Fifth Review of the Variable Resource Requirement Curve

REFERENCE TECHNOLOGY

PRESENTED BY

Samuel Newell

Michael Hagerty

Travis Carless

Kathleen Spees

PRESENTED TO

PJM Market Implementation Committee

OCTOBER 8, 2021

Brattle

Presentation Agenda

- VRR Objectives and Net CONE
- Stakeholder Feedback
- Reference Technology Screening Analysis
- Proposed Specifications
- Next Steps

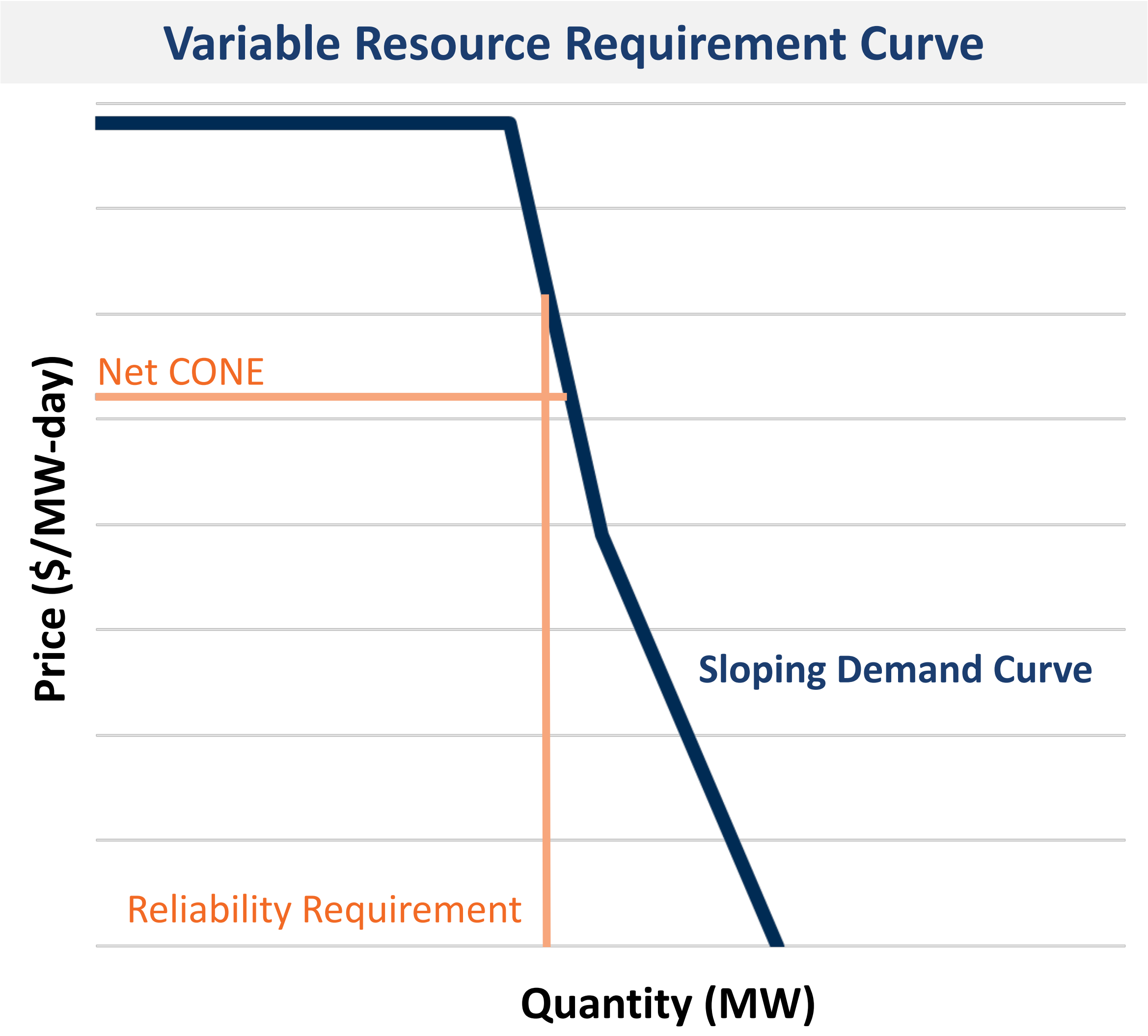
VRR Objectives and Net CONE

The Quadrennial Review evaluates the VRR curve and recommends changes

Recall that the primary objective of RPM and the VRR curve is to procure the required reserve margin

It does so by specifying “demand” as a P-Q schedule that procures the required reserve margin when the price is that at which new resources would be willing to enter and provide capacity (i.e., true Net CONE)

Achieving resource adequacy thus depends on estimating true Net CONE accurately



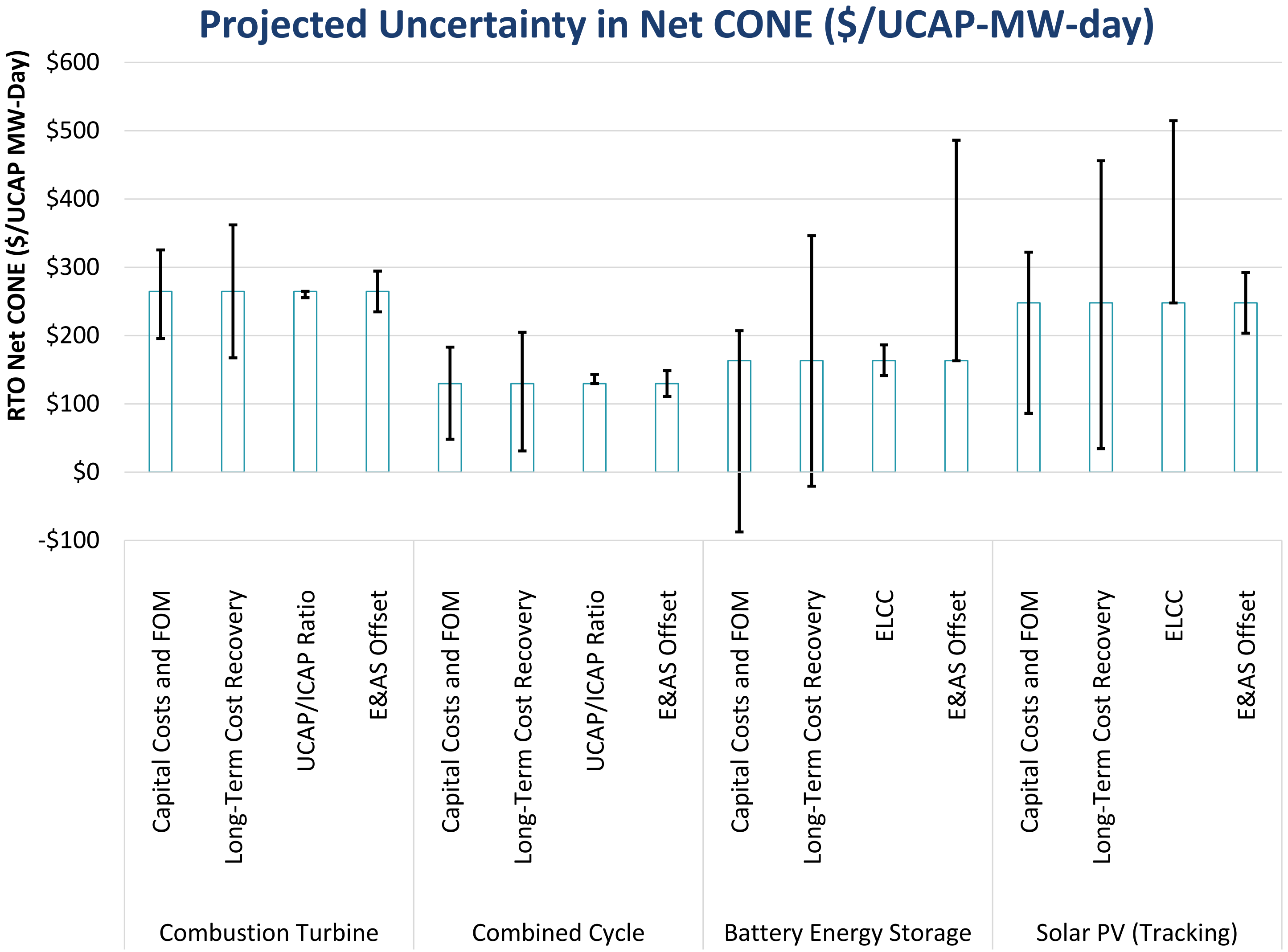
Context: Higher Uncertainty about True Net CONE

True Net CONE is highly uncertain in the current environment

- Changing technologies, market fundamentals, and policies affect all technologies' economics
- Even traditional capacity resources face new threats affecting their lifetime revenues and the price at which they would enter

We are examining and quantifying these uncertainties as a key part of the Quadrennial Review, both within and across technologies

These uncertainties have implications for VRR curve design…



Impact of Net CONE Uncertainty on VRR Curve

With greater uncertainty in true Net CONE and all else being equal, VRR curves must be steeper (and possibly with a higher price cap) to meet the target quantity

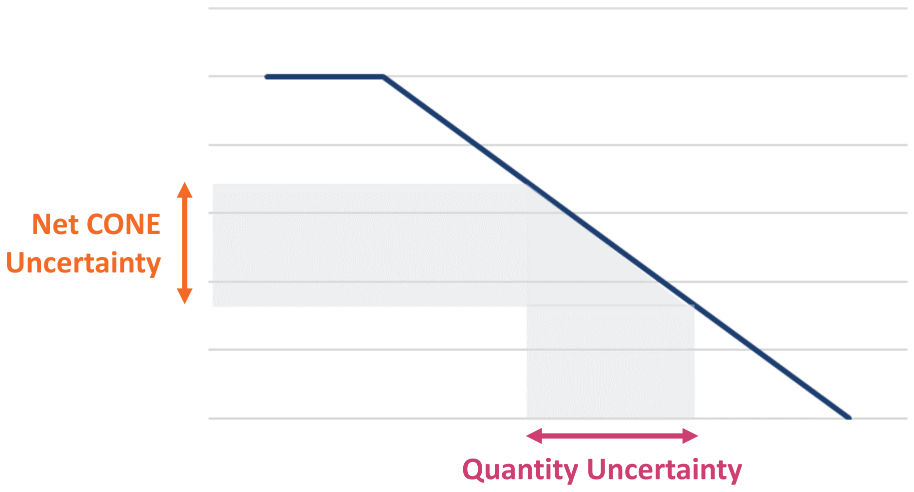
- With a flat curve, uncertainty in true Net CONE translates to a wide range of possible reserve margin outcomes
- With a steep curve, outcomes cluster around the target, and errors in estimating true Net CONE do not matter as much

Although other factors still argue for some flatness in the VRR curve

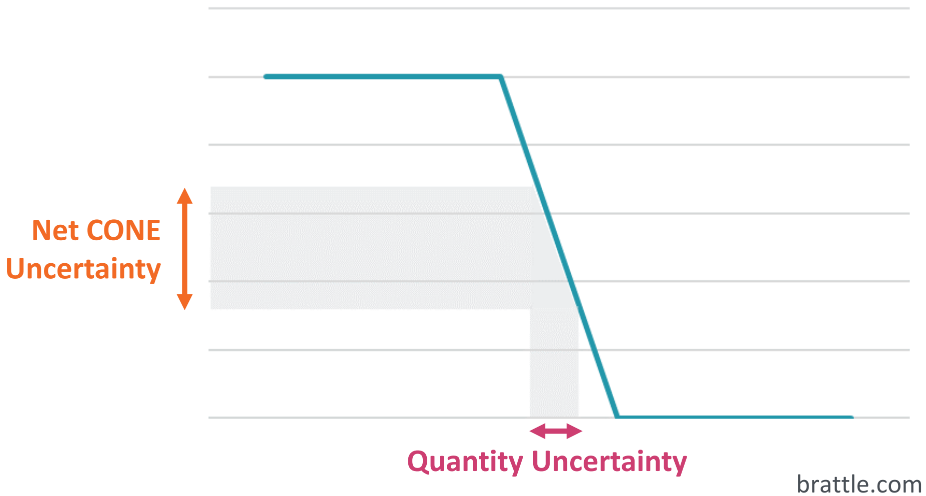
- Incremental value of capacity
- Mitigation of price volatility and market power
- Perhaps load forecast uncertainty

We are analyzing these considerations in our concurrent VRR curve analysis

Flatter Demand Curve



Steeper Demand Curve



Reference Technology Selection and Net CONE Estimation in that Context

If the VRR curve is steeper, one doesn't have to worry as much about all elements of estimating true Net CONE (choice of reference technology, its cost, CoC, revenue trajectory and implications for year-1 revenue needs, E&AS)

Other qualifiers:

- The choice of reference technology and Net CONE estimates are only to develop a VRR curve that aims to procure enough resource adequacy credits
- The choice of reference technology **does not dictate which resources will enter the market**
- The administrative Net CONE value **does not determine capacity prices**; long-run prices depend primarily on the supply curve

Still, as the VRR curve is likely to remain sloped and anchored on our estimate of Net CONE, we aim to estimate Net CONE as accurately as possible

Stakeholder Feedback

Response to Stakeholder Feedback

Stakeholder Feedback	Responses
Address how the proposed criteria differ from **PJM's past justification** for the selection of reference technology Evaluate the **time to market** for each resource and whether such a consideration should be included as a consideration for the selection of the reference technology	We reviewed PJM's justification for selecting the CT as the reference technology during the previous Quadrennial Review and considered how those factors align with the proposed criteria and whether they are applicable in the current market. See slide 9.
Consider whether it is **feasible to build gas-fired resources** in certain states in PJM	We discuss findings on slide 14.
Include at least one **non-fossil resource** in the study	We are assessing non-fossil resources based on the same criteria as fossil resources and will include a non-fossil resource as a possible reference technology in case some areas cannot build additional fossil-fired generation.
Consider the ability to **finance a new thermal asset** in the 2026-2030 timeframe given ESG concerns within the investment community, including a review of the recent transaction of PSEG's fossil assets	We are reviewing the recent PSEG transaction and other relevant market data in our determination of reasonable assumptions for the cost of capital as well as the asset life for developing the CONE values
Provide **justification** for CT and CC configurations and turbine models	We reviewed recent builds of the most frequently CTs and CCs by configuration and turbine model. See slides 19 – 21.

Response to Stakeholder Feedback

Stakeholder Feedback	Response
Evaluate **considerations other than just the least cost** resource	The proposed criteria are broader than cost, including feasibility to build, economic source of incremental capacity, and the accuracy of the Net CONE estimate. The criterion concerning whether a resource is an economic source of capacity considers whether its Net CONE is much higher than other candidates. As such, the reference technology will not be selected based just on the least cost resource.
Evaluate uncertainties associated with developing the reference technology in various settings (greenfield and brownfield) and the E&AS revenue offset	We evaluated the accuracy of the Net CONE estimates for each technology under consideration based on our review of a reasonable range of key input assumptions. See slides 17– 18.
Present context for selected **E&AS and net CONE sensitivities** and the likelihood of achieving the selected sensitivities	
Evaluate using **empirical Net CONE** as the price parameter, or as the basis for a collar on the administrative Net CONE	Similar to the 2018 Quadrennial Review, we will benchmark the estimated Net CONE values against recent clearing prices as a check on the reasonableness of the administratively-determined estimates
Set the **CC as the reference technology** and assume a 35 year (or longer) asset life	We will be further analyzing the CC as well as other technologies and whether the asset life should be adjusted.

Previous Considerations for Selecting Reference Technology

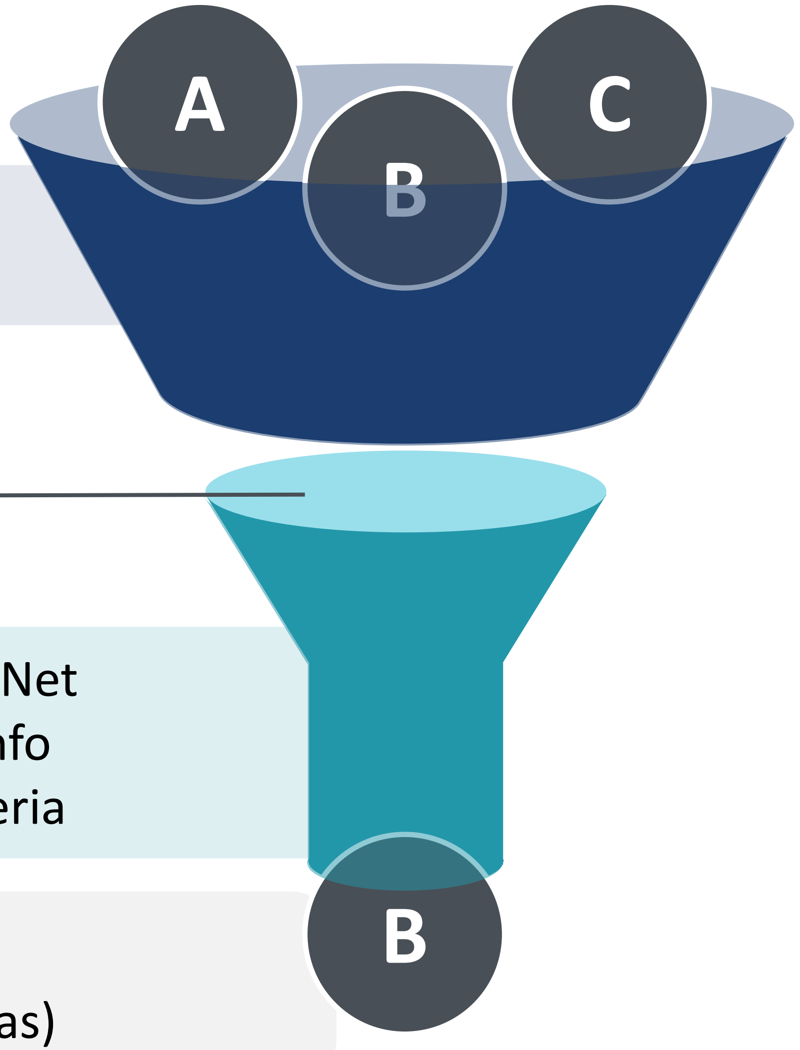
Based on stakeholder input, we reviewed PJM's justification for selecting the CT as the reference technology during the previous review and how they apply to the market conditions we are currently assessing

Proposed Criteria	PJM's Considerations in 2017-18 Quadrennial Review	Considerations in 2021-22 Quadrennial Review
Feasible to build for the delivery year	• CTs are cheapest and fastest technology that could be brought to the market	• Multiple technologies can currently be built within the forward period, including CCs, CTs, battery storage, and solar
Economic source of incremental capacity	• 1,600 MW of new CTs added thru RPM, including two merchant CTs since 2014	• Assessing more recent development in current review due to rapidly shifting resource mix, including whether technology has recently been built/proposed to be built and is projected to remain economic going forward based on Net CONE
	• CTs can meet essential need for capacity, even as resource mix evolves	• All technologies assessed on a UCAP basis to account for contributions to meeting the capacity need (ELCC uncertainty considered in analysis of Net CONE accuracy)
Costs, net E&AS revenues, and RA contribution per MW can be assessed accurately	• CC more prone to misestimation because of larger E&AS offset, which is uncertain	• Multiple sources of Net CONE estimation error being assessed (see slides 17 - 18) • With a forward-looking E&AS approach, CC E&AS estimation error smaller than CT
	• CC-based VRR Curve "fails reliability standards if the CC Net CONE estimate is understated."	• Other approaches to mitigate reliability risks of Net CONE uncertainty, such as an up/right-shift of curve or a steeper curve • Use of "empirical Net CONE" as benchmark can increase confidence in demand curve to procure enough capacity

Reference Technology Screening Analysis

Process for Selecting

Screening Analysis: Apply criteria to all candidate technologies



SHORT LIST PROPOSED TECHNOLOGIES

Detailed Analysis: Conduct detailed analysis of Net CONE for proposed technologies; incorporate info from 2023/24 BRA; then re-apply selection criteria

Recommend Reference Technology
(or technologies if appropriate for different areas)

Criteria for Selecting Reference Technology

Feasible to build for the delivery year, given local laws/regulations and technical factors

Economic source of incremental capacity

- Demonstrated by recent merchant entry, not in anomalous situations
- Not having a Net CONE much higher than other candidates
- Likely to remain economic through the end of the review period (2029/30)

Costs, net E&AS revenues, and RA contribution per MW can be assessed accurately

- Evidence of capital and operating costs exists from commercial experience
- Costs are uniform when scaled, rather than increasing steeply as best sites are exhausted
- Has stable UCAP/ICAP ratio or ELCC, rather than changing steeply with penetration or fleet composition
- Has high UCAP/ICAP ratio or ELCC, else uncertainties are amplified per kW UCAP
- Not largely dependent on revenues that are difficult to forecast (AS, energy volatility, RECs)

Four Technologies Passed Initial Screening Analysis

Based on our initial review of potential reference technologies presented in August, we continued to assess four technologies against the reference technology criteria:

- Gas Combustion Turbine (CT)
- Gas Combined Cycle (CC)
- 4-Hour Battery Storage
- Tracking Solar PV

We screened out several technologies that do not meet the criteria:

- Onshore Wind: Net CONE much higher than other technologies based on 2023/24 MOPR
- Energy Efficiency/Demand Response: Inability to accurately estimate Net CONE
- Uprates/Conversions: Inability to accurately estimate Net CONE
- Emerging Technologies: Not feasible to build by Delivery Year

Screened out solar PV plus storage technology as its inclusion would not provide additional information for developing Net CONE for the VRR curve as we are considering each technology separately

Updated Screening Analysis Results

- Gas CC and CT best meet the Reference Technology criteria…wherever they are feasible to build
- Battery Storage and Tracking Solar PV (although likely to be built in PJM going forward) do not meet the criteria as well, due to the lack of merchant entry and lower Net CONE estimation accuracy, but may still be relevant in case gas-fired resources cannot be developed in some areas

Updated Reference Technology Screening Analysis

Technology	Feasible to Build for Delivery Year	Economic Source of Capacity	Accuracy of Net CONE Estimates
Gas CC	**Yes** (seeking additional input on whether unable to build in certain LDAs)	**Yes** (significant recent entry; lowest 2023/24 Net CONE)	**Highest**
Gas CT	**Yes** (seeking additional input on whether unable to build in certain LDAs)	**Unclear** (few recently built; highest 2023/24 Net CONE among candidates)	**High** (greater E&AS uncertainty than Gas CC)
4-Hour Battery Storage	**Yes**	**Unclear** (no cleared capacity to date; 2023/24 Net CONE second lowest)	**Low** (uncertain future AS revenues; falling costs)
Tracking Solar PV	**Yes**	**Unclear** (limited evidence of entry without RECs; 2023/24 Net CONE similar to CT)	**Low** (REC-dependence; falling costs; highly uncertain ELCC)

Proposal for Completing our Analysis of Reference Technologies

- Develop bottom-up Gross CONE estimates for Gas CT and Gas CC
- Continue to investigate whether any areas within PJM might prohibit entry of new gas-fired generation, such that their estimated costs provide an inaccurate measure of the marginal cost of capacity and choosing them as a reference technology underlying the VRR curve would threaten reliability
- Develop high-level Net CONE estimate for 4-Hour Battery Storage that will sharpen the outlook of future merchant entry and Net CONE estimation accuracy in case the gas-fired resources are infeasible to be built

Our analysis aims to provide the best information for PJM to decide how to set its VRR curves to meet the objectives of its capacity auctions; neither our recommendation nor PJM's ultimate selection dictates which resources will be built in PJM (nor does it even determine the long-run price, which will depend on supply offers)

Feasibility to Build for the Delivery Year

Criterion: Feasible to build for the delivery year, given local laws/regulations & other factors

We requested stakeholder input on whether Gas CCs and CTs are feasible in all LDAs in PJM

- We did not receive feedback identifying state or local laws/regulation that ban building new gas-fired plants
- Gas plants built in states with stringent GHG requirements as recently as 2018 (Sewaren CC in NJ; Keys CC and Wildcat CC in MD), but currently no new plants under construction

We are aware that permitting gas-fired plants may be sufficiently challenging in states with stringent decarbonization goals that developers may determine it is infeasible to do so

- PJM is continuing to seek input from states to better understand whether gas-fired resources could receive the necessary permits to be built across the PJM market
- We would also accept additional input demonstrating cases in which regulators denied permits or developers pulled their applications for a permit due to the challenges

We are not proposing to screen out Gas CCs and CTs for being infeasible to build but will include a non-fossil resource as a possible reference technology in case some areas cannot build new gas plants

Economic Resources in PJM Market

Criterion: Economic source of incremental capacity

2023/24 BRA Net CONE for Battery Storage and Solar PV (Tracking) are in the range of the CT & CC

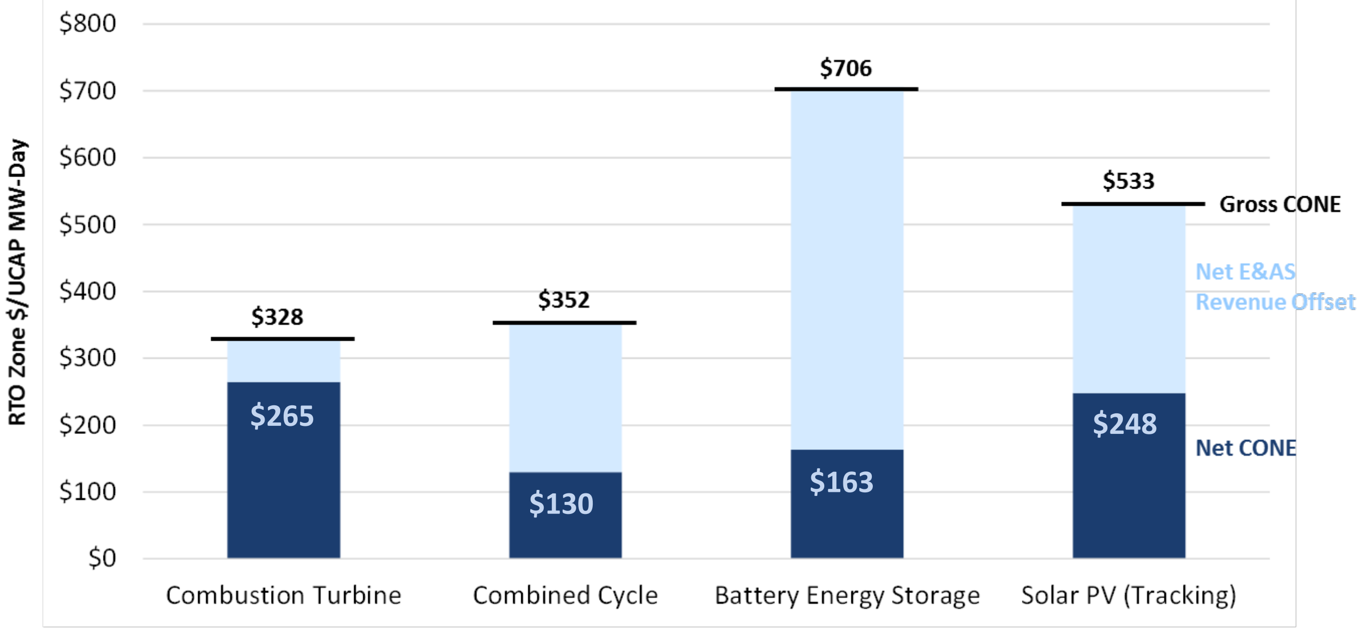
- CT Net CONE remains 2x higher than CC
- Battery Storage E&AS much higher than other technologies due to high historical AS (RegD) prices
- Solar PV (Tracking) does not include REC revenues

Several changes could shift Battery Storage and Solar PV Net CONE values through 2029/30 BRA

- Battery Storage & Solar cost declines
- High Battery Storage E&AS revenues unlikely to persist
- Federal tax credits could reduce Battery Storage and Solar PV costs

Gas CC is only technology with recent demonstrated evidence of merchant entry in PJM

2023/24 BRA MOPR Values for RTO ($/UCAP-MW-day)



Sources and Notes: 2023-2024 BRA Default MOPR Floor Offer Prices for New Entry Capacity Resources with State Subsidy, $/MW-Day (UCAP Basis), PJM Interconnection LLC, August 2, 2021

Accurately Assess Net CONE

Criterion: Costs, net E&AS revenues, and RA contribution per MW can be assessed accurately

We analyzed the accuracy of estimating Net CONE for each technology by adjusting several key assumptions that have a significant impact on the results

Net CONE Uncertainty Analysis Assumptions

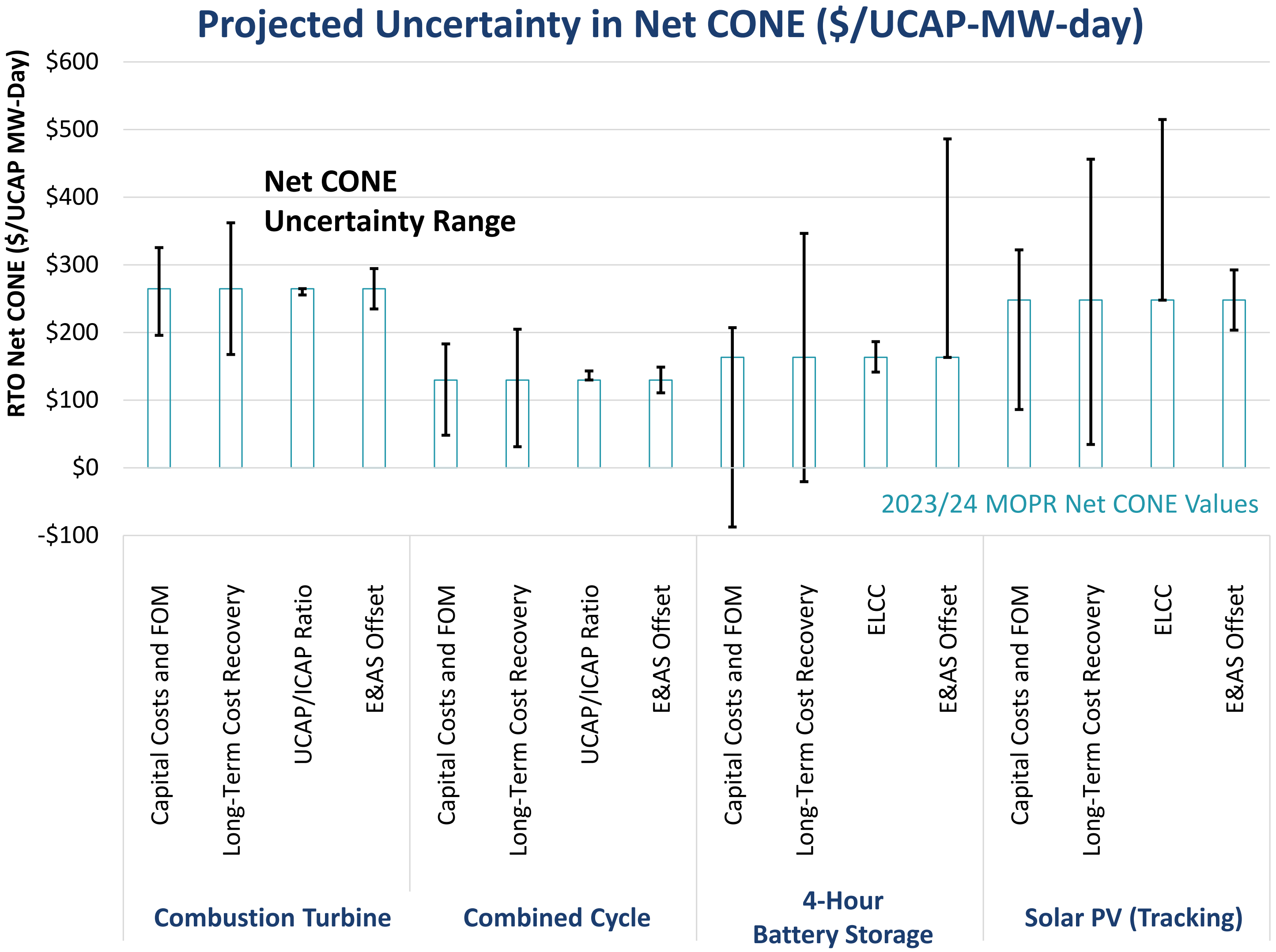
Assumption	Gas CC	Gas CT	4-Hour Battery Storage	Solar PV (Tracking)
Capital and Fixed O&M Costs	+/- 20% of 2018 CONE Study costs		(1) Applied cost decline from NREL ATB Moderate case to 2023/24 costs (2) Analyzed range based on NREL ATB Conservative and Aggressive cases	
Long-Term Cost Recovery	*Low Case*: Longer economic life of 35 years (20 years for Battery Storage) and back-loaded cost recovery ("level-real", rising at 2.2%/year); *High Case*: Shorter economic life of 15 years (10 years for Battery Storage) and front-loaded cost recovery (declining at 2.2%/year)			
ICAP/UCAP	Historical EFORd range	Historical EFORd range	69% – 91% based on projected ELCC range through 2030	26% – 54% based on projected ELCC range through 2030
E&AS Offset	Heat rate uncertainty (+/- 200 Btu/kWh)	(1) Heat rate uncertainty (2) fuel cost uncertainty (+/- 10%) (3) price volatility (based on 2018-20)	AS revenue uncertainty (lower RegD revenues decrease E&AS from $420/MW-day to $235/MW-day)	Capacity factor uncertainty (+/- 15%)

Notes: Base case uses the 2026 ELCC value of 70% for battery storage and 44% for solar PV (tracking)

Battery Storage & Solar PV Net CONE More Uncertain than Gas CT/CC

Net CONE estimation error for Battery Storage and Tracking Solar PV are significantly greater than Gas CC and CT

- Greater uncertainty for Battery Storage and Solar PV reflects the quickly evolving market prices, higher Gross CONE value, and lower UCAP/ICAP ratio
- Battery Storage Net CONE will be higher if RegD prices fall with increasing storage capacity installed; lower E&AS may be offset by declining capital costs
- Declining Solar PV ELCC is highly dependent on amount of solar entry through 2029/30, which reduces accuracy of developing Net CONE estimates for future BRAs



Proposed Specifications

Proposed Gas CC and CT Specifications

Proposed Gas CT and CC Detailed Specifications

Characteristic	Combustion Turbine	Combined Cycle
Turbine Model	**GE 7FA.05** or **7HA.02**	GE 7HA.02
Configuration	TBD	**1x1**
Power Augmentation	Evaporative Cooling, no inlet chillers	Evaporative Cooling, no inlet chillers
CC Supplemental Firing	---	TBD
CC Cooling System	---	Cooling Towers
Fuel Supply	Dual Fuel	Dual Fuel, except SWMAAC (firm gas)
Environmental Controls	SCR and CO Catalyst	SCR and CO Catalyst
Net ISO Rating	240 – 380 MW	500 – 700 MW
Net ISO Heat Rate (HHV)	8,900 – 10,000 Btu/kWh	6,000 – 6,300 Btu/kWh

Input Requested:
- Is the smaller F-class or larger H-class turbine more attractive in the current market?
- Are there other specifications that should be modified?

PROPOSED SPECIFICATIONS

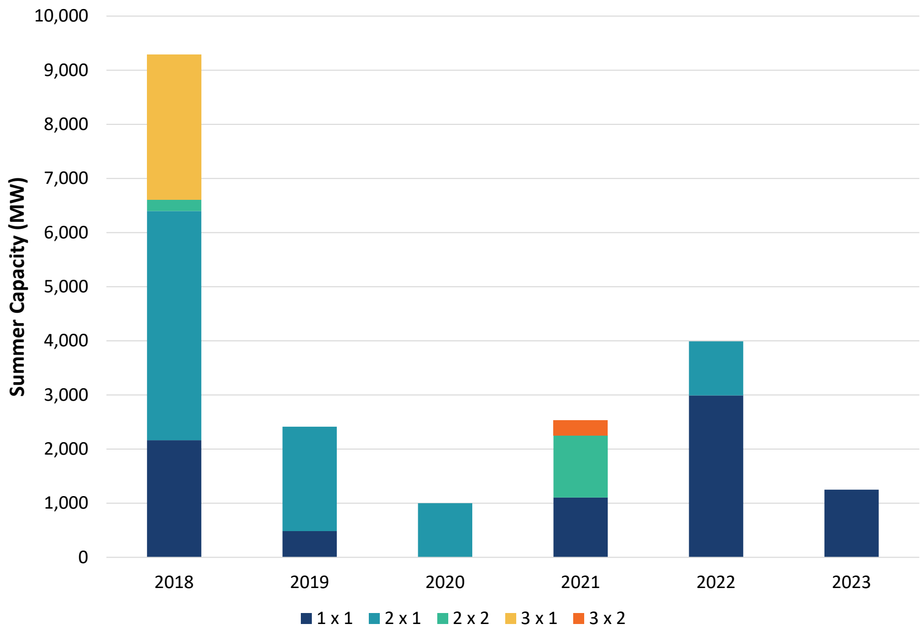
CC Capacity Configuration Since 2018 in PJM

New Gas CCs are shifting away from larger 2x1 units (>700 MW) specified in the 2018 CONE Study to smaller and more flexible 1x1 units (<700 MW)

- Development is equally split between the 2x1 and the 1x1 units since 2018
- But majority of new units that completed construction in 2021 or are currently under construction are 1x1 units

The GE 7HA continues to be the most frequently installed turbine for CCs in PJM and nationwide

Gas CC Configuration by Year



CC Turbine Models Built or Under Construction since 2018

Turbine Model	PJM Installed Capacity *(MW)*	US Installed Capacity *(MW)*
General Electric 7HA	7,211	12,203
Mitsubishi M501J	3,645	3,645
Siemens SGT6-8000H	1,856	1,856
Mitsubishi M501G	1,444	4,015
General Electric 7F	828	4,130
Siemens SGT6-5000F	755	1,426
General Electric A650	717	717
Siemens SGT6-500	703	703
General Electric 6B.03	276	276
General Electric GRT	210	210
General Electric MS7001	0	1,000
Siemens SGT6-2000	0	232
Siemens SGT6-800	0	224
Solar Turbines Titan 130	0	29

Sources and Notes: Ventyx Energy Velocity Suite, Accessed August 2021. Includes operational or units under construction (operating, under construction, site prep, converted, standby, testing, steam only, restarted)

Gas-Fired Turbine Models

Limited new frame-type CTs built in PJM to support a specific turbine model

- The 7HA turbine specified in the 2018 CONE Study (and in other CONE studies) has been installed in New England (Canal 3) and recently proposed to be built in NY (Astoria)
- F-class turbines are the only new frame-type CTs built in PJM since 2011 and are the most common frame turbine in other parts of the U.S.
- Aeroderivative turbines (e.g., GE LM6000) have been added in PJM and other regions but consistently have higher Net CONE than frame turbines; tend to be built to take advantage of local market conditions

CT Turbine Models Built or Under Construction since 2011

Turbine Model	Turbine Class	PJM		US	
		(count)	*(MW)*	*(count)*	*(MW)*
General Electric LM6000	Aeroderivative	7	331	69	3,101
General Electric 7FA	Frame	2	330	14	2,462
Pratt & Whitney FT4000	Aeroderivative	2	120	2	120
Rolls Royce Corp Trent 60	Aeroderivative	2	119	2	119
Pratt & Whitney FT8	Aeroderivative	1	57	4	189
Siemens Unknown	N.A.	1	28	2	545
General Electric LMS100	Aeroderivative	0	0	47	4,664
Siemens SGT6-5000F	Frame	0	0	10	1,892
Rolls Royce Corp Unknown	N.A.	0	0	10	599
General Electric 7EA	Small Frame	0	0	7	417
Siemens AG SGT	Frame	0	0	7	401
General Electric 7HA	Frame	0	0	1	330
All Other Turbine Models		0	0	14	1,297
Total		**15**	**985**	**189**	**16,136**

Sources: ABB Inc.'s Energy Velocity Suite, Accessed August 2021 and S&P Global Market Intelligence, Accessed September 2021.

Next Steps

Schedule for Reference Technology Selection

Review approach to selecting the reference technology; seeking input on the reference technology criteria and potential resource types

Present proposed Reference Technologies based on criteria; request feedback on the Ref Tech and specifications

Present draft CONE results for each proposed Ref Tech; request feedback on CONE inputs

Present updated CONE and recommended Ref Tech based on criteria; request feedback on CONE and Recommended Ref Tech

2021

August 6th

Overview and VRR Curve Presentation

August 17th

CONE and E&AS Offset Presentation

October

Reference Technology Presentation

December

Draft Results Presentation

2022

February

Near-Final Results Presentation

May

VRR Curve and CONE Reports

October

Filing date for VRR parameters (2026/27 thru 2029/30)

Incorporate feedback into screening analysis for proposed Reference Technologie(s) and develop detailed specs

Develop bottom-up cost estimates, financial assumptions, and levelization for calculating CONE

Incorporate stakeholder input into CONE calculations

Incorporate stakeholder input into CONE and recommended reference technology

Stakeholder Input to Inform the Quadrennial Review

Provide input on reference technology screening analysis and specification by October 15 to Melissa.Pilong@pjm.com or Gary.Helm@pjm.com

2021				2022		
August 6	**August 17**	**October 8**	**December**	**February**	**May**	**October**
Overview and VRR Curve Presentation	CONE and E&AS Offset Presentation	Reference Technology Presentation	Draft Results Presentation	Near-Final Results Presentation	VRR Curve and CONE Reports	Filing date for VRR parameters (2026/27 thru 2029/30)

Milestones for Stakeholder Input

Oct 15

Contact Information

Sam Newell

PRINCIPAL | BOSTON

Sam.Newell@brattle.com

+1 (781) 801-2652

Kathleen Spees

PRINCIPAL | WASHINGTON DC

Kathleen.Spees@brattle.com

+1 (202) 419-3390

Michael Hagerty

SR. ASSOCIATE | WASHINGTON DC

Michael.Hagerty@brattle.com

+1 (202) 419-3323

Travis Carless

ASSOCIATE | BOSTON

Travis.Carless@brattle.com

+1 (617) 234-5268