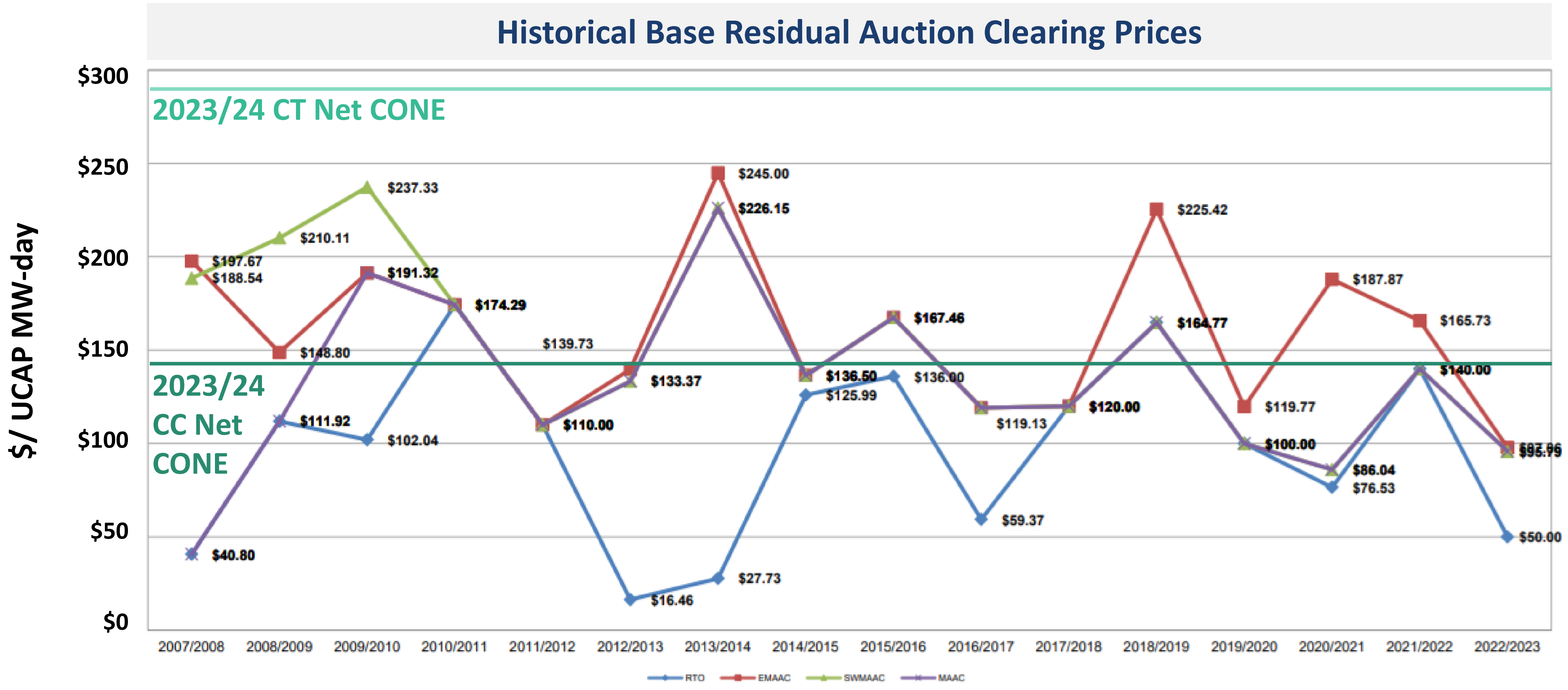
- Monte Carlo model of 3-year forward capacity market and prompt markets
- Accounts for variability in:
  - Supply curve shapes
  - BRA supply quantity and demand quantity
  - Incremental Auction supply availability and load forecast uncertainty
- All model inputs derived from historical market data
- Assesses long-run equilibrium conditions
- Produces an expected distribution of price, quantity, and reliability outcomes at both 3-year forward and prompt periods that are compared to design objectives

Supply and Demand Variability
(Illustrative)



Note: For a more details on modeling approach, see Appendix.

Combined cycle is likely a better reference technology



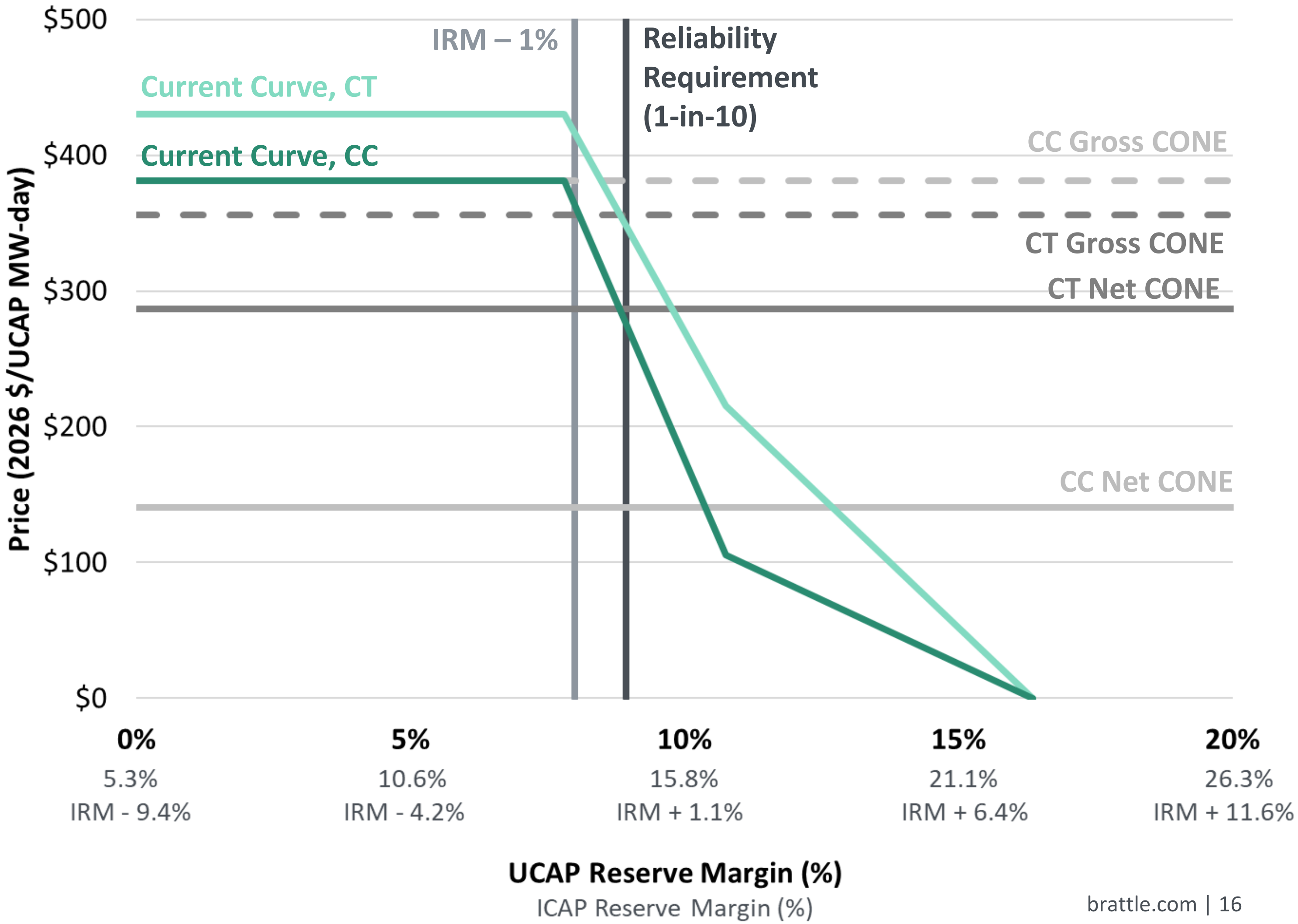
Source and Notes: Annotated Net CONE values are from 2023-2024 BRA Default MOPR, elevated to $2026 using an inflation rate of 2.7%
Figure source PJM, 2022/2023 RPM Base Residual Auction Results, Figure 2.

Adopting a gas CC as reference technology

Updating the current curve based on a CC as reference technology results in:

- Steeper and left-shifted curve (reduces over-procurement)
- For CC, since 1 x CONE is higher than 1.5 x Net CONE (due to high E&AS), 1 x CONE applies as the price cap
- Maintains a relatively high price cap and some protection against error in Net CONE)

Current Curves with Varying Net CONE Values



Source and Notes: Annotated Gross and Net CONE values are from 2023-2024 BRA Default MOPR, elevated to $2026 using an inflation rate of 2.7%.

Updating the reference tech could mitigate over-procurement

Demand Curve	Measured After the 3-Year Forward BRA								
	Price			**Reliability**					**Cost**
	Average *($/MW-d)*	Standard Deviation *($/MW-d)*	Frequency at Cap *(%)*	Average LOLE *(events/yr)*	Average Excess (Deficit) *(MW)*	Average Excess (Deficit) *(IRM + X %)*	Frequency Below Reliability Requirement *(%)*	Frequency Below IRM - 1% *(%)*	Average Procurement Cost *($ mln/yr)*
Vertical Curve, True Net CONE = CC	$141	$72	0.6%	0.100	-5	0.0%	0.6%	0.1%	$6,824
Current VRR Curves, True Net CONE = CC									
Current Curve, CT	$141	$54	0.0%	0.026	4,590	4.0%	0.0%	0.0%	$7,023
Current Curve, CC	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905

Updating the reference technology would reduce average excess procurement, but reliability would still exceed the 0.1 LOLE target under base modeling assumptions.

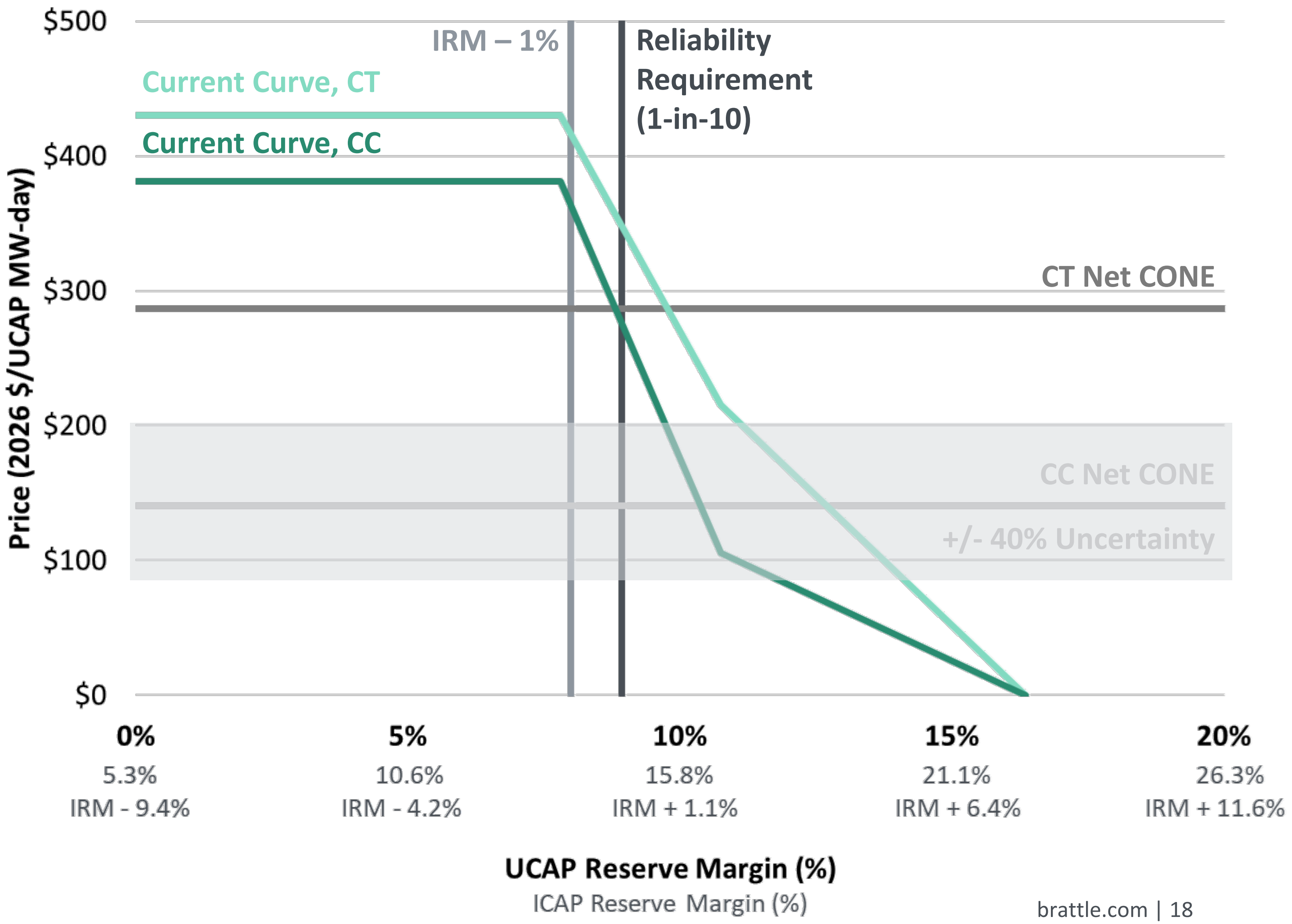
Note: All dollar values are in $ 2026 / MW-day.

Sensitivity to Net CONE uncertainty

- What if the reference technology is wrong?
- What if true net CONE is 40% lower or 40% higher than administrative net CONE?

Looking for: Reliability risks if Net CONE is underestimated, and over-procurement costs if Net CONE is over-estimated

Current Curves Performance with Varying True Net CONE



Source and Notes: Annotated Gross and Net CONE values are from 2023-2024 BRA Default MOPR, elevated to $2026 using an inflation rate of 2.7%.

Sensitivity Analysis of Current Curve

Sensitivity to uncertainty in true net CONE

Demand Curve	Measured After the 3-Year Forward BRA								
	Price			Reliability					Cost
	Average ($/MW-d)	Standard Deviation ($/MW-d)	Frequency at Cap (%)	Average LOLE (events/yr)	Average Excess (Deficit) (MW)	Average Excess (Deficit) (IRM + X %)	Frequency Below Reliability Requirement (%)	Frequency Below IRM - 1% (%)	Average Procurement Cost ($ mln/yr)
Current Curve, CC									
True Net CONE = 0.6 x CC Net CONE	$84	$51	0.0%	0.033	4220	3.7%	0.0%	0.0%	$4,179
True Net CONE = CC	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905
True Net CONE = 1.4 x CC Net CONE	$197	$69	1.9%	0.076	1,050	0.9%	11.1%	2.9%	$9,602
True Net CONE = CT	$287	$75	20.9%	0.141	-640	-0.5%	51.9%	25.4%	$13,807
Current Curve, CT									
True Net CONE = CC	$141	$54	0.0%	0.026	4,590	4.0%	0.0%	0.0%	$7,023
True Net CONE = CT	$287	$80	9.9%	0.089	900	0.8%	23.2%	12.0%	$13,963

CC-based curve is robust to reliability risks even if Net CONE is under-estimated to price cap minimum at 1xCONE. Supports 1-in-7 LOLE even if CT is the true reference technology.

Potential for over-procurement if true Net CONE is lower than the administrative estimate, especially when clearing on the "foot" of the VRR curve.

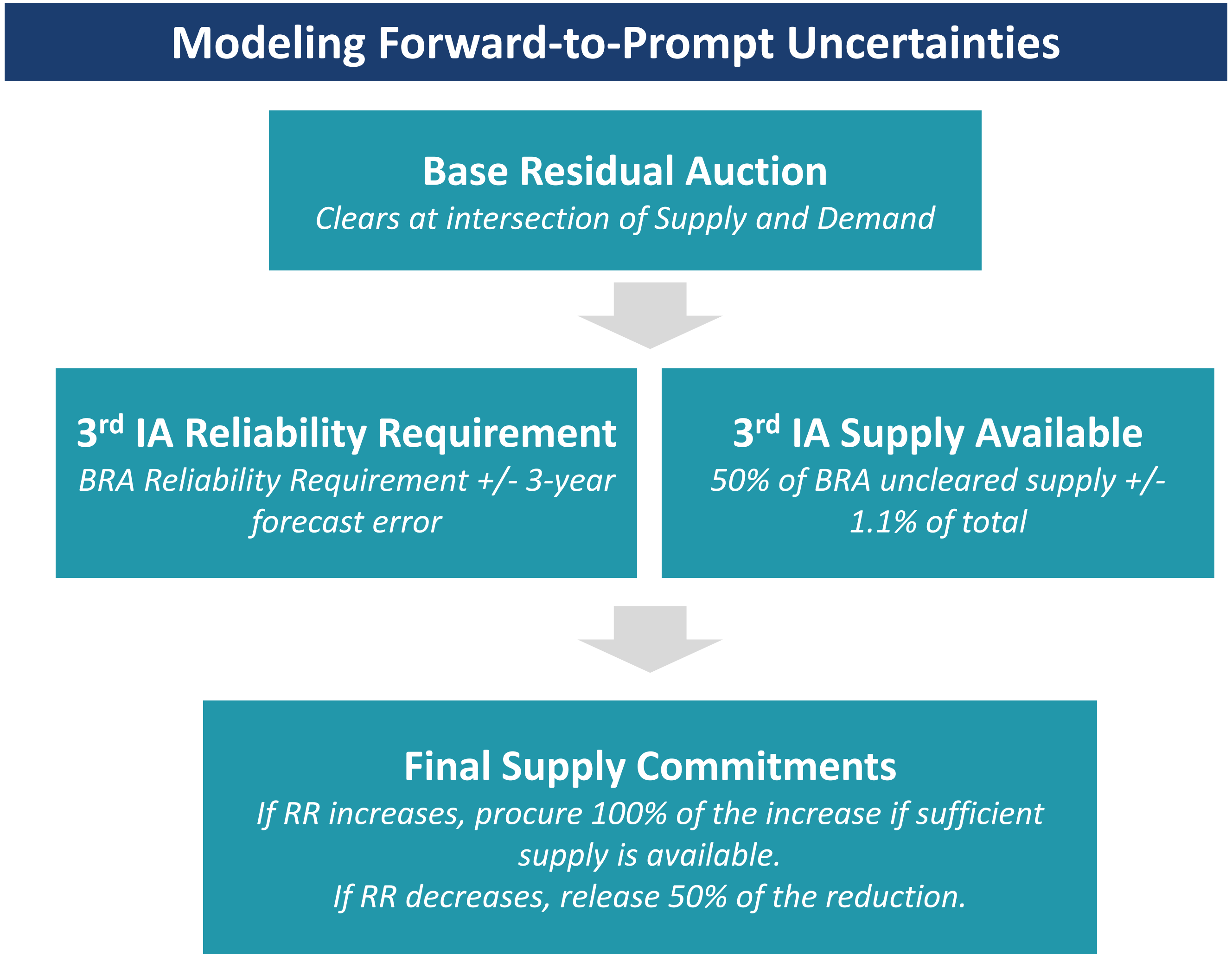
Note: All dollar values are in $ 2026 / MW –day.

Sensitivity to forward-to-prompt uncertainties

Updated modeling approach assesses the impact of load forecast error on VRR performance

Looking at:

- How load forecast bias affects performance
- How unbiased load forecast error affects performance
- Whether short-term supply availability could justify lower procurement volumes in the BRA



Sensitivity to forward load forecast bias

Demand Curve	Measured After the 3-Year Forward BRA									Measured After the Last Incremental Auction				
	Price			Reliability					Cost	Reliability				
	Average ($/MW-d)	Standard Deviation ($/MW-d)	Frequency at Cap (%)	Average LOLE (events/yr)	Average Excess (Deficit) (MW)	Average Excess (Deficit) (IRM + X %)	Frequency Below Reliability Requirement (%)	Frequency Below IRM - 1% (%)	Average Procurement Cost ($ mln/yr)	Average LOLE (events/yr)	Average Excess (Deficit) (MW)	Average Excess (Deficit) (IRM + X %)	Frequency Below IA Reliability Requirement (%)	Frequency Below IRM - 1% (%)
Current Curve, CC, PJM IA Mechanism														
Over-forecast bias = +4%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.023	4,781	4.3%	0.0%	0.0%
Over-forecast bias = +2%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.036	3,510	3.1%	0.3%	0.0%
Load forecast bias = 0%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.050	2,551	2.2%	0.9%	0.4%
Under-forecast bias = -2%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.060	2,033	1.7%	5.0%	2.5%

Opportunity to procure additional supply in the IAs may provide a small boost to reliability, protecting against reliability concerns.

As expected, over-forecast bias causes excess procurement.

Note:
Over-forecast bias means BRA reliability requirement is consistently above the Incremental Auction reliability requirement.
Under-forecast bias means BRA reliability requirement is consistently below the Incremental Auction reliability requirement.
Bias percentages in terms of 3rd Incremental Auction reliability requirement. All dollar values are in $ 2026 / MW-day.

Sensitivity to forward unbiased load forecast error

Demand Curve	Measured After the 3-Year Forward BRA									Measured After the Last Incremental Auction				
	Price			Reliability					Cost	Reliability				
	Average	Standard Deviation	Frequency at Cap	Average LOLE	Average Excess (Deficit)	Average Excess (Deficit)	Frequency Below Reliability Requirement	Frequency Below IRM - 1%	Average Procurement Cost	Average LOLE	Average Excess (Deficit)	Average Excess (Deficit)	Frequency Below IA Reliability Requirement	Frequency Below IRM - 1%
	($/MW-d)	*($/MW-d)*	*(%)*	*(events/yr)*	*(MW)*	*(IRM + X %)*	*(%)*	*(%)*	*($ mln/yr)*	*(events/yr)*	*(MW)*	*(IRM + X %)*	*(%)*	*(%)*
Current Curve, CC														
Forecast error = 0.8%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.051	2,369	2.1%	0.2%	0.0%
Forecast error = 1.65%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.050	2,551	2.2%	0.9%	0.4%
Forecast error = 3%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.051	2,737	2.4%	3.8%	2.2%
Forecast error = 4%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.058	2,754	2.5%	7.9%	5.0%

If load forecast error is high, there is a greater chance that increases in demand could exceed short-term supply availability. This could modestly reduce reliability.

Note: Historically observed forecast error = 1.65% of 3rd Incremental Auction reliability requirement. All dollar values are in $ 2026 / MW-day.

Sensitivity to short-term supply availability

Demand Curve	Measured After the 3-Year Forward BRA									Measured After the Last Incremental Auction				
	Price			Reliability					Cost	Reliability				
	Average	Standard Deviation	Frequency at Cap	Average LOLE	Average Excess (Deficit)	Average Excess (Deficit)	Frequency Below Reliability Requirement	Frequency Below IRM - 1%	Average Procurement Cost	Average LOLE	Average Excess (Deficit)	Average Excess (Deficit)	Frequency Below IA Reliability Requirement	Frequency Below IRM - 1%
	($/MW-d)	*($/MW-d)*	*(%)*	*(events/yr)*	*(MW)*	*(IRM + X %)*	*(%)*	*(%)*	*($ mln/yr)*	*(events/yr)*	*(MW)*	*(IRM + X %)*	*(%)*	*(%)*
Current Curve, CC, PJM IA Mechanism														
Prompt supply = 0%	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.065	1,927	1.7%	15.2%	6.6%
Prompt supply = 50% of historical	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.053	2,413	2.1%	4.2%	1.5%
Prompt supply = 100% of historical	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.050	2,551	2.2%	0.9%	0.4%
Prompt supply = 150% of historical	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905	0.049	2,580	2.2%	0.2%	0.0%

If no prompt supply is available, average system reliability decreases from approximately 1-in-18 to 1-in-15 LOLE

Note: All dollar values are in $ 2026 / MW-day.

Alternative Curves

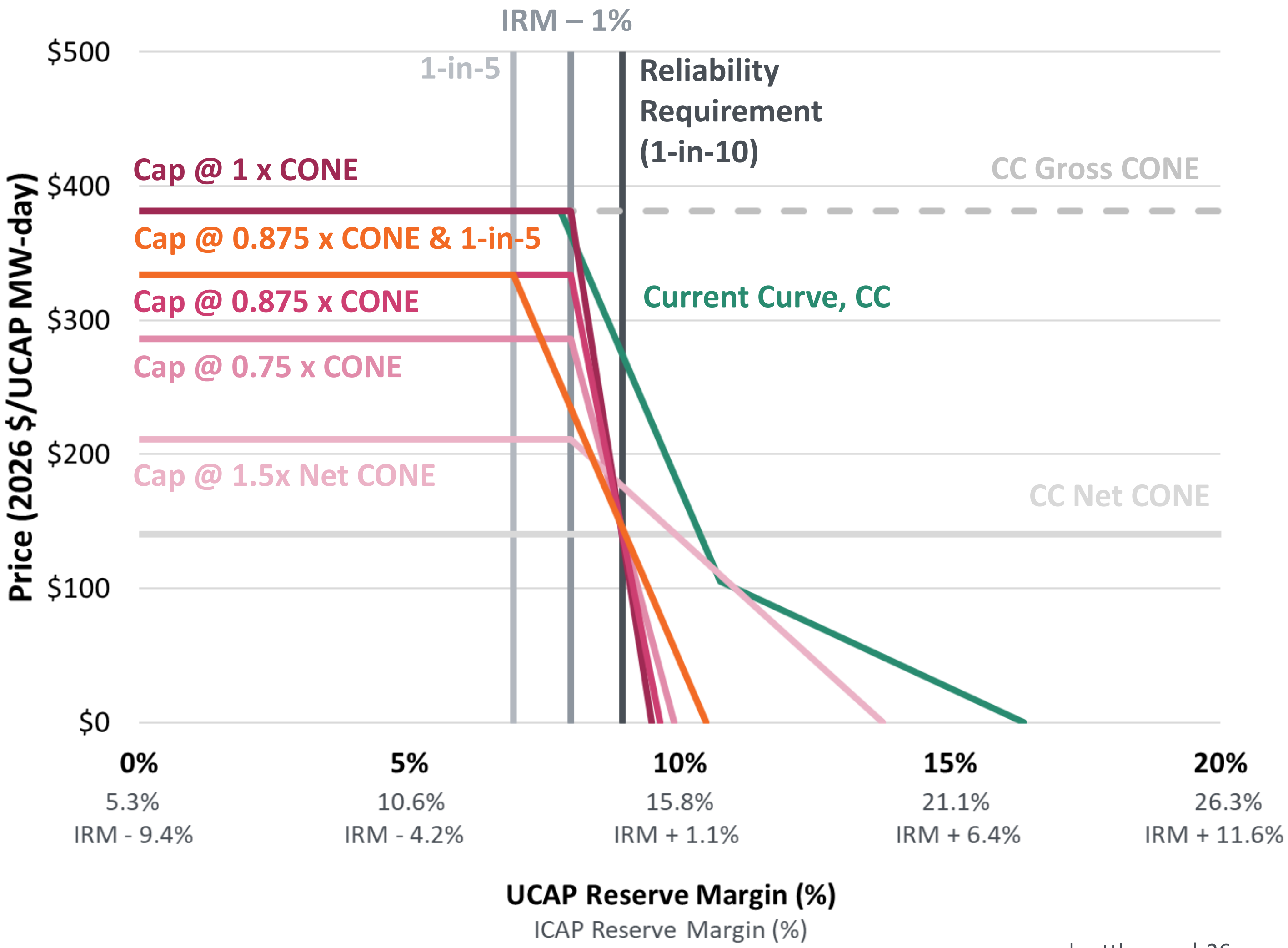
Curves "tuned" to 1-in-10 LOLE

"Tuned" curves are those we estimate to achieve 1-in-10 LOLE on average

Considerations:

- **Shape**: A somewhat steeper and left-shifted curve may be justified to further mitigate over-procurement (downside higher price volatility)
- **Quantity at the cap**: Should be at or above reliability backstop threshold (currently at IRM – 1%)
- **Price at the cap:** Should stay high enough to manage Net CONE uncertainties

Curves Tuned to 1-in-10 LOLE in BRA



Note: All straight-line (pink) curves are tuned to achieve an average of 1-in-10 LOLE in the BRA.

Curves "tuned" to 1-in-10 LOLE

Demand Curve	Measured After the 3-Year Forward BRA								
	Price			Reliability					Cost
	Average ($/MW-d)	Standard Deviation ($/MW-d)	Frequency at Cap (%)	Average LOLE (events/yr)	Average Excess (Deficit) (MW)	Average Excess (Deficit) (IRM + X %)	Frequency Below Reliability Requirement (%)	Frequency Below IRM - 1% (%)	Average Procurement Cost ($ mln/yr)
Current Curve, CC	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905
Straight Curve, CC, Price Cap Quantity (IRM -1%)									
Price cap (1.5 x Net CONE)	$141	$49	12.0%	0.100	863	0.8%	26.8%	12.0%	$6,825
Price cap (0.75 x CC Gross CONE)	$141	$64	1.0%	0.100	6	0.0%	45.9%	1.0%	$6,809
Price cap (0.875 x CC Gross CONE)	$141	$66	0.4%	0.100	-9	0.0%	47.5%	0.4%	$6,813
Price cap (CC Gross CONE)	$141	$67	0.2%	0.100	-11	0.0%	47.5%	0.2%	$6,815
Straight Curve, CC, Price Cap Quantity (BRA 1-in-5)									
Price cap (0.875 x CC Gross CONE)	$141	$62	0.0%	0.100	47	0.0%	45.8%	7.1%	$6,806

Steeper curves would modestly increase price volatility (but substantially mitigated by high elasticity in the supply stack).

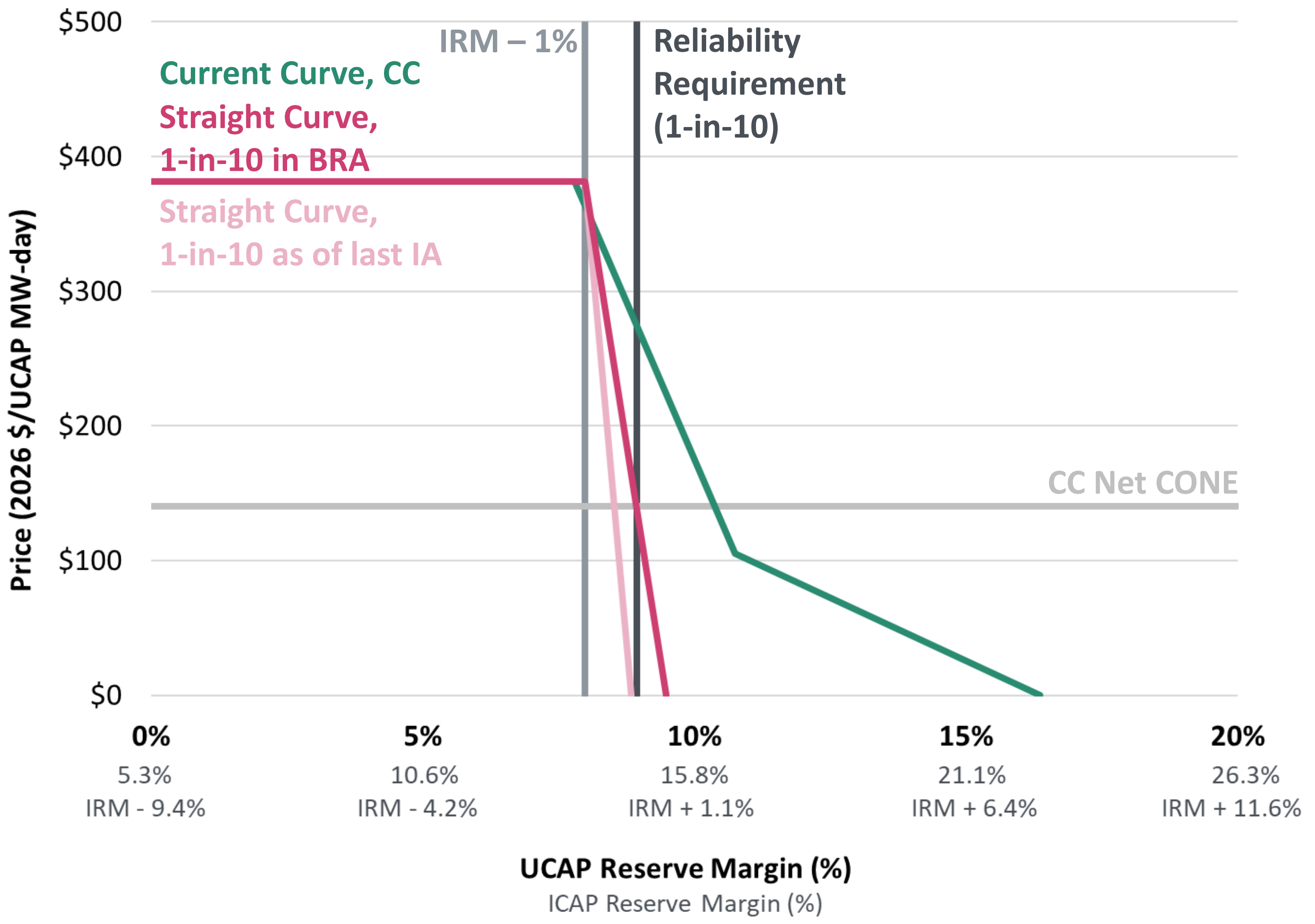
Tuned curves effectively eliminate over-procurement. Different from prior QER analyses since lower Net CONE and more supply elasticity enable more "right sizing" of procurements in all years

Note: All curves are tuned to achieve 1-in-10 LOLE in the BRA on average.
All dollar values are in $ 2026 / MW-day.

Should the VRR curve be left-shifted in the BRA to rely on short-term procurements?

- Tuning the demand curve to achieve 1-in-10 as of the last IA (rather than the BRA) would result in a modest left-shift of the VRR curve
- Not recommended until more experience and evidence that supply will be available in the incremental auctions during shortage conditions

Curves Tuned to 1-in-10 LOLE in BRA and IA

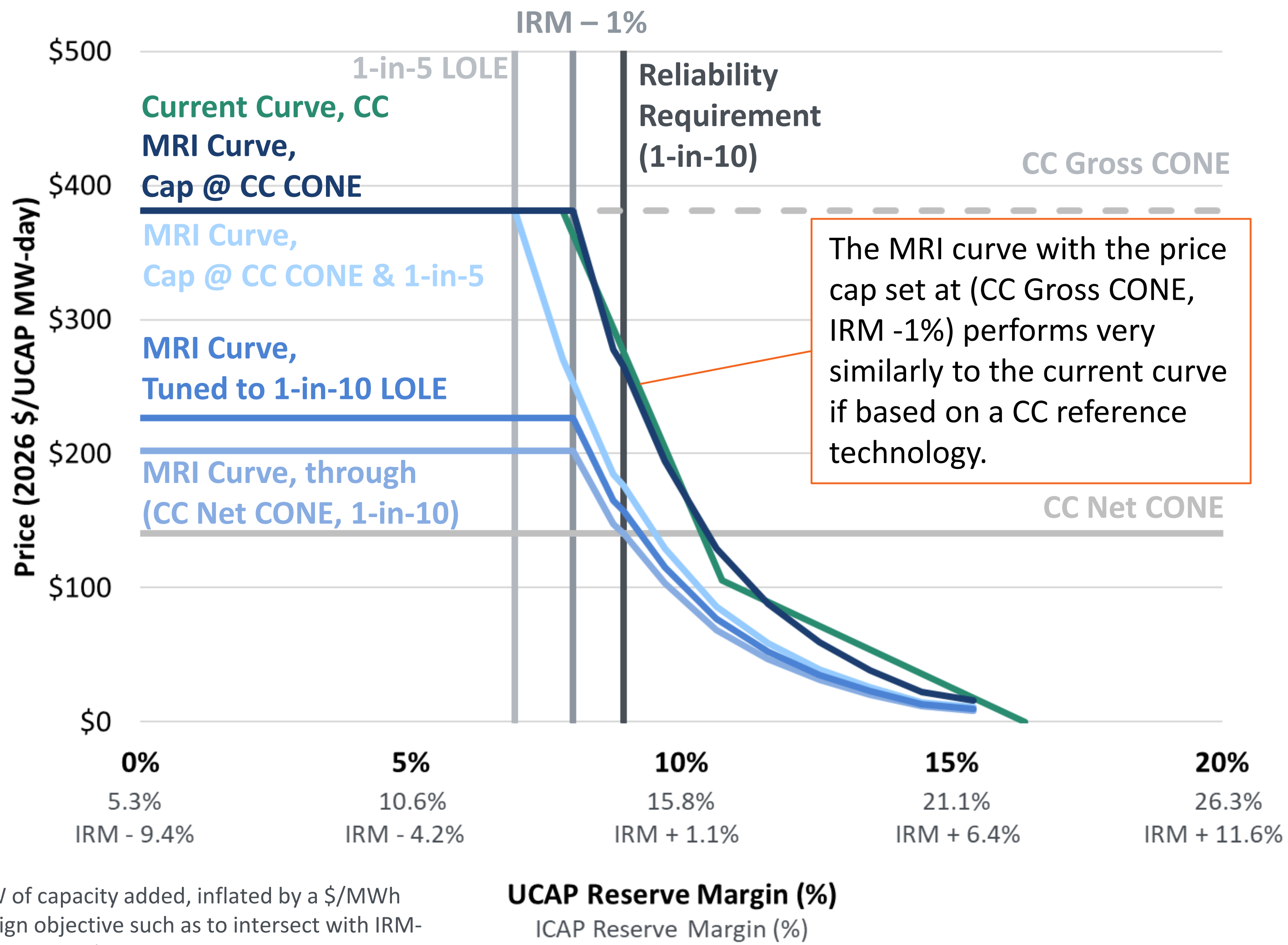


Note: IA = Incremental Auction; BRA = Base Residual Auction

How does a curve proportional to Marginal Reliability Impact perform?

- A demand curve based on the Marginal Reliability Impact (MRI) of capacity reflects the expected improvement in reliability associated with adding incremental capacity
- Convex shape has conceptual basis aligned with reliability value, prices increase at higher rate at low reliability while they decrease gradually at high reliability

Marginal Reliability Impact Curves



Note: MRI-based curves are calculated as the avoided expected unserved energy (EUE) per UCAP MW of capacity added, inflated by a $/MWh multiplier to translate into units of capacity price. The $/MWh multiplier is chosen to achieve the design objective such as to intersect with IRM-1% at CC Gross CONE (Cap @ CC CONE), intersect with 1-in-5 LOLE at CC Gross CONE (Cap @ CC CONE & 1-in-5), chosen so the curve will obtain 1-in-10 LOLE on average (Tuned to 1-in-10 LOLE), or to intersect with the reliability requirement @ CC Net CONE (CC Net CONE, 1-in-10 LOLE).

MRI-based VRR curves

Demand Curve	Measured After the 3-Year Forward BRA								
	Price			Reliability					Cost
	Average *($/MW-d)*	Standard Deviation *($/MW-d)*	Frequency at Cap *(%)*	Average LOLE *(events/yr)*	Average Excess (Deficit) *(MW)*	Average Excess (Deficit) *(IRM + X %)*	Frequency Below Reliability Requirement *(%)*	Frequency Below IRM - 1% *(%)*	Average Procurement Cost *($ mln/yr)*
Current Curve, CC	$141	$57	0.0%	0.055	2,172	1.9%	0.7%	0.0%	$6,905
Tested MRI Curves, CC									
Cap @ CC CONE	$141	$57	0.0%	0.054	2,162	1.9%	1.6%	0.0%	$6,904
Cap @ CC CONE & 1-in-5	$141	$57	0.0%	0.080	938	0.8%	26.8%	2.3%	$6,841
Tuned to 1-in-10 LOLE	$141	$54	7.8%	0.100	421	0.4%	36.5%	7.8%	$6,810
Through (CC Net CONE, 1-in-10)	$141	$48	20.8%	0.152	-586	-0.5%	50.5%	20.8%	$6,748

MRI curves (or kinked curves with parameters informed by MRI) could be within a workable range of performance.

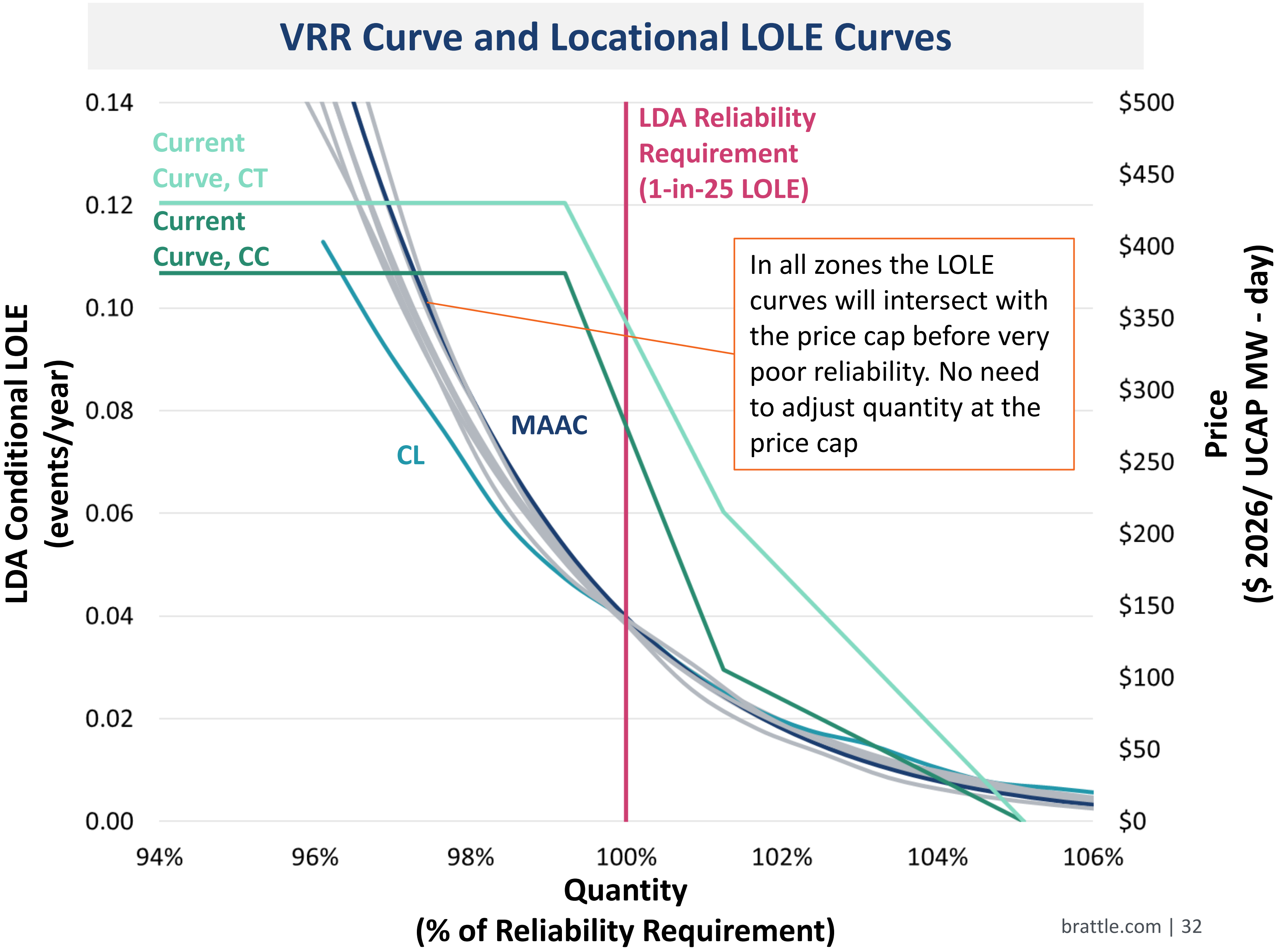
Note: All prices are in $2026/MW-day.

Locational VRR Curves

Locational VRR curves

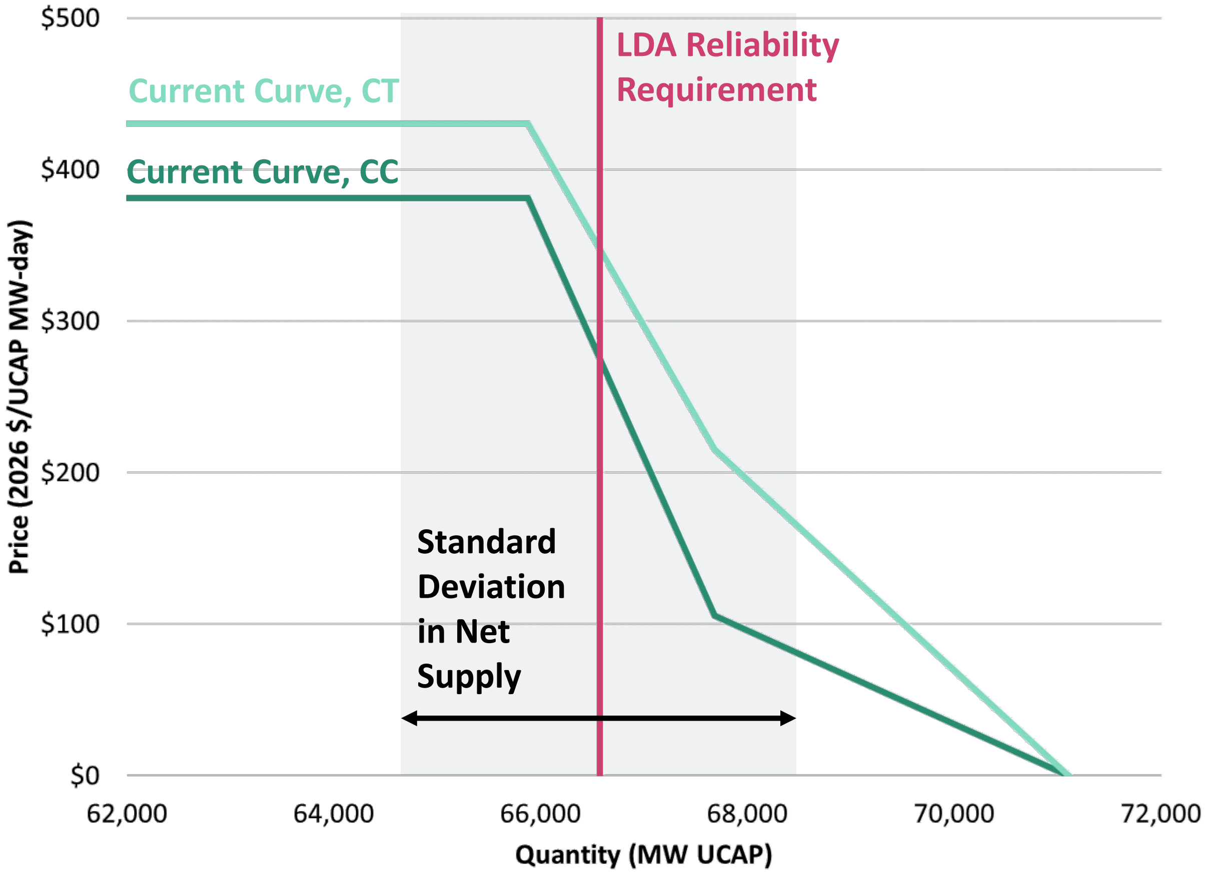
Locational VRR curves presently use the same formula as the system curve, though LDAs are subject to distinct considerations:

- **Width:** slope needs to be large as a % of LDA size in order to provide meaningful supports for price stability (one plant can drive differences between the price cap and floor in small LDAs)
- **Price cap:** may need to account for greater uncertainty in Net CONE in some locations (e.g. if the reference technology cannot be developed there)
- **Reliability**: prices should rise to the cap before very poor reliability is observed
- **Approach for consideration in RASTF:** Locational MRI-based demand curves (see New England's approach) that would reduce price volatility and have stronger conceptual basis

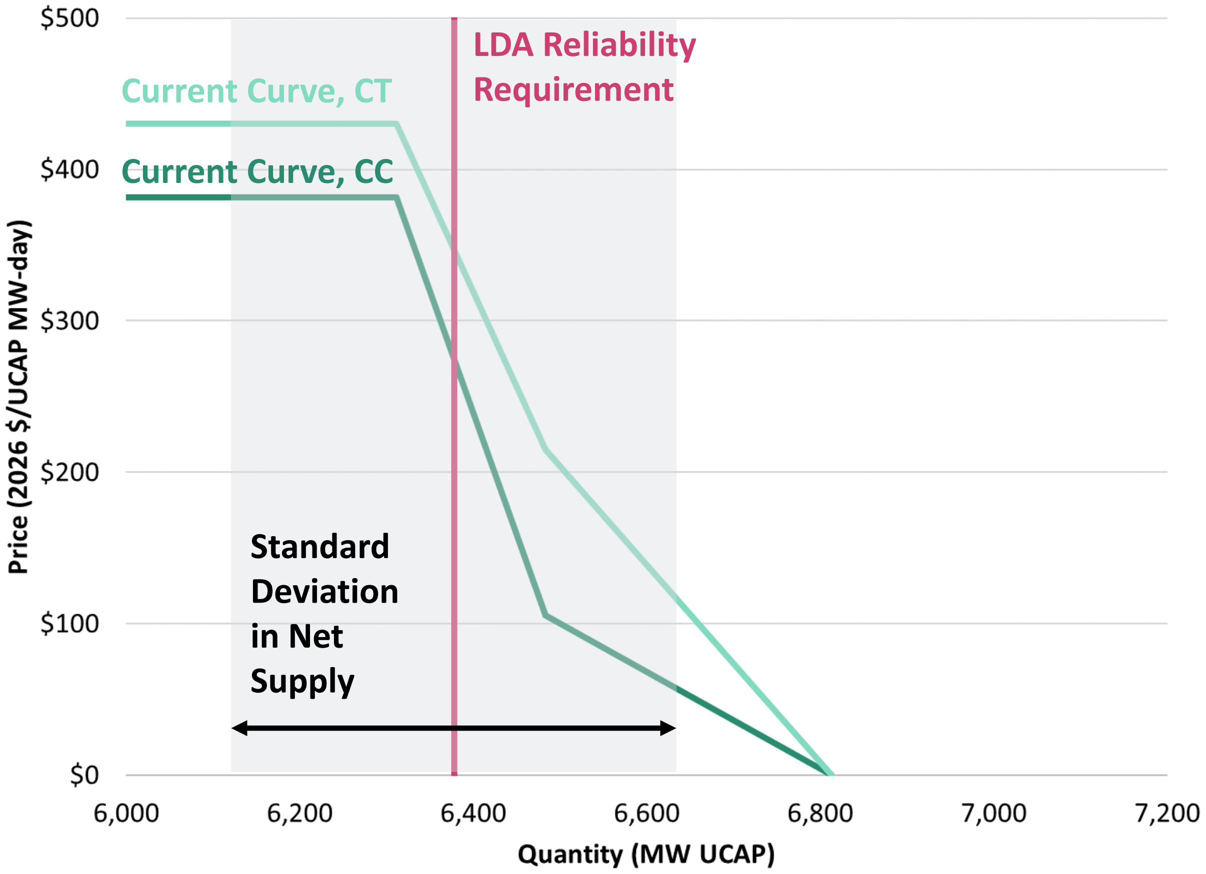


Locational supply variability may justify wider LDA curves

MAAC



PS North

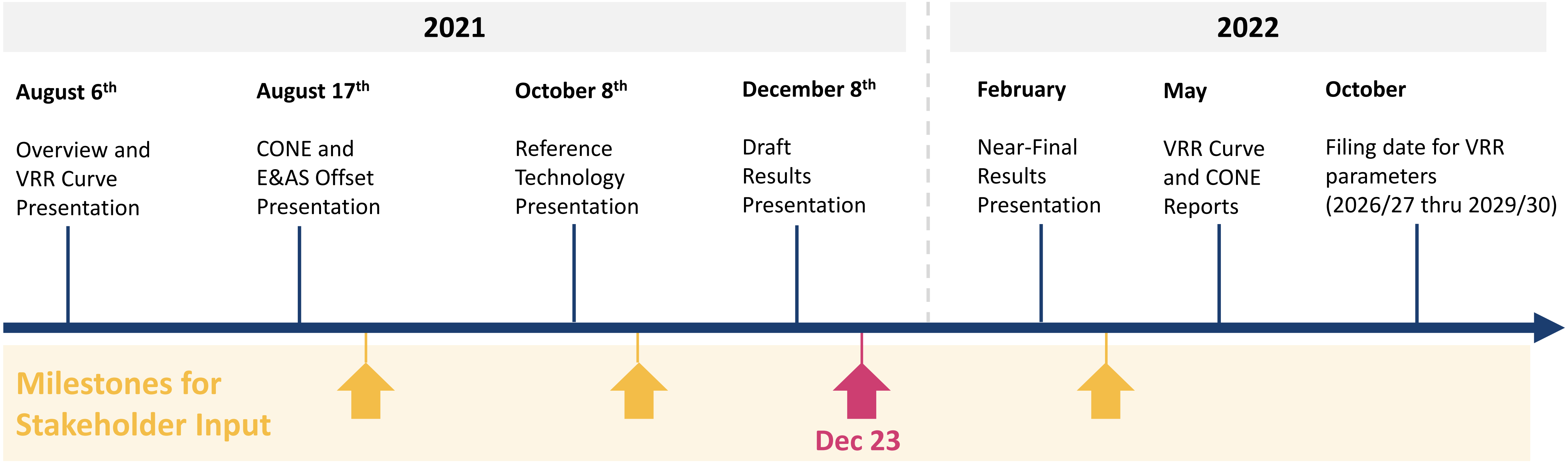


Note: Net Supply = Supply + CETL – Reliability Requirement. The standard deviation of net supply is 3,851 MW for MAAC and 506 MW for PS North. Variability as observed over 2013/14-2021/22 delivery years.

Discussion

Stakeholder input to inform the Quadrennial Review

Provide initial input on draft results by **December 23** to **Melissa.Pilong@pjm.com** or **Gary.Helm@pjm.com**



Appendix: Modeling Details

Input assumptions

- Gross and net CONE values are placeholder values
- All supply and demand variability parameters are derived from historical market data

Input Assumptions

PJM System Parameters	
Peak Load, adjusted for FRR *(MW)*	121,693
UCAP Reserve Margin *(UCAP %)*	8.9%
Reliability Requirement, adjusted for FRR *(UCAP MW)*	132,573
Net CONE	
CC Net CONE *($2026/MW-day)*	$141
CC Gross CONE *($2026/MW-day)*	$381
CT Net CONE *($2026/MW-day)*	$287
CT Gross CONE *($2026/MW-day)*	$356
Variability	
BRA Supply Variability *(Std. dev as a % of total supply offers)*	3.2%
BRA Reliability Requirement Variability *(Std. dev as a % of BRA reliability requirement)*	2.2%
Forward to Prompt Supply Variability *(Std. dev as a % of BRA total supply offered)*	1.1%
Forward to Prompt Reliability Requirement Variability *(Std. dev as a % of 3rd IA reliability requirement)*	1.7%

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