Reserve Nesting, Unnesting and Price Formation

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April 13, 2026

Introduction

- PJM is providing a few simple numerical examples to be responsive to stakeholder questions about the implications of reserve nesting/unnesting on energy price formation.

- These examples are not intended to be indicative of actual market clearing outcomes but simply to build a fundamental understanding of outcomes of the co-optimization.

- A write-up describing these examples with additional written narrative has been posted to the RCSTF page as a standalone document titled *Reserve Nesting, Unnesting and Price Formation Examples*.

- A detailed mathematical description of the optimization and incentive compatibility has also been provided in *RCSTF Supplement: Incentive Compatibility via Interactions between Reserve and Energy Prices.*

Example Set-Up

- Assume two generators, both are online and capable of providing reserves
- There is no congestion or losses on the system, and therefore, a single system marginal energy price
- There are three reserve services, all in the up direction:
  - Synchronized Reserves (SR)
  - 10-Min Ramp/Uncertainty Reserves (10-Min RUR)
  - 30-Min Ramp/Uncertainty Reserves (30-Min RUR)
- These examples do not include reserve offers, and so the reserve market clearing prices are driven by lost opportunity cost and reserve penalty factors
- Across these examples, everything aside from the load is held constant.

Nested Reserve Constraints

$$SR >= SR\ Requirement$$

$$SR + 10Min\ RUR >= 10Min\ RUR\ Requirement^{*}$$

$$SR + 10Min\ RUR + 30Min\ RUR >= 30Min\ RUR\ Requirement^{*}$$

Unnested Reserve Constraints

$$SR >= SR\ Requirement$$

$$10Min\ RUR >= 10Min\ RUR\ Requirement$$

$$30Min\ RUR >= 30Min\ RUR\ Requirement$$

**Requirements in the nested reserve design are inclusive of the lower value service requirement quantities.*

Generator and Reserve Parameters

Generator	Economic Minimum	Economic Maximum	Ramp Rate	Energy Offer
G1	20 MW	70 MW	2 MW/min	$5
G2	20 MW	70 MW	1 MW/min	$10

Service	Nested Requirement	Unnested Requirement	Penalty Factor
SR	9 MW	9 MW	$40
10-Min RUR	18 MW	9 MW	$20
30-Min RUR	37 MW	19 MW	$20

These quantities are held constant through all following example scenarios. The only input that changes and drives the different results is the quantity of load.

Scenario 1: Sufficient Unloaded Headroom

- **Load:** 80 MW
- There is sufficient free, unloaded headroom to meet all reserve requirements.
- All reserve services clear at $0/MWh.

Generator assignments:

	Energy	SR	10-Min RUR	30-Min RUR
G1	60 MW	9 MW	0 MW	0 MW
G2	20 MW	0 MW	9 MW	19 MW

Market clearing prices:

	Nested	Unnested
Energy	$5/MWh	$5/MWh
SR	$0/MWh	$0/MWh
10-Min RUR	$0/MWh	$0/MWh
30-Min RUR	$0/MWh	$0/MWh

Scenario 2: Generator 1 Incurs Lost Opportunity Cost

- **Load:** 90 MW
- G1's economic operating point would be at its EcoMax of 70 MW, but it is backed down to provide 8 MW of reserves, incurring a $5/MWh lost opportunity cost.
- Because the same reserve capability is eligible to provide both SR and 10-Min RUR and there are no reserve offers, there is price parity between these two reserve market clearing prices.

Generator assignments:

	Energy	SR	10-Min RUR	30-Min RUR
G1	62 MW	0 MW	8 MW	0 MW
G2	28 MW	9 MW	1 MW	19 MW

Market clearing prices:

	Nested	Unnested
Energy	$10/MWh	$10/MWh
SR	$5/MWh	$5/MWh
10-Min RUR	$5/MWh	$5/MWh
30-Min RUR	$0/MWh	$0/MWh

Scenario 3: One RUR Service Clears at the Penalty Factor

- **Load:** 110 MW
- SR procurement is prioritized in both cases, but because the reserve penalty factors for the two reserve services are the same at $20/MWh, the dispatch outcomes are different between the nested and the unnested cases.
- In the nested case, the nested hierarchy causes the shortage to occur in the 30-Min RUR service while in the unnested case, the shortage can occur in the 10-Min RUR service, which reduces the overall production cost as more of the load can be served by lower cost energy.
- In the nested case, the optimal solution has a 7 MW 30-Min RUR shortage, while in the unnested case, the 7 MW shortage occurs in the 10-Min RUR service

Generator assignments for Nested Reserves:

	Energy	SR	10-Min RUR	30-Min RUR
G1	62 MW	0 MW	8 MW	0 MW
G2	48 MW	9 MW	1 MW	12 MW

Generator assignments for Unnested Reserves:

	Energy	SR	10-Min RUR	30-Min RUR
G1	69 MW	0 MW	1 MW	0 MW
G2	41 MW	9 MW	1 MW	19 MW

Market clearing prices:

	Nested	Unnested
Energy	$30/MWh	$25/MWh
SR	$25/MWh	$20/MWh
10-Min RUR	$25/MWh	$20/MWh
30-Min RUR	$20/MWh	$15/MWh

Scenario 3: Explanation of Results in Nested Case

- The 30-Min RUR clearing price is set based on the $20/MWh reserve penalty factor.
- The next MW of 10-Min RUR would come from backing down G1 at a cost of $5/MWh. The 10-Min RUR clearing price is the sum of this cost plus the cost of going short 30-Min RUR, leading to a total market clearing price of $25/MWh.
- The SR service is not binding, and so the SR market clearing price is also $25/MWh.
- The system marginal energy price is based on the cost of clearing 1 MW additional on G2. This would come at the cost of 1 MW of additional 30-Min RUR shortage at $20/MWh plus the cost of energy, which is $10/MWh based on G2's energy offer. This leads to an energy price of $30/MWh.

Generator assignments for Nested Reserves:

	Energy	SR	10-Min RUR	30-Min RUR
G1	62 MW	0 MW	8 MW	0 MW
G2	48 MW	9 MW	1 MW	12 MW

Market clearing prices:

	Nested	Unnested
Energy	$30/MWh	$25/MWh
SR	$25/MWh	$20/MWh
10-Min RUR	$25/MWh	$20/MWh
30-Min RUR	$20/MWh	$15/MWh

Scenario 3: Explanation of Results in Unnested Case

- The 10-Min RUR clearing price is set based on the $20/MWh reserve penalty factor.
- The next MW of 30-Min RUR would come from backing down G2, requiring G1 to ramp up 1 MW and causing an additional 1 MW of 10-Min RUR shortage. The cost of the 10-Min RUR shortage is $20/MWh, but since the cost of energy from G1 is $5/MWh less than G2, the total cost is $15/MWh.
- The next MW of SR comes from incurring 1 MW of additional 10-Min RUR shortage at a cost of $20/MWh.
- The system marginal energy price is based on the cost of clearing 1 MW additional on G1, leading to 1 MW of additional 10-Min RUR shortage at $20/MWh plus the cost of energy, which is $5/MWh based on G1's energy offer. This leads to an energy price of $25/MWh.

Generator assignments for Unnested Reserves:

	Energy	SR	10-Min RUR	30-Min RUR
G1	69 MW	0 MW	1 MW	0 MW
G2	41 MW	9 MW	1 MW	10 MW

Market clearing prices:

	Nested	Unnested
Energy	$30/MWh	$25/MWh
SR	$25/MWh	$20/MWh
10-Min RUR	$25/MWh	$20/MWh
30-Min RUR	$20/MWh	$15/MWh

Scenario 4: Both RUR Services Clear at the Penalty Factor

- **Load:** 130 MW
- SR procurement is prioritized in the nested case through the reserve hierarchy and in the unnested case through the penalty factor hierarchy.
- While the dispatch outcomes are the same, there are differences in pricing outcomes between the nested and unnested cases.
- In both cases, G2 is indifferent to providing reserves and energy because of the relationship between the reserve and energy clearing prices.

Generator assignments:

	Energy	SR	10-Min RUR	30-Min RUR
G1	70 MW	0 MW	0 MW	0 MW
G2	60 MW	9 MW	1 MW	0 MW

Market clearing prices:

	Nested	Unnested
Energy	$50/MWh	$30/MWh
SR	$40/MWh	$20/MWh
10-Min RUR	$40/MWh	$20/MWh
30-Min RUR	$20/MWh	$20/MWh

Scenario 4: Explanation of Pricing Differences

- Clearing an incremental MW of energy would come from G2 at a cost of $10/MWh and lead to 1 MW of additional SR shortage.
- Clearing an incremental MW of SR would lead to 1 MW of additional 10-Min RUR shortage.
- In the nested case, the cost of SR shortage is $40/MWh because the penalty cost of 1 MW of additional 10-Min RUR shortage is the sum of the 10-Min RUR and 30-Min RUR penalty prices. This results in a SR clearing price of $40/MWh and an energy price of $50/MWh.
- In the unnested case, the cost of SR shortage is $20/MWh because the penalty cost of 1 MW of additional 10-Min RUR shortage is the 10-Min RUR penalty price. This results in a SR clearing price of $20/MWh and an energy price of $30/MWh.

Generator assignments:

	Energy	SR	10-Min RUR	30-Min RUR
G1	70 MW	0 MW	0 MW	0 MW
G2	60 MW	9 MW	1 MW	0 MW

Market clearing prices:

	Nested	Unnested
Energy	$50/MWh	$30/MWh
SR	$40/MWh	$20/MWh
10-Min RUR	$40/MWh	$20/MWh
30-Min RUR	$20/MWh	$20/MWh

Scenario 5: All Reserves Clear at the Penalty Factor

- **Load:** 135 MW
- SR procurement is prioritized in the nested case through the reserve hierarchy and in the unnested case through the penalty factor hierarchy.
- All reserve services are in shortage, and there are again differences in pricing outcomes between the nested and unnested cases.
- In both cases, G2 is indifferent to providing reserves and energy because of the relationship between the reserve and energy clearing prices.

Generator assignments:

	Energy	SR	10-Min RUR	30-Min RUR
G1	70 MW	0 MW	0 MW	0 MW
G2	65 MW	5 MW	0 MW	0 MW

Market clearing prices:

	Nested	Unnested
Energy	$90/MWh	$50/MWh
SR	$80/MWh	$40/MWh
10-Min RUR	$40/MWh	$20/MWh
30-Min RUR	$20/MWh	$20/MWh

Scenario 5: Explanation of Pricing Differences

- Clearing an incremental MW of energy would come from G2 at a cost of $10/MWh and lead to 1 MW of additional SR shortage.
- Clearing an incremental MW of SR would be at the SR penalty factor.
- In the nested case, the cost of SR shortage is $80/MWh because it results in 1 MW of shortage at each of the three reserve penalty factors. This results in a SR clearing price of $80/MWh and an energy price of $90/MWh.
- In the unnested case, the cost of SR shortage is $40/MWh because the penalty cost of 1 MW of additional SR shortage is the SR penalty price. This results in a SR clearing price of $40/MWh and an energy price of $50/MWh.

Generator assignments:

	Energy	SR	10-Min RUR	30-Min RUR
G1	70 MW	0 MW	0 MW	0 MW
G2	65 MW	5 MW	0 MW	0 MW

Market clearing prices:

	Nested	Unnested
Energy	$90/MWh	$50/MWh
SR	$80/MWh	$40/MWh
10-Min RUR	$40/MWh	$20/MWh
30-Min RUR	$20/MWh	$20/MWh

Observations

- Resources are indifferent to providing reserves and energy in both designs because of the co-optimization between energy and reserves. The lost opportunity cost incurred by resources providing reserves rather than energy appears in reserve market clearing prices.

- If the same resources are eligible to provide multiple reserve services, these resources could incur lost opportunity cost for providing one service rather than another. If applicable, this lost opportunity cost will appear in reserve market clearing prices through the co-optimization.

- At the point at which all reserve services are clearing at their respective penalty factors, the hierarchy in the reserve penalty factors will dictate how reserves are cleared. If there are insufficient reserves to meet any of the requirements, all the available reserves will clear for the reserve service with the highest penalty factor.

Practical Design Note: Reserve Offers

- These examples assume that resources would be indifferent to providing each reserve service.
- In practice, this is unlikely to hold true because of the increased performance obligations and consequences for non-performance imposed on resources with a Synchronized Reserve assignment during a Synchronized Reserve Event.
- PJM anticipates that this will lead resources to submit higher offers for providing Synchronized Reserves, which is supported by the proposed offer rules.

Practical Design Note: Reserve Penalty Factors

- The same penalty factors have been used for both the nested and unnested designs to simplify the examples and allow for an apples-to-apples comparison that illustrates the implications of the nesting/unnesting of the reserves on price formation.

- PJM has proposed increasing the SR penalty price in its package both to reflect the value of this service and to recognize the unnesting of the reserves.

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Acronyms

Acronym	Term & Definition
SR	**Synchronized Reserves** are reserves provided by resources that are synchronized to the grid and can respond within 10 minutes.
ORDC	An **Operating Reserve Demand Curve** is an administrative pricing curve that represents the markets willingness to pay for reserves at different reserve levels.
RUR	**Ramping/Uncertainty Reserves** are reserves that would be procured to manage forecasted ramp and uncertainty operational flexibility needs.
MW	A **Megawatt** is a unit of power equaling one million watts (1 MW = 1,000,000 watts) or one thousand kilowatts (1 MW = 1,000 KW).


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