ERCOT Concept Paper for

Real-Time Market Improvements:

Co-optimization of Energy and Ancillary Services

&

Multi-Interval Real-Time Market

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Revision History

|  |  |  |  |
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| 09/19/2014 | 0.1 | Initial Working Draft  | ERCOT Team |
| 09/26/2014 | 0.2 | Added description on how AS is deployed from Load Resources | ERCOT Team |
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| 2/9/2016 | 0.5 | Clarification for Option 2 RT co-optimization on the co-ordination of the prices on the demand curves for SOR and NSOR. Corrections to the equations in the appendix for RT co-optimization | ERCOT Team |

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# Executive Summary

ERCOT stakeholders are considering new initiatives to improve the efficiency of Real-Time Market operations. The effort may consist of one or both of the following components:

* Real-Time Co-optimization of Energy and Ancillary Services. Co-optimization is the process of simultaneously procuring energy and Ancillary Services (AS) from available Resources, at the lowest production cost[[1]](#footnote-1) to meet the Real-Time system demand for energy and AS. This results in the optimal allocation of all Resources’ capacity between energy and AS. The ERCOT Day-Ahead Market (DAM) currently co-optimizes in its execution. However, the current Real-Time (RT) market is unable to consider capacity reserved for AS (e.g., capacity above the Resource’s High Ancillary Services Limit, or HASL) even if the energy offer or bid for that capacity would be economical. Using Real-Time Co-optimization, the Real-Time Market clearing process would consider all available capacity to serve system demand for energy and procure AS capacity at the lowest possible cost1. Market clearing is designed to normally occur every 5 minutes. The process under consideration would be similar to the clearing process for energy and AS in the DAM. Accordingly, Real-Time Co-optimization can be thought of as “running the DAM every five minutes in Real-Time.” The objectives of Real-Time Co-optimization are to enable appropriate scarcity pricing through optimal use of a Resource’s capacity for energy and AS, and to enable market participants to adjust their energy and AS portfolios in Real-Time. A market design change, which was implemented on June 1, 2014, represents an approximation of a Real-Time Co-optimization based on the Operating Reserve Demand Curve (ORDC).
* Multi-Interval Real-Time Market. The main objectives of the proposed Multi-Interval Real-Time (RT) Market are to enable additional Resources to contribute to Real-Time price formation and to expand access to the Real-Time Energy Market, thus enhancing competition and lowering overall costs to Load-serving Entities.

This enhancement would enable the Real-Time Market to, apart from considering offers and bids from the existing portfolio of Resources, to also consider offers and bids from other Resources that can be committed and/or dispatched only in blocks of MWs and/or have time-related (temporal) constraints. This is achieved by allowing the Real-Time Market to analyze, in conjunction with current system conditions (system demand for energy or Generation To Be Dispatched - GTBD) for the current five-minute interval, and forecasted system conditions (ERCOT Short Term Load Forecast or STLF) for the next consecutive future five-minute intervals, to a maximum of 30 minutes out.

This could enable increased participation in the Real-Time Market by Load Resources with the following attributes:

* + Resources with temporal constraints, including but not limited to start-up time or ramp period longer than the current 5-minute SCED, minimum or maximum run times, or return-to-service times;
	+ Resources that are “blocky” and therefore unable to deliver incremental fractions of their offers or bids, as is required of marginal units under current SCED.

In the Multi-Interval RT Market, Locational Marginal Prices (LMPs) (and AS Market Clearing Price for Capacity, or AS MCPCs if RT Co-optimization is included) would be binding for only the first (current) five-minute interval. In addition, Commitment Instructions issued by the Multi-Interval RT Market would be binding. Resources thus committed based on forecasted future conditions would be eligible for make-whole payments if actual Real-Time binding prices left them insufficiently compensated.

These initiatives, which are already in place in other Independent System Operator/Regional Transmission Organization (ISO/RTO) markets, may be considered and implemented separately or together.

ERCOT Staff has developed this concept paper as a starting point for stakeholder consideration of these Real-Time Market improvements.

# RT energy and AS Co-optimization

Co-optimization is the process of simultaneously procuring energy and Ancillary Services (AS) at the lowest production cost [[2]](#footnote-2) while meeting system demand for energy and AS. The result is optimal allocation of all Resources’ capacity between energy and AS.

In other words, the energy and AS Co-optimization clearing process ensures that, while maintaining the lowest cost for procuring the required MWs, the pricing outcomes for energy and AS — Locational Marginal Prices, or LMPs, and AS Market Clearing Prices for AS Capacity, or MCPCs), are such that, the Resources are provided the best possible total revenue outcome from the energy and AS awards.

The objectives of Real-Time Co-optimization are to enable appropriate scarcity pricing through optimal use of Resource’s capacity for energy and AS, and to enable market participants to adjust their energy and AS portfolios in Real-Time.

This concept document presents two options. The first option (referred to as Option 1) is the original version in concept paper that does not change the current AS product set (Reg-Up, Reg-Down, RRS, Non-Spin). The second option (referred to as Option 2 has been modified version of Option 1 which proposes a modification to the current AS product set. The modification is to replace the Non-Spin product with two new products – Spinning Operating Reserve (SOR) and Non-Spinning Operating Reserve (NSOR). The high level mathematical formulations for Option 2 is presented in the appendix. The mathematical formulation for Option 1 can be derived from the equations for Option 2.

Option 1 (Original):

This option (original concept paper version), keeps the current set of AS products — namely, Regulation Up (Reg-Up), Fast Responding Regulation Service-Up (FRRS-Up), Regulation Down (Reg-Down), Fast Responding Regulation Service-Down (FRRS-Down), Responsive Reserve Service (RRS) and Non-Spin. The concepts presented in this option are equally applicable to the proposed Future AS product set — Reg-Up, Reg-Down, FRRS-Up, FRRS-Down, Fast Frequency Response Service (FFRS), Primary Frequency Responsive Service (PFRS), Contingency Reserve Service (CRS), and Supplemental Reserve Service (SRS).

Option 2 (Modified):

This option proposes a change from the current set of AS products. The change is to replace the Non-Spin AS product with two products – Spinning Operating Reserve (SOR) and Non-Spinning Operating Reserve (NSOR). The other products (Regulation, Responsive Reserve) remain the same.

Spinning Operating Reserve (SOR): This is the available On-Line headroom minus the Regulation Up and RRS awards/responsibility. The qualification criteria proposed are the same as what is currently in place for Resources to be eligible to receive the On-Line Reserve Price Adder.

Non-Spinning Operating Reserve (NSOR): This is the available Off-Line capacity that can be converted to energy in 30 minutes. The qualification criteria proposed are the same as what is currently in place for Resources to be eligible to receive the Off-Line Reserve Price Adder.

The concepts presented in this option are applicable to the proposed Future AS product set — Reg-Up, Reg-Down, FRRS-Up, FRRS-Down, Fast Frequency Response Service (FFRS), Primary Frequency Responsive Service (PFRS), and Contingency Reserve Service (CRS) remain as is. However, the Supplemental Reserve Service (SRS) will be replaced with Spinning Operating Reserve (SOR) and Non-Spinning Operating Reserve (NSOR).

The table below summarizes the key features of the two options under discussion for Real-Time energy and AS Co-Optimization.

**Table 1: High Level Comparison of the two options for RT Co-Optimization of energy and Ancillary Services**

|  |  |  |
| --- | --- | --- |
|  | Option 1 (Original) | Option 2 (Modification) |
| AS Products | Day-Ahead | * Reg-Up,
* Reg-Down,
* RRS,
* Non-Spin
 | Only awarded if offers submitted. i.e. willing seller | Day-Ahead | * Reg-Up,
* Reg-Down,
* RRS,
* Spinning Operating Reserve (SOR),
* Non-Spinning Operating Reserve (NSOR)
 | Only awarded if offers submitted. i.e. willing seller |
| Real-Time | * Reg-Up,
* Reg-Down,
* RRS,
* Non-Spin
 | 1. For On-Line Non-Spin, if qualified, then automatically considered to be offered at zero $/MW
2. For other types of AS, will be awarded only if AS offer submitted.
3. Same MCPC for both On-Line and Off-Line Non-Spin
 | Real-Time | * Reg-Up,
* Reg-Down,
* RRS,
* Spinning Operating Reserve (SOR),
* Non-Spinning Operating Reserve (NSOR)
 | 1. For SOR, automatically considered to be offered at zero $/MW
2. For other types of AS, will be awarded only if AS offer submitted.
3. Separate prices (MCPC) for SOR and NSOR
 |
| AS Demand Curves | * The value of the maximum price on the ORDC needs to be coordinated with VOLL, SWOC.
* Demand Curves for Regulation (Up/Down), and RRS are carved out of the ORDC for spinning (On-Line) reserves
* Demand Curve for Non-Spin (includes On-Line and Off-Line) is carved out of the ORDC that represents both spinning and non-spinning (On-Line + Off-Line) reserves
 | * The value of the maximum price on each AS demand curve needs to be coordinated with VOLL,SWOC
* Demand Curves for Regulation (Up/Down), and RRS do NOT have to be based on ORDC
* Demand curve for SOR can be either the current ORDC for spinning (On-Line) reserves or based on EUE
* Demand curve for NSOR can be either the current ORDC for spinning and non-spinning reserves (On-Line + Off-Line) or based on EUE
 |
| AS MCPC |  | * The SOR MCPC is the sum of the shadow prices of the constraints to procure SOR and NSOR
 |

Finally, RT Co-optimization (both Option 1 and Option 2) as described here is equally applicable to either a single interval or a Multi-Interval RT Market.

Please note that the descriptions in the sections below are applicable for both options (Option 1 and Option 2) unless explicitly stated otherwise.

## High Level Description of the Clearing Process and Outputs

Under Co-optimization, the RT market clearing **procures** the following, nominally once every 5 minutes (for the current 5 minutes):

1. Energy, in the form of Base Points, to meet the system demand for energy as represented by Generation To be Dispatched (GTBD); and
2. Reserve capacity sufficient to meet the AS demand. Each type of AS will have its own ‘bid-to-buy’ demand curve. Each AS demand curve is developed from a disaggregation of the Operational Reserve Demand Curve (ORDC) in use in the current RT market.

Put another way, every 5 minutes the market clearing would result in the following:

1. Base Points for energy to all Resources to meet the system demand for energy (GTBD). These Base points are valid for the next 5 minutes or until the next clearing of the RT market. This is the same as in the current RT Market.
2. LMPs at all required locations that are binding for the next 5 minutes or until the next clearing of the RT market. This is the same as in the current RT Market
3. Reg-Up and Reg-Down awards and associated Reg-Up and Reg-Down MCPCs. This capacity is procured as Regulation Reserve Service and will be utilized by the ERCOT Load Frequency Control (LFC) engine to send regulation signals every LFC cycle – 4 seconds for the next 5 minutes or until next clearing of the RT market
4. RRS awards and RRS MCPC. This procured capacity must be available to be converted into energy, if required, in the next 10 minutes (like a call option). This responsibility to deliver exists for the next 5 minutes or until the next clearing of the RT market
5. Option 1 (Original): Non-Spin awards and Non-Spin MCPC. This procured capacity (Online and/or Offline) must be available to be converted into energy, if required, within the next 30 minutes following an instruction and must also be able to sustain the energy deployment for a 1 hour period (like a call option). This responsibility to deliver exists for the next 5 minutes or until the next clearing of the Real-Time market. On-Line Non-Spin capacity must be available to SCED for dispatch.

Resources with Non-Spin awards in RT are **not** eligible for Make-Whole payments. This treatment is the same as in the current design.

In order to award an Offline Resource Non-spin, the following factors are considered

* + 1. Is it qualified for Non-Spin?
		2. Has the resource satisfied its minimum down time?
		3. Can the Resource startup in 30 minutes and reach LSL (check the warmth state and the associated cold, intermediate and hot startup times)?
		4. Does it have adequate ramping capability to meet the performance requirements associated with its award?

Option 2 (Modified):

Spinning Operating Reserve (SOR): This capacity is On-Line and available to SCED for dispatch. This capacity is capable of being converted into energy, if required, through successive SCED dispatch or manual instruction over the next 30 minutes and must also be able to sustain the energy deployment for a 1 hour period (like a call option). This responsibility to deliver exists for the next 5 minutes or until the next clearing of the Real-Time market.

Non-Spinning Operating Reserve (NSOR): This capacity is Off-Line and can be converted to energy, if required, within the next 30 minutes following an instruction and must also be able to sustain the energy deployment for a 1 hour period (like a call option). This responsibility to deliver exists for the next 5 minutes or until the next clearing of the Real-Time market.

Resources with Non-Spinning Operating Reserve (NSOR) awards in RT are **not** eligible for Make-Whole payments.

In order to award an Off-Line Resource NSOR, the following factors are considered

* + 1. Is it qualified for NSOR?
		2. Has the resource satisfied its minimum down time?
		3. Can the Resource startup in 30 minutes and reach LSL (check the warmth state and the associated cold, intermediate and hot startup times)?
		4. Does it have adequate ramping capability to meet the performance requirements associated with its award?

1. Appropriate constraints are enforced to limit energy and AS awards based on the Resources’ telemetered ramp rates. This is to ensure that the awards for energy and AS are ramp feasible.
	1. Stakeholder discussions will be required to develop methodology to share the ramp rates between energy and AS (similar to the ramp sharing between current Security Constrained Economic Dispatch or SCED and LFC).
	2. When to use Emergency Ramp Rates?
2. AS MW awards and associated MCPCs are published simultaneously with energy Base Points and associated LMPs — i.e. after every RT market clearing (nominally every 5 minutes). QSEs will not be required to immediately incorporate these AS awards into their control systems; i.e., there is no hand shaking between ERCOT and the QSEs representing Resources with regard to receipt and acknowledgement of AS awards. Rather, this is intrinsically done via the AS offer that can be updated at any time by the QSE.
3. Market clearing can be re-initiated by ERCOT, prior to the normal 5-minutes, as with the current design.
4. Resources in Start Up or Shut Down mode are not considered as available for energy dispatch nor are they considered available to provide AS.
5. The key performance metric for the Resource is its ability to follow the energy Base Point. Like the current RT Market, the results of the proposed RT Market with energy and AS Co-optimization are effective immediately; i.e., the Base Points, LMPs, AS awards and AS MCPCs are binding upon RT Market clearing.

### Pricing Run Changes (modifications to NPRR 626)

A pricing run based on NPRR 626 (Reliability Deployment Price Adder) will be required to mitigate price reversals associated with the deployment of Load Resources and/or out-of-market reliability deployments that may otherwise reduce the total Real-Time price in times of scarcity. The objective of the pricing run will remain the same — that is, to determine the positive change to System Lambda when Load Resources or out-of-market reliability deployments occur. This positive change to System Lambda is added to all original energy prices (LMPs), and under RT Co-optimization the same positive change to System Lambda would be added to all the original MCPCs.

This pricing run will not require the modification of dispatch limits (High Dispatch Limit or HDL, and Low Dispatch Limit or LDL) for “in-market” Resources because in RT Co-optimization, the concept of High Ancillary Service Limit or HASL does not exist. Rather, the Resource’s entire capacity (between its Low Sustained Limit or LSL and High Sustained Limit or HSL) is considered available for allocation between energy and AS.

## Settlements

In general, the current approach described in the ERCOT Nodal Protocols for AS imbalance settlements for ORDC will be employed for the settlement of AS in Real-Time. The changes from the current approach will be that each AS type will have its own AS imbalance settlement. Each AS type will have a 15 minute MCPC that is computed as a time-weighted average of the individual RT Market (i.e., 5 minute) AS MCPCs.

There will be checks on comparing the 5 minute average of the integrated HSL with the sum of the energy Base Points and AS Awards to ensure that Resources are providing sufficient capacity between consecutive SCED executions.

The 15 minute Settlement Interval AS MCPC is calculated as:

RTASMCPC =  (WF *y* \* RTASSP *y*)

The AS imbalance settlement for a given AS type is calculated as:

ASImbalanceAmount ($) =

0.25\*(DAASAwd – RTASAvgAwd)\*RTASMCPC

RTASAvgAwd = (WF *y* \* RTASAwd *y*)

WF *y* = TLMP *y* / TLMP *y*

|  |  |  |
| --- | --- | --- |
| Variable | Unit | *Description* |
| RTASMCPC | $/MW per hour | *Real-Time AS Market Clearing Price for Capacity* The Real-Time AS MCPC for the 15-minute Settlement Interval. |
| RTASSP*y* | $/MW per hour | *Real-Time AS Shadow Price* The Real-Time AS constraint Shadow Price for the SCED interval *y*. |
| DAASAwd | MW per hour | *Day-Ahead AS MW Award* |
| RTASAvgAwd | MW | *Real-Time Time Weighted Average AS MW Award* The Real-Time Time Weighted Average MW AS Award for the 15-minute Settlement Interval. |
| RTASAwd | MW | *Real-Time AS MW Award* The Real-Time AS MW Award for the SCED interval y. |
| WF *y* | none | *Weighting Factor per interval*The time weight used for the portion of the SCED interval *y* within the Settlement Interval in calculating a given Settlement Interval AS MCPC. |
| TLMPy | second | *Duration of SCED interval per interval*⎯The duration of the portion of the SCED interval *y* within the Settlement Interval. |
| y | none | *A SCED interval in the 15-minute Settlement Interval.  The summation is over the total number of SCED runs that cover the 15-minute Settlement Interval.* |

### Are There any Make-Whole Payments to Resources?

There are no Make-Whole Payments to Resources that can be directly attributed to the conceptual market design changes presented here. Make-Whole provisions to Resources that exist in the current market design may still apply (e.g. Emergency Base Point Settlements).

### Is There Any Uplift Required?

No changes from current market.

Just as occurs in the current Real-Time AS Imbalance Settlement process, as implemented by NPRR 568, etc., any occurrence of uplift to load on a Load-Ratio-Share basis arises only when the Real-Time AS Imbalance Settlement process results in a net payment to Resources.

## Telemetry Changes for Generation and Controllable Load Resources

Currently, the QSE representing the Generation Resources or Controllable Load Resource sends every 2 seconds, for each Resource, their respective AS Responsibility (Reg-Up, Reg-Down, RRS, Non-Spin) and corresponding applicable AS Schedule (RRS and Non-Spin).

Under RT Co-Optimization, the telemetry for AS responsibility and schedule are not required. The Resource specific AS Offers can be updated at any point in time and will represent the willingness of the QSE representing the Resource to sell capacity for AS in the upcoming next RT Market.

The proposed RT Market considers the following Resource specific data to optimally allocate the Resource’s capacity:

1. Telemetered HSL, LSL (for Controllable Load Resource or CLR it is the Maximum Power Consumption or MPC and Low Power Consumption or LPC) , and ramp-rates, every 2 seconds
2. Energy Offer Curve or EOC that is locked down by the end of the adjustment period (for CLR, this is the Real-Time Market Energy Bid)
3. AS Offer that can be modified at any point in time

Further discussion via the stakeholder process will be needed to determine the proper timeline for updating AS Offers and EOCs. There may be a need for additional telemetry to be used in conjunction with the AS offer to provide QSEs more flexibility.

## Telemetry Changes for Load Resources with UFR

One key issue involved in integrating Load Resources armed with high-set Under Frequency Relays (UFRs) into RT Co-optimization will be the practicality and necessity of arming/disarming the UFRs based on RRS awards. If determined to be impractical or infeasible, then these Load Resources would be ineligible to actively participate in the RT Market; instead their AS responsibilities originating from DAM, Trades, etc. would not be re-cleared in the RT Market —and they would effectively become price takers in the RT Market. This requires further discussion by ERCOT staff and stakeholders.

Update based on SAWG discussions:

Load Resource (LR) with UFR carrying RRS Responsibility (blocky AS):

1. Upon deployment will be exempt from AS imbalance charge
2. In RT, LR with UFR carrying RRS responsibility will be considered to be price takers (i.e. RRS offer from these LR = 0$/MW). i.e. no reduction of RRS demand curve by the amount of RRS responsibility from Load Resources.
3. However, when deployed, LR will be considered to be still providing RRS till the 3 hour limit after recall.
4. Need to develop process to account and differentiate scenarios where RRS from LR is deployed versus failure to provide, etc. This has impact on the AS imbalance settlement

Note 1: The above exemptions from AS Imbalance charges is a deviation from current practice

Note 2: Need to allow/account for non-frequency responsive capacity telemetered by Resource

Accounting for Resource providing "truly" Offline Non-Spin (Option 1) and NSOR (Option 2):

Should these Resources be exempt from AS Imbalance charges upon deployment? Note - We do not do that currently with the ORDC price adder settlements.

## AS Deployment Process

* 1. Regulation Up and Regulation Down:

No material change from current process.

Change is that LFC, will get as input, after every RT market clearing (usually every 5 minutes), a new set of QSE level Reg-Up and Reg-Down Responsibilities based on the Resource specific Reg-Up and Reg-Down awards.

* 1. Responsive Reserve Service or RRS:
		1. Self-Deployment of UFR-type Load Resources due to frequency deviation from a forced outage (Unit Trips):

No change

* + 1. ERCOT release of RRS capacity to SCED:

Major change

Under RT Co-optimization, the current process of ERCOT reserving RRS capacity and releasing it under scarcity conditions would be discontinued and

 replaced with a “HASL-free” operation in which RRS is procured until the RRS supply and demand curves intersect — i.e., “RRS supply” = “RRS demand”. Under scarcity conditions, energy to be served is given priority and smaller amounts of RRS would be procured — effectively similar to the release of RRS to SCED in current market. This results in scarcity pricing through the ORDC.

The current ability for the operator to manually enter an offset to GTBD will be retained to allow ERCOT the ability to react to persistent frequency deviations.

* + 1. ERCOT deployment of RRS from Load Resource with High Set Under Frequency Relay:

Even under a RT Co-optimization, similar mechanism as the current market design would be employed to deploy RRS from Load Resources with High Set Under Frequency Relay. ERCOT can, depending on the analysis of current and forecasted conditions, instruct deployment of RRS from Load Resources with RRS responsibility (at that time). The pricing run will mitigate price reversals due to this type of ERCOT deployment.

* 1. On-Line Non-Spin (Option 1) or Spinning Operating Reserve (SOR – Option 2):
	2. On-Line Non-Spin (including Quick Start Generation Resource with telemetered status of On-Line) or SOR:

No change. Currently the online Non-Spin capacity is always available to SCED. Under RT Co-optimization, the “HASL-free” operation described above would allow this capacity to be converted to energy, if required.

* 1. Off-Line Non-Spin (truly Off-Line) (Option 1) or Non-Spinning Operating Reserve (NSOR) that is truly Off-Line (Option 2)

Even under a RT Co-optimization, similar mechanism as the current market design would be employed to deploy truly Off-Line Non-Spin or truly Off-Line NSOR. ERCOT can, depending on the analysis of current and forecasted conditions, instruct Offline Resources with Non-Spin or NSOR responsibility (at that time) to come Online. These Resources have the responsibility to deliver for 1 hour after they come online in or are recalled whichever comes first.

Further ERCOT staff and stakeholder discussions will be required to revisit the current procedures for deploying truly Offline Non-Spin or NSOR to mitigate local congestion when no market solution is available.

Under RT Co-optimization, consistent with current practice, Resources with Non-Spin or NSOR Responsibility that are Offline and deployed for Non-Spin or NSOR are **not** made whole to their Energy Offer Curve, **nor** are they made whole on their Startup Costs and Minimum Energy Costs.

## Setup of AS Demand Curves

Under RT Co-optimization of energy and AS, the AS requirements for each type of AS (Reg-Up, Reg-Down, RRS, Non-Spin) to be procured are modeled as a demand curve. The AS demand curves for AS serve the same purpose as the Power Balance Penalty Curve for energy.

Option 1 (Original): Disaggregation of the ORDC into Reg-Up, RRS, Non-Spin Demand Curves

The Operating Reserve Demand Curve (ORDC), which is based on statistical distributions (mean and standard deviation) of Online Reserves will be used to setup the AS demand curves for each AS type.

~~Note: If RRS from Load Resources are not part of the RT market (i.e. price takers), then the RRS demand curve will need to be modified (reduced) by the amount of price taking RRS MW from Load Resources. However, in the event of an ERCOT manual deployment of RRS from Load Resources, the RRS demand curve will be augmented by the deployed amount of RRS from Load Resources.~~

For Non-Spin, the demand curve continues on until the price on the ORDC is zero (0 $/MW) — which is currently around 7,000 MW of total reserve.

AS Plan MW Requirements are used to disaggregate the ORDC as shown in the figure below.

Figure 1: Option 1 : Disaggregation of the ORDC into Reg-Up, RRS, Non-Spin Demand Curves

MW Reserves

Minimum Contingency X=2000 MW

$/MW

$/MW

MW Reserves

Reg-Up Demand Curve

RRS Demand Curve

NSpin Demand Curve

ORDC – Spinning Reserves Reserves

ORDC – Combined Spinning & Non-Spinning Reserves

Minimum Contingency X=2000 MW

Option 2 (Modified)

The Regulation Up and Responsive Reserve Demand Curve are rectangles as shown below.

Figure 2: Option 2 : AS Demand Curves where only SOR and NSOR are derived from disaggregation of the ORDC

Reg-Up Demand Curve

$/MW

$/MW

RRS Demand Curve

MW

MW

The SOR and NSOR demand curves are based on the ORDC as shown below.

SOR Demand Curve from ORDC Spinning Reserves with Minimum Contingency (X) removed

NSOR Demand Curve from ORDC Combined Spinning & Non-Spinning Reserves with Minimum Contingency (X) removed

$/MW

$/MW

MW

MW

The table below summarizes the current thoughts on the AS Demand Curves with the Future Ancillary Service products for Option 1 (Original) and Option 2(Modified)

|  |  |  |
| --- | --- | --- |
| AS Products | Original Proposal Demand Curve | Modified Proposal Demand Curve |
| Reg-Up Requirement Reg-Down RequirementPFR + FFR = PFR + ratio\*(FFR1 + FFR2) RequirementsCR = CR1 + CR2 RequirementsSR = SR1+SR2 Requirements | No change PFR & FFR map to RRSCR – New out of SpinningCR is “new”SR maps to Non-Spin (On-Line+Off-Line ORDC) |  No change PFR & FFR maps to RRSCR is “new” $/MWMWCR Demand CurveSR Replaced by SOR and NSORThe sum of the maximum prices of the two demand curves for SOR and NSOR is equal to the original ORDC Spinning Reserve Demand curve with Minimum Contingency (X) removed. e.g. 50% of each of the curves as is currently done for the ORDC price  |

### Discussion Items:

1. For Non-Spin, should the statistical distribution of Online Reserves be used or Online+Offline Reserves or some combination? Note that the price on the Non-Spin demand curve will be lower if the statistical distribution of the Online+Offline Reserves is used.

Update from SAWG discussions: Use the statistical distribution of Online+Offline Reserves to build the Non-Spin (Option 1) or NSOR (Option 2) Demand Curve. For SOR (Option 2) use the statistical distribution of Online Reserves to build the SOR Demand Curve

1. How should the demand curve for Reg-Down be determined? Is it the same as the Reg-Up demand curve?

Update from SAWG discussions: Reg-Down Demand Curve will have the same shape as the Reg-Up Demand Curve. Reg-Down Demand Curve width (MW required for Reg-Down)) will be based on ERCOT operational requirements. The price points on the Reg-Down Demand Curve will be the same as the Reg-Up Demand Curve till the Reg-Down MW requirement.

1. Do we need to model AS demand curves based on ORDC in the DAM?

Update from SAWG discussions: AS Demand Curves will be used in DAM. The setup of the AS Demand Curves will depend upon the choice of Option 1 or Option 2. The AS demand curves will be the same in DAM and Real-Time

1. If we model AS demand curves in the DAM, as the DAM is voluntary, are there any issues? Resources do not have to participate since it is not mandatory to submit Resource specific Offers for energy and AS.

Update from SAWG discussions: Consensus that this is not an issue

1. If we model AS demand curves in the DAM, then what is the process of achieving required levels of AS procurement in the DAM when the DAM process does not procure enough? Is it Reliability Unit Commitment or RUC?

Update from SAWG discussions: Prefer to go into Real-Time with AS insufficiency or need to develop procedure to deal with AS insufficiency in DAM if it is unacceptable to go into RT with AS insufficiency

1. If AS demand curves are **not** modeled in the DAM, then AS procurement is effectively given higher priority than energy — that is, in DAM, all energy demand has a price and hence can be curtailed, whereas the AS penalty is extremely high. This ensures that the AS Plan MW Requirements are procured. However, in RT, AS demand curves are modeled based on ORDC. The amount of Non-Spin procured depends on the intersection of the Non-Spin demand curve and the offer stack for Non-Spin. Hence, the procured amounts of Non-Spin can exceed or be less than the AS Plan MW Requirement for Non-Spin. If there is more Non-Spin procurement than the AS Plan, then loads are charged this amount on a Load-Ratio-Share. This is the same as the current process of AS Imbalance Settlements.

Update from SAWG: Consensus is to model AS demand curves in DAM. For AS demand curves with a “long tail” – e.g. Non-Spin (Option 1) or SOR/NSOR (Option 2), ERCOT may procure more AS than required for reliability if it is economical. Please note that a QSE attempting to self-arrange 100 % of AS obligation for Non-Spin (Option 1) or SOR/NSOR (Option 2) may still get charged if the procured amounts exceed the amounts required for reliability.

1. From SAWG discussions on AS Offer Submission rule changes to increase substitutability/liquidity and also promote price cascading of AS MCPC from higher quality AS to lower quality AS.
	1. Rule 1: In the Day-Ahead Market, If MW capacity offered for Reg-Up, then the same MW capacity offer is also considered for Non-Spin (Option 1) or SOR (Option 2) at the same price as Reg-Up if the QSE did not enter an offer price for Non-Spin (Option 1) or SOR (Option 2)
	2. Rule 2: In the Day-Ahead Market, If MW capacity offered for RRS, then the same MW capacity offer is also considered for Non-Spin (Option 1) or SOR (Option 2) at the same price as RRS if the QSE did not enter an offer price for Non-Spin (Option 1) or SOR (Option 2)
	3. Rule 3: In Real-Time, all SCED dispatchable capacity (LSL to HSL) for On-Line Resources considered to be offering Non-Spin (Option 1) or SOR (Option 2) at zero $/MW, this includes QSGR telemetering a status of ON, i.e. in Real-Time, On-Line Resources have mandatory participation in Non-Spin (Option 1) or SOR (Option 2).
	4. Rule 4: Develop exception rules where Resources can inform ERCOT of their inability to provide MW capacity for a particular AS. Is withdrawal of AS Offers or reduction in offered AS MW capacity an acceptable solution? If so, delete this rule.
2. From SAWG discussions on need to develop timeline for updating AS Offers and Energy Offers. There may be a need for additional telemetry to be used in conjunction with the AS offer to provide QSEs more flexibility.
3. Accounting for Resource providing "truly" Offline Non-Spin (Option 1) and NSOR (Option 2):

Should these Resources be exempt from AS Imbalance charges upon deployment?

Note - We do not do that currently with the ORDC price adder settlements.

1. Load Resource Deployment for RRS: Need to develop process to account and differentiate scenarios where RRS from LR is deployed versus failure to provide, etc. This has impact on the AS imbalance settlement
	1. What other metrics apart from following Base Points, GREDP are required?

Update based on SAWG discussions:

Load Resource (LR) with UFR carrying RRS Responsibility (blocky AS):

1. Upon deployment will be exempt from AS imbalance charge
2. In RT, LR with UFR carrying RRS responsibility will be considered to be price takers (i.e. RRS offer from these LR = 0$/MW). i.e. no reduction of RRS demand curve by the amount of RRS responsibility from Load Resources.
3. However, when deployed, LR will be considered to be still providing RRS till the 3 hour limit after recall.

Note 1: The above exemptions from AS Imbalance charges is a deviation from current practice

1. Stakeholder discussions will be required to develop methodology to share the ramp rates between energy and AS (similar to the ramp sharing between current Security Constrained Economic Dispatch or SCED and LFC).
2. When to use Emergency Ramp Rates? Only upon ERCOT notification?
3. No Make Whole payments if Resources financially harmed with respect to Day-Ahead positions due to RT energy+AS co-optimization.

SAWG Discussion on 2/25/2015:

Under Real-Time co-optimization when a Resource buys out of its Day ahead AS responsibility, the QSE representing the Resource could get financially harmed by the Real-Time imbalance settlement for energy and AS if it had made sales for AS from that Resource in the Day-Ahead Market. There are specific conditions under which this can occur:

1. System conditions are such that there is shortage/scarcity in one AS but surplus of capacity for energy. i.e. scarcity pricing for AS is not reflected in the energy prices (LMPs)

2. Resource is ramp constrained (how much it can move in 5 minutes) and the awards are limited by this. For example, if a Resource is generating energy at HSL and the next RT co-optimization results in a very high price for RRS, then the Resource MW award for RRS is how much it can be ramped down in 5 minutes.

3. QSE has made a sale of AS on this Resource in the Day-Ahead Market

Note: if a Resource has not made a Day-Ahead Sale for AS, then this scenario does not apply.

SAWG consensus to NOT have make-whole payments for this type of scenario.

For the proposed Future Ancillary Service product set, the determination of the statistical distribution parameters (mean and standard deviation) will need to convert the Hourly Reliability Unit Commitment or HRUC time snapshot of FFRS reserves and SCED snapshot of FFRS reserves into PFRS Reserve equivalents using the applicable ratio (R).

## Co-ordination of the Power Balance Penalty Curve, Maximum value of ORDC, and Value Of Lost Load (VOLL)

In scarcity conditions, the AS demand curves sets the AS MCPC, similar to how the Power Balance Penalty Curve sets LMPs in the energy market under scarcity conditions.

The design of a Real-Time energy and AS Co-optimization is such that the market clearing will ensure that serving the inelastic system demand for energy (GTBD) is given priority over reserving capacity for AS. This means that the relationship between the prices for energy (LMP) and AS (MCPC) are such that the awards (Base Points) to serve energy will be prioritized over awards for AS.

This will be achieved by setting the maximum value ($/MW/h) on the AS demand curves (one curve for each AS type) and coordinating these values with the maximum value of the Power Balance Penalty Curve for energy. AS demand curves will be based on the ORDC.

This co-ordination ensures that in the worst case scenario, the minimum excess revenue a supplier can receive from energy sales (LMP minus EOC) is greater than the maximum excess revenue the supplier could receive from the sale of AS (MCPC minus AS Offer).

Excess revenue per MWh of energy award, over and above the submitted EOC from the sale of energy, is (in $/MWh)

LMP – EOC

Excess revenue per MW of AS award, over and above the submitted AS Offer from the sale of AS, is (in $/MW/h)

MCPC – AS Offer

Thus, in a worst case scenario, a supplier’s minimum excess revenue per MWh of energy sales occurs when the Power Balance Penalty curve sets the energy price (LMP) and the supplier has submitted its EOC at System Wide Offer Cap or SWOC, as follows:

Minimum Excess Revenue per MWh of energy award =

Maximum value of Power Balance Penalty Curve minus SWOC =

VOLL+1 – SWOC

Similarly, in a worst case scenario, a supplier’s maximum excess revenue per MW/h of AS sales occurs when the AS demand curve sets the AS price (MCPC) and the supplier has submitted its AS Offer at 0 $/MW/h, as follows:

Maximum Excess Revenue per MW/h of AS award =

Maximum value of ORDC minus AS Offer of 0$/MW/h =

Maximum value of ORDC

Therefore, the design parameters should be such that the maximum excess revenue per MW/h of AS award is less than minimum excess revenue per MWh of energy award, as follows:

Maximum Value of ORDC < VOLL+1-SWOC

The figure below lists the maximum value of ORDC possible for different values of VOLL, SWOC and maximum value on the PBPC.

Table 2: Table of various combinations to set the maximum price ($/MW/h) on the AS Demand Curve

|  |  |  |  |
| --- | --- | --- | --- |
| VOLL($/MWh) | SWOC($/MWh) | Maximum PBPC ($/MWh) | Maximum value of ORDC ($/MW/h) |
| 9000 | 9000 | 9001 | 0.99 |
| 9000 | 7000 | 9001 | 2000.99 |
| 9000 | 1000 | 9001 | 8000.99 |
| 18000 | 9000 | 18001 | 9000.99 |

Note: The top row represents current VOLL and SWOC as established in PUCT and ERCOT market rules. Values for VOLL and/or SWOC in the lower rows would require changes to PUCT and/or market rules.

# Multi-Interval Real-Time Market

The main objectives of the proposed Multi-Interval Real-Time (RT) Market are to enable additional Resources to contribute to Real-Time price formation and to expand access to the Real-Time Energy Market, thus enhancing competition and lowering overall costs to Load-serving Entities.

This enhancement would enable the Real-Time Market to, apart from considering offers and bids from the existing portfolio of Resources, to also consider offers and bids from other Resources that can be committed and/or dispatched only in blocks of MWs and that may have time-related (temporal) constraints. This is achieved by allowing the Real-Time Market to analyze, in conjunction with current system conditions (GTBD) for the current five-minute interval, also the forecasted system conditions (STLF) for consecutive future five-minute intervals, up to a maximum of 30 minutes out.

This could enable increased participation in the Real-Time Market by Load Resources with the following attributes:

1. Resources with temporal constraints, including but not limited to start-up times or ramp periods longer than the current 5-minute SCED, minimum or maximum run times, or return-to-service times;
2. Resources that are “blocky” and therefore unable to deliver incremental fractions of their offers or bids, as is required of marginal units under current SCED parameters.

In the Multi-Interval RT market, Locational Marginal Prices (LMPs) and AS MCPCs (if Multi-Interval RT Market includes RT Co-optimization) would be binding for only the first (current) five-minute interval. In addition, Commitment Instructions issued by the Multi-Interval RT Market would be binding. Resources committed based on forecasted future conditions would be eligible for make-whole payments if actual Real-Time binding prices left them insufficiently compensated.

This section provides a high-level description of the concepts involved in a Multi-Interval RT Market. This description of the Multi-Interval RT Market is from the perspective of not considering RT Co-optimization. Where applicable, notes are added to inform the reader of the impacts of including RT Co-optimization.

## High Level Description of the Inputs, Clearing Process and Outputs

The Multi-Interval RT Market is cleared (normally) every 5-minutes, in which, the market clearing process considers a set of consecutive 5-minute intervals, of up to a maximum of 30 minutes, starting with the current 5-minute interval.

This market clearing process is similar to a DAM process in that multiple intervals (24 hourly intervals in the DAM and up to 6 five-minute intervals here) are simultaneously optimized. One of the major differences is the consideration of Resource Ramp Rates in the Multi-Interval RT Market clearing process. This is required to ensure that the awarded energy Base Points (and if RT Co-optimization is included, the awarded AS) are feasible.

The inputs to setup the data for the current (first) five-minute interval of a given market clearing process in the Multi-Interval RT market will be the same as the current single interval SCED — i.e., based on telemetry. To set up necessary data for the future five-minute intervals, additional information will be used, notably:

1. Short-Term Load Forecast – to setup the energy demand for the future intervals under analysis
2. eTag data – to setup the total DC-Tie export/import to be added to the total energy demand for future intervals

More discussions will be required to decide, when setting up necessary data for future 5-minute intervals, on whether to persist current telemetered data on Resources for Status, Limits (HSL, LSL), Output Schedule, etc. or to consider Current Operating Plan or COP data and wind forecast data (if available with a 5-minute granularity for Wind Resource HSLs).

More discussions will also be required on the modeling of Resources with telemetered Status of Start Up or Shut Down for future 5-minute intervals for a given instance of a RT market clearing.

The outputs of each Multi-Interval Market clearing are:

1. Binding energy Base Points and LMPs for the current (first) 5-minute interval
	1. If RT Co-optimization is included, then, Binding AS awards and MCPCs for the current (first) 5-minute interval;
2. Binding commitment instructions for Resources (e.g. Load Resource curtailment instructions) at the start of any 5-minute interval (including current 5-minute interval) in the analysis window of up to a maximum of 30 minutes and
3. Advisory or indicative Base Points and LMPs for the future 5-minute intervals
	1. If RT Co-optimization is included, then also include, advisory or indicative AS awards and MCPCs for the future 5-minute intervals

The figure below illustrates a sequence of Multi-Interval RT Market clearing.

Figure 3: Multi-Interval RT Market Overview

*8:40 8:45 8:50 8:55 9:00 9:05 9:10 9:15 9:20 9:25 9:30 9:35*

Intervals where **ONLY** Commitment Instructions are **binding** and the LMPs and MW awards (energy, AS) are **indicative**

Interval where the LMPs, MW awards (energy, AS) and Commitment Instructions are **ALL** **binding** commitment instructions

Sequence of Multi-Interval RT Markets

Analysis window of rolling 30 minutes

RT Market Execution: Depicts the start and end times of the clearing process and the length of symbol is indicative of maximum time allowed to clear market

### Execution/Run Times for Multi-Interval RT Market Clearing

The hardware and software implemented to clear the market should be such that the execution/run time is shortened as much as possible.

### Transmission Constraints

Transmission constraints to be considered are input to the Multi-Interval RT Market clearing process via the Transmission Constraint Manager or TCM as they are now. Transmission constraint data is persisted for the entire analysis time frame. Further discussion will be required to determine how to integrate known future topology changes into TCM in order for potential transmission constraints in the near future to be considered by the Multi-Interval RT Market.

### Short Term Load Forecast

The accuracy of the short term load forecast is critical for proper functioning of the Multi-Interval RT Market. It will be necessary to setup the required metrics on short term load forecasting in order to monitor and measure its performance. Forecasting system demand will never be perfect; consensus must be achieved on a definition of what is ‘good enough’.

### Wind Forecasting

The accuracy of the short term wind forecast is also important for a proper functioning of the Multi-Interval RT Market — specifically translating to the setup of the Wind Resources’ HSL in future five-minute intervals. Determining appropriate required metrics will be critical. Forecasting Wind Resource HSL will never be perfect; consensus must be achieved on a definition of what is ‘good enough’.

### Multi-Interval RT Market analysis window

This concept paper contemplates the use of an analysis window of 30 minutes divided into 6 five-minute intervals. Based on discussions with stakeholders this can be changed and is dependent on the accuracy of the Short Term load Forecast and Wind Forecast.

### Pricing Run Changes (modifications to NPRR 626)

The pricing run as described in NPRR 626 (Reliability Deployment Price Adder) will continue to be used in the proposed Multi-Interval RT Market. It will be setup to treat each five-minute interval in the analysis window separately.

The following modifications to the pricing run will be required:

1. Enabling ‘blocky MW’ committed by the Multi-Interval RT Market clearing process to participate in price formation. This treatment is similar to how Load Resources deployed for RRS are handled in the current market, with the exception that the strike price for their energy is submitted by the QSE representing the committed Resource.
2. Enabling ramp-constrained Resources to participate in price formation.

The primary objective of the pricing run will remain the same; that is, to determine the positive change to System Lambda when Load Resources, out-of-market reliability or ‘blocky” MWs, or ramp-constrained Resource deployments occur. This positive change to System Lambda is added to all original energy prices (LMPs) and the same positive change to System Lambda is added to the original ORDC price adder. (The change would also be added to original MCPCs if RT Co-optimization is included).

## Three Part Offer/Bid or Single Part Offer/Bid from a Load Resource

Further discussions will be required to determine what the components of a Three Part Offer or Bid from a Load Resource would mean; whether there is a need for validation; and whether a single part offer or bid from a Load Resource would be the preferred approach for simplicity.

The use of Offers to sell from a Load Resource will depend on the resolution of “LMP-G” discussions underway at the Demand Side Working Group (DSWG).

## Settlements

The changes to settlement that are directly attributed to the proposed Multi-interval RT Market are new potential Make-Whole payments to Resources, and potential uplift to consumers to cover the Make-Whole payments to Resources.

If RT Co-optimization is included then the Settlement section of the RT Co-optimization description in this document describes the necessary settlement changes

### What Are the Make-Whole Payments That May be Necessary For Resources?

The Multi-Interval RT Market will require two categories of Make-Whole Payments.

**Resources that are ramp-constrained and are awarded a binding Base Point that is uneconomical for them.** The impact of considering Resource Ramp Rates may, in some scenarios, lead to a Resource being awarded a binding Base Point and corresponding binding LMP for the first (current) 5-minute interval that is not consistent with its EOC. For example, when the clearing process awards a higher Base Point to a Resource with a high ramp rate and a higher EOC to catch the increased forecasted (future) demand for energy in comparison to the Base Point this Resource would have been awarded in a single interval SCED. In such cases, this Resource is eligible for Make-Whole payments for the intervals (with binding Base Point and LMP) in which the Resource is ramp-constrained.

**Resources that are committed for a future interval and, after following the commitment instruction, the binding RT LMPs (and MCPCs) for that interval are uneconomical for them.** A Resource could be issued and successfully follow a commitment instruction only to experiences binding RT prices (LMPs and MCPCs) that are uneconomical due to forecast errors. In such cases, this Resource would be eligible for a Make-Whole payment. The Resource that was issued a commitment instruction would be made whole for X 5-minute intervals (where X=3,4,5,6 5-minute intervals?). The Resource’s QSE will need to factor in the maximum duration of the Make-Whole payment in its Resource Offer or Bid.

The pricing run should mitigate the magnitude of the Make-Whole payments and associated uplift to consumers.

Current market design Make-Whole provisions to Resources may still apply (e.g. Emergency Base Point Settlements).

Further discussion will be required on this topic as well as potential alternative approaches to uplift.

### Is There Any Uplift Required?

Make-Whole payments to Resources that are either ramp-constrained or Resources following commitment instructions that turn out to be uneconomical will inevitably result in market uplift. As noted earlier, the pricing run should mitigate the magnitude of the Make-Whole payments and reduce the amount of uplift required.

Alternative approaches to uplift may be considered.

# Appendix 1: High Level Mathematical Formulation of energy and AS Co-Optimization for Option 2

The simplified formulation of the optimization problem (objective, constraints, pricing analysis) is presented below where energy and the various AS products are co-optimized in both Day-Ahead and Real-Time Markets.

Simplifications:

1. Transmission constraints in both Day-Ahead and Real-Time, PTPs, block offers and bids in Day-Ahead are not considered
2. Constraints on how much AS can be awarded to a single resource based on a % of HSL or ramp capability are not considered
3. are the submitted bids ($/MWh), energy offers ($/MWh), AS offers ($/MW) respectively. For simplicity, these bids and offers are considered to be constant for the entire MW bid or offered.
4. In the Day-Ahead Market, Resources must submit offers to sell energy and AS (all the types) in order to be awarded.
5. The equations below are describing the modified approach. If the reader is interested in the equations for the original approach in the concept paper, then in the equations below:
	1. Consider SOR offers (spinning operating reserve) as Non-Spin (both On-Line and Off-Line)
	2. Replace the demand curve for SOR with Non-Spin demand curve.
	3. Remove terms with NSOR (non-spinning operating reserve) – off-line non-spin is already included in (v) a. above.

**Day-Ahead Market Objective Function:**

**Real-Time Market Objective Function:**

**Subject to:**

Ignoring transmission constraints and focusing on power balance, AS procurement and the main Resource limit constraints, the set of constraints are given below:

**System wide constraints:**

1. Power Balance: (Shadow price = )

**Day-Ahead:**

**Real-Time:**

1. Reg-Up Procurement (including FRRS-Up): (Shadow price = )
2. FRRS-Up maximum procurement limit: (Shadow price = )
3. Reg-Down Procurement (including FRRS-Down): (Shadow price = )
4. FRRS-Down maximum procurement limit: (Shadow price = )
5. RRS Procurement: (Shadow price = )
6. RRS maximum procurement from “blocky” Load Resource: (Shadow price = )
7. SOR Procurement: (Shadow price = )
8. NSOR Procurement: (Shadow price = )

**Individual Energy Bid constraints:**

1. Energy Bid MW constraint for every energy bid : (Shadow price = respectively)

**Individual Resource constraints:**

Each Resource will have its own set of constraints to ensure awards are within bounds of its own upper (HSL/MPC) and low (LSL/LPC) limits.

1. LSL Constraint for every modeled Generation Resource : (Shadow price = )
2. HSL Constraint for every modeled Generation Resource : (Shadow price = )

On-Line:

Off-Line:

1. AS Offer MW constraint for every modeled Generation Resource : (Shadow price = respectively)

On-Line:

Off-Line:

1. MPC & LPC Constraint for every modeled “Blocky” Load Resource : (Shadow price = )

Note that a “blocky” Load Resource is awarded only one AS product.

or

1. AS Offer MW constraint for every modeled “Blocky” Load Resource : (Shadow price = )

or

1. MPC & LPC Constraint for every modeled Controllable Load Resource : (Shadow price = )
2. AS Offer MW constraint for every Controllable Load Resource : (Shadow price = respectively)
3. HSL & LSL Constraint for every “Quick/Fast” Resource qualified for FRRS-Up and FFR1 and partly modeled as Generation Resource : (Shadow price = )
4. AS Offer MW constraint for every “Quick/Fast” Resource qualified for FRRS-Up and FFR1 and partly modeled as Generation Resource : (Shadow price = )
5. MPC & LPC Constraint for every “Quick/Fast” Resource qualified for FRRS-Up, FRRS-Down and RRS and partly modeled as Controllable Load Resource : (Shadow price = )
6. AS Offer MW constraint for every “Quick/Fast” Resource qualified for FRRS-Up and FRRS-Down and partly modeled as Controllable Load Resource : (Shadow price = respectively)

**Lagrangian Function:**

The objective and constraints are combined to form the Lagrange function:

At optimal solution (optimality condition)

i.e. the partial derivative of with respect to each award

 and the shadow prices will equate to zero at the optimal solution.

 Taking the partial derivative of with respect to each award

and rearranging the terms by

we get:

1. **Day Ahead:** For each energy bid , the following equation holds true

If the energy bid *i* is marginal to the power balance constraint, then and the energy bid *i* sets the shadow price for the power balance constraint (System Lambda )

**Real-Time:** If the Power Balance Penalty Curve is marginal to energy, the following equation holds true and the Power Balance Penalty Curve sets the shadow price for the power balance constraint (System Lambda ):

1. For each energy offer from modeled Generation Resource , the following equation holds true

If the energy offer *i* is marginal to the power balance constraint, then, and the energy offer *i* sets the shadow price for the power balance constraint (System Lambda )

1. For each Reg-Up offer from modeled Generation Resource , the following equation holds true

If the Reg-Up offer *i* is marginal to the Reg-Up Procurement constraint, then in most cases, and the Reg-Up Offer *i* sets the shadow price for the Reg-Up Procurement constraint ( this is the Reg-Up MCPC )

1. For each Reg-Down offer from modeled Generation Resource , the following equation holds true

If the Reg-Down offer *i* is marginal to the Reg-Down Procurement constraint, then, in most cases, and the Reg-Down Offer *i* sets the shadow price for the Reg-Down Procurement constraint ( this is the Reg-Down MCPC )

1. For each RRS offer from modeled Generation Resource , the following equation holds true

If the RRS offer *i* is marginal to the RRS Procurement constraint, then, and the RRS Offer *i* sets the shadow price for the RRS Procurement constraint (this is the RRS MCPC )

1. For each SOR offer from modeled Generation Resource , the following equation holds true

If the SOR offer *i* is marginal to the SOR Procurement constraint, then, .

Please note that the MCPC for SOR is the sum of the shadow price for the SOR and NSOR () procurement constraints.

1. For each NSOR offer from modeled offline Generation Resource , the following equation holds true

If the NSOR offer *i* is marginal to the SNSOR Procurement constraint, then, .

Note that the MCPC for NSOR is the shadow price for the NSOR procurement constraint

1. For each RRS offer from modeled “blocky” Load Resource , the following equation holds true

If the RRS offer *i* is marginal to the RRS Procurement constraint, then, and the RRS Offer *i* sets the shadow price for the RRS Procurement constraint (this is the RRS MCPC )

Note that if the RRS offer MW is submitted as a **block**, then, this offer **cannot** set the MCPC

If the RRS maximum procurement constraint from “blocky” Load Resource is binding then . In this case the MCPC for RRS is still the shadow price of the RRS procurement constraint () and the RRS awards to “blocky” Load Resources will be paid this price

1. For each SOR offer from modeled “blocky” Load Resource , the following equation holds true

If the SOR offer *i* is marginal to the SOR Procurement constraint, then, and the SOR Offer *i* sets the shadow price for the SOR Procurement constraint (this is the SOR MCPC )

Note that if the SOR offer MW is submitted as a **block**, then, this offer **cannot** set the MCPC

1. For each Reg-Up offer from modeled Controllable Load Resource , the following equation holds true
2. For each Reg-Down offer from modeled Controllable Load Resource , the following equation holds true
3. For each RRS offer from modeled Controllable Load Resource , the following equation holds true
4. For each SOR offer from modeled Controllable Load Resource , the following equation holds true
5. For each FRRS-Up offer from “Quick/Fast” Resource partly modeled as Generation Resource , the following equation holds true

If the FRRS-Up offer *i* is marginal to the Reg-Up Procurement constraint, then, and the FRRS-Up Offer *i* sets the shadow price for the Reg-Up Procurement constraint (this is the Reg-Up MCPC )

If the FRRS-Up maximum procurement constraint from “Quick/Fast” Resource is binding then . In this case the MCPC for Reg-Up is still the shadow price of the Reg-Up procurement constraint () and the FRRS-Up awards to “Quick/Fast” Resources will be paid this price

1. For each FRRS-Up offer from “Quick/Fast” Resource partly modeled as Load Resource , the following equation holds true

If the FRRS-Up offer *i* is marginal to the Reg-Up Procurement constraint, then, and the FRRS-Up Offer *i* sets the shadow price for the Reg-Up Procurement constraint (this is the Reg-Up MCPC )

If the FRRS-Up maximum procurement constraint from “Quick/Fast” Resource is binding then . In this case the MCPC for Reg-Up is still the shadow price of the Reg-Up procurement constraint () and the FRRS-Up awards to “Quick/Fast” Resources will be paid this price

1. For each FRRS-Down offer from “Quick/Fast” Resource partly modeled as Load Resource , the following equation holds true

If the FRRS-Down offer *i* is marginal to the Reg-Down Procurement constraint, then, and the FRRS-Down Offer *i* sets the shadow price for the Reg-Down Procurement constraint (this is the Reg-Up MCPC )

If the FRRS-Down maximum procurement constraint from “Quick/Fast” Resource is binding then . In this case the MCPC for Reg-Down is still the shadow price of the Reg-Down procurement constraint () and the FRRS-Up awards to “Quick/Fast” Resources will be paid this price

Note: If there is scarcity in any of the AS (Reg-Up, Reg-Down, RRS, SOR and NSOR), then the demand curves prices at the last cleared MW AS demand on the respective demand curves will set the Shadow Prices of the applicable procurement constraints.

**MCPC formula (from shadow prices)**

|  |  |  |
| --- | --- | --- |
| AS Product | MCPC | Comments |
| Reg-Up  |  | Shadow price of the Reg-Up procurement (including FRRS-Up) constraint |
| FRRS-Up |  | FRRS-Up is valued the same as Reg-Up |
| Reg-Down  |  | Shadow price of the Reg-Down procurement (including FRRS-Down) constraint |
| FRRS-Down |  | FRRS-Down is valued the same as Reg-Down |
| RRS |  | Shadow Price of the RRS procurement constraint |
| SOR |  | Sum of the Shadow Prices of the SOR and NSOR procurement constraints |
| NSOR |  | Shadow Price of the NSOR procurement constraint |

1. The term Production Costs refers to the use of submitted Energy Offer Curves, AS Offers, and Energy Bid Curves (if applicable) and any associated mitigation of the Energy Offer Curves due to transmission congestion. [↑](#footnote-ref-1)
2. The term Production Costs refers to the use of submitted Energy Offer Curves, AS Offers, and Energy Bid Curves (if applicable) and any associated mitigation of the Energy Offer Curves due to transmission congestion. [↑](#footnote-ref-2)