

Regulation Uplift and Lost Opportunity Cost: Sample Calculations

Section 1: Background

The business rule for regulation uplift or lost opportunity cost is detailed in Section 3.2.7.4 of [M-11; Energy & Ancillary Services Market Operations](#).

Additional information can be found in Section 4.2.2 of [M-28; Operating Agreement Accounting](#).

In general, Regulation Uplift or Lost Opportunity Cost (see Figure 1 below) further referred to as “RegLOC” is the difference in net compensation from the Energy Market between what a resource receives when providing Regulation and what it would have received for providing energy only. The purpose is to quantify the foregone revenue or increased costs incurred by a resource when it is dispatched uneconomically to provide regulation service.

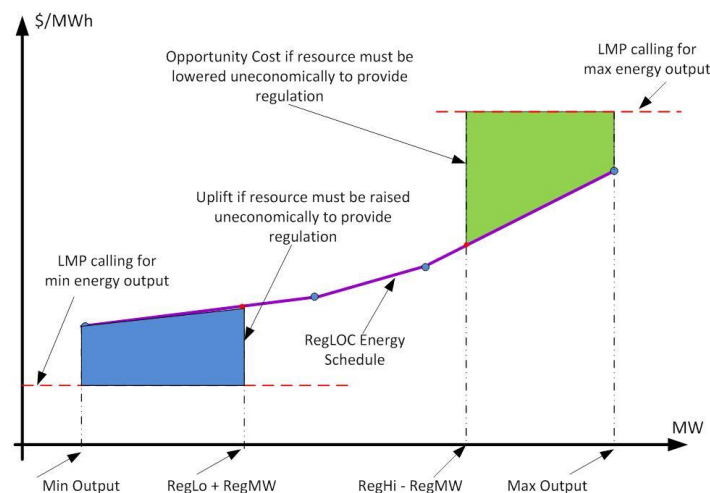


Figure 1: Regulation Hour Uplift or Lost Opportunity Cost Area

RegLOC:

- Is calculated only for pool scheduled regulation resources; \$0 for self-scheduled regulation resources
- Is calculated only for resources providing energy along with regulation service; \$0 for non-energy regulation resources
- Is \$0 for DSR resource types
- Is calculated only within the economic limits of the resource. That is, for a regulation MW output within a resource’s economic minimum and economic maximum range.

Note that a resource's regulation range is only allowed to be within its economic limits

- Can only be positive, otherwise it will be \$0
- Is a component of the Regulation Market Clearing Price

Section 1.1 – Three Components of RegLOC

RegLOC is divided into three components (see Figure 2 below). They are as follows:

- Shoulder Hour Before (RegLOC_shb): which captures the cost incurred in the hour preceding the initial regulating hour while the unit moves uneconomically into its regulating band to comply with the next hour's regulation assignment;
- Regulation Hour (RegLOC_rh): which captures the cost incurred in the actual regulating hour from reducing or raising the unit's output uneconomically for the purpose of providing regulation; and
- Shoulder Hour After (RegLOC_sha): which captures the cost incurred in the shoulder hour following the final hour of the regulation assignment while the unit moves from its uneconomic regulation set-point back to its economic dispatch set-point.

That is,

$$RegLOC_{total} = RegLOC_{shb} + RegLOC_{rh} + RegLOC_{sha} \quad \text{----- eqn. (1)}$$

In the Ancillary Service Optimizer (ASO) that clears regulation one hour ahead of the target interval, only forecasted RegLOC_shb and forecasted RegLOC_rh are factored into the clearing.

In the actual operating hour, actual RegLOC_rh is considered in the 5 minute regulation pricing.

In Settlements after-the-fact, actual RegLOC_shb and actual RegLOC_sha are evaluated for each qualified resource.

Resource type combustion turbine (CT) and Hydro are not eligible for shoulder hour components of RegLOC.

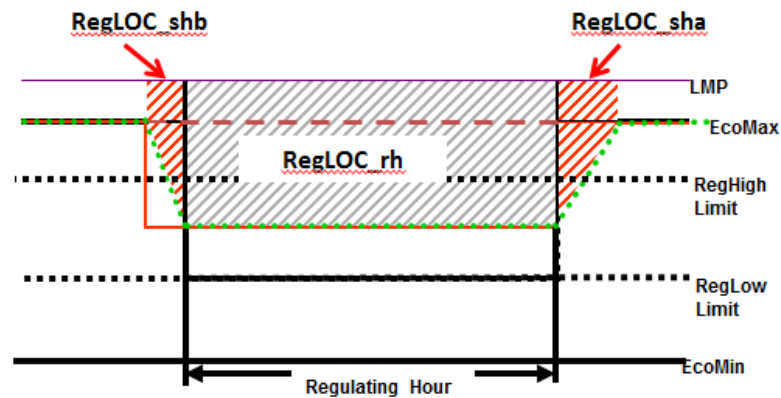


Figure 2: RegLOC Components

Section 1.2 – RegLOC Calculation Formulation

The approximate formula for RegLOC in the shoulder hours is defined as:

$$RegLOC_{sh} = |LMP_{sh} - ED| * GENOFF * TIME \text{ ----- eqn. (2)}$$

Where:

LMP_{sh} is the forecasted (or actual) shoulder hour LMP at the generator bus,

ED is the price from the lost opportunity cost energy schedule associated with the set-point the resource must maintain to provide its full amount of regulation,

$GENOFF$ is the MW deviation between economic dispatch and the regulation set-point, and

$TIME$ is the percentage of the hour it would take the unit to reduce $GENOFF$ MWs using the applicable offer-in ramp rate.

Note: In after-the-fact settlement, the preceding three 5-minute intervals (including limits and assigned MW) before the regulation hour are the ramp-in 5-minute intervals. Lost opportunity costs from the ramp-in 5-minute intervals are applied to the first 5-minute interval of the regulating hour. The following three 5-minute intervals (including limits and assigned MW) after the regulation hour are the ramp-out 5-minute intervals. Lost opportunity costs from the ramp-out 5-minute intervals are applied to the last 5-minute interval of the regulating hour.

The approximate formula for RegLOC incurred during the regulating hour is defined as:

$$RegLOC_{rh} = |LMP_{rh} - ED| * GENOFF \text{ ----- eqn. (3)}$$

Where:

LMP_{rh} is the forecasted hourly LMP or real-time LMP at the generator bus,

ED is the price from the lost opportunity cost energy schedule associated with the set-point the resource must maintain to provide its full amount of regulation, and

$GENOFF$ is the MW deviation between economic dispatch and the regulation set-point.

All resource specific RegLOC is further adjusted by the benefits factor of the resource and its historic performance score, thus:

$$\text{Adjusted RegLOC} = \frac{\text{RegLOC}}{\text{Benefits Factor} * \text{Historic Performance Score}} \quad \text{----- eqn. (4)}$$

Section 2 - Numerical Examples of RegLOC Calculation (Non-Hydro)

RegLOC energy schedule = min [price-based energy schedule, max (available cost-based energy schedule)]

Assume the resource is online generating and following economic dispatch (and not currently regulating). Its evaluation for regulation clearing for the next hour will include opportunity cost for the shoulder hour before the regulating hour. RegLOC_shb will capture the cost associated with the period during which the resource has to abandon its economic dispatch and move uneconomically in time to its regulation set-point at the beginning of the regulation hour.

Unit Schedule Curve			Unit Parameters	Regulation Offers
Segment	MW	\$	Economic Minimum (EcoMin): 100 MW	Reg Offer = 50 MW
1	100	20	Economic Maximum (EcoMax): 500 MW	Capability Cost = \$6.15
2	200	30	Regulation Minimum (RegMin): 300 MW	Performance Cost = \$0.45
3	300	40	Regulation Maximum (RegMax): 450 MW	Capability Price = \$12.14
4	400	50	Energy Ramp Rate: 12 MW/Minute	Performance Price = \$0.85
5	500	60		

Table 1: RegLOC energy schedule, unit parameters and regulation offers

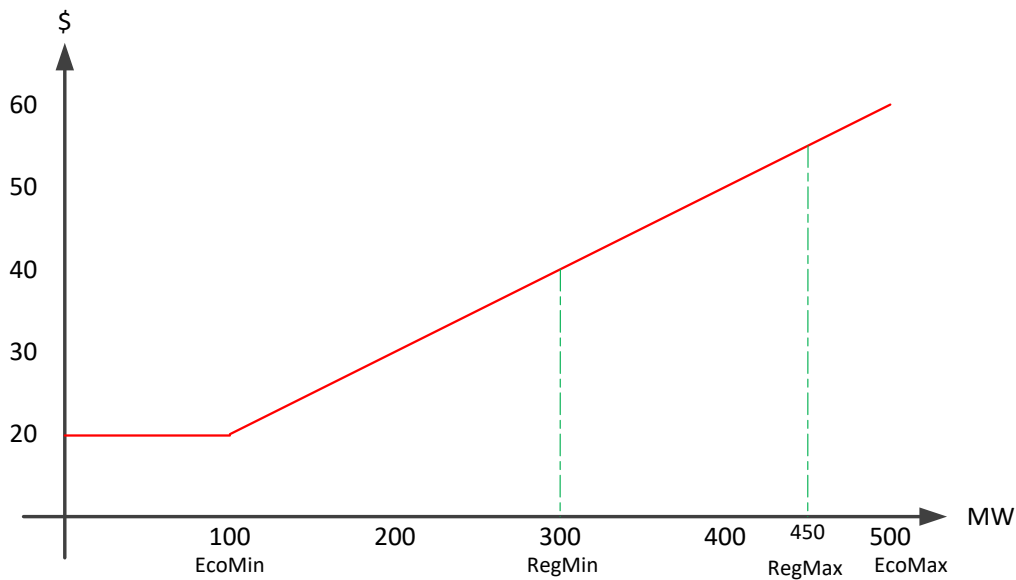


Figure 3: RegLOC Energy Schedule with Regulation Limits

Equation of the energy curve is given by:

$$\$ = \frac{MW}{10} + 10$$

Section 2.1 – RegLOC Evaluation for Regulation Clearing in ASO

Unit is providing energy only and following economic dispatch. If the forecasted LMP at its bus is \$70, then unit is assumed to be operating at its EcoMax of 500 MW.

For the unit to be considered for regulation clearing, it will need to be backed down uneconomically to its projected regulation set-point.

Regulation set-point = RegHi – Reg Offer MW

Where RegHi = min [EcoMax, RegMax] = 450 MW, and

RegLo = max [EcoMin, RegMin] = 300 MW

Reg set-point = 450 – 50 = 400 MW

Note: Regulation band or regulation range is defined as RegHi to RegLo. The maximum regulation MW that can clear ranges from 0 to min [0.5(RegHi – RegLo), Reg Offer MW]

So, the unit output will need to be reduced by 100 MW; that is, from EcoMax of 500 MW to Reg set-point of 400 MW.

If the unit cleared for regulation for 50 MW, then from the 400 MW regulation set-point the unit will be able to raise to 450 MW, which is within RegHi, and lower to 350 MW, which is within RegLo, following PJM regulation signal.

The 100 MW reduction from economic output of the unit in order to get set to provide regulation in the next hour is captured in RegLOC_shb.

$$\text{Time required to move unit to reg set-point} = \frac{\Delta MW}{\text{Ramp Rate}} = \frac{100}{12} = 8.33 \text{ minutes}$$

That is, the unit must start to deviate from economic dispatch and move to the regulation set-point by 9 minutes before the regulation operating hour.

Converting 8.33 minutes to a percentage of the hour,

$$\frac{8.33}{60} = 0.139 = 13.9 \%$$

That is, the unit reduced an equivalent of 100 MW for 13.9% of the hour proceeding the regulation operation hour.

RegLOC_shb

- Revenue lost @ EcoMax = (LMP – Marginal cost at EcoMax) * MW reduction/RegMW
= (70 – 60)*100/50 = \$20/MW
- Revenue lost @ reg set-point = (Marginal Cost @ EcoMax – Marginal Cost @ reg set-point)* MW reduction/RegMW = (60 – 50)*100/50 = \$20/MW
- Adding the two segments → 20 + 20 = \$40/MW
- Unit reduced an equivalent of 100 MW for 13.9% of the hour
- Therefore RegLOC_shb = \$40/MW * 13.9% = \$5.56/MW

RegLOC_rh is calculated as:

- Assuming LMP at the unit bus is forecasted at \$70 for the regulation hour, the unit is assumed to provide regulation around 400 MW reg set-point
- Revenue lost @ Reg set-point = {[(LMP – Marginal cost @ EcoMax)*(MW Reduction/Reg MW)] + [(Marginal Cost @ EcoMax - Marginal cost @ Reg set-point)* (MW Reduction/Reg MW)]} = {[(70 – 60)*(100/50)] + [(60 – 50) (100/50)]} = \$40/MW

Assuming the unit's historic performance score of 0.891 and benefits factor of 1, then

Adjusted RegLOC = RegLOC_shb + RegLOC_rh) / (historic Performance Score* Benefits Factor)

$$= (5.56 + 40) / (0.891 * 1) = \underline{\$51.13/\text{MW}}$$

This unit in this scenario must have its forecasted Adjusted Total Cost less than or equal forecasted adjusted total cost of the last resource that satisfied the regulation effective MW requirement (RegTPS steps not included for simplicity).

For the unit in this scenario, the forecasted Adjusted Total Cost =

Adjusted Capability Offer + Adjusted Performance Offer + Adjusted RegLOC

Section 2.2 – RegLOC Calculation for Regulating Interval in Real-Time (LPC)

Assuming the sample unit cleared for regulation from the hour-ahead study in ASO (Section 2.1 above), then unit will provide regulation service in real-time. Each resource providing regulation service in real-time is evaluated every 5 minutes by LPC for its cost, which includes its adjusted offer price plus adjusted real-time regulation opportunity cost. The table 2 below describes RegLOC_rh for each 5 minutes of 12 intervals of a regulation hour.

Interval	EcoMin	RegMin	RegLo	RegMax	EcoMax	RegHi	Reg MW Cleared	Reg MW Setpoint	Marginal Cost @ Reg Setpoint	LMP	Desired MW @ LMP	RegLOC \$/MW	RegLOC Total (\$)
HH_01	100	300	300	450	500	450	50	400	50	70	500	40	2000
HH_02	100	300	300	450	500	450	50	400	50	75	500	50	2500
HH_03	100	300	300	450	500	450	50	400	50	90	500	80	4000
HH_04	100	300	300	450	500	450	50	400	50	90	500	80	4000
HH_05	100	300	300	450	500	450	50	400	50	85	500	60	3000
HH_06	100	300	300	450	500	450	50	400	50	80	500	40	2000
HH_07	100	300	300	450	500	450	50	400	50	70	500	40	2000
HH_08	100	300	300	450	500	450	50	400	50	70	500	40	2000
HH_09	100	300	300	450	500	450	50	400	50	60	500	20	1000
HH_10	100	300	300	450	500	450	50	400	50	60	500	20	1000
HH_11	100	300	300	450	500	450	50	400	50	50	400	0	0
HH_12	100	300	300	450	500	450	50	350	45	40	300	5	250
Hourly Integrated Value												39.58	1979.17

Table 2: Sample of twelve 5-minute intervals and Hourly Integrated RegLOC

The five-minute RegLOC credit for the sample scenario is the five-minute interval RegLOC multiplied by the five-minute performance score/12.

Section 3 - Numerical Examples of RegLOC Calculation (Hydro Unit)

The business rule for RegLOC for hydro unit is detailed in Section 3.2.8 of [M-11; Energy & Ancillary Services Market Operations](#).

Additional information can be found in Section 4.2.2.1 of [M-28; Operating Agreement Accounting](#).

Since hydro units operate on a schedule and do not have an energy bid, the opportunity cost for these units are calculated differently from that of conventional units.

RegLOC for hydro units is meant to model the value of the water saved when reducing real-time output to provide regulation. The average LMP concept is used to quantify the value of the water saved during regulation.

Hours where the plant is not scheduled to run are used in the average LMP calculation because the water saved during regulation can be used to generate in the non-operational hours.

The approximate formula for Hydro unit RegLOC is defined as:

For Hydro where energy scheduled MW > 0

- Pump Storage or Run-Off River;

$$RegLOC = \max [LMP - ED, 0] \quad \text{----- eqn. (5);}$$

- Hydro in spill condition,

$$RegLOC = \max [LMP, 0] \quad \text{-----eqn. (6);}$$

For Hydro where energy scheduled MW ≤ 0

- Pump Storage or Run-Off River

$$RegLOC = \max [ED - LMP, 0] \quad \text{-----eqn. (7);}$$

Where:

LMP is the LMP at the hydro unit bus. Forecasted value is used in the hour-ahead regulation clearing in ASO while the actual value is used in the real-time pricing and in settlement;

ED is the average of LMPs at the hydro unit bus for the appropriate on-peak or off-peak period excluding those hours during which all available units at the hydro plant were operating. Off-

Peak hours are HE1 through HE7, and HE24. On-Peak hours are HE8 through HE23. Day-Ahead LMPs are used to calculate ED in the hour-ahead regulation clearing in ASO and in real-time pricing while the real-time LMP after the fact is used in settlements.

	Units at Hydro Plant			1	2	3	
Day-Ahead Period	Hour Ending	Day_Ahead LMP	Include in Ave_LMP Calculation	MW	MW	MW	
Off-Peak	1	17.74	N	-200	-200	-200	Off-Peak Ave_LMP = $(23.14+33.46+30.36)/3 =$ 28.99
	2	17.37	N	-200	-200	-200	
	3	16.73	N	-200	-200	-200	
	4	18.78	N	-200	-200	-200	
	5	22.68	N	-200	-200	-200	
	6	23.14	Y	0	0	0	
	7	33.46	Y	0	0	0	
On-Peak	8	35.29	Y	0	0	0	On-Peak Ave_LMP = $(35.29+56.77+71.01+75.89+80.18+56.76+35.79)/7 =$ 58.81
	9	56.77	Y	0	0	0	
	10	71.01	Y	0	0	0	
	11	89.92	N	100	100	100	
	12	89.45	N	100	100	100	
	13	94.58	N	100	100	100	
	14	86.06	N	100	100	100	
	15	75.89	Y	0	0	0	
	16	82.48	N	100	100	100	
	17	90.22	N	100	100	100	
	18	96.5	N	100	100	100	
	19	92.98	N	100	100	100	
	20	85.08	N	100	100	100	
	21	80.18	Y	0	100	100	
	22	56.76	Y	0	0	0	
	23	35.79	Y	0	0	0	
Off-Peak	24	30.36	Y	0	0	0	

Table 3: Hydro Schedule

Let's assume a hydro unit with the following parameters:

EcoMax = 100, Regulation Offer MW = 25

Scenario 1:

Unit 1 was pool scheduled for Regulation for HE 11 for 25 MW. The forecasted LMP at the unit bus = \$62.10

- Energy scheduled MW > 0
- The unit is pump storage hydro or a run-off river but not spilling
- $\text{RegLOC} = \max[\text{LMP} - \text{ED}, 0] = \max[(62.10 - 58.81), 0] = \$3.29/\text{MW}$

Scenario 2:

Unit 2 was pool scheduled for Regulation for HE 13 for 25 MW. The forecasted LMP at the unit bus = \$56.78

- Energy scheduled MW > 0
- The unit is pump storage hydro or a run-off river but not spilling
- $\text{RegLOC} = \max[\text{LMP} - \text{ED}, 0] = \max[(56.78 - 58.81), 0] = 0$
- That is, **No RegLOC**

Scenario 3:

Unit 3 was pool scheduled for Regulation for HE 20 for 25 MW. The forecasted LMP at the unit bus = \$65

- Energy scheduled MW > 0
- The unit is a run-off river and spilling
- $\text{RegLOC} = \max[\text{LMP}, 0] = \max[65, 0] = \$65/\text{MW}$

Scenario 4:

Unit 1 was brought out of schedule to provide regulation by PJM dispatcher in HE 10. Actual LMP at the hydro unit bus = \$70

- Scheduled MW < = 0
- The unit is a pump storage hydro
- $\text{RegLOC} = \max[\text{ED} - \text{LMP}, 0] = \max[(58.81 - 70), 0] = 0$
- That is, **No RegLOC**

Scenario 5:

Unit 2 was brought out of schedule to provide regulation by PJM dispatcher in HE 09. Actual LMP at the hydro unit bus = \$45

- Scheduled MW < = 0
- The unit is a pump storage hydro
- $\text{RegLOC} = \max[\text{ED} - \text{LMP}, 0] = \max[(58.81 - 45), 0] = \$13.81/\text{MW}$

Note:

Lost opportunity cost credits for regulation are calculated for the regulation intra-hour and shoulder intervals. Resources supplying pool-scheduled Regulation, PJM sums the resource's Regulation offer and lost opportunity lost credits, including shoulder intervals' lost opportunity cost credits, then compares it to its 5-minute Regulation Clearing Price credits. If the resulting amount is positive, then lost opportunity cost credits are allocated, however, if the resulting amount is negative, then the credit is \$0. Resource supply self-scheduled Regulation are not eligible for lost opportunity cost credits.

Please send any questions on these examples to PJM Member Relations at custsvc@pjm.com or call 610-666-8980.