Flexible Ramping Product
Technical appendix working group

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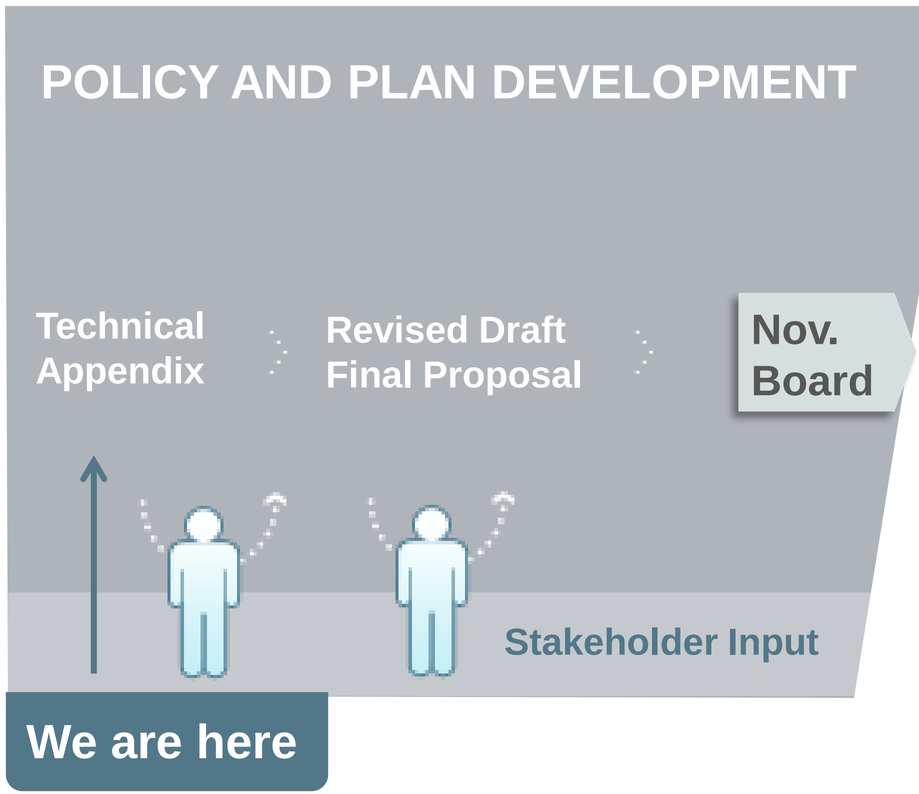
Stakeholder Working Group Agenda – 6/17/15

Time	Topic	Presenter
10:00 – 10:10	Introduction and updates to the initiative	Carrie Bentley
10:10 – 10:45	Flexible ramping product objective	George Angelidis and Carrie Bentley
10:45 – 11:15	Histogram construction	
11:15 – 11:45	Flexible ramping product requirement	
11:45 – 12:00	Flexible ramping resource constraints	
12:00 – 1:00	Lunch	
1:00 – 2:00	Flexible ramping product examples	Lin Xu
2:00 – 2:15	Break	
2:15 – 2:45	Settlements and Cost Allocation	Carrie Bentley
2:45 – 2:55	BARR Tool	
2:55 – 3:00	Next steps	Kristina Osborne

ISO Policy Initiative Stakeholder Process



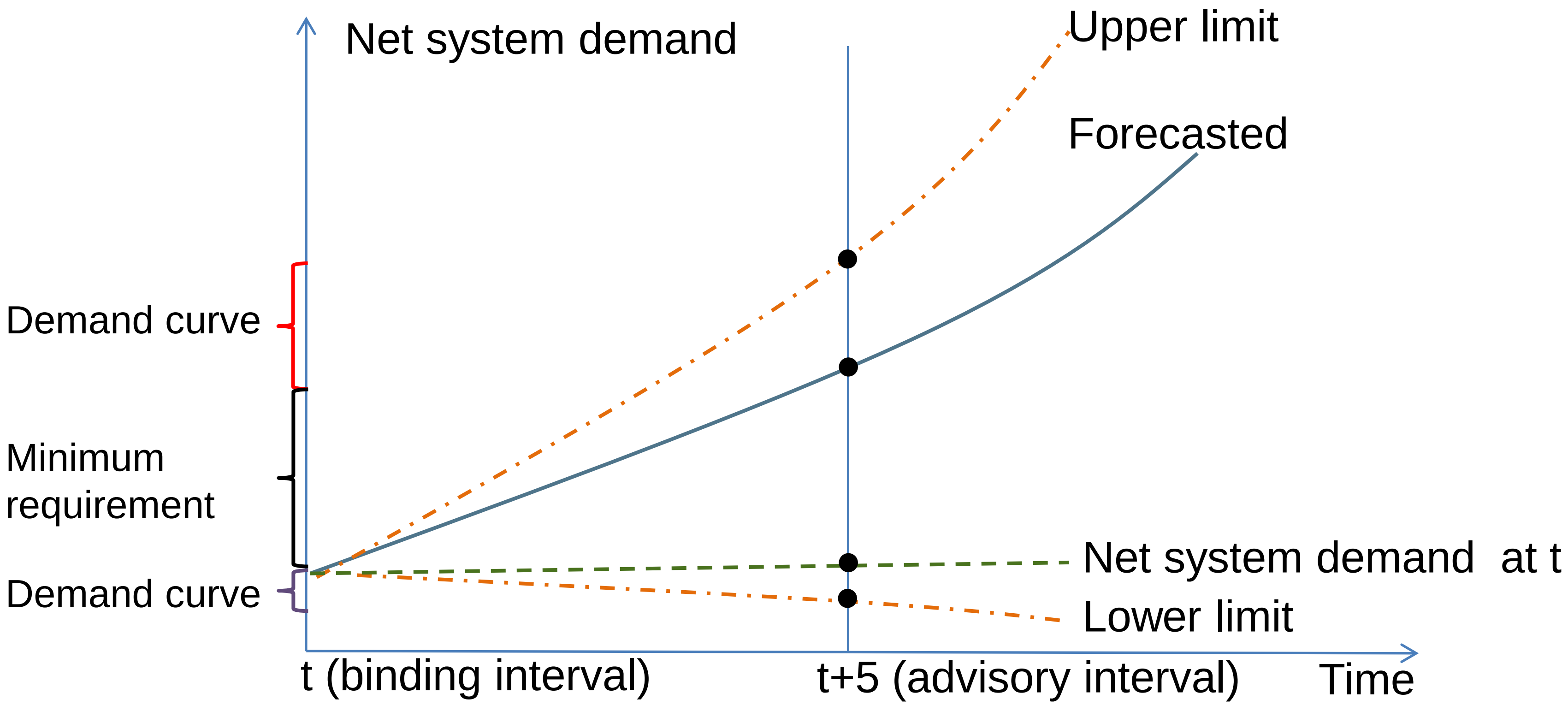
Updates on Flexible Ramping Product

- The ISO will not procure FRP in the day-ahead market
- Clarifications and enhancements have been made to:
  - formulation of the flexible ramping product
  - histogram and demand curve construction
- The ISO has simplified the “no pay” proposal and modeled the rules to be more similar to energy settlement rather than ancillary services settlement
- Data is expected to be released in Q3 2015
- The new target BOG date is November

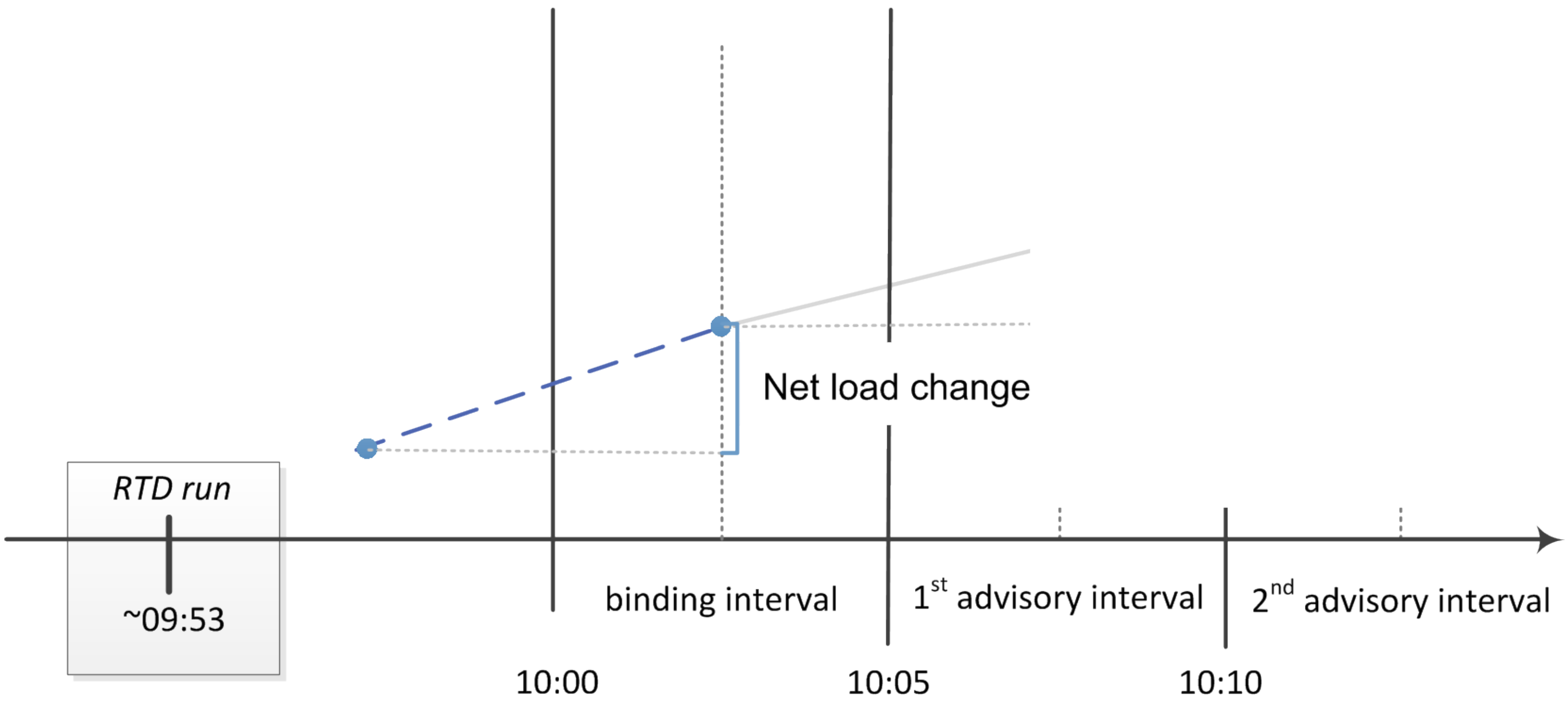
Flexible Ramping Product

- FRP will help the system to maintain and use upward and downward dispatchable capacity
- It will be dispatched to meet five minute to five minute net system demand changes and will be modeled as a ramping capability constraint
  - FRP will meet real ramping need and load forecast uncertainty
- Both real time dispatch (RTD) and real time unit commitment (RTUC) will schedule FRP throughout their dispatch horizon

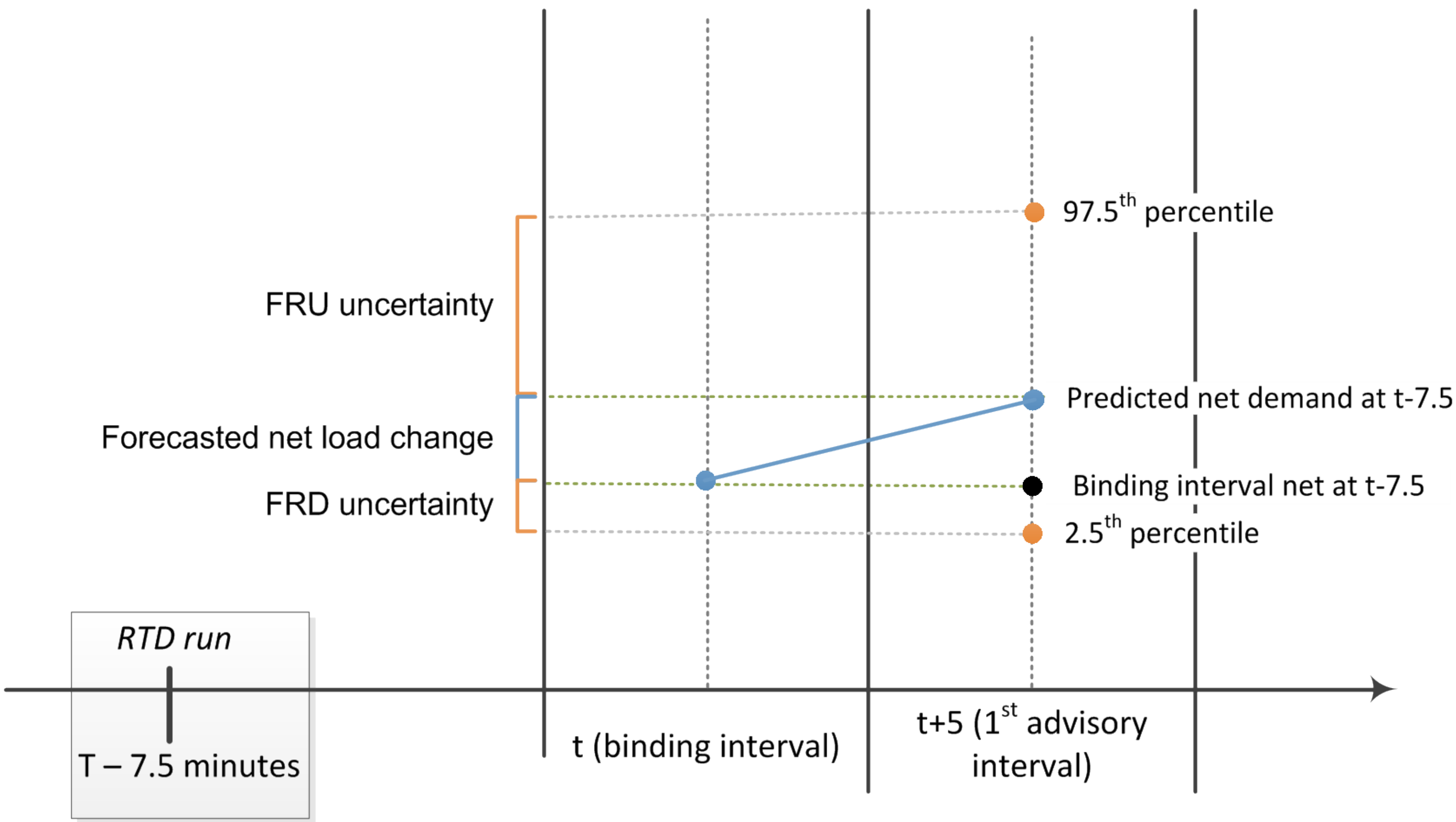
Flexible Ramping Product to meet real ramping need



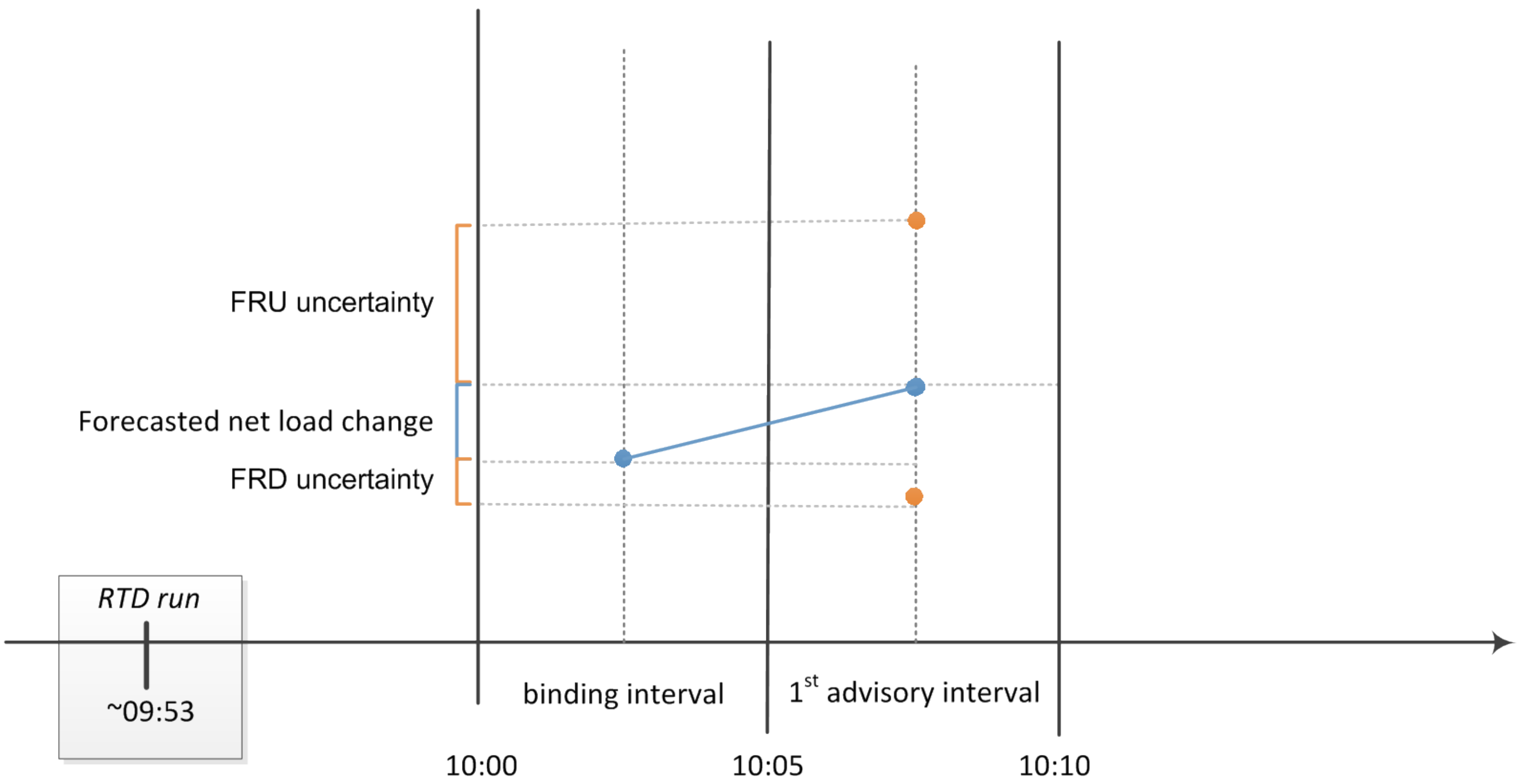
RTD: binding interval net load change and advisory runs



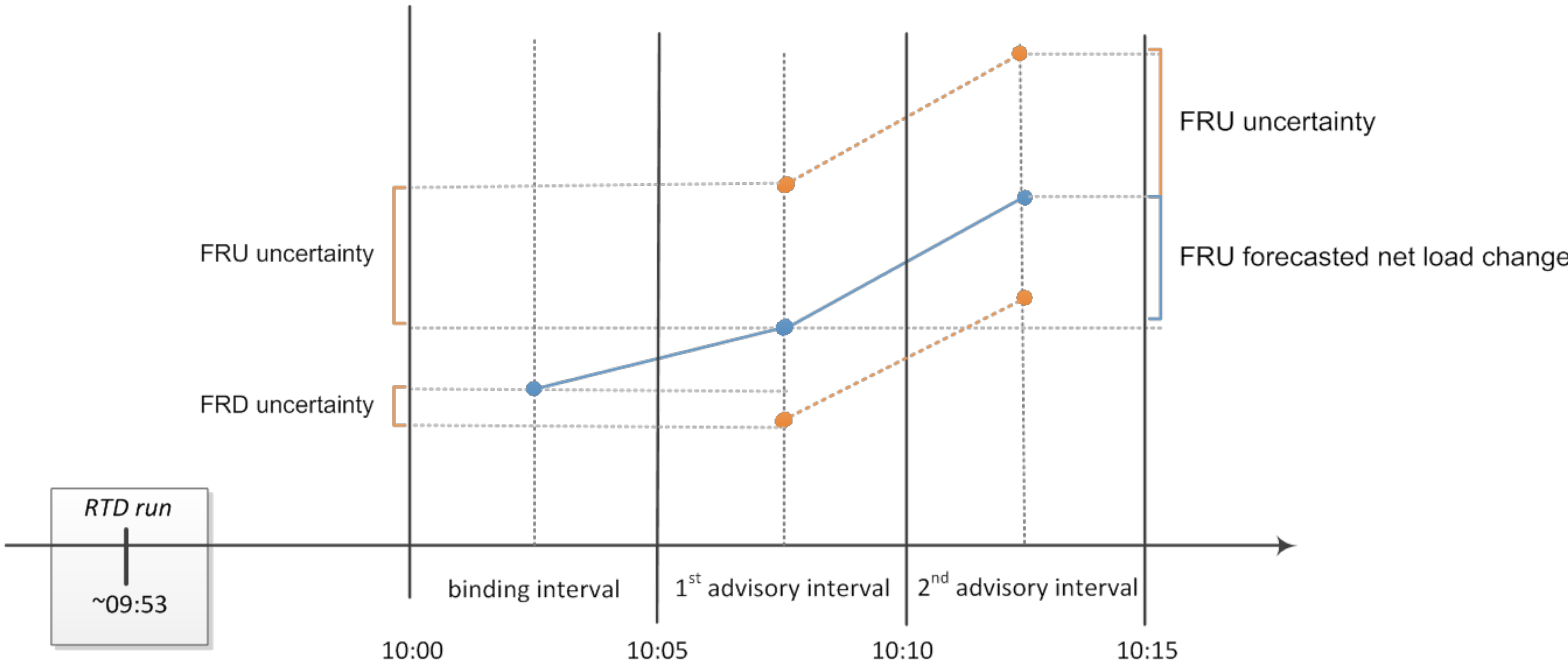
Flexible Ramping Product updated depiction



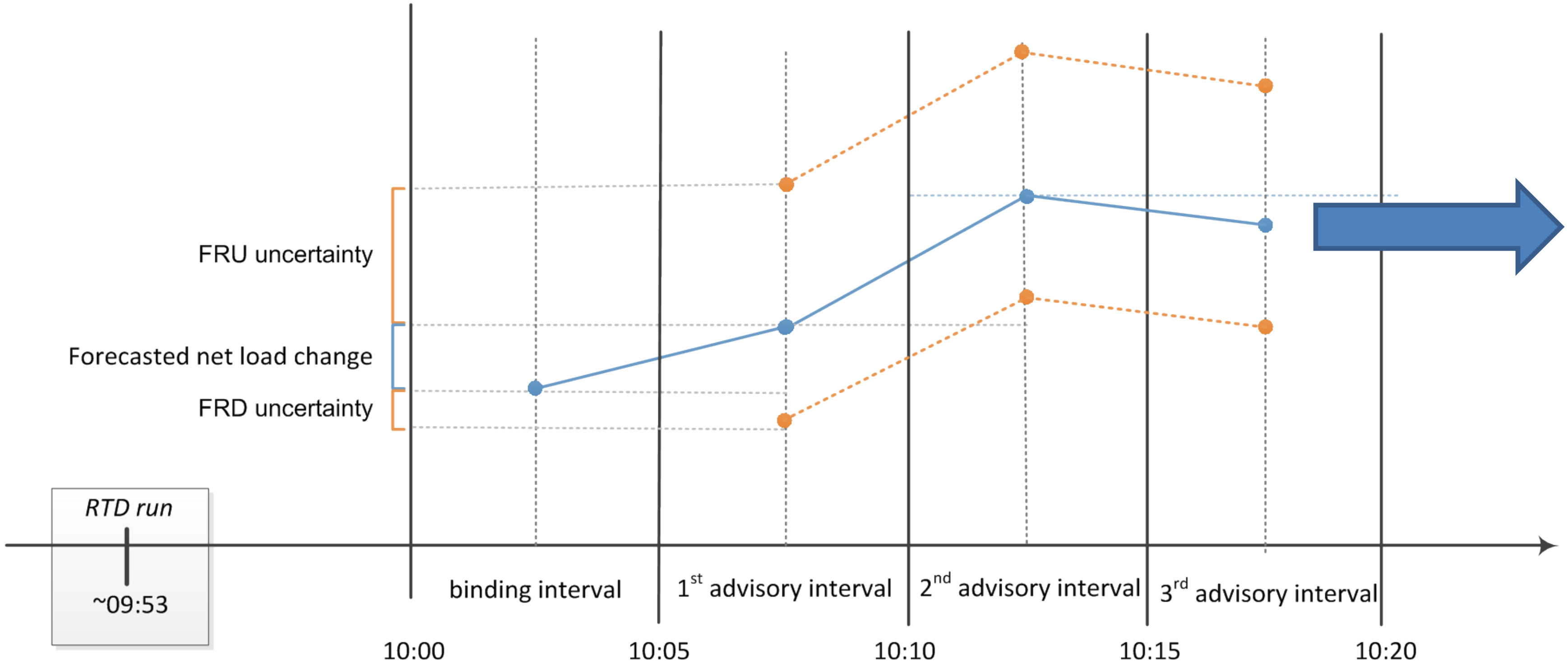
Flexible Ramping Product updated depiction



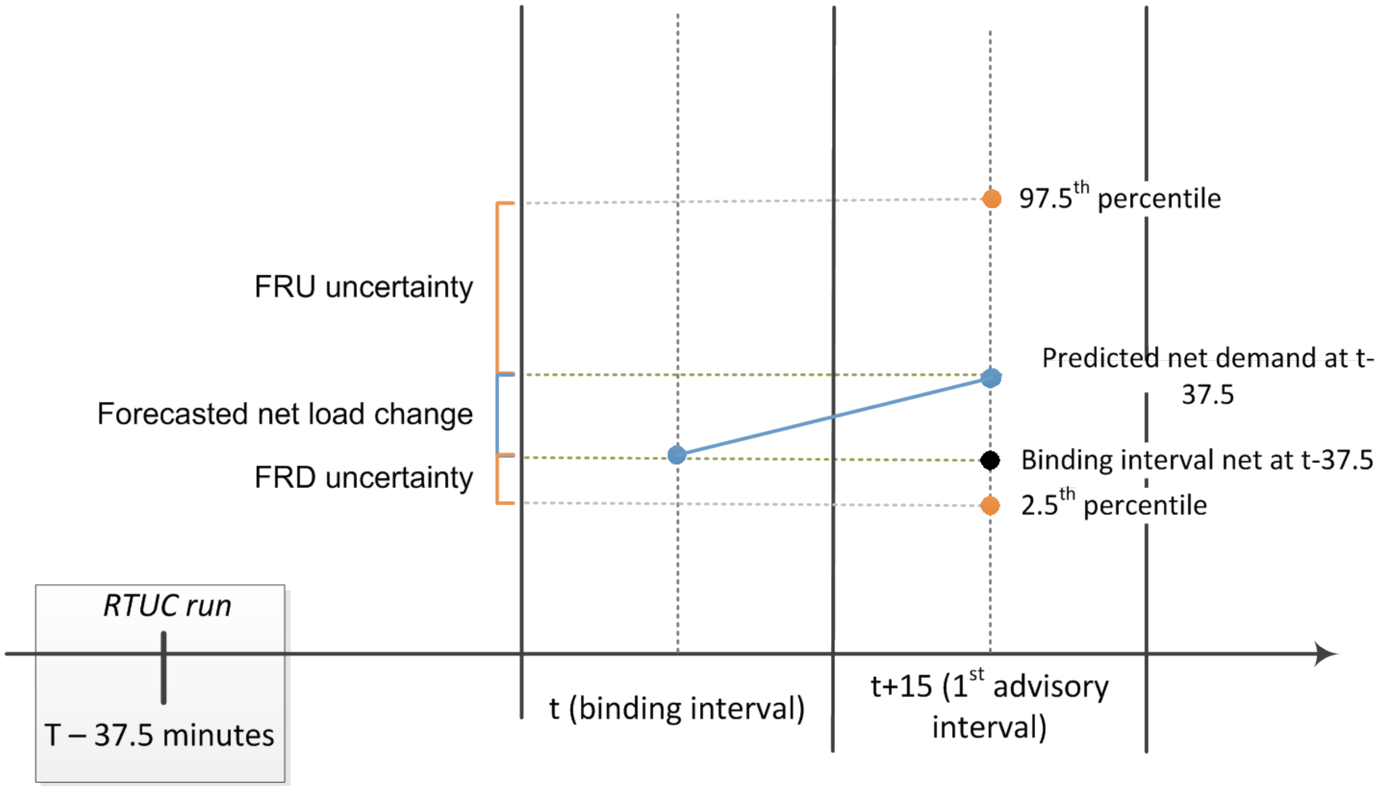
Flexible Ramping Product updated depiction



Flexible Ramping Product updated depiction



Flexible Ramping Product RTUC



OBJECTIVE FUNCTION

Objective Function

- The FRP will be procured to meet the predicted net demand variation and uncertainty requirements using a demand curve at the cost of expected power balance violations in absence of FRP

$$C = \cdots + \sum_{t=1}^{N} \int_{0}^{FRUS_t} C\dot{S}U_t(FRUS_t)\, de + \sum_{t=1}^{N} \int_{0}^{FRDS_t} C\dot{S}D_t(FRDS_t)\, de$$

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Objective Function

- The surplus variable is used to determine the expected cost of not procuring a portion of the uncertainty

$$\left.\begin{aligned} CSU_t(FRUS_t) &= PC \int_{EU_t - FRUS_t}^{EU_t} e\, p_t(e)\, de\,, 0 \le FRUS_t \le FRUR_{Ut} \\ CSD_t(FRDS_t) &= PF \int_{ED_t}^{ED_t - FRDS_t} e\, p_t(e)\, de\,, 0 \ge FRDS_t \ge FRDR_{Ut} \end{aligned}\right\}, t = 1,2,\dots, N$$

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Objective Function

- And the incremental FRU/FRD surplus cost function is extended to the total flexible ramp requirement:

$$\left.\begin{array}{l} C\dot{S}U_t(FRUS_t) = C\dot{S}U_t(FRUR_{Ut}), FRUR_{Ut} < FRUS_t \leq FRUR_t \\ C\dot{S}D_t(FRDS_t) = C\dot{S}D_t(FRDR_{Ut}), FRDR_{Ut} > FRUS_t \geq FRDR_t \end{array}\right\}, t = 1,2, \ldots, N$$

FLEXIBLE RAMPING PRODUCT REQUIREMENT

Flexible Ramping Product Requirement

- The binding interval’s market run enforces a constraint for the predicted net demand variation and net demand uncertainty between each consecutive interval in the market run

Flexible Ramping Product Requirement

- The binding interval's market run enforces a constraint for the predicted net demand variation and net demand uncertainty between each consecutive interval in the market run

$$\left.\begin{array}{l} FRUR_t = FRUR_{\mathrm{ND}t} + FRUR_{\mathrm{U}t} \\ FRDR_t = FRDR_{\mathrm{ND}t} + FRDR_{\mathrm{U}t} \end{array}\right\}, t = 1,2, \ldots, N$$

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Flexible Ramping Product Requirement

- The forecast net load change in FRP is the forecasted real ramping need between intervals
- For each binding interval, the market will use the requirement below to procure enough flexible ramping need to meet the forecasted net demand in the next advisory interval

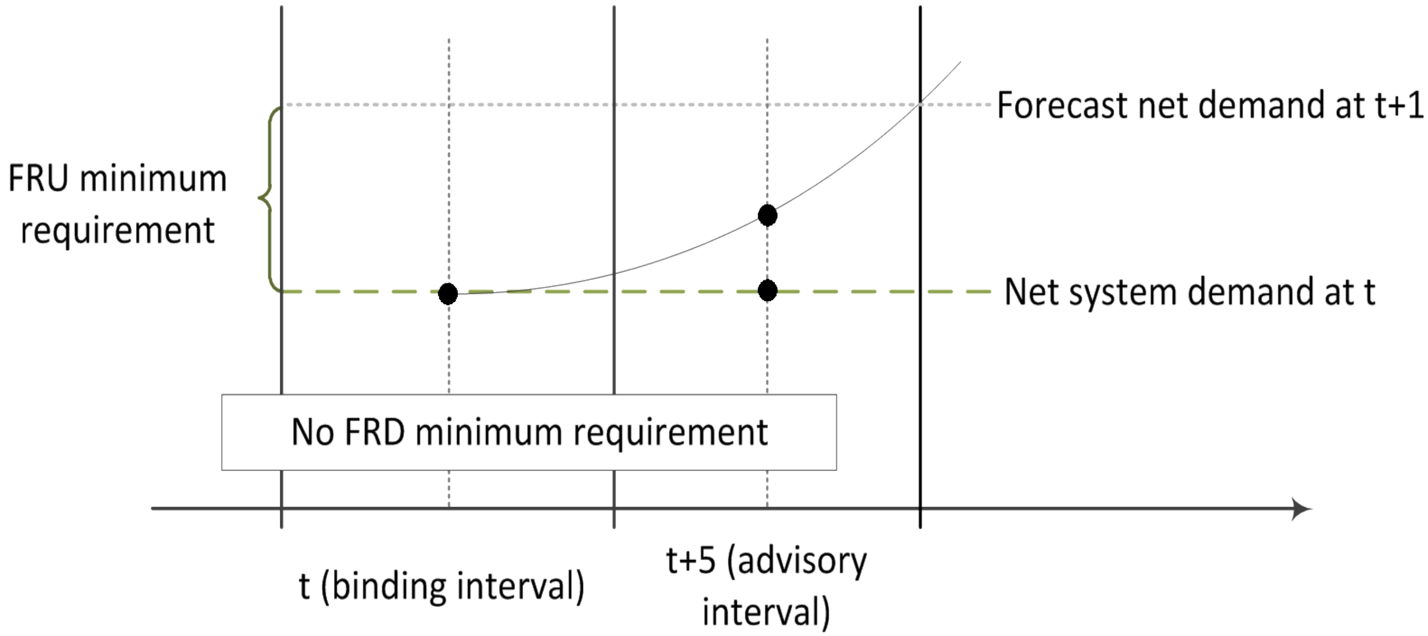
$$\left.\begin{aligned} FRUR_{\mathrm{ND}t} &= \max(0, \Delta ND_t) \\ FRDR_{\mathrm{ND}t} &= \min(0, \Delta ND_t) \end{aligned}\right\}, t = 1,2,\ldots,N$$

Where: $\Delta \mathrm{ND}_{\mathrm{t}} = ND_{t+1} - ND_t$

$and\ t = -1$ is the initial condition

Flexible Ramping Product Requirement

- The minimum flexible ramp requirement is the forecasted real ramping need between intervals



Flexible Ramping Product Requirement

- The ISO market will procure additional flexible capacity using demand curve based on net demand forecast uncertainty
- If the supply price is lower, FRP will be procured closer to the maximum ramping requirement. If the supply price is higher, FRP will be procured closer to the minimum requirement

Flexible Ramping Product Requirement

$$\left.\begin{array}{l} FRUR_{Ut} = \max\left(0, EU_t + FRDR_{\mathrm{ND}t}\right) \\ FRDR_{Ut} = \min\left(0, ED_t + FRUR_{\mathrm{ND}t}\right) \end{array}\right\}, t = 1,2, \dots, N$$

Where:

$$\left.\begin{array}{l} EU_t = \max(0, PU_t) \\ \int_{-\infty}^{PU_t} p_t(\varepsilon)\, d\varepsilon = CLU \end{array}\right\}, t = 1,2, \dots, N$$

$$\left.\begin{array}{l} ED_t = \min(0, PD_t) \\ \int_{-\infty}^{PD_t} p_t(\varepsilon)\, d\varepsilon = CLD \end{array}\right\}, t = 1,2, \dots, N$$

Flexible Ramping Product Requirement

- The FRU and FRD minimum requirements plus the FRU and FRD demand curve requirements will equal the FRU and FRD total requirements

$$\left.\begin{aligned} \sum_i FRU_{i,t} + FRUS_t = FRUR_t \\ \sum_i FRD_{i,t} + FRDS_t = FRDR_t \end{aligned}\right\}, t = 1,2, \ldots, N$$

Flexible Ramping Product Requirement

- The surplus variable, i.e. the amount of FRP procured to meet uncertainty evaluated in the model, will be bounded by 0 and the total FRP requirement

$$\left.\begin{array}{c} 0 \leq FRUS_t \leq FRUR_t \\ 0 \geq FRDS_t \geq FRDR_t \end{array}\right\}, t = 1,2, \ldots, N$$

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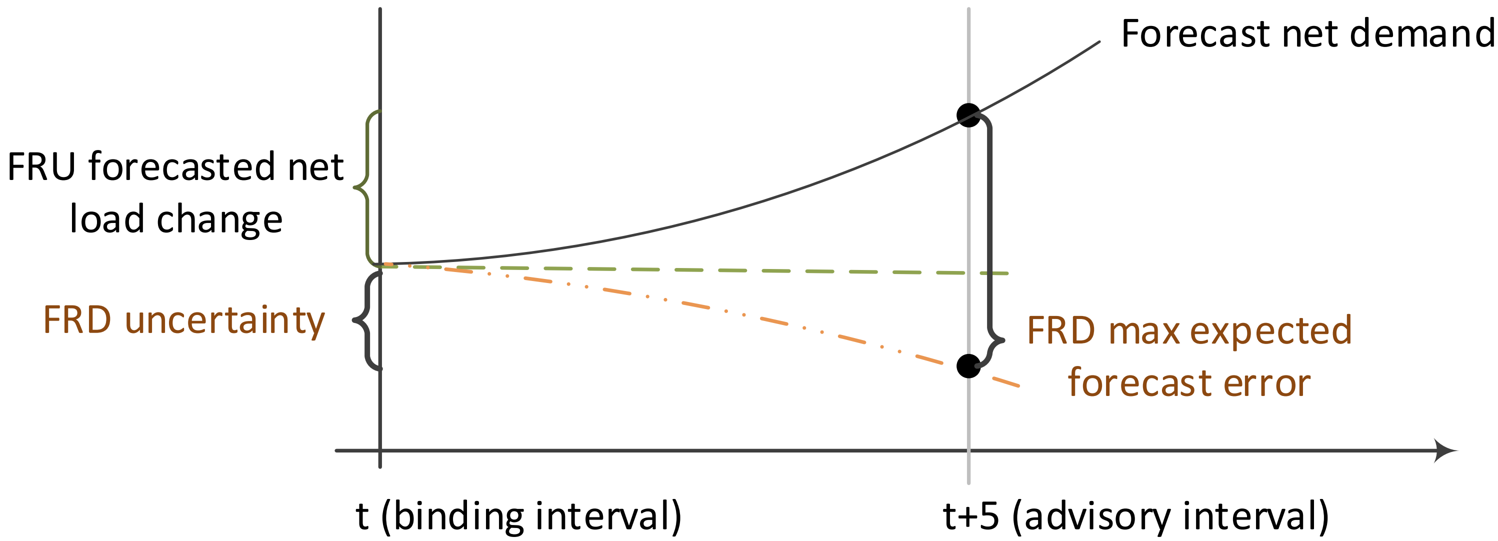
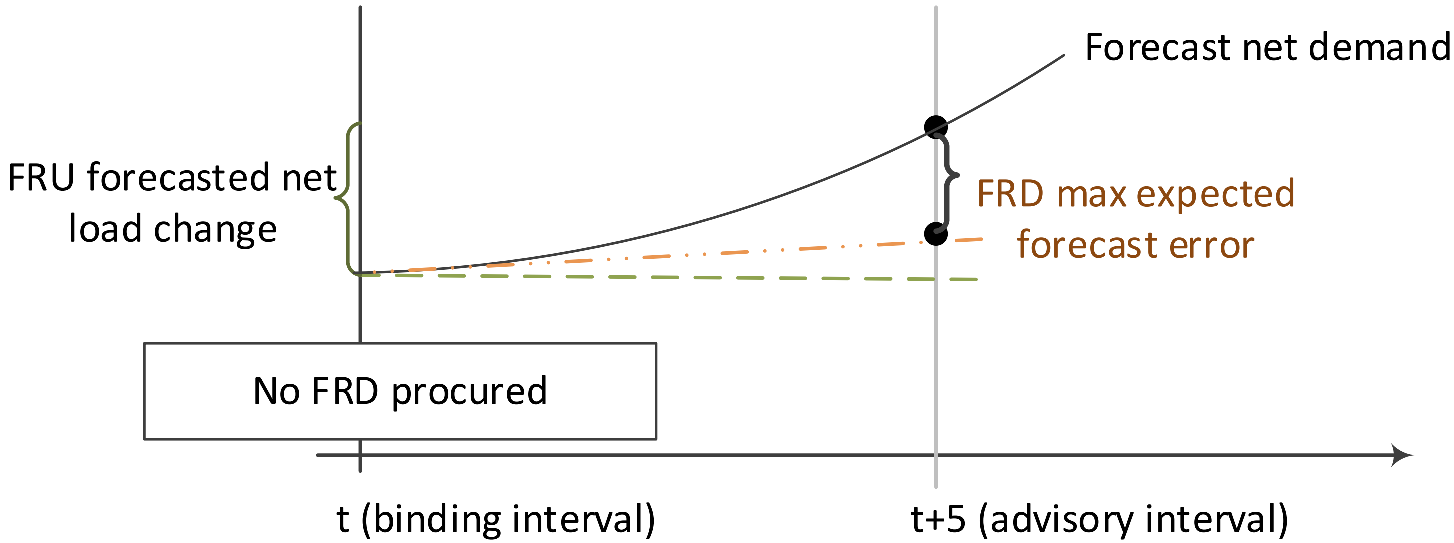
Flexible Ramping Product Requirement



- The ISO will procure using a demand curve the portion between the maximum expected forecast error (95th percentile) and net load forecast at time t

Flexible Ramping Product Requirement



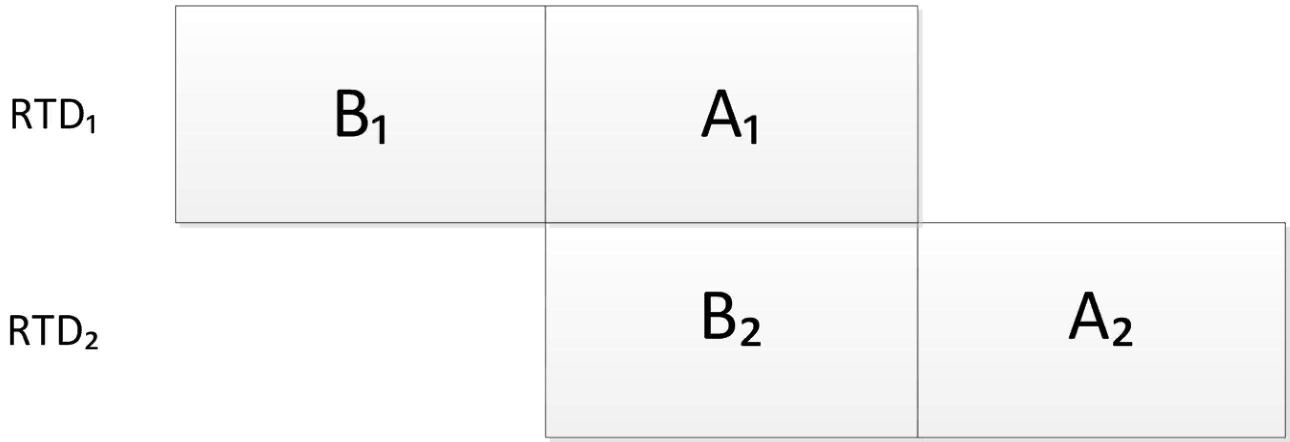
When the maximum expected downward forecast error (max $\{ED_t\}$) is less than the FRU minimum requirement, the ISO will not need additional FRD energy and therefore will not hold back FRD capacity

HISTOGRAM CONSTRUCTION

Histogram Construction

- The ISO will construct histograms as an approximation of the probability distribution of net demand forecast errors. It will construct separate histograms for FRU and FRD for each hour, separately for RTD and RTUC
- For FRU, the histograms will be constructed based on the difference of the net demand the market used in the FMM for the first advisory RTUC interval and the maximum net demand the market used for the three corresponding RTD intervals

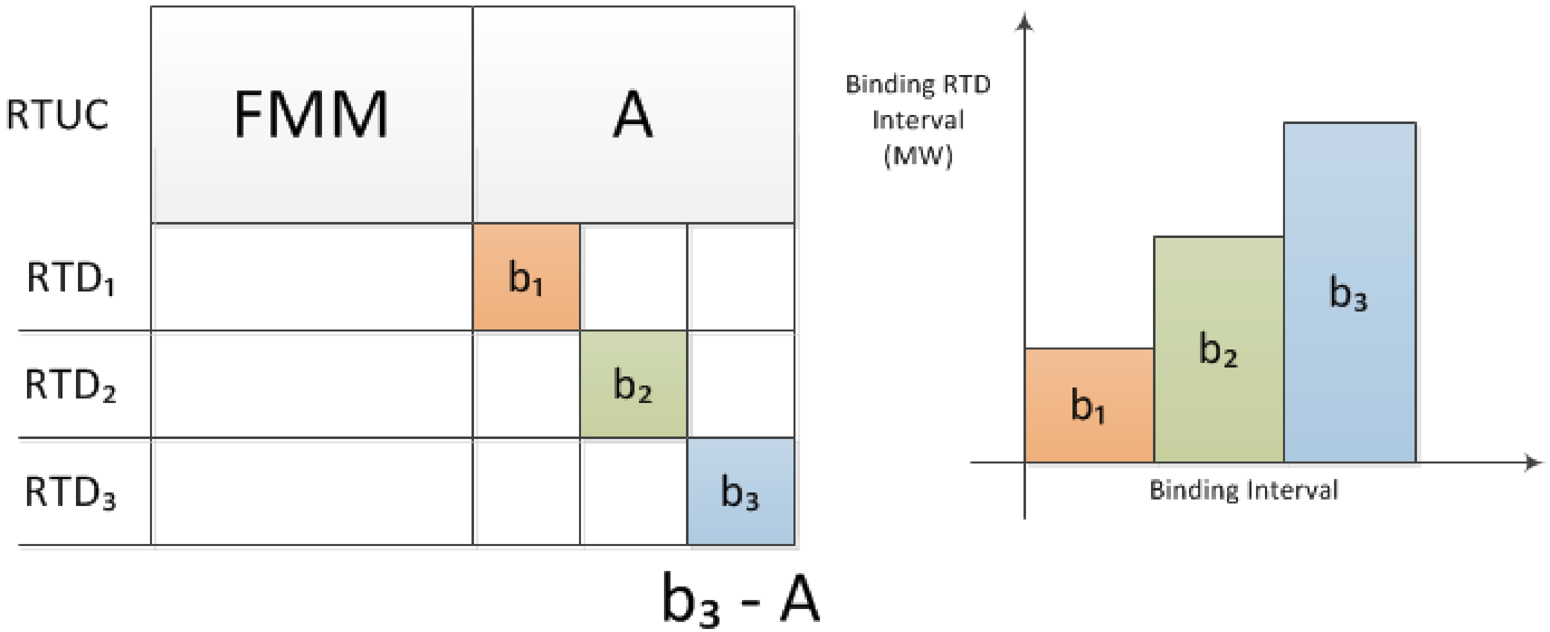
Histogram Construction- RTD



$$B_2 - A_1$$

The ISO will construct the histograms by subtracting the net demand the first market run used for the first advisory interval (A1) from the net demand the second market run used for the binding interval (B_2).

Histogram Construction- RTUC



The FRU histogram will be constructed by comparing the net demand the FMM used for the first advisory RTUC interval to the maximum net demand the market used for the corresponding three RTD binding intervals (b_2,b_3,b_4)

Demand curve example

The power balance penalty cost function:

Power Balance MW violation	Penalty ($/MWh)
-300 to 0	$-150
0 to 400	$1000

The net load forecast error probability distribution function:

Net Load Forecast Error MW bin	Probability
-300 to -200	1%
-200 to -100	2%
-100 to 0	44.8%
0 to 100	50%
100 - 200	1.4%
200 - 300	0.5%
300 - 400	0.3%

FRD	Surplus (MW)	Probability	Penalty ($/MWh)	Surplus Cost ($)	Surplus Incremental Cost ($/MWh)
	0	0	–150	0	
	–100	0.01	–150	–100 × 0.01 × (–150) = 150	(150 – 0) / (–100) = –1.5
	–200	0.02	–150	150 – 100 × 0.02 × (–150) = 450	(450 – 150) / (–100) = –3
	–300	0.448	–150	450 – 100 × 0.448 × (–150) = 7,170	(7170 – 450) / (–100) = –67.2
	400	0.5	1,000	2200 + 100 × 0.5 × 1000 = 52,200	(52200 – 2200) / 100 = 500
	300	0.014	1,000	800 + 100 × 0.014 × 1000 = 2,200	(2200 – 800) / 100 = 14
	200	0.005	1,000	300 + 100 × 0.005 × 1000 = 800	(800 – 300) / 100 = 5
	100	0.003	1,000	100 × 0.003 × 1000 = 300	(300 – 0) / 100 = 3
	0	0	1,000	0	
FRU	Surplus (MW)	Probability	Penalty ($/MWh)	Surplus Cost ($)	Surplus Incremental Cost ($/MWh)

FLEXIBLE RAMPING RESOURCE CONSTRAINTS

Flexible Ramping Resource Constraints

- To be eligible for FRP:
  - The resource must have an energy bid
  - Resource must not be in a forbidden operating region or in state of transition if it is a Multi-Stage Generator
- Demand response resource eligibility:
  - Resource must be 5-minute dispatchable
  - Meter settlement for FRP is the same as energy settlement

Flexible Ramping Resource Constraints

Capacity constraints for an online resource on regulation:

$$\left.\begin{array}{c}\max\left(LOL_{i,t+1}, LRL_{i,t+1}\right) \le EN_{i,t} + AF\ FRD_{i,t} + RD_{i,t+1} \\ EN_{i,t} + AF\ FRU_{i,t} + NR_{i,t+1} + SR_{i,t+1} + RU_{i,t+1} \le \min\left(UOL_{i,t+1}, URL_{i,t+1}, CL_{i,t+1}\right) \\ LEL_{i,t+1} - AF\ FRD_{i,t} \le EN_{i,t} \le UEL_{i,t+1} - AF\ FRU_{i,t}\end{array}\right\} \forall i, t$$

$$= 1, 2, \ldots, N-1$$

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Flexible Ramping Resource Constraints

Capacity constraints for an online resource not on regulation:

$$\left.\begin{array}{c} LOL_{i,t+1} \leq EN_{i,t} + AF\ FRD_{i,t} \\ EN_{i,t} + AF\ FRU_{i,t} + NR_{i,t+1} + SR_{i,t+1} \leq \min\left(UOL_{i,t+1}, CL_{i,t+1}\right) \\ LEL_{i,t+1} - AF\ FRD_{i,t} \leq EN_{i,t} \leq UEL_{i,t+1} - AF\ FRU_{i,t} \end{array}\right\} \forall i, t$$

$$= 1,2, \dots, N-1$$

FLEXIBLE RAMPING EXAMPLES

Flexible Ramping Up Example

Generation	Energy Bid	Initial Condition	Ramp Rate (MW/min)	Pmin	Pmax
G1	$25	400 MW	100	0	500 MW
G2	$30	0 MW	10	0	500 MW

Assume there are two 500 MW online resources in the system that could provide FRU. G1 has a 100 MW/minute ramp rate, and G2 has a 10 MW/minute ramp rate. G1 is more economic in energy than G2. They both have zero cost bids for providing flexible ramping.

Flexible Ramping Up Example

Two-interval RTD optimization with load (t) = 420 MW and load (t+5) = 590 MW

Scenario 1: without flex ramp

Scenario 2: with flex ramp to cover 10 MW of upward uncertainty

S1: without flex ramp	Interval t (LMP=$25)		Interval t (LMP=$35)	
Generation	**Energy**	**Flex-ramp up**	**Energy**	**Flex-ramp up**
G1	380 MW	N/A	500 MW	N/A
G2	40 MW	N/A	90 MW	N/A

S2: without flex ramp	Interval t (LMP=$30, FRUP=$5)		Interval t (LMP=$30, FRUP=$0)	
Generation	**Energy**	**Flex-ramp up**	**Energy**	**Flex-ramp up**
G1	370 MW	130	500 MW	0
G2	50 MW	50	90 MW	0

Flexible Ramping Up Example

- Units may be dispatched differently with flex ramp product constraints being enforced.
  - The fast resource G1 has to be backed down to create more upward ramping capability.
- The flex ramp price is set by G1's opportunity cost.
  - G1 is economic but is dispatched down to provide flex ramp, which incurs opportunity cost of $5 = $30 - $25.
- By having flex ramp to cover uncertainty, the LMP in the binding interval is consistent with bids.
  - Without flex ramp, the LMP in the binding interval is not consistent with G2's bid.

Flexible Ramping Down Example

Generation	Energy Bid	Initial Condition	Ramp Rate (MW/min)	Pmin	Pmax
G1	$25	300 MW	10	0	500 MW
G2	$30	100 MW	100	0	500 MW

Assume two 500 MW resources are online in the system that can provide flexible ramping. G1 has 10 MW/minute ramp rate, and G2 has 100 MW/minute ramp rate. G1 is more economic in energy than G2. They both have zero cost for providing flexible ramping.

Flexible Ramping Down Example

Two-interval RTD optimization with load (t) = 380 MW and load (t+5) = 210 MW

Scenario 1: without flex ramp

Scenario 2: with flex ramp to cover 10 MW of downward uncertainty

S1: without flex ramp	**Interval t (LMP=$30)**		**Interval t (LMP=$20)**	
Generation	**Energy**	**Flex-ramp dn**	**Energy**	**Flex-ramp dn**
G1	260 MW	N/A	210 MW	N/A
G2	120 MW	N/A	0 MW	N/A

S2: without flex ramp	**Interval t (LMP=$25, FRDP=$5)**		**Interval t (LMP=$25, FRDP=$0)**	
Generation	**Energy**	**Flex-ramp dn**	**Energy**	**Flex-ramp dn**
G1	250 MW	50	210 MW	0
G2	130 MW	130	0 MW	0

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Flexible Ramping Down Example

- Units may be dispatched differently with flex ramp product constraints being enforced
  - The fast resource G2 has to be dispatched up to create more downward ramping capability
- The flex ramp price is to make G2 revenue adequate
  - G2 is losing \$5 = \$30 - \$25 per MWh for the energy generated in the binding interval, which will be covered by the flex ramp payment
- By having flex ramp to cover uncertainty, the LMP in the binding interval is consistent with bids
  - Without flex ramp, the LMP in the binding interval would be inconsistent with G1's bid

SETTLEMENT

Settlement

- The ISO will financially settle FRP in the fifteen-minute market and the five-minute market
- The ISO proposes to implement real-time economic buy-back rules that is similar to uninstructed imbalance energy (UIE) settlement
- The proposed real time economic buy-back rules will prevent resources from receiving an FRP payment if they cannot provide what the real-time market awarded

Settlement

- The ISO is proposing two alternative methods of measuring unavailable FRP capacity:
  1. Compare a resource’s metered output, upper and lower economic limits to the FRP award to determine if the resource could provide its awarded FRP (similar to the “undispatchable” and “unavailable” no-pay provisions)
  2. Simply assume any positive UIE makes the corresponding amount of FRU unavailable and any negative UIE makes the corresponding amount of FRD unavailable

Settlement- Energy Settlement Example

	SCHEDULE (MW)			PRICE ($/MWH)		
TIME	**7:00**	**7:05**	**7:10**	**7:00**	**7:05**	**7:10**
FMM	402	402	402	$30	$30	$30
RTD	302	415	402	$25	$36	$25
METER	420	420	430	$25	$36	$36
FMM IIE (MWH)	33.5	33.5	33.5	$30	$30	$30
RTD IIE (MWH)	-8.33	1.08	0.00	$25	$36	$25
UIE (MWH)	9.83	0.42	2.33	$25	$36	$25

Settlement- Energy Settlement Example

SETTLEMENT ($)						
TIME	7:00	7:05	7:10	7:00	7:05	7:10
FMM	FMM/12 * FMM PRICE	FMM/12 * FMM PRICE	FMM/12 * FMM PRICE	$1,005	$1,005	$1,005
RTD	(RTD IIE)* RTD PRICE	(IIE)* RTD PRICE	(IIE)* RTD PRICE	-$208.33	$39.00	$0.00
METER	(UIE) * RTD PRICE	(UIE) * RTD PRICE	(UIE) * RTD PRICE	$245.83	$15.00	$58.33
TOTAL	SUM COLUMN	SUM COLUMN	SUM COLUMN	$1,043	$1,059	$1,063

Settlement- Flex Ramp Up Settlement Example

	Schedule (MW)			Price ($/MWh)		
Time	7:00	7:05	7:10	7:00	7:05	7:10
FMM	15	15	15	$6.00	$6.00	$6.00
RTD	6	15	20	$5.00	$10.00	$12.00
RTD Delta (MW)	-9	0	5	$5.00	$10.00	$12.00
Upper economic limit	435	435	435			
Meter	420	420	430			
Available ramping	15	15	5			

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Settlement- Flex Ramp Up Settlement Example

Settlement ($)						
Time	7:00	7:05	7:10	7:00	7:05	7:10
FMM	FRU FMM/12 * FRU FMM price	FRU FMM/12 * FRU FMM price	FRU FMM/12 * FRU FMM price	$7.50	$7.50	$7.50
RTD	RTD Delta FRU / 12* FRU RTD price	RTD Delta FRU / 12* FRU RTD price	RTD Delta FRU / 12* FRU RTD price	-$3.75	$0.00	$5.00
Meter	Unavailable FRU /12 * FRU RTD price	Unavailabl e FRU /12 * FRU RTD price	Unavailable FRU /12 * FRU RTD price	$0.00	$0.00	-$15.00
Total	Sum column	Sum column	Sum column	$3.75	$7.50	-$2.50

COST ALLOCATION

Cost Allocation

- The ISO will allocate the costs for the flexible ramping product based upon supply and demand "movement" that requires the ISO market to dispatch other resources in the five-minute real-time dispatch
- The ISO will use gross uninstructed imbalance energy to determine the share of flexible ramping costs attributable to load
- The supply category will be allocated based upon the five minute-resource specific movement

DATA RELEASE

FRP data to participants

- Requirement and demand curve
- Individual resource movement

- Expected Q3 2015

NEXT STEPS

Next Steps

Item	Date
Post Technical Appendix	June 10, 2015
Technical Appendix Working Group	June 17, 2015
Stakeholder Comments	July 1, 2015
Post Revised Draft Final Proposal	TBD
Stakeholder Call	TBD
Board of Governors Decision	November 5-6, 2015

Please submit written comments to initiativecomments@caiso.com by close of business July 1

Materials related to this initiative are available on the ISO website at http://www.caiso.com/informed/Pages/StakeholderProcesses/FlexibleRampingProduct.aspx

FORMULA REFERENCES

Formula References

$$\max(EN_t + FRU_t, EN_{t+1}) \leq UEL_{t+1}$$
$$\min(EN_t + FRD_t, EN_{t+1}) \geq LEL_{t+1}$$
$$RRD(EN_t, T) \leq FRD_t \leq 0$$
$$0 \leq FRU_t \leq RRU(EN_t, T)$$
$$RRD(EN_t, T) \leq EN_{t+1} - EN_t \leq RRU(EN_t, T)$$

$EN_{i,t}$	Energy schedule of Resource i in time period t (positive for supply and negative for demand).
$FRU_{i,t}$	Flexible Ramp Up award of Resource i in time period t.
$FRD_{i,t}$	Flexible Ramp Down award (non-positive) of Resource i in time period t.
$UEL_{i,t}$	Upper Economic Limit of Resource i in time period t.
$LEL_{i,t}$	Lower Economic Limit of Resource i in time period t.
$RRU_i(EN, T)$	Piecewise linear ramp up capability function of Resource i for time interval T.
$RRD_i(EN, T)$	Piecewise linear ramp down capability function (non-positive) of Resource i for time interval T.

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Formula References

$$C = \cdots + \sum_{t=1}^{N} \int_{0}^{FRUS_t} C\dot{S}U_t(FRUS_t)\, de \; + \sum_{t=1}^{N} \int_{0}^{FRDS_t} C\dot{S}D_t(FRDS_t)\, de$$

e	Average 5min net demand forecast error of portion of uncertainty not procured
$FRUS_t$	Flexible Ramp Up surplus in time period t.
$FRDS_t$	Flexible Ramp Down surplus in time period t.
$CSU_t(FRUS_t)$	Flexible Ramp Up surplus cost function in time period t.
$CSD_t(FRDS_t)$	Flexible Ramp Down surplus cost function in time period t.
C	Objective function.

Formula References

$$\left.\begin{aligned} CSU_t(FRUS_t) &= PC \int_{EU_t - FRUS_t}^{EU_t} e\, p_t(e)\, de\,, 0 \le FRUS_t \le FRUR_{Ut} \\ CSD_t(FRDS_t) &= PF \int_{ED_t}^{ED_t - FRDS_t} e\, p_t(e)\, de\,, 0 \ge FRDS_t \ge FRDR_{Ut} \end{aligned}\right\} , t = 1,2, \ldots , N$$

e	Average 5min net demand forecast error of portion of uncertainty not procured
$p_t(e)$	Probability distribution function for the average 5min net demand forecast error in time period t, approximated by a histogram compiled from historical observations.
$FRUS_t$	Flexible Ramp Up surplus in time period t.
$FRDS_t$	Flexible Ramp Down surplus in time period t.
$CSU_t(FRUS_t)$	Flexible Ramp Up surplus cost function in time period t.
$CSD_t(FRDS_t)$	Flexible Ramp Down surplus cost function in time period t.
$FRUR_{Ut}$	Flexible Ramp Up requirement due to uncertainty within specified confidence interval in time period t.
$FRDR_{Ut}$	Flexible Ramp Down requirement due to uncertainty within specified confidence interval in time period t.
PC	Bid Price ceiling, currently $1,000/MWh.
PF	Bid Price floor, currently –$150/MWh.
EU_t	Flexible Ramp Up uncertainty at the upper confidence level in time period t.
ED_t	Flexible Ramp Down uncertainty (negative) at the lower confidence level in time period t.

Formula References

$$\left.\begin{array}{l}C\dot{S}U_t(FRUS_t) = C\dot{S}U_t(FRUR_{Ut}), FRUR_{Ut} < FRUS_t \leq FRUR_t \\ C\dot{S}D_t(FRDS_t) = C\dot{S}D_t(FRDR_{Ut}), FRDR_{Ut} > FRUS_t \geq FRDR_t\end{array}\right\}, t = 1,2,\ldots,N$$

e	Average 5min net demand forecast error of portion of uncertainty not procured
$p_t(e)$	Probability distribution function for the average 5min net demand forecast error in time period t, approximated by a histogram compiled from historical observations.
$FRUS_t$	Flexible Ramp Up surplus in time period t.
$FRDS_t$	Flexible Ramp Down surplus in time period t.
$CSU_t(FRUS_t)$	Flexible Ramp Up surplus cost function in time period t.
$CSD_t(FRDS_t)$	Flexible Ramp Down surplus cost function in time period t.
$FRUR_{Ut}$	Flexible Ramp Up requirement due to uncertainty within specified confidence interval in time period t.
$FRDR_{Ut}$	Flexible Ramp Down requirement due to uncertainty within specified confidence interval in time period t.
PC	Bid Price ceiling, currently $1,000/MWh.
PF	Bid Price floor, currently –$150/MWh.
EU_t	Flexible Ramp Up uncertainty at the upper confidence level in time period t.
ED_t	Flexible Ramp Down uncertainty (negative) at the lower confidence level in time period t.

Formula References

$$\left.\begin{array}{l} FRUR_t = FRUR_{NDt} + FRUR_{Ut} \\ FRDR_t = FRDR_{NDt} + FRDR_{Ut} \end{array}\right\}, t = 1,2,\ldots,N$$

$FRUR_t$	Total Flexible Ramp Up requirement in time period t.
$FRUR_{\mathrm{ND}t}$	Flexible Ramp Up requirement due to net demand forecast change in time period t.
$FRUR_{\mathrm{U}t}$	Flexible Ramp Up requirement due to uncertainty within specified confidence interval in time period t.
$FRDR_t$	Total Flexible Ramp Down requirement (non-positive) in time period t.
$FRDR_{\mathrm{ND}t}$	Flexible Ramp Down requirement (non-positive) due to net demand forecast change in time period t.
$FRDR_{\mathrm{U}t}$	Flexible Ramp Down requirement due to uncertainty within specified confidence interval in time period t.

Formula References

$$\left.\begin{aligned} FRUR_{\mathrm{ND}t} &= \max(0, \Delta ND_t) \\ FRDR_{\mathrm{ND}t} &= \min(0, \Delta ND_t) \end{aligned}\right\}, t = 1,2,\ldots,N$$

Where: $\Delta\mathrm{ND}_{\mathrm{t}} = ND_{t+1} - ND_t$
and $t = -1$ is the initial condition

$FRUR_{\mathrm{ND}t}$	Flexible Ramp Up requirement due to net demand forecast change in time period t.
$FRDR_{Ut}$	Flexible Ramp Down requirement due to uncertainty within specified confidence interval in time period t.
ND_t	Net demand forecast in time period t.

Formula References

$$\left.\begin{aligned} FRUR_{Ut} &= \max\left(0, EU_t + FRDR_{\mathrm{ND}t}\right) \\ FRDR_{Ut} &= \min\left(0, ED_t + FRUR_{\mathrm{ND}t}\right) \end{aligned}\right\}, t = 1,2,\dots,N$$

Where:

$$\left.\begin{aligned} EU_t &= \max(0, PU_t) \\ \int_{-\infty}^{PU_t} p_t(\varepsilon)\, d\varepsilon &= CLU \end{aligned}\right\}, t = 1,2,\dots,N$$

$$\left.\begin{aligned} ED_t &= \min(0, PD_t) \\ \int_{-\infty}^{PD_t} p_t(\varepsilon)\, d\varepsilon &= CLD \end{aligned}\right\}, t = 1,2,\dots,N$$

$FRUR_{\mathrm{U}t}$	Flexible Ramp Up requirement due to uncertainty within specified confidence interval in time period t.
$FRDR_{\mathrm{U}t}$	Flexible Ramp Down requirement due to uncertainty within specified confidence interval in time period t.
$FRUR_{\mathrm{ND}t}$	Flexible Ramp Up requirement due to net demand forecast change in time period t.
$FRDR_{\mathrm{ND}t}$	Flexible Ramp Down requirement (non-positive) due to net demand forecast change in time period t.
EU_t	Flexible Ramp Up uncertainty at the upper confidence level in time period t.
ED_t	Flexible Ramp Down uncertainty (negative) at the lower confidence level in time period t.
$p_t(\varepsilon)$	Probability distribution function for the average five minute net demand forecast error in time period t, approximated by a histogram compiled from historical observations.
PU_t	Cumulative probability of net demand forecast error at or below the upper confidence level in time period t.
PD_t	Cumulative probability of net demand forecast error at or below the lower confidence level in time period t.
CLU	Flexible ramp uncertainty upper confidence level, e.g., 97.5%.
CLD	Flexible ramp uncertainty lower confidence level, e.g., 2.5%.

Formula References

$$\left.\begin{aligned}\sum_i FRU_{i,t} + FRUS_t = FRUR_t \\ \sum_i FRD_{i,t} + FRDS_t = FRDR_t\end{aligned}\right\}, t = 1,2,\ldots,N$$

$FRUR_t$	Total Flexible Ramp Up requirement in time period t.
$FRDR_t$	Total Flexible Ramp Down requirement (non-positive) in time period t.
$FRUS_t$	Flexible Ramp Up surplus in time period t.
$FRDS_t$	Flexible Ramp Down surplus (non-positive) in time period t.
$FRU_{i,t}$	Flexible Ramp Up award of Resource i in time period t.
$FRD_{i,t}$	Flexible Ramp Down award (non-positive) of Resource i in time period t.

Formula References

$$\left.\begin{matrix} 0 \leq FRUS_t \leq FRUR_t \\ 0 \geq FRDS_t \geq FRDR_t \end{matrix}\right\}, t = 1,2, \dots, N$$

$FRUR_t$	Total Flexible Ramp Up requirement in time period t.
$FRDR_t$	Total Flexible Ramp Down requirement (non-positive) in time period t.
$FRUS_t$	Flexible Ramp Up surplus in time period t.
$FRDS_t$	Flexible Ramp Down surplus (non-positive) in time period t.
$FRU_{i,t}$	Flexible Ramp Up award of Resource i in time period t.
$FRD_{i,t}$	Flexible Ramp Down award (non-positive) of Resource i in time period t.

Formula References

$$\left.\begin{array}{c}\max\left(LOL_{i,t+1}, LRL_{i,t+1}\right) \le EN_{i,t} + AF\ FRD_{i,t} + RD_{i,t+1} \\ EN_{i,t} + AF\ FRU_{i,t} + NR_{i,t+1} + SR_{i,t+1} + RU_{i,t+1} \le \min\left(UOL_{i,t+1}, URL_{i,t+1}, CL_{i,t+1}\right) \\ LEL_{i,t+1} - AF\ FRD_{i,t} \le EN_{i,t} \le UEL_{i,t+1} - AF\ FRU_{i,t}\end{array}\right\} \forall i, t$$

$$= 1,2, \dots, N-1$$

AF	Averaging factor.
$UOL_{i,t}$	Upper Operating Limit of Resource i in time period t.
$LOL_{i,t}$	Lower Operating Limit of Resource i in time period t.
$URL_{i,t}$	Upper Regulating Limit of Resource i in time period t.
$LRL_{i,t}$	Lower Regulating Limit of Resource i in time period t.
$UEL_{i,t}$	Upper Economic Limit of Resource i in time period t.
$LEL_{i,t}$	Lower Economic Limit of Resource i in time period t.
$CL_{i,t}$	Capacity Limit for Resource i in time period t; $LOL_{i,t} \le CL_{i,t} \le UOL_{i,t}$; it defaults to $UOL_{i,t}$.
$EN_{i,t}$	Energy schedule of Resource i in time period t (positive for supply and negative for demand).
$RU_{i,t}$	Regulation Up award of Resource i in time period t.
$RD_{i,t}$	Regulation Down award (non-positive) of Resource i in time period t.
$SR_{i,t}$	Spinning Reserve award of Resource i in time period t.
$NR_{i,t}$	Non-Spinning Reserve award of Resource i in time period t.
$FRU_{i,t}$	Flexible Ramp Up award of Resource i in time period t.
$FRD_{i,t}$	Flexible Ramp Down award (non-positive) of Resource i in time period t.

Formula References

$$\left.\begin{aligned} LOL_{i,t+1} &\leq EN_{i,t} + AF\ FRD_{i,t} \\ EN_{i,t} + AF\ FRU_{i,t} + NR_{i,t+1} + SR_{i,t+1} &\leq \min\left(UOL_{i,t+1}, CL_{i,t+1}\right) \\ LEL_{i,t+1} - AF\ FRD_{i,t} \leq EN_{i,t} &\leq UEL_{i,t+1} - AF\ FRU_{i,t} \end{aligned}\right\} \forall i, t = 1,2, \dots, N-1$$

AF	Averaging factor.
$UOL_{i,t}$	Upper Operating Limit of Resource i in time period t.
$LOL_{i,t}$	Lower Operating Limit of Resource i in time period t.
$URL_{i,t}$	Upper Regulating Limit of Resource i in time period t.
$LRL_{i,t}$	Lower Regulating Limit of Resource i in time period t.
$UEL_{i,t}$	Upper Economic Limit of Resource i in time period t.
$LEL_{i,t}$	Lower Economic Limit of Resource i in time period t.
$CL_{i,t}$	Capacity Limit for Resource i in time period t; $LOL_{i,t} \leq CL_{i,t} \leq UOL_{i,t}$; it defaults to $UOL_{i,t}$.
$EN_{i,t}$	Energy schedule of Resource i in time period t (positive for supply and negative for demand).
$RU_{i,t}$	Regulation Up award of Resource i in time period t.
$RD_{i,t}$	Regulation Down award (non-positive) of Resource i in time period t.
$SR_{i,t}$	Spinning Reserve award of Resource i in time period t.
$NR_{i,t}$	Non-Spinning Reserve award of Resource i in time period t.
$FRU_{i,t}$	Flexible Ramp Up award of Resource i in time period t.
$FRD_{i,t}$	Flexible Ramp Down award (non-positive) of Resource i in time period t.

Formula References

$$\left.\begin{array}{l} 0 \leq FRU_{i,t} \leq RRU_i(EN_t, T_5) \\ RRD_i(EN_t, T_5) \leq FRD_{i,t} \leq 0 \end{array}\right\} \forall i, t = 1,2, \dots, N-1$$

AF	Averaging factor.
$FRU_{i,t}$	Flexible Ramp Up award of Resource i in time period t.
$FRD_{i,t}$	Flexible Ramp Down award (non-positive) of Resource i in time period t.
$RRU_i(EN, T)$	Piecewise linear ramp up capability function of Resource i for time interval T.
$RRD_i(EN, T)$	Piecewise linear ramp down capability function (non-positive) of Resource i for time interval T.

Formula References

$$\left.\begin{array}{l} 0 \le AF\ FRU_{i,t} \le RRU_i(EN_t, T) \\ RRD_i(EN_t, T) \le AF\ FRD_{i,t} \le 0 \end{array}\right\} \forall i, t = 1,2, \dots, N-1$$

Where *T* is the relevant market interval duration:

$$T = \begin{cases} T_5 & \text{in RTD} \\ T_{15} & \text{in RTUC} \end{cases}$$

And the averaging factor is defined as follows:

$$AF = \begin{cases} 1 & \text{in RTD} \\ \dfrac{T_{15}}{T_5} & \text{in RTUC} \end{cases}$$

AF	Averaging factor.
$FRU_{i,t}$	Flexible Ramp Up award of Resource i in time period t.
$FRD_{i,t}$	Flexible Ramp Down award (non-positive) of Resource i in time period t.
$RRU_i(EN, T)$	Piecewise linear ramp up capability function of Resource i for time interval T.
$RRD_i(EN, T)$	Piecewise linear ramp down capability function (non-positive) of Resource i for time interval T.