Quadrennial Review of VRR Curve Parameters

PRESENTED TO

PJM Market Implementation Committee

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THE Brattle GROUP

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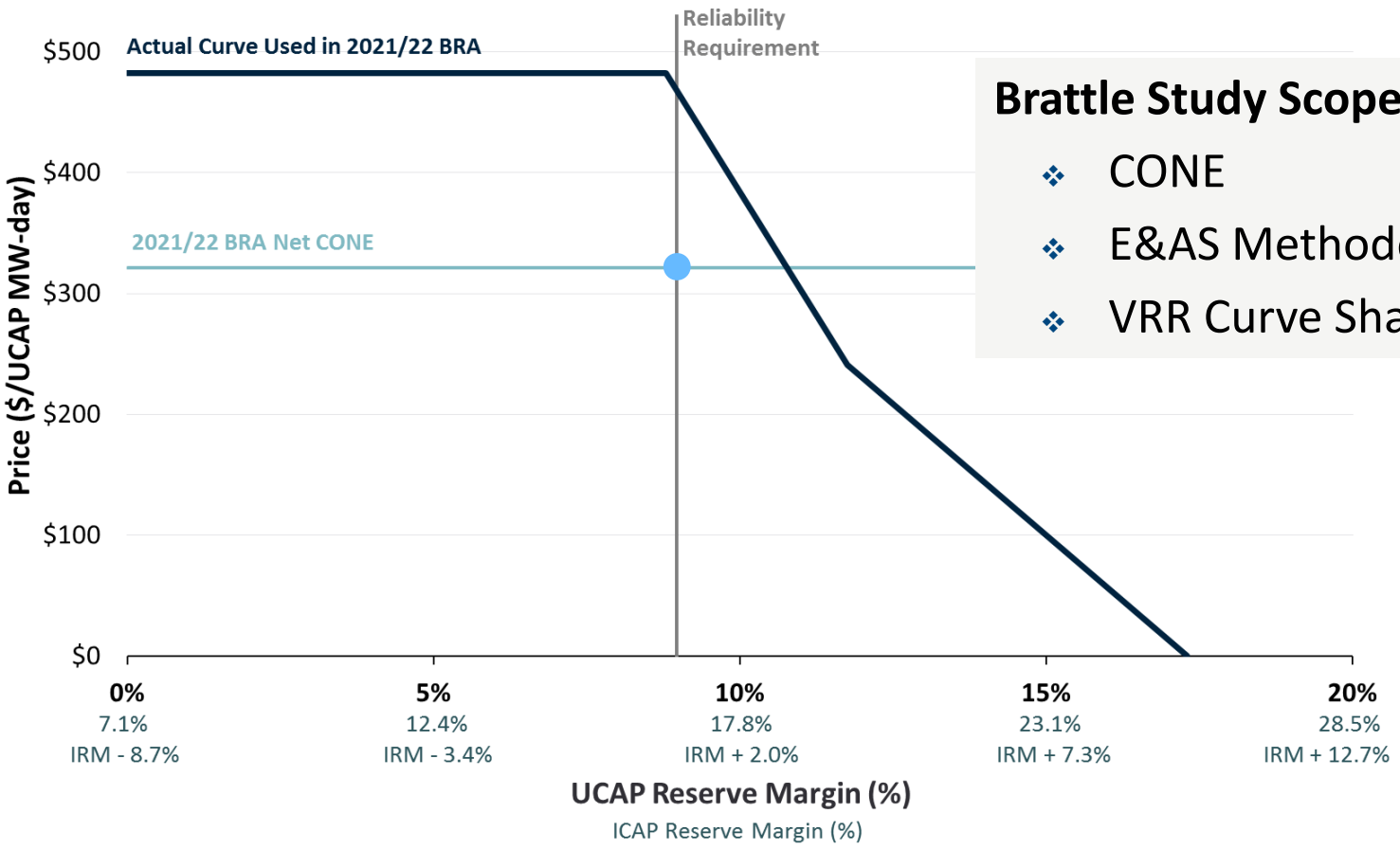
Background and Scope of Work

Current System VRR Curve



Brattle Study Scope

- CONE
- E&AS Methodology
- VRR Curve Shape

CONE Study Results

Updated RTO CONE Estimates ($/ICAP MW-year)

	CT	CC
2021/22 Auction Parameter	$135,309	$186,186
…Escalated to 2022/23	$139,100	$191,400
Updated 2022/23 CONE	**$104,200**	**$114,400**
Difference from Prior CONE	-25%	-40%

Source and notes:
Average across all CONE Areas. Table ES-1 of PJM 2018 CONE Study.

E&AS Revenue Offset Takeaways

Tariff-mandated historical E&AS approach is reasonable

We recommend several refinements:

- Update representative gas hubs for 6 zones
- Update operating characteristics
- Include gas balancing cost adder for CTs
- Add net Capacity Performance payments
- Calculate E&AS margins for RTO and other multi-zone LDAs based on median across zones

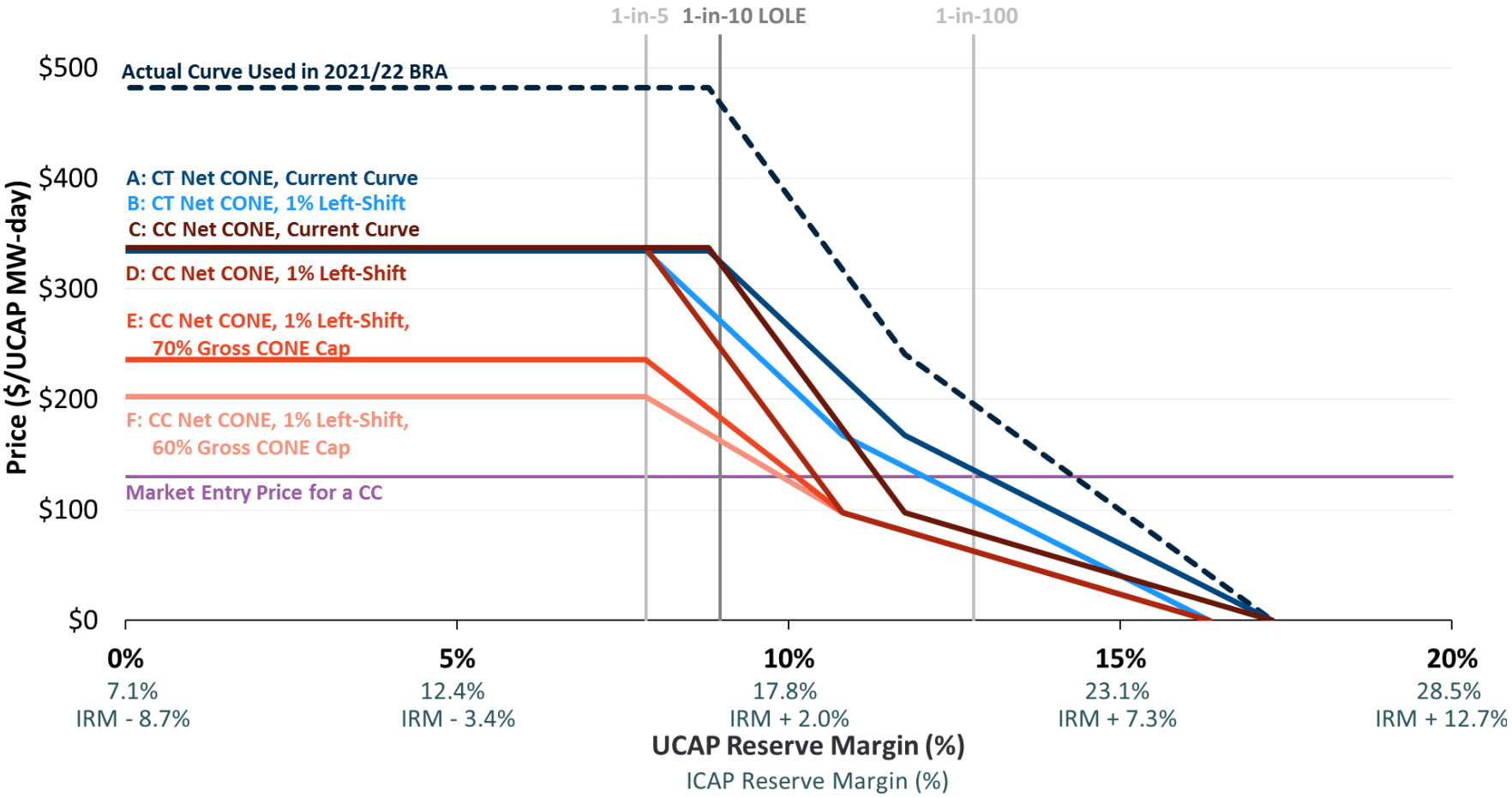
Developed forward-looking approach for CC E&AS offsets

Indicative RTO Net CONE

		2021/22 BRA	2022/23 Brattle Estimate	
		CT	CT	CC
Gross CONE	*$/MW-year ICAP*	$135,300	$104,200	$114,400
E&AS Margin	*$/MW-year ICAP*	$24,800	$28,400	$70,600
Net CONE	*$/MW-year ICAP*	$110,500	$75,800	$43,800
Net CONE	***$/MW-day UCAP***	**$322**	**$222**	**$129**

Sources:
VRR Curve Report, Table ES-1.

VRR Curve Evaluation



Source and Notes:
VRR Curve Report, Figure ES-1.
Current VRR curve parameters taken from 2021/22 BRA parameters.

VRR Curve Conclusions

Candidate Curves' Simulated Performance in Long-Run Equilibrium

	Average Excess over IRM (IRM + X%)	Average LOLE		Cost Savings vs. Curve A ($m/Yr)
		Base Conditions (Ev/Yr)	Stress Conditions* (Ev/Yr)	
CT as Reference Technology				
A: Current Curve	4.3%	0.01	0.02	-
B: 1% Left-Shift	3.3%	0.02	0.04	$74
CC as Reference Technology				
C: Current Curve	2.8%	0.03	0.05	$100
D: 1% Left-Shift	1.8%	0.05	0.07	$171
E: 1% Left-Shift, 70% CONE Cap	1.4%	0.07	0.16	$212
F: 1% Left-Shift, 60% CONE Cap	1.1%	0.09	0.33	$233

Source and Notes:
VRR Curve Report, Table 11. Current VRR curve parameters taken from 2021/22 BRA parameters.
* "Stress Conditions" assume the realized market entry price is 20% higher than we estimated.

Contents

CONE Study

Updated Technical Specifications

Plant Characteristic	Combustion Turbine	Combined Cycle
Turbine Model	7HA.02	7HA.02
Configuration	1x0	2x1
Power Augmentation	Evaporative Cooling, no inlet chillers	Evaporative Cooling, no inlet chillers
CC Supplemental Firing	---	+125 MW (+13%)
CC Cooling System	---	Cooling Towers
Fuel Supply	Dual Fuel	Dual Fuel, except in SWMAAC (firm gas)
Environmental Controls	SCR and CO Catalyst, except Rest of RTO	SCR and CO Catalyst
Net Summer ICAP	**321 – 355 MW**	**1,126 – 1,160 MW**
Net Heat Rate (HHV)	9,221 – 9,274 Btu/kWh	6,295 – 6,312 Btu/kWh

Sources and notes: PJM 2018 CONE Study, Table 4 and Table 5. Net Summer ICAP and Net Heat Rate based on average summer ambient conditions. CC ICAP is with duct firing and net heat rate is without duct firing (adds about 240 Btu/kWh).

Updated Cost of Capital

ATWACC now 7.5% vs. 8.0% in 2014 review

Prior to tax reform, market data indicated 7.0% ATWACC

- Publicly-traded merchant generation companies (5.4% to 6.5%)
- Sensitivities for alternative risk-free rates and cost of debt (4.8% to 7.0%)
- Recent fairness opinion discount rates (5.8% to 7.3%)
- Qualitative adjustment for relative risk of merchant plant

Adjusted for lower tax rates, ATWACC increases to 7.5%

	Prior to 2017 Tax Reform	Adjusted for 2017 Tax Reform
Combined Tax Rate	40.5%	29.5%
Debt Ratio	65%	65%
Cost of Debt	6.5%	6.5%
Return on Equity	12.8%	12.8%
ATWACC	7.0%	7.5%

$$\text{ATWACC} = ROE \times \%Equity + COD \times \%Debt \times (1 - Tax\ Rate)$$

CONE Study

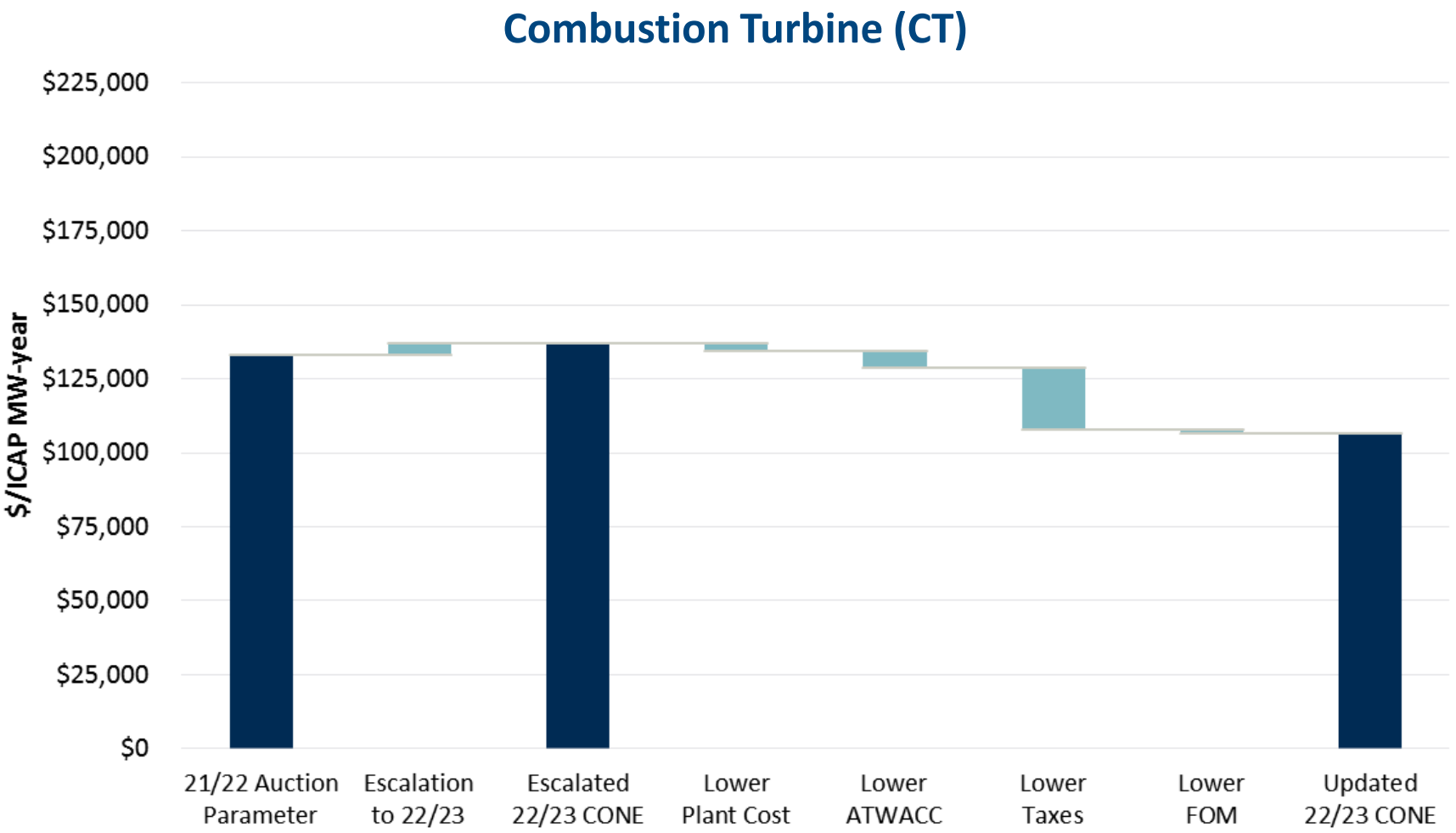
Updated CONE Calculations

		Simple Cycle			
		EMAAC	SWMAAC	Rest of RTO	WMAAC
Net Summer ICAP	*MW*	352	355	321	344
Overnight Costs	*$/kW*	$898	$836	$799	$886
Effective Charge Rate	*%*	10.1%	10.1%	10.0%	10.0%
Plant Costs	*$/MW-yr*	$90,300	$84,300	$80,300	$88,900
Fixed O&M	*$/MW-yr*	$16,100	$24,100	$17,900	$14,900
Levelized CONE	***$/MW-yr***	**$106,400**	**$108,400**	**$98,200**	**$103,800**
Levelized CONE	***$/MW-day***	**$292**	**$297**	**$269**	**$284**

		Combined Cycle			
		EMAAC	SWMAAC	Rest of RTO	WMAAC
Net Summer ICAP	*MW*	1,152	1,160	1,138	1,126
Overnight Costs	*$/kW*	$873	$772	$815	$853
Effective Charge Rate	*%*	10.6%	10.6%	10.5%	10.5%
Plant Costs	*$/MW-yr*	$92,200	$81,800	$85,900	$89,900
Fixed O&M	*$/MW-yr*	$23,800	$38,400	$23,900	$21,900
Levelized CONE	***$/MW-yr***	**$116,000**	**$120,200**	**$109,800**	**$111,800**
Levelized CONE	***$/MW-day***	**$318**	**$329**	**$301**	**$306**

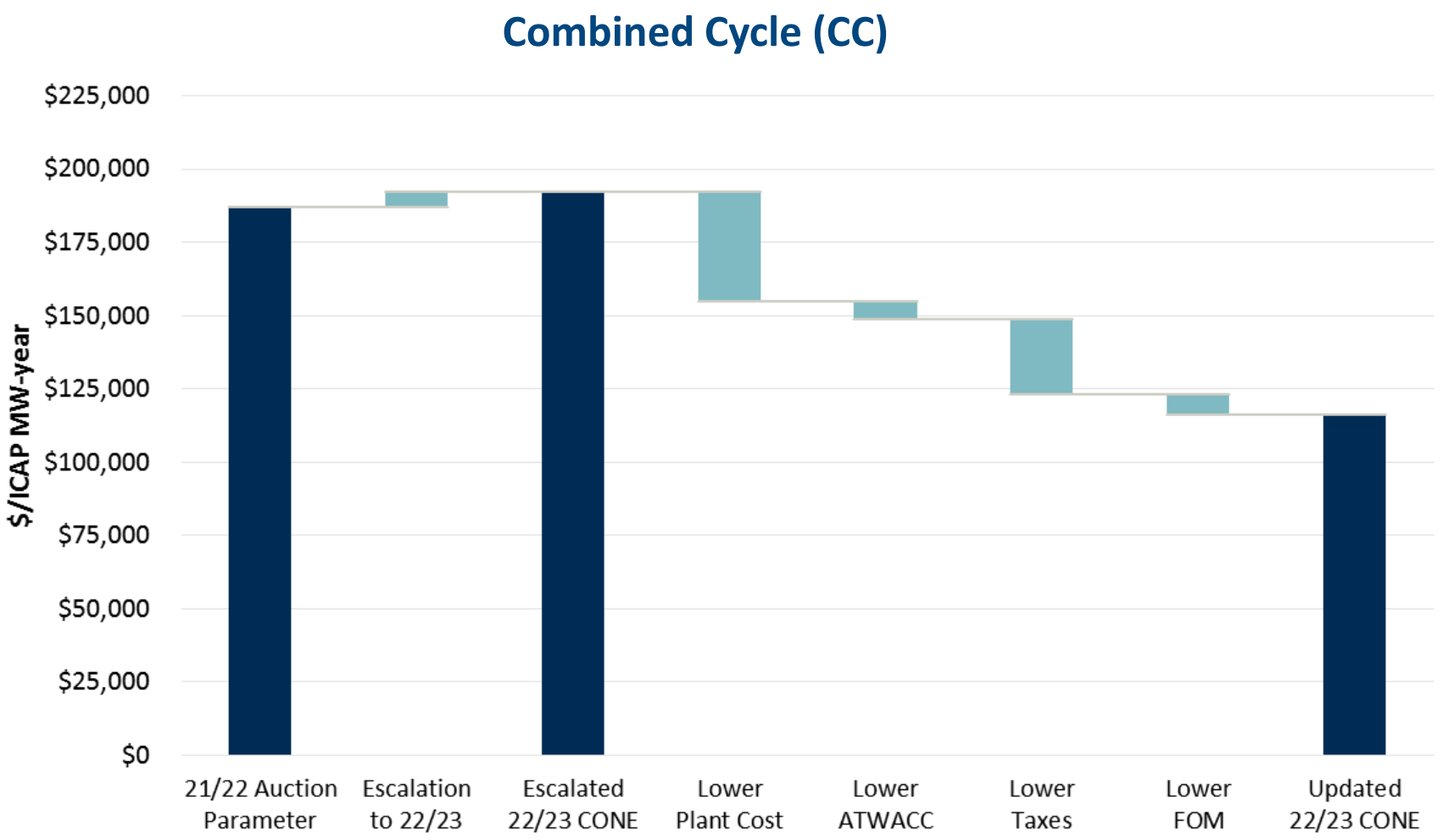
Source and notes: PJM 2018 CONE Study, Table ES-2 and Table ES-3. All capacity values are ICAP.

Change in EMAAC CT CONE from 2014 Study



Source: PJM 2018 CONE Study, Figure ES-1a.

Change in EMAAC CC CONE from 2014 Study



Source: PJM 2018 CONE Study, Figure ES-1b.

Annual CONE Updates

Continue to escalate CONE with composite cost index prior to each BRA

- Still use BLS turbine, material, and labor indices
- Shift weighting to reflect updated capital costs components

Add adjustment of +2%/year for annual decline in bonus depreciation

Contents

Approach to Evaluating E&AS Methodology

Evaluated tariff-mandated historical approach

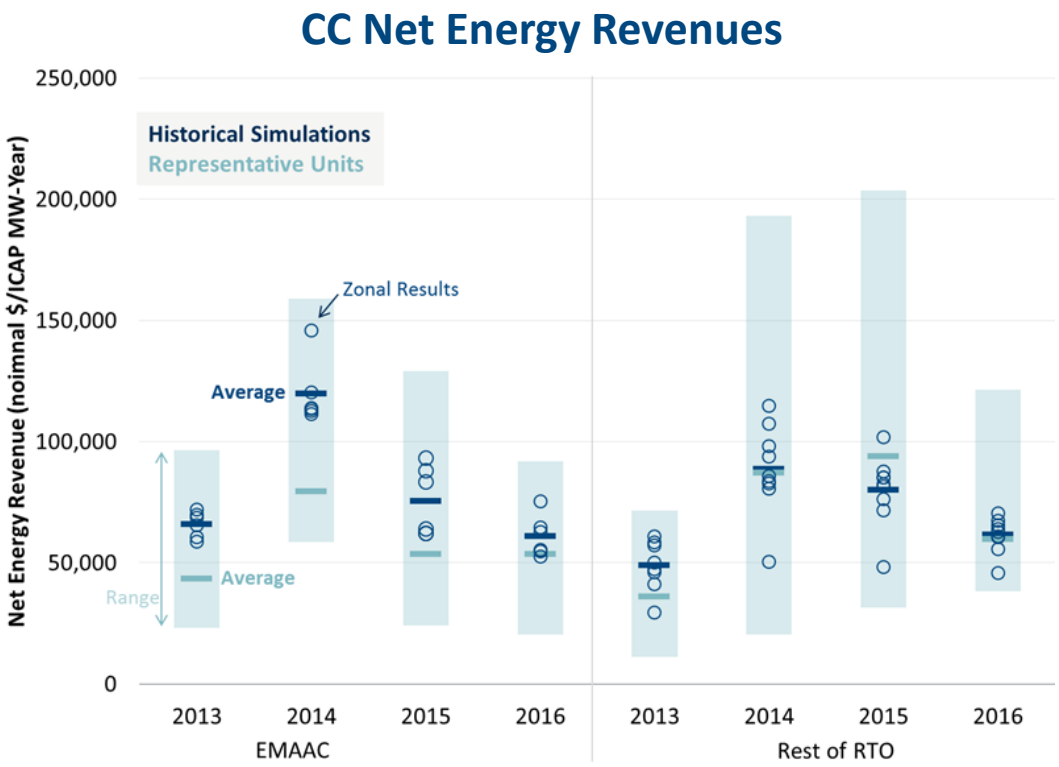
- Reasonableness of cost assumptions
- Comparison to IMM's approach
- Comparison to representative units' actual margins

Considered forward-looking approach

Evaluated approach to RTO and multi-zone LDA estimate

Comparison to Representative Units' Margins

Simulated CC energy margins (blue circles) generally fall within range of representative existing unit net revenues (teal bars)



Source: VRR Curve Report, Figure 2.

But for CTs, too few representative existing units to compare

Refinements to Current E&AS Approach

Inputs to tariff-mandated historical simulations:

- Update gas trading hubs for 6 zones
- Update unit characteristics (heat rate, VOM) based on CONE Study
- Add gas balancing costs for CTs, e.g., by applying 10% adder

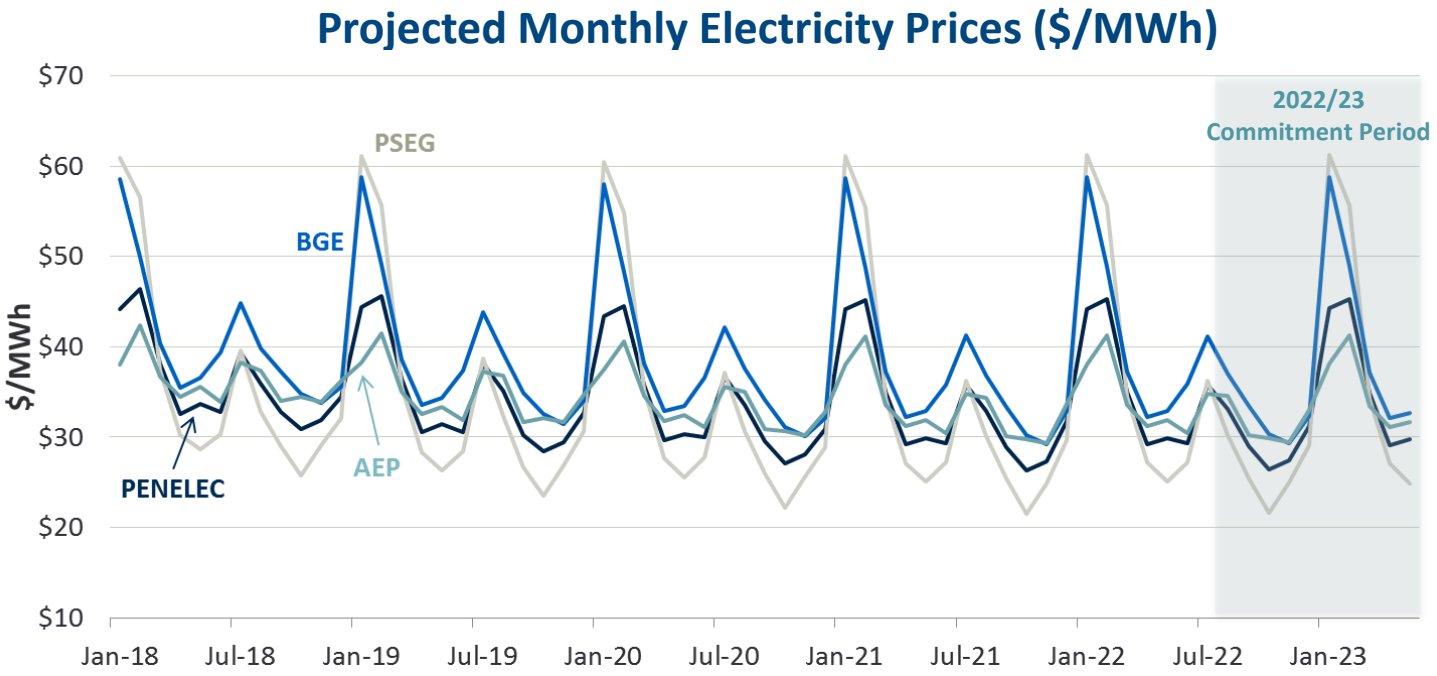
Add net Capacity Performance payments

Use median E&AS margin for the RTO and multi-zone LDAs

CC Forward-Looking Approach

Forward-looking E&AS approach better represents developer's expectation for E&AS margins and reduces volatility of Net CONE

- CC margins reasonably approximated by on-peak 5x16 futures; not the case for CTs
- Key is having reasonable, market-based electricity and gas prices 3 years forward
- Forward-looking CC margins are lower than 2015-2017 average in most zones



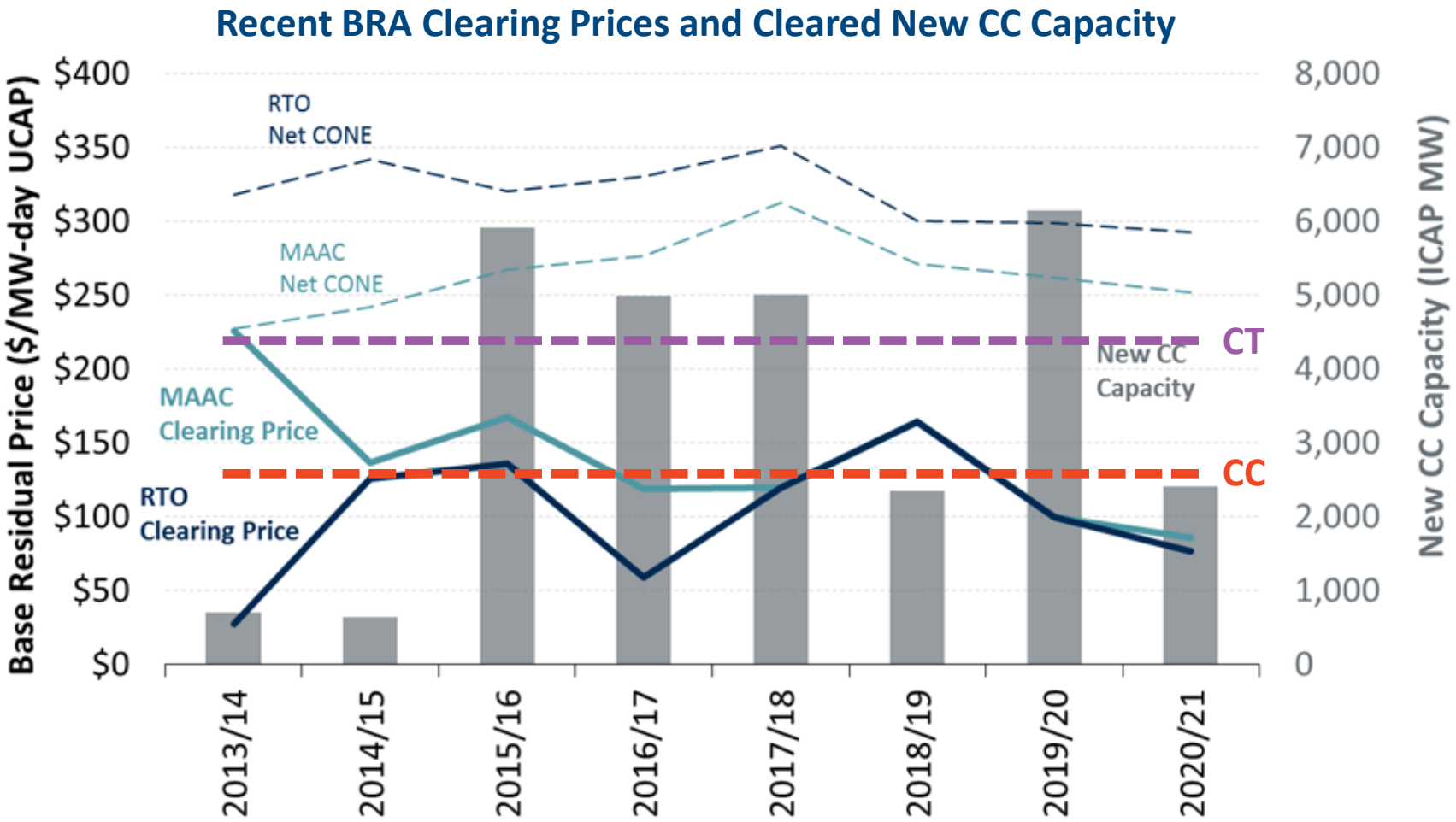
Source:
VRR Curve Report, Figure 6.

Indicative RTO Net CONE

		2021/22 BRA	2022/23 Brattle Estimate	
		CT	CT	CC
Gross CONE	*$/MW-year ICAP*	$135,300	$104,200	$114,400
E&AS Margin	*$/MW-year ICAP*	$24,800	$28,400	$70,600
Net CONE	*$/MW-year ICAP*	$110,500	$75,800	$43,800
Net CONE	***$/MW-day UCAP***	**$322**	**$222**	**$129**

Sources:
VRR Curve Report, Table ES-1.

Comparison to Recent Market Outcomes



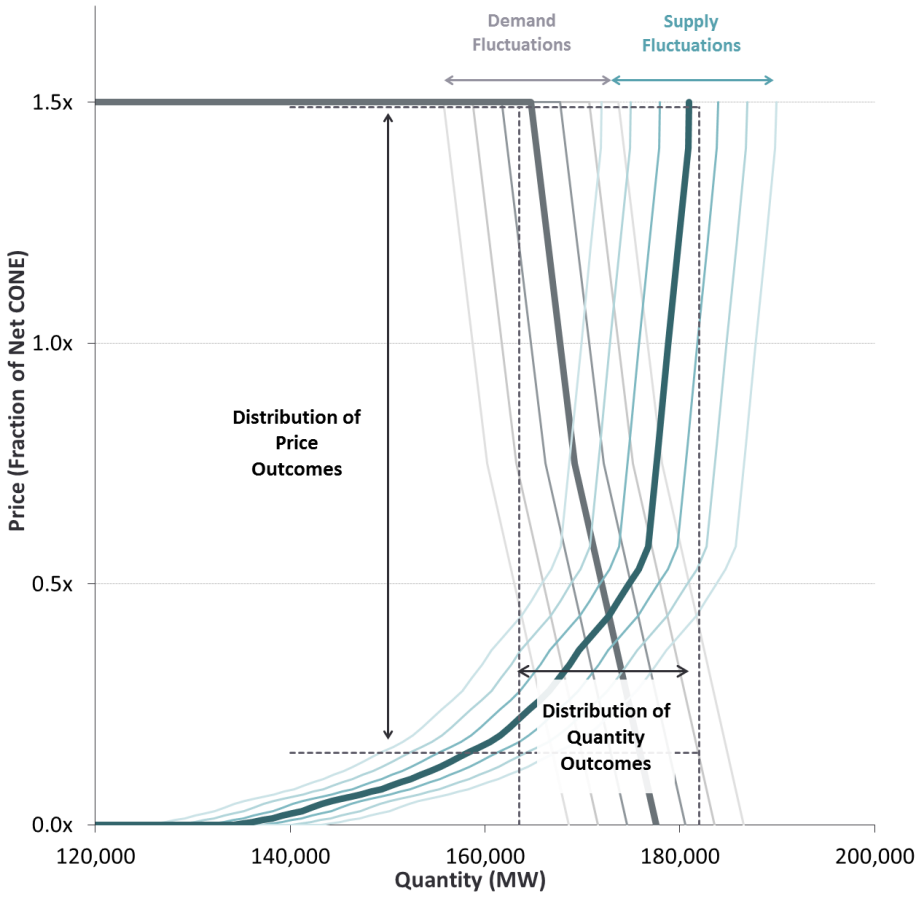
Source:
VRR Curve Report, Figure 8.

Contents

Simulation Model Overview

- **Inputs:** locational supply and demand curves and transmission parameters
- **Outputs:** price, quantity, and reliability
- **Model Engine:** locational market clearing engine generates prices and quantities
- **Monte Carlo Simulations:** uses a range of realistic "fluctuations" in supply, demand, and imports
- **Equilibrium condition:** long-run average price equals Net CONE

Stylized Supply and Demand Fluctuations



Source:
VRR Curve Report, Figure 9.

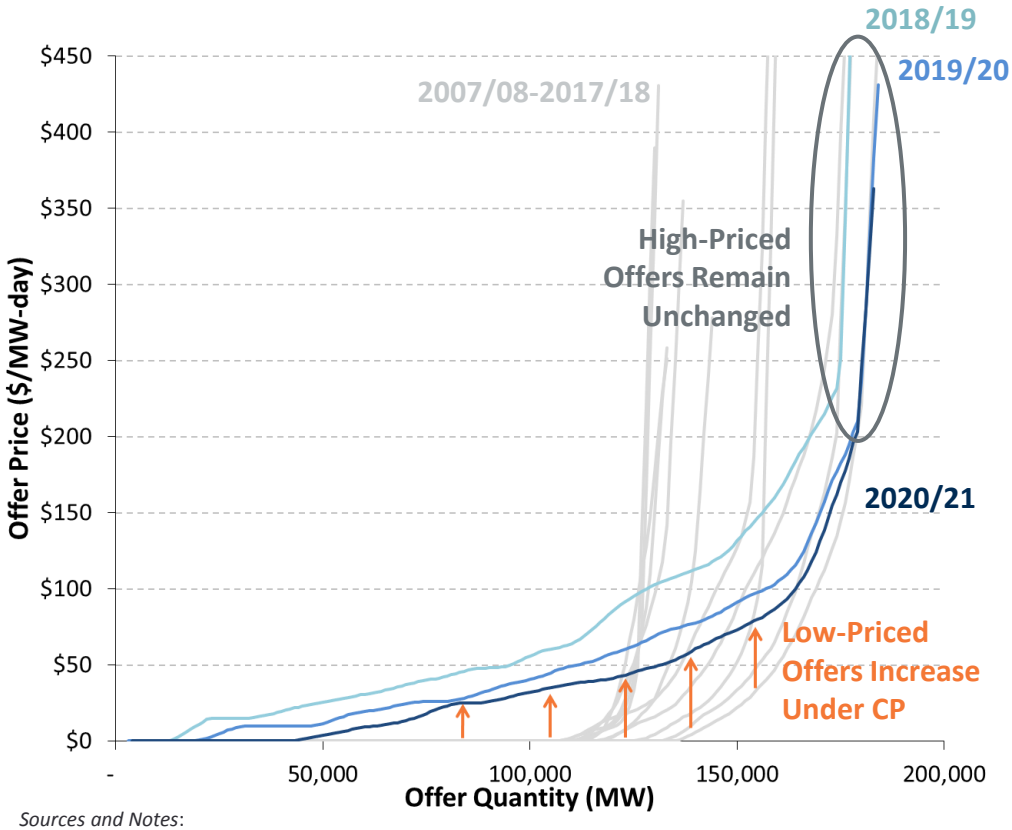
Supply Curves Under Capacity Performance

Capacity Performance has altered the low-price portion of the supply curve

- **Higher Offer Prices:** a capacity obligation implies a short position on performance and a minimum offer price
- **Range of Offer Prices:** reflect market's range of expectations about performance hours (H)

Supply curves in our simulations reflect this

Capacity Performance Supply Curves in Simulation Model



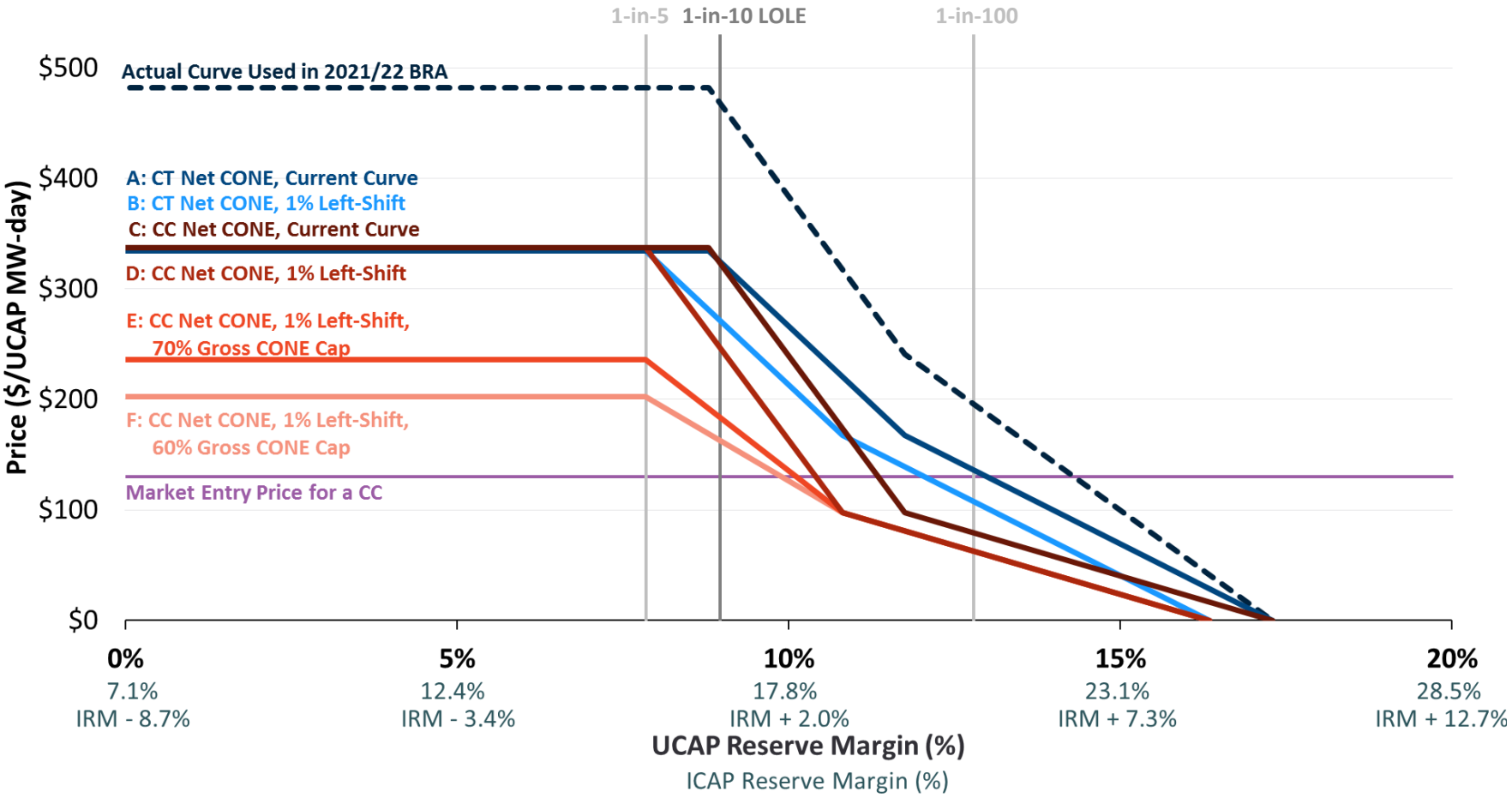
Sources and Notes:
VRR Curve Report, Figure 13.
Average H and diversity of expectations in H derived using supply curve data provided by PJM.

Other Simulation Model Inputs

- **Administratively Defined VRR Curve:** shape, reliability requirement, and reference technology Net CONE
- **Market Entry Price:** indicative CC Net CONE estimate
- **Import Limits:** based on 2020/21 BRA parameters
- **Fluctuations:** informed by historical variability in supply, demand, and transmission

Assessment of VRR Curve Shape

Candidate Curves



Source and Notes:
VRR Curve Report, Figure ES-1.
Current VRR curve parameters taken from 2021/22 BRA parameters.

Assessment of VRR Curve Shape

Performance of Candidate Curves

Curve E strikes a balance across design objectives

All Results Assume Market Entry Price = CC Net CONE

	Admin Net CONE	Price and Procurement Costs			Reliability					
		Avg. Price (= Market Entry Price)	Standard Deviation of Price	Average Cost (P × Q)	Average LOLE	Stress LOLE *	Average Excess (Deficit)	Reserve Margin Standard Deviation	Frequency Below Reliability Requirement	Frequency Below 1-in-5
	($/MW-d)	*($/MW-d)*	*($/MW-d)*	*($mil)*	*(Ev/Yr)*	*(Ev/Yr)*	*(IRM + X%)*	*(% ICAP)*	*(%)*	*(%)*
CT as Reference Technology										
A: Current Curve	$222	$129	$34	$8,139	0.011	0.023	4.3%	1.1%	0%	0%
B: 1% Left-Shift	$222	$129	$34	$8,065	0.023	0.041	3.3%	1.1%	0%	0%
CC as Reference Technology										
C: Current Curve	$129	$129	$58	$8,039	0.031	0.046	2.8%	1.1%	1%	0%
D: 1% Left-Shift	$129	$129	$58	$7,969	0.053	0.072	1.8%	1.1%	5%	0%
E: 1% Left-Shift, 70% Gross CONE Cap	$129	$129	$50	$7,927	0.071	0.163	1.4%	1.5%	15%	4%
F: 1% Left-Shift, 60% Gross CONE Cap	$129	$129	$46	$7,906	0.091	0.331	1.1%	1.7%	20%	6%

Downward and left-shifted curves reduce customer costs (2.6% for curve E)

All curves exceed 1-in-10 standard

Under stress conditions, curve with 60% gross CONE cap performs poorly

Recommended curve reliability performance is comparable to PJM's right-shifted curve in our 2014 Review

Sources and Notes:
VRR Curve Report, Table 11. Current VRR curve parameters taken from 2021/22 BRA parameters.
* "Stress LOLE" assumes the market entry price is 20% higher than the value used to anchor the VRR curve.

VRR Curve Takeaways

CC entry is available at low cost, supporting VRR curve performance

We therefore recommend that PJM consider adopting a CC-based VRR curve with two additional changes (curve E):

- **Left-shift by 1%** since main rationale for the right-shift in 2014 no longer applies
- **Reduce alternative price cap to 70% of Gross CONE** to avoid excess procurement with CCs' high E&AS almost always triggering the alternative price cap

These changes would satisfy reliability objectives and save > $ 200 million annually relative to simply updating the current CT-based curve

Other considerations for adopting CC as Reference Technology:

- Estimation error is lower than for CT
- Year-to-year variability in Net CONE parameter mitigated by forward E&AS
- Low risk that CC is only a temporarily lower cost resource

VRR Curves in the LDAs

No matter which candidate curve PJM adopts, translating it to the LDAs will support reliability under current conditions

If PJM selects curves E or F, it should *consider* a minimum local curve width of 25% of CETL to protect against:

- Higher variability in supply and demand than the RTO on a % basis,
- Volatility in the import limit contributing to greater net supply variability, and
- Potential future conditions where import limits are binding and LDAs have higher market entry price than their parents

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Detailed Cost Estimates

Plant Capital Cost Estimates

Combustion Turbine (CT)

Capital Costs (in $millions)	CONE Area 1 EMAAC 352 MW	2 SWMAAC 355 MW	3 Rest of RTO 321 MW	4 WMAAC 344 MW
Owner Furnished Equipment				
Gas Turbines	$74.4	$74.4	$74.4	$74.4
SCR	$26.6	$26.6	$0.0	$26.6
Sales Tax	$6.7	$6.1	$4.7	$6.4
Total Owner Furnished Equipment	**$107.7**	**$107.1**	**$79.1**	**$107.4**
EPC Costs				
Equipment				
Other Equipment	$25.7	$25.6	$28.5	$25.7
Construction Labor	$43.5	$31.8	$31.0	$37.6
Other Labor	$16.5	$15.3	$12.9	$16.0
Materials	$6.6	$6.5	$6.5	$6.6
Sales Tax	$2.1	$1.9	$2.2	$2.0
EPC Contractor Fee	$20.2	$18.8	$16.0	$19.5
EPC Contingency	$22.2	$20.7	$17.6	$21.5
Total EPC Costs	**$136.8**	**$120.5**	**$114.8**	**$128.9**
Non-EPC Costs				
Project Development	$12.2	$11.4	$9.7	$11.8
Mobilization and Start-Up	$2.4	$2.3	$1.9	$2.4
Net Start-Up Fuel Costs	$2.6	$1.7	$0.2	$0.6
Electrical Interconnection	$7.8	$7.8	$7.1	$7.6
Gas Interconnection	$29.1	$29.1	$29.1	$29.1
Land	$0.4	$0.7	$0.3	$0.5
Fuel Inventories	$3.0	$3.0	$2.7	$2.9
Non-Fuel Inventories	$1.2	$1.1	$1.0	$1.2
Owner's Contingency	$4.7	$4.6	$4.2	$4.5
Financing Fees	$8.0	$7.5	$6.5	$7.7
Total Non-EPC Costs	**$71.4**	**$69.2**	**$62.6**	**$68.3**
Total Capital Costs	**$316.0**	**$296.8**	**$256.5**	**$304.7**
Overnight Capital Costs ($million)	**$316**	**$297**	**$257**	**$305**
Overnight Capital Costs ($/kW)	**$898**	**$836**	**$799**	**$886**
Installed Cost ($/kW)	**$938**	**$874**	**$835**	**$925**

Combined Cycle (CC)

Capital Costs (in $millions)	CONE Area 1 EMAAC 1152 MW	2 SWMAAC 1160 MW	3 Rest of RTO 1138 MW	4 WMAAC 1126 MW
Owner Furnished Equipment				
Gas Turbines	$173.2	$167.5	$173.2	$173.2
HRSG / SCR	$55.4	$53.6	$55.4	$55.4
Sales Tax	$15.1	$13.3	$14.5	$14.5
Total Owner Furnished Equipment	**$243.8**	**$234.4**	**$243.1**	**$243.1**
EPC Costs				
Equipment				
Condenser	$5.8	$5.8	$5.8	$5.8
Steam Turbines	$47.1	$45.5	$47.1	$47.1
Other Equipment	$74.7	$72.1	$74.7	$74.7
Construction Labor	$211.1	$159.3	$167.4	$187.2
Other Labor	$56.5	$50.6	$52.5	$54.3
Materials	$51.5	$51.2	$51.5	$51.5
Sales Tax	$11.9	$10.5	$11.4	$11.4
EPC Contractor Fee	$70.2	$62.9	$65.3	$67.5
EPC Contingency	$77.3	$69.2	$71.9	$74.3
Total EPC Costs	**$606.1**	**$527.3**	**$547.6**	**$573.7**
Non-EPC Costs				
Project Development	$42.5	$38.1	$39.5	$40.8
Mobilization and Start-Up	$8.5	$7.6	$7.9	$8.2
Net Start-Up Fuel Costs	$0.8	-$5.5	-$10.5	-$7.2
Electrical Interconnection	$25.5	$25.6	$25.2	$24.9
Gas Interconnection	$29.1	$29.1	$29.1	$29.1
Land	$1.5	$2.7	$1.0	$2.0
Fuel Inventories	$6.9	$0.0	$6.8	$6.7
Non-Fuel Inventories	$4.2	$3.8	$4.0	$4.1
Owner's Contingency	$9.5	$8.1	$8.2	$8.7
Emission Reduction Credit	$2.2	$2.2	$2.2	$2.2
Financing Fees	$25.5	$22.7	$23.5	$24.3
Total Non-EPC Costs	**$156.1**	**$134.4**	**$136.9**	**$143.9**
Total Capital Costs	**$1,006.0**	**$896.1**	**$927.6**	**$960.7**
Overnight Capital Costs ($million)	**$1,006**	**$896**	**$928**	**$961**
Overnight Capital Costs ($/kW)	**$873**	**$772**	**$815**	**$853**
Installed Cost ($/kW)	**$951**	**$841**	**$887**	**$929**

O&M Cost Estimates

Combustion Turbine (CT)

O&M Costs	CONE Area 1 EMAAC *352 MW*	2 SWMAAC *355 MW*	3 Rest of RTO *321 MW*	4 WMAAC *344 MW*
Fixed O&M (2022$ million)				
LTSA	$0.3	$0.3	$0.3	$0.3
Labor	$1.1	$1.2	$0.8	$0.9
Maintenance and Minor Repairs	$0.5	$0.5	$0.5	$0.5
Administrative and General	$0.2	$0.2	$0.2	$0.2
Asset Management	$0.5	$0.6	$0.4	$0.4
Property Taxes	$0.3	$4.1	$1.8	$0.3
Insurance	$1.9	$1.8	$1.5	$1.8
Working Capital	$0.04	$0.03	$0.03	$0.03
Total Fixed O&M (2022$ million)	**$4.8**	**$8.7**	**$5.6**	**$4.4**
Levelized Fixed O&M (2022$/MW-yr)	**$13,600**	**$24,400**	**$17,300**	**$12,600**
Variable O&M (2022$/MWh)				
Consumables, Waste Disposal, Other VOM	1.10	1.10	0.95	1.10
Total Variable O&M (2022$/MWh)	**1.10**	**1.10**	**0.95**	**1.10**
Major Maintenance - Starts Based ($/factored start, per turbine)	**23,464**	**23,464**	**23,464**	**23,464**

Combined Cycle (CC)

O&M Costs	CONE Area 1 EMAAC *1152 MW*	2 SWMAAC *1160 MW*	3 Rest of RTO *1138 MW*	4 WMAAC *1126 MW*
Fixed O&M (2022$ million)				
LTSA	$0.5	$0.5	$0.5	$0.5
Labor	$5.8	$6.3	$4.4	$4.6
Maintenance and Minor Repairs	$5.9	$6.1	$5.4	$5.5
Administrative and General	$1.3	$1.4	$1.1	$1.2
Asset Management	$1.6	$1.7	$1.2	$1.3
Property Taxes	$2.0	$12.3	$7.1	$1.9
Insurance	$6.0	$5.4	$5.6	$5.8
Firm Gas Contract	$0.0	$9.7	$0.0	$0.0
Working Capital	$0.1	$0.1	$0.1	$0.1
Total Fixed O&M (2022$ million)	**$23.3**	**$43.5**	**$25.4**	**$20.9**
Levelized Fixed O&M (2022$/MW-yr)	**$20,200**	**$37,500**	**$22,300**	**$18,600**
Variable O&M (2022$/MWh)				
Major Maintenance - Hours Based	1.44	1.44	1.44	1.44
Consumables, Waste Disposal, Other VOM	0.67	0.67	0.67	0.67
Total Variable O&M (2022$/MWh)	**2.11**	**2.11**	**2.11**	**2.11**