Narrative on Energy and Reserve Co-Optimization and Price Capping Impacts of Reserve Shortages

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Contents

I. Revision History

4.4.2022 – Original Version

4.15.2022 – Updated to include Example 13

II. Assumptions for Examples

- Only RTO level reserve requirements are considered for simplicity. Sub-zone reserve requirements are not considered.
- Each example addresses the load requirement as the first priority followed by meeting the reserve requirement with remaining resource capability (as available).
- The Energy dispatch time horizon is 5 minutes. This means that units can only be dispatched within the range of (initial MW + [5*ramp rate]) and (Initial MW – [5*ramp rate]) in current dispatch interval bounded by other unit related parameters such as EcoMin and EcoMax.
- As the examples are for a dispatch problem, the commitment status of units (i.e. whether on or off) is fixed and provided as input to the clearing engine.
- A single step ORDC with a Penalty cost of $850 is considered for each reserve product.
- Ramp rates for all units are 1 MW/Min.
    - Online unit's synchronized reserve capability is [10*ramp rate] = 10 MW.
    - Online unit's secondary reserve capability is [30*ramp rate – 10*ramp rate] = [30*1-10*1] = 20 MW.
- Unit 3 is offline and has start-up plus notification time of 10 minutes. This means the unit, if called on, can achieve EcoMin in 10 min. (Please note that only Example 1 and 2 have considered Unit 3).
    - Unit 3's non-synchronized reserve capability = EcoMin + ([10 - start-up plus notification]*ramp rate]) = 10 + ([10-10]*1) = 10 MW.
    - Unit 3's offline secondary reserve capability = EcoMin + ([30 - start-up plus notification]*ramp rate]) – non-synchronized reserve capability = 10 + ([30-10]*1) – 10 = 20 MW.
- For purposes of these examples, the optimization solution is the same for both the Dispatch Run and Pricing Run because the committed resources (Unit 1 and Unit 2) are assumed to not be Fast-Start capable

III. Example 1 – Shortage in SR with no effect on Energy Price

The various requirements considered in this example are below:

Load (MW)	205
Synchronized Reserve (SR) Requirement (MW)	16
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	25

Unit parameters and offers are below:

	Unit 1	Unit 2	Unit 3
EcoMin (MW)	0	0	10
EcoMax (MW)	200	100	50
Energy Offer ($/MWh)	20	50	150
Initial MW (MW value at which the unit is currently operating)	200	10	0
Ramp Rate (MW/Min)	1	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW
Unit 3	0 MW

Energy only solution:

In order to meet the load requirement of 205 MW, the least cost resource, unit 1, provides the maximum MW toward meeting the requirement with respect to available capability. Based on the available Energy Dispatchable Range, unit 1 will provide 200 MW of energy. The next most economic resource is unit 2 which will meet the remaining MW of load to be served (205 – 200) = 5 MW, which is within the Energy Dispatchable Range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	200
Unit 2	5-15 MW	5
Unit 3	0 MW	0

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet 16 MW of SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted toward fulfilling the SR requirement. There is no additional unloaded online reserve capability available because Unit 1 is being dispatched to its EcoMax value as a result of the Energy only solution and Unit 3 is offline.

To procure the needed SR reserves, the energy output of Unit 1 can be reduced to create room to provide reserves. Unit 1 cannot be lowered below 195 MW for energy as that is the lowest energy dispatch point (based on energy ramp limitation as calculated above) based on input parameters. Because Unit 1 is dispatched down by 5 MW, Unit 2 will then be dispatched up 5 MW (from the energy only solution) to be at 10 MW in order to meet the load requirement.

As a result, Unit 1 will provide 5 MW of SR toward fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (10 + 5) = 15 MW. The system is still short of the SR requirement by (16 - 15) = 1 MW. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	195	5
Unit 2	5-15 MW	10	10
Unit 3	0 MW	0	0

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW contribute to meeting the PR requirement. Therefore, the system already has 15 MW (cleared SR) of PR. The non-synchronized capability of 10 MW from unit 3 can further contribute to the PR requirement bringing the total cleared MW for primary reserve to (15 + 10) = 25 MW. Based on the PR requirement ORDC curve, the price at 25 MW is $0 and therefore the shadow price of the PR requirement is $0.

The table below summarizes the energy dispatch MW, SR and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	195	5	0
Unit 2	5-15 MW	10	10	0
Unit 3	0 MW	0	0	10

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW contribute to meeting 30-Min Reserve requirement. Hence, the system already has 25 MW of 30-Min Reserve. Unit 2 has an unloaded online Secondary reserve capability of 20 MW. Unit 3 can provide offline secondary reserve of 20 MW which brings the total cleared 30 min reserve to be (25 + 20 + 20) = 65 MW. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 65 MW is $0 and, therefore, the shadow price of 30-Min Reserve requirement is $0.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	195	5	0	0
Unit 2	5-15 MW	10	10	0	20
Unit 3	0 MW	0	0	10	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 195 MW and unit 2 is dispatched to 10 MW. To meet the next MW of energy, unit 2, as the marginal resource, needs to provide the additional MW at a cost of $50. Unit 1 cannot be dispatched up because it would reduce 1 MW of SR which costs $850. Therefore, the shadow price of power balance constraint is $50. This sets an energy clearing price of $50/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $0
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $0 +$0 = $0
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $0 +$0+$850 = $850

IV. Example 2 –Shortage in SR with Penalty cost reflected in Energy Price

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	16
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	25

Unit parameters and offers are below:

	Unit 1	Unit 2	Unit 3
EcoMin (MW)	0	0	10
EcoMax (MW)	200	100	50
Energy Offer ($/MWh)	20	50	150
Initial MW (MW value at which the unit is currently operating)	200	10	0
Ramp Rate (MW/Min)	1	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW
Unit 3	0 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the least cost resource, unit 1, provides the maximum MW toward meeting the requirement with respect to available capability. Based on the available Energy Dispatchable Range, unit

1 will provide 200 MW of energy. The next most economic resource is unit 2 which will meet the remaining MW of load to be served ((211 – 200) = 11 MW), which is within the Energy Dispatchable Range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	200
Unit 2	5-15 MW	11
Unit 3	0 MW	0

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet the 16 MW SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted towards fulfilling the SR requirement. There is no additional unloaded online reserve capability available because Unit 1 is being dispatched to its EcoMax value as a result of the Energy only solution and Unit 3 is offline.

To procure the needed SR reserves, the energy output of Unit 1 can be reduced to create room to provide reserves. Unit 1 cannot be lowered below 196 MW for energy, as Unit 2 needs to be moved up to meet the load and Unit 2 cannot be moved higher than 15 MW (based on energy ramp limitation as calculated above) based on input parameters. Because Unit 1 is dispatched down by 4 MW, Unit 2 will then be dispatched up 4 MW (from energy only solution) to be at 15 MW in order to meet the load requirement.

As a result, Unit 1 will provide 4 MW of SR towards fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (4 + 10) = 14 MW. The system is still short of the SR requirement by (16 - 14) = 2 MW. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	196	4
Unit 2	5-15 MW	15	10
Unit 3	0 MW	0	0

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meeting the PR requirement. Therefore, the system already has 14 MW (cleared SR) of PR. The non-synchronized capability of 10 MW from unit 3 (EcoMin of unit 3) can further contribute to the PR requirement bringing the total cleared MW for PR to (14 + 10) = 24 MW. Based on the PR requirement ORDC curve, the price at 24 MW is $0 and, therefore, the shadow price of the PR requirement is $0.

The table below summarizes the energy dispatch MW, SR and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	196	4	0
Unit 2	5-15 MW	15	10	0
Unit 3	0 MW	0	0	10

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW can contribute to meeting 30-Min Reserve requirement. Therefore, the system already has 24 MW of 30-Min Reserve. Unit 2 has unloaded online Secondary reserve capability of 20 MW. Unit 3 can provide offline secondary reserve of 20 MW which brings the total cleared 30-Min reserve to (24 + 20 + 20) = 64 MW. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 64 MW is $0 and, therefore, the shadow price of 30-Min Reserve requirement is $0.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	196	4	0	0
Unit 2	5-15 MW	15	10	0	20
Unit 3	0 MW	0	0	10	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 196 MW and unit 2 is dispatched to 15 MW. To meet the next MW of energy, unit 1 needs to provide the additional MW at a cost of $20 because the unit 2 can't be dispatched up further as Unit 2 is ramp limited (based on energy ramp limitation and initial MW). The next energy MW from Unit 1 will further reduce the SR MW cleared from Unit 1 by 1 MW which would cost $850 as that 1 MW of SR will have to come from penalty cost of the SR ORDC curve. Therefore, the shadow price of power balance constraint is ($20 + $850) = $870. This sets an energy-clearing price of $870/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $0
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $0 +$0 = $0
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $0 +$0+$850 = $850

V. Example 3 –Shortage in PR with no effect on Energy Price

The various requirements considered in this example are below:

Load (MW)	206
Synchronized Reserve (SR) Requirement (MW)	8
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	25

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	200	15
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	10-20 MW

Energy only solution:

In order to meet the load requirement of 206 MW, the more expensive resource, Unit 2, needs to be dispatched down. However, Unit 2 cannot be dispatched down below 10 MW due to an energy ramp limitation and the Initial MW (as calculated above). Unit 1 will meet the remaining MW of load to be served ((206-10) = 196 MW) which is within the Energy Dispatchable Range of Unit 1.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	196
Unit 2	5-15 MW	10

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet 8 MW of SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted toward fulfilling the SR requirement. Unit 1's unloaded online reserve capability of 4 MW will also be counted toward fulfilling the SR requirement.

This provides enough reserve to meet SR reserve requirement. There is no additional unloaded online reserve capability available.

As a result, Unit 1 will provide 4 MW of SR and Unit 2 will provide 10 MW of SR towards fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (4 + 10) = 14 MW. Therefore, the shadow price of SR requirement is $0 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	196	4
Unit 2	10-20 MW	10	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW contribute to meeting the PR requirement. Therefore, the system already has 14 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that can contribute to the PR requirement. The system is still short of PR. In this case, Unit 1 can be backed down by 1 more MW (as it can't be further backed down due to energy ramp limitation and based on Initial MW of Unit 1). This requires Unit 2 to provide 1 more MW for energy and, hence, Unit 2 will now clear 11 MW for energy. Total cleared MW for primary reserve will be (14 + 1) = 15 MW. Based on the PR requirement ORDC curve, the price at 15 MW is $850 and therefore the shadow price of the PR requirement is $850.

The table below summarizes the energy dispatch MW, SR and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	195	5	0
Unit 2	10-20 MW	11	10	0

30 Min – Reserve Requirement

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW contribute to meeting 30-Min Reserve requirement. Therefore, the system already has 15 MW of PR. Unit 2 has unloaded online Secondary reserve capability of 20 MW which brings the total cleared 30 min reserve to be (15+20) = 35 MW. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 35 MW is $0 and therefore the shadow price of 30-Min Reserve requirement is $0.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	195	5	0	0
Unit 2	10-20 MW	11	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 195 MW and unit 2 is dispatched to 11 MW. To meet next MW of energy, unit 2 needs to provide the additional MW, at a cost of $50, as that is the most economic approach to procure the next MW. Therefore, the shadow price of power balance constraint is $50. This sets an energy-clearing price at $50/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $0
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $0 +$850 = $850
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $0 +$850+$0 = $850

VI. Example 4 –Shortage in PR with Penalty Cost reflected in Energy Price

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	8
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	25

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	200	10
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the least cost resource, unit 1, provides the maximum MW toward meeting the requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 1 will provide 200 MW of energy. The next most economic resource is unit 2 which will provide the balance of the remaining MW of load to be served ((211 – 200) = 11 MW), which is within the Energy Dispatchable Range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	200
Unit 2	5-15 MW	11

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet 8 MW of SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted towards fulfilling the SR requirement.

This provides enough reserve to fulfill SR reserve requirement. There is no additional unloaded online reserve capability available.

As a result, Unit 2 will provide 10 MW of SR toward fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (0 + 10) = 10 MW. Therefore, the shadow price of SR requirement is $0 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	200	0
Unit 2	5-15 MW	11	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meeting the PR requirement. Therefore, the system already has 10 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that contribute to the PR requirement. The system is still short of PR. In this case, Unit 1 can be backed down by 4 MW (as it can't be further backed down due to Unit 2 being energy ramp limited as Unit 2 had to increase its output by 4 MW to 15 MW in order to meet the load requirement). This requires Unit 2 to provide 4 more MW for energy and, therefore, Unit 2 will now clear 15 MW for energy. Total cleared MW for primary reserve will be (10 + 4) = 14 MW. Based on the PR requirement ORDC curve, the price at 14 MW is $850 and therefore the shadow price of the PR requirement is $850.

The table below summarizes the energy dispatch MW, SR and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	196	4	0
Unit 2	5-15 MW	15	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW can contribute to meeting 30-Min Reserve requirement. Therefore, the system already has 14 MW of 30-Min Reserve. Unit 2 has unloaded online Secondary reserve capability of 20 MW which brings the total cleared 30 min reserve to (14+20) = 34 MW. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 34 MW is $0 and, therefore, the shadow price of 30-Min Reserve requirement is $0.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	196	4	0	0
Unit 2	5-15 MW	15	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 196 MW and unit 2 is dispatched to 15 MW. To meet next MW of energy, unit 1 needs to provide the additional MW (as Unit 2 can't provide any more MW of energy as it is ramp limited for energy dispatch), at a cost of $20 but it also reduces 1 MW of synchronized Reserve which would further cost $850 as that reserve MW has to come from penalty cost (by virtue of the increased PR requirement deficiency). Therefore, the shadow price of power balance constraint is ($20+$850) = $870. This sets an energy-clearing price of $870/MWh.

Reserve Clearing Prices

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $0
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $0 +$850 = $850
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $0 +$850+$0 = $850

VII. Example 5 –Shortage in SR & PR with no effect on Energy Price

The various requirements considered in this example are below:

Load (MW)	205
Synchronized Reserve (SR) Requirement (MW)	16
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	25

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	200	10
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW

Energy only solution:

In order to meet the load requirement of 205 MW, the least expensive resource, unit 1, provides the maximum MW toward meeting the requirement with respect to available capability. Based on the Energy Dispatchable Range, the unit 1 will provide 200 MW of energy. The next economic resource is unit 2 which will provide the balance of the remaining MW of load to be served ((205 – 200) = 5 MW), which is within the Energy Dispatchable Range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	200
Unit 2	5-15 MW	5

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet the 16 MW SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted towards fulfilling the SR requirement. There is no additional unloaded online reserve capability available.

The system is still below SR requirement. In order to procure the needed SR reserves, the energy output of Unit 1 can be reduced to create additional SR. Unit 1 cannot be lowered below 195 MW for energy as that is the lowest energy dispatch point (based on energy ramp limitation as calculated above) based on input parameters. Because Unit 1 is dispatched down by 5 MW, Unit 2 will then be dispatched up 5 MW (from energy only solution) to 10 MW in order to meet the load requirement.

As a result, Unit 1 will provide 5 MW of SR towards fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (5 + 10) = 15 MW. The system is still short of the SR requirement by (16 - 15) = 1 MW. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	195	5
Unit 2	5-15 MW	10	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meeting the PR requirement. Therefore, the system already has 15 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that contribute to the PR requirement. The system is still short of PR but there are also no other units available that can be reduced to provide additional reserves. The total cleared MW for PR will be 15 MW. Based on the PR requirement ORDC curve, the price at 15 MW is $850 and, therefore, the shadow price of the PR requirement is $850.

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	195	5	0
Unit 2	5-15 MW	10	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW contribute to meeting 30-Min Reserve requirement. Therefore, the system already has 15 MW of 30-Min Reserve. Unit 2 has unloaded online Secondary reserve capability of 20 MW which brings the total cleared 30 min reserve to be (15 + 20) = 35 MW. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 35 MW is $0 and therefore the shadow price of 30-Min Reserve requirement is $0.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	195	5	0	0
Unit 2	5-15 MW	10	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 195 MW and unit 2 is dispatched to 10 MW. To meet the next MW of energy, unit 2 needs to provide the additional MW at a cost of $50 as unit 1 cannot be dispatched up, otherwise, it would reduce 1 MW of SR which costs $850. Therefore, the shadow price of power balance constraint is $50. This sets an energy-clearing price of $50/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $0
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $0 +$850 = $850
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $0 +$850+$850 = $1700

VIII. Example 6 –Shortage in SR & PR with Penalty cost reflected in Energy Price

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	16
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	25

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	200	10
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the least cost resource, unit 1, would provide the maximum MW toward meeting this requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 1 will provide 200 MW of energy. The next economic resource is unit 2 which will provide the balance of the remaining MW of load to be served ((211 – 200) = 11 MW), which is within the Energy Dispatchable Range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	200
Unit 2	5-15 MW	11

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet the 16 MW SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted towards fulfilling the SR requirement. There is no additional unloaded online reserve capability available.

The system is below the SR requirement. In order to procure the needed SR reserves, the energy output of Unit 1 can be reduced to create room for SR. Unit 1 cannot be lowered below 196 MW for energy as this will require an increase in the energy MW from Unit 2 but Unit 2 can't be dispatched more than 15 MW due to an energy ramp limitation based on the Initial MW. Because Unit 1 is dispatched down by 4 MW, Unit 2 will then be dispatched up 4 MW (from energy only solution) to 15 MW in order to meet the load requirement.

As a result, Unit 1 will provide 4 MW of SR towards fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (4 + 10) = 14 MW. The system is still short of the SR requirement by (16-14) = 2 MW. Therefore, the shadow price of the SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	196	4
Unit 2	5-15 MW	15	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meeting the PR requirement. Therefore, the system already has 14 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that contribute to the PR requirement. The system is still short of PR but there are also no other units available that can be reduced to create the room for reserve. The total cleared MW for PR to be 14 MW. Based on the PR requirement ORDC curve, the price at 14 MW is $850 and therefore the shadow price of the PR requirement is $850.

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	196	4	0
Unit 2	5-15 MW	15	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW can contribute to meeting 30-Min Reserve requirement. Therefore, the system already has 14 MW of 30-Min Reserve. Unit 2 has unloaded online Secondary reserve capability of 20 MW which brings the total cleared 30 min reserve to be (14 + 20) = 34 MW. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 34 MW is $0 and therefore the shadow price of 30-Min Reserve requirement is $0.

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	196	4	0	0
Unit 2	5-15 MW	15	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 196 MW and unit 2 is dispatched to 15 MW. To meet next MW of energy, unit 1 needs to provide the additional MW (as Unit 2 can't provide any more MW of energy as it is ramp limited for energy dispatch), at a cost of $20. But it also reduces 1 MW of SR which results in an $850 cost for SR and an $850 cost for PR as that reserve MW has to come from penalty curves. Therefore, the shadow price of power balance constraint is ($20 + $850 + $850) = $1720. This sets an energy-clearing price of $1,720/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $0
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $0 +$850 = $850
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $0 + $850 + $850 = $1700

IX. Example 7 –Shortage in 30 Min Reserve with no effect on Energy Price

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	8
Primary Reserve (PR) Requirement (MW)	12
30-Min Reserve Requirement (MW)	65

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	150	60
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined as below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	145-155 MW
Unit 2	55-65 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the most economic resource, unit 1, provides the maximum MW toward meeting the requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 1 will provide 155 MW of energy. The next least cost resource is unit 2 which will provide the balance of the remaining MW of load to be served ((211 – 155) = 56 MW), which is within the Energy Dispatchable Range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	145-155 MW	155
Unit 2	55-65 MW	56

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet the 8 MW SR reserve requirement, the unloaded online reserve capability from both Unit 1 and Unit 2 will be counted toward fulfilling the SR requirement.

As a result, Unit 1 and Unit 2 will each provide 10 MW of SR towards fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (10 + 10) = 20 MW. Therefore, the shadow price of SR requirement is $0 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	145-155 MW	155	10
Unit 2	55-65 MW	56	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meeting the PR requirement. Hence, the system already has 20 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that contribute to the PR requirement. However, the cleared 20 MW of SR is enough to fulfill the PR requirement. Based on the PR requirement ORDC curve, the price at 20 MW is $0 and therefore the shadow price of the PR requirement is $0.

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	145-155 MW	195	10	0
Unit 2	55-65 MW	56	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of the 30-Min Reserve requirement, all cleared PR MW contribute to meeting 30-Min Reserve requirement. Hence, the system already has 20 MW of 30-Min Reserve. Both Unit 1 and Unit 2 have unloaded online Secondary reserve capability of 20 MW each which brings the total cleared 30-min reserve to (20 + 20 + 20) = 60 MW. The system is still below the 30-Min Reserve Requirement. However, there are neither any

unloaded capability available nor a unit that can be reduced to create additional reserve. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 60 MW is $850 and, therefore, the shadow price for 30-Min Reserve requirement is $850.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	145-155 MW	155	10	0	20
Unit 2	55-65 MW	56	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 155 MW and unit 2 is dispatched to 56 MW. To meet the next MW of energy, unit 2 needs to provide the additional MW (as Unit 1 cannot provide any additional MW of energy as it is ramp limited for energy dispatch), at a cost of $50. This next MW from Unit 2 will not affect any reserve assignments. Therefore, the shadow price of power balance constraint is $50. This sets the energy-clearing price of $50/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $850
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $850 +$0 = $850
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $850 +$0+$0 = $850

X. Example 8 –Shortage in 30 Min Reserve with Penalty Cost reflected in Energy Price

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	8
Primary Reserve (PR) Requirement (MW)	12
30-Min Reserve Requirement (MW)	35

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	200	10
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate is determined, as below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the most economic resource, unit 1, provides the maximum MW it can provide toward meeting this requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 1 will provide 200 MW of energy. The next most economic resource is unit 2 which will provide the

balance of the remaining MW of load to be served ((211 – 200) = 11 MW), which is within the energy dispatchable range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	200
Unit 2	5-15 MW	11

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet 8 MW of SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted toward fulfilling the SR requirement.

This provides enough reserve to fulfill the SR reserve requirement. There is no additional unloaded online reserve capability available.

As a result, Unit 2 will provide 10 MW of SR toward fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (0 + 10) = 10 MW. Therefore, the shadow price of SR requirement is $0 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	200	0
Unit 2	5-15 MW	11	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW contribute to meeting the PR requirement. Therefore, the system already has 10 MW (cleared SR) of PR. There is no non-synchronized reserve capability available to contribute to the PR requirement. The system still needs 2 MW of reserve to fulfill the PR requirement. Unit 1 can be reduced to provide the 2 MW which will require Unit 2 to increase by 2 MW (which is still within energy dispatchable range for Unit 2). The shadow price of PR requirement will be $0. This is not reasonable because, as previously mentioned, the market clearing engine co-optimizes energy and all reserve product simultaneously so in order to understand the shadow price we first need to look at the solution for 30 Min Reserve Requirement.

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	198	2	0
Unit 2	5-15 MW	13	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW can contribute to meeting the 30-Min Reserve requirement. Therefore, the system already has 12 MW of 30-Min Reserve. Unit 2 has unloaded online Secondary reserve capability of 20 MW which brings the total cleared 30 min reserve to be (12 + 20) = 32 MW. The system still needs 3 MW of reserve. There is no additional unloaded capability available that can provide Secondary Reserve. However, Unit 1 can be further backed down by 2 MW to 196 MW which requires Unit 2 to increase its output by 2MW to 15 MW. Unit 2's output cannot be increased further as unit is energy ramp limited which will not allow Unit 1 to further back down in order to maintain power balance or to meet the load. This brings the total cleared MW for 30-Min reserve to (32 + 2) = 34 MW. The system is still short of 30-Min reserve by 1 MW and, hence, based on 30-Min Reserve requirement ORDC curve, the price at 34 MW is $850 and, therefore, the shadow price of 30-Min Reserve requirement is $850.

Ultimately, the cleared SR MW from Unit 1 and Unit 2 is (10 + 4) = 14 MW which is more than required to fulfill PR requirement. Hence, based on ORDC curve of the PR reserve requirement, the shadow price of PR requirement will be $0.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	196	4	0	0
Unit 2	5-15 MW	15	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 196 MW and unit 2 is dispatched to 15 MW. To meet the next MW of energy, unit 1 needs to provide the additional MW (as Unit 2 cannot provide any additional MW of energy as it is ramp limited for energy dispatch), at a cost of $20. However, this will further reduce the SR reserve by 1 MW which needs to come from Penalty curve of the 30-Min Reserve requirement ORDC as it reduces the 30-Min cleared reserve by 1 MW. Hence, the total increase in cost for 1 more MW of energy costs the system ($20 + $850) = $870. Therefore, the shadow price of power balance constraint is $870. This sets the energy-clearing price of $870/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $850
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $850 +$0 = $850
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $850 + $0 + $0 = $850

XI. Example 9 –Shortage in SR, PR, and 30 Min Reserve with no effect on Energy Price

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	25
Primary Reserve (PR) Requirement (MW)	30
30-Min Reserve Requirement (MW)	65

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	155	55
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined as below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	150-160 MW
Unit 2	50-60 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the least cost resource, unit 1, provides the maximum MW toward meeting this requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 1 will

provide 160 MW of energy. The next economic resource is unit 2 which will provide the balance of the remaining MW of load to be served ((211 – 160) = 51 MW), which is within the energy dispatchable range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	150-160 MW	160
Unit 2	50-60 MW	51

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet the 25 MW SR reserve requirement, both Unit 1 and Unit 2's unloaded online reserve capability of 10 MW each will be counted toward fulfilling the SR requirement. There is no additional unloaded Synchronized Reserve capability available and no more units can be reduced to meet the reserve requirement.

As a result, Unit 1 and Unit 2 each will provide 10 MW of SR towards fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (10 + 10) = 20 MW. The system is below the SR reserve requirement. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	150-160 MW	160	10
Unit 2	50-60 MW	51	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meeting the PR requirement. Hence, the system already has 20 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that can contribute to the PR requirement. The system still needs (30 - 20) = 10 MW of reserve to fulfill the PR requirement. However, there are no units to be reduced to help meet the reserve requirement. The system is below the PR reserve requirement. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	150-160 MW	160	10	0
Unit 2	50-60 MW	51	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min reserve requirement, all cleared PR MW can contribute to meeting 30-Min Reserve requirement. Hence, the system already has 20 MW of PR. Unit 1 and Unit 2 have an unloaded online Secondary Reserve capability of 20 MW each which brings the total cleared 30-Min reserve to be (20 + 20 + 20) = 60 MW. The system still needs 5 MW of reserve. There is no additional unloaded capability available and there are no units that can be reduced to provide the additional Secondary Reserve needed. Hence, based on 30-Min Reserve requirement ORDC curve, the price at 60 MW is $850 and, therefore, the shadow price of 30-Min Reserve requirement is $850.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	150-160 MW	160	10	0	20
Unit 2	50-60 MW	51	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 160 MW and unit 2 is dispatched to 51 MW. To meet the next MW of energy, unit 2 needs to provide the additional MW (as Unit 1 cannot provide any additional MW of energy as it is ramp limited for energy dispatch), at a cost of $50 without effecting any reserve assignments. Therefore, the shadow price of power balance constraint is $50. This sets the energy-clearing price of $50/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $850
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $850 +$850 = $1,700
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $850 +$850+$850 = $2,550

These prices reflect uncapped values and would be representative of the Dispatch Run solution. The pricing run would administratively cap the PR Reserve Clearing Price to $1275 and the SR Clearing Price to $1700.

XII. Example 10 –Shortage in SR, PR, and 30 Min Reserve with Penalty cost reflected in Energy Price

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	15
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	35

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	20	50
Initial MW (MW value at which the unit is currently operating)	200	10
Ramp Rate(MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined as below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the least cost resource, unit 1, would provide the maximum MW toward meeting this requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 1

will provide 200 MW of energy. The next economic resource is unit 2 which will meet the remaining MW of load to be served ((211 – 200) = 11 MW), which is within the Energy Dispatchable Range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	200
Unit 2	5-15 MW	11

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet 15 MW of SR reserve requirement, Unit 2's unloaded online reserve capability of 10 MW will be counted towards fulfilling the SR requirement. The system still requires (15 - 10) = 5 MW of SR. The energy output of Unit 1 can be reduced to create room for reserves. Unit 1 cannot be lowered below 196 MW for energy, as Unit 2 needs to be moved up to meet load and Unit 2 cannot be moved higher than 15 MW (due to energy ramp limitation as calculated above) based on input parameters. Because Unit 1 is dispatched down by 4 MW, Unit 2 will then be dispatched up 4 MW (from energy only solution) to be at 15 MW in order to meet the load requirement.

As a result, Unit 1 will provide 4 MW of SR towards fulfilling the SR requirement. The total cleared SR from Unit 1 and Unit 2 is (4 + 10) = 14 MW. The system is still below the SR requirement by 1 MW ((15-14) = 1). Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	196	4
Unit 2	5-15 MW	15	10

Primary Reserve Requirement:

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meeting the PR requirement. Therefore, the system already has 14 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that contribute to the PR requirement. The system still needs (20 - 14) = 6 MW of reserve to fulfill the PR requirement. However, there are no units to be reduced to meet the reserve requirement. The system is below the PR reserve requirement. Therefore, the shadow price of the PR requirement is $850 (from SR ORDC curve).

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	196	4	0
Unit 2	5-15 MW	15	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min reserve requirement, all cleared PR MW can contribute to meeting 30-Min Reserve requirement. Hence, the system already has 14 MW of 30-Min reserve. Unit 2 has unloaded online Secondary reserve capability of 20 MW which brings the total cleared 30 -Min reserve to be (14 + 20) = 34 MW. The system still needs 1 MW of reserve. There is no additional unloaded capability available and there are no units that can be backed down to make meet the Secondary reserve requirement (Unit 1 can't be backed down further as Unit 2 is ramp limited to meet the load requirement). Hence, based on 30-Min Reserve requirement ORDC curve, the price at 34 MW is $850 and, therefore, the shadow price of 30-Min Reserve requirement is $850.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	196	4	0	0
Unit 2	5-15 MW	15	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 196 MW and unit 2 is dispatched to 15 MW. To meet the next MW of energy, unit 1 needs to provide the additional MW (because Unit 2 can't provide any additional MW of energy as it is ramp limited for energy dispatch), at a cost of $20. But, at the same time, it reduces the SR reserve by 1 MW and, hence, each of three reserve products need to provide that 1 MW from penalty cost which will further increase the cost of that 1 MW by ($850 + $850 + $850) = $2,550. Therefore, the shadow price of power balance constraint is ($20 + $2,550) = $2,570. This sets the energy-clearing price of $2,570/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $850
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $850 +$850 = $1,700
3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $850 +$850+$850 = $2,550

These prices reflect uncapped values and would be representative of the Dispatch Run solution. The pricing run would administratively cap the PR Reserve Clearing Price to $1275 and the SR Clearing Price to $1700.

XIII. Example 11 –Reserve Price Capping Scenario

This example is same as Example 10. However, this example illustrates the price capping to be utilized under Reserve Price Formation when establishing reserve clearing prices. The Synchronized Reserve Clearing Price will be $1,700 and Primary Reserve Clearing Price will be replaced to $1,275.

Price capping is administratively performed only in the Pricing Run. The Dispatch Run would result in the uncapped prices (noted in struck language in example).

XIV. Example 12 –Energy and Reserve Price Capping Scenario

The various requirements considered in this example are below:

Load (MW)	211
Synchronized Reserve (SR) Requirement (MW)	15
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	35

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	2000	50
Initial MW (MW value at which the unit is currently operating)	200	10
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined as below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	195-200 MW
Unit 2	5-15 MW

Energy only solution:

In order to meet the load requirement of 211 MW, the least cost resource, unit 2, provides the maximum MW toward meeting the requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 2 will provide 15 MW of energy. The next economic resource is unit 1 which will meet the remaining MW of load to be served ((211 – 15) = 196 MW), which is within the energy dispatchable range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	195-200 MW	196
Unit 2	5-15 MW	15

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet 15 MW of SR reserve requirement, Unit 1's unloaded online reserve capability of 4 MW and Unit 2's unloaded online reserve capability of 10 MW will be counted towards fulfilling the SR requirement. The system still requires (15 – 4 - 10) = 1 MW of SR. Unit 1 cannot be lowered below 196 MW for energy as Unit 2 needs to be moved up to meet the load and Unit 2 can't be moved higher than 15 MW(based on energy ramp limitation as calculated above) based on input parameters.

The total cleared SR from Unit 1 and Unit 2 is (4 + 10) = 14 MW. The system is still short of (15 - 14) =1 MW of SR requirement. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	195-200 MW	196	4
Unit 2	5-15 MW	15	10

Primary Reserve Requirement

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meet the PR requirement. Therefore, the system already has 14 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that contribute to the PR requirement. The system still needs (20 - 14) = 6 MW of reserve to fulfil the PR requirement. However, there are no units to be backed down to make a room for reserve. The system is short of PR reserve. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	195-200 MW	196	4	0
Unit 2	5-15 MW	15	10	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW can contribute to meeting the 30-Min Reserve requirement. Hence, the system already has 14 MW of 30-Min reserve. Unit 2 has unloaded online Secondary reserve capability of 20 MW which brings the total cleared 30-Min reserve to be (14 + 20) = 34 MW. The system still needs 1 MW of reserve. There is no additional unloaded capability available and there are no units that can be backed down to meet Secondary Reserve requirement (Unit 1 can't be backed down further as it needs Unit 2 to be moved up but Unit 2 is ramp limited). Hence, based on 30-Min Reserve requirement ORDC curve, the price at 34 MW is $850 and, therefore, the shadow price of 30-Min Reserve requirement is $850.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	195-200 MW	196	4	0	0
Unit 2	5-15 MW	15	10	0	20

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 196 MW and unit 2 is dispatched to 15 MW. To meet the next MW of energy, unit 1 needs to provide the additional MW (as Unit 2 can't provide any additional MW of energy as it is ramp limited for energy dispatch), at a cost of $2,000 but at the same time it reduces the SR reserve by 1 MW and hence each of three reserve products need to provide that 1 MW at the penalty cost which will further increase the cost of that 1 MW by ($850 + $850 + $850) = $2,550. Therefore, the shadow price of power balance constraint is ($2000 + $2,550) = $4,550. This sets the energy-clearing price of $4,550/MWh.

Reserve Clearing Prices:

1. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $850
2. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $850 +$850 = $1,700

3. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $850 +$850+$850 = $2,550

However, Energy and Reserve clearing prices will be capped and replaced at the values shown below:

- Energy Clearing Price will be replaced to $3,700.
- SR Reserve Clearing Price will be replaced to $1,700.
- PR Reserve Clearing Price will be replaced to $1,275.
- 30-Min Reserve Clearing Price will not be replaced and kept at $850.

Price capping is administratively performed only in the Pricing Run. The Dispatch Run would result in the uncapped prices (noted in struck language in example)

XV. Example 13 –Energy and Reserve Price Capping Scenario under Emergency Conditions - NEW

The various requirements considered in this example are below:

Load (MW)	291
Synchronized Reserve (SR) Requirement (MW)	15
Primary Reserve (PR) Requirement (MW)	20
30-Min Reserve Requirement (MW)	35

Unit parameters and offers are below:

	Unit 1	Unit 2
EcoMin (MW)	0	0
EcoMax (MW)	200	100
Energy Offer ($/MWh)	2000	50
Initial MW (MW value at which the unit is currently operating)	190	95
Ramp Rate (MW/Min)	1	1

Solution:

The Optimization engine performs the co-optimization of energy and reserve simultaneously. However, for the purpose of this explanation, it is presented below separately.

Energy Dispatchable Range:

The Energy Dispatch Range for each unit, which is based on initial MW, energy time horizon, and ramp rate, is determined as below:

Lowest energy dispatch point = Maximum ([Initial MW – ramp rate*5], EcoMin)

Highest energy dispatch point = Minimum ([Initial MW + ramp rate*5], EcoMax)

Unit specific dispatchable range based on input parameters are as below:

	Energy Dispatchable Range
Unit 1	185-195 MW
Unit 2	90-100 MW

Energy only solution:

In order to meet the load requirement of 291 MW, the least cost resource, unit 2, provides the maximum MW toward meeting the requirement with respect to available capability. Based on the Energy Dispatchable Range, unit 2 will provide 100 MW of energy. The next economic resource is unit 1 which will meet the remaining MW of load to be served ((291 – 100) = 191 MW), which is within the energy dispatchable range of unit 2.

The table below summarizes the energy dispatch MW resulting from the Energy only solution.

	Energy Dispatchable Range	Energy MW
Unit 1	185-195 MW	191
Unit 2	90-100 MW	100

Co-optimization of Energy and Reserve

Synchronized Reserve Requirement:

In order to meet 15 MW of SR reserve requirement, Unit 1's unloaded online reserve capability of 9 MW will be counted towards fulfilling the SR requirement. The system still requires (15 – 9) = 6 MW of SR. Unit 1 cannot be lowered below 191 MW for energy as Unit 2 needs to be moved up to meet the load and Unit 2 can't be moved higher than 100 MW(EcoMax of Unit 2 is 100 MW).

The total cleared SR from Unit 1 is 9 MW. The system is still short of (15 - 9) =6 MW of SR requirement. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the updated energy dispatch MW and initial SR assignment resulting from the co-optimized Energy and Synchronized Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW
Unit 1	185-195 MW	191	9
Unit 2	90-100 MW	100	0

Primary Reserve Requirement

As the SR requirement is a sub-set of the PR requirement, all cleared SR MW can contribute to meet the PR requirement. Therefore, the system already has 9 MW (cleared SR) of PR. There is no non-synchronized reserve capability available that contribute to the PR requirement. The system still needs (20 - 9) = 11 MW of reserve to fulfil

the PR requirement. However, there are no units to be backed down to make a room for reserve. The system is short of PR reserve. Therefore, the shadow price of SR requirement is $850 (from SR ORDC curve).

The table below summarizes the energy dispatch MW, SR, and NSR assignments resulting from the co-optimized Energy, Synchronized Reserve and Primary Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW
Unit 1	185-195 MW	191	9	0
Unit 2	90-100 MW	100	0	0

30 Min – Reserve Requirement:

As the PR requirement is a sub-set of 30-Min Reserve requirement, all cleared PR MW can contribute to meeting the 30-Min Reserve requirement. Hence, the system already has 9 MW of 30-Min reserve. There is no unloaded capability available that can provide Secondary Reserve and there are no units that can be backed down to meet Secondary Reserve requirement (Unit 1 can't be backed down further as it needs Unit 2 to be moved up but Unit 2 is at EcoMax). Hence, based on 30-Min Reserve requirement ORDC curve, the price at 9 MW is $850 and, therefore, the shadow price of 30-Min Reserve requirement is $850.

The table below summarizes the energy dispatch MW, SR, NSR, and Secondary Reserve assignments resulting from the co-optimized Energy, Synchronized Reserve, Primary Reserve and 30-minute Reserve solution.

	Energy Dispatchable Range	Energy MW	Sync Reserve MW	NSR MW	Sec Res MW
Unit 1	185-195 MW	191	9	0	0
Unit 2	90-100 MW	100	0	0	0

Power Balance (or Energy) constraint shadow price:

Unit 1 is dispatched to 191 MW and unit 2 is dispatched to 100 MW. To meet the next MW of energy, unit 1 needs to provide the additional MW (as Unit 2 can't provide any additional MW of energy as it is EcoMax for Energy dispatch), at a cost of $2,000 but at the same time it reduces the SR reserve by 1 MW and hence each of three reserve products need to provide that 1 MW at the penalty cost which will further increase the cost of that 1 MW by ($850 + $850 + $850) = $2,550. Therefore, the shadow price of power balance constraint is ($2000 + $2,550) = $4,550. This sets the energy-clearing price of $4,550/MWh.

Reserve Clearing Prices:

4. 30-Min Reserve clearing price = shadow price of 30-Min Reserve requirement = $850
5. PR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement = $850 +$850 = $1,700

6. SR Reserve clearing price = shadow price of 30-Min Reserve requirement + Shadow price of PR Requirement + Shadow price of SR requirement= $850 +$850+$850 = $2,550

However, Energy and Reserve clearing prices will be capped and replaced at the values shown below:

- Energy Clearing Price will be replaced to $3,700.
- SR Reserve Clearing Price will be replaced to $1,700.
- PR Reserve Clearing Price will be replaced to $1,275.
- 30-Min Reserve Clearing Price will not be replaced and kept at $850.

Price capping is administratively performed only in the Pricing Run. The Dispatch Run would result in the uncapped prices (noted in struck language in example)