Energy Storage Enhancements

State of Charge Implementation - Update

October 2, 2023

Market Policy Development

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1 Background

The ISO introduced policy changes to the way that storage resources are modeled in the market during the energy storage enhancements stakeholder initiative. Most of the policy developed for storage resources was done at a time when there was very little storage participation in the market, and it was done in anticipation of a large influx of storage resources. Today, there are more than 5,000 MW of storage resources participating on the grid and changes are needed to the legacy models in place to adapt to the needs of the stakeholders using the existing models and discovering where improvements can be made.

One aspect of the energy storage enhancements stakeholder policy included changes to how the state of charge was modeled in both the day-ahead and real-time markets for regulation. The proposal was an attempt to better reconcile the modeled state of charge with the reality of how state of charge changes for storage resources that receive energy and regulation awards. The policy also sought to address an operational concern where storage resources were becoming unable to respond to automatic generator control instructions when receiving ancillary service awards for multiple consecutive hours.

This solution was originally intended to be implemented with the spring 2023 software release. However, when changes to the state of charge equation were made in the testing environment negative prices for regulation down were detected, which is not supported by rules specified in the tariff. In response to these findings the ISO chose not to release this aspect of the software changes during the spring 2023 release.

The ISO plans to host a workshop to review different alternatives that could be implemented in the future. These changes may be implemented as soon as Fall 2023.

2 Policy Alternatives

As a quick reference this provides very high level implementation alternatives:

- (*ESE Proposal*) Model impact from regulation on state of charge
  - Introduces an intertemporal connection between energy and regulation services
  - Can result in negative regulation prices
- (*Envelope Equations*) Use envelope equations to limit regulation awards
  - Concept developed in the DAME initiative
  - Expand into the real-time market
  - May be more restrictive than the status quo model

    - Need a process to develop multipliers
    - May need to consider application in real-time
- (*No Change*) Do not update current/planned constraints on storage
    - May not meet address initial concerns from policy
    - Could allow additional time to develop more robust solutions

3 Modeling State of Charge

The energy storage enhancements initiative proposed to update the state of charge equation from the definition currently used, described in equation 1, to a new equation, described in equation 2. The current equation only includes impacts from energy schedules, and – when charging – considers resource specific round-trip efficiencies. The proposed updates to the equation retains the existing parameters, but also introduces additional parameters that incorporate a fractional impact from regulation awards on state of charge.

Today, state of charge for a storage resource is governed by the following formula:

$$SOC_{i,t} = SOC_{i,t-1} - \left(P_{i,t}^{(+)} + \eta_i P_{i,t}^{(-)}\right) \qquad (1)$$

Where

$SOC_{i,t}$	State of charge for resource *i* at time *t*
$P_{i,t}^{()}$	Discharging (+) or charging (-) instruction for resource *i* at time *t*
η_i	Round trip efficiency for resource *i*

This equation states that state of charge changes as the resource receives dispatch instructions. For example, if the resource receives an award to discharge 60 MW during a specific hour in the day-ahead market, the state of charge for that resource will be 60 MWh less at the end of the hour compared to the start of the hour. Further, if the storage resource is awarded a charging schedule for 60 MW during a specific hour, that resource will have 60 MWh * η_i of additional state of charge at the end of the hour compared to the start of the hour. A typical round trip efficiency might be around 85%, making the increase in state of charge 51 MWh, or 60 MWh * .85.

This equation does not consider ancillary service awards. For example, if a resource is awarded 60 MW of regulation up for a specific hour without an energy award, this equation assumes that the resource will have the same state of charge at the beginning and end of the hour. In practice this will not be true. In the real-time market, resources that receive regulation awards receive 4-second automatic generator control (AGC) instructions from the market. In aggregate in real-time, the resource will certainly have less state of charge than at the start of the hour. However, the exact amount of state of charge is uncertain and will depend on real-time system conditions.

The proposal will also help to ensure that charging or discharging schedules do not exceed physical limits of the storage resource while determining the state of charge during any particular interval.[1] The proposal is to update the model governing state of charge in the day-ahead and real-time markets to the following formula:

$$SOC_{i,t} = SOC_{i,t-1} - \left(P_{i,t}^{(+)} + \eta_i P_{i,t}^{(-)} + \mu_1 RU_{i,t} - \mu_2 \eta_i RD_{i,t}\right) \qquad (2)$$

Where

$RU_{i,t}$	Regulation up awarded to resource *i* at time *t*
$RD_{i,t}$	Regulation down awarded to resource *i* at time *t*
μ	Multiplier, applicable for a specific hour

This formula denotes energy awards as *P*, where this value can be positive, representing discharge awards, or negative, representing charge awards. Discharge awards only impact the formula in the $P_{i,t}^{(+)}$ term, and the values for this term are positive and reduce the state of charge. Charge awards only impact the formula in the $P_{i,t}^{(-)}$ term, and the values for this term are negative and increase the state of charge. Values for both regulation up and regulation down awards are positive.

This formula illustrates that state of charge, in any interval, is a function of the state of charge in the previous interval, the energy dispatch instructions during the previous interval and a fraction of the regulation awards in the previous interval. The proposal notes that only the fraction μ of the full amount of regulation will factor into the state of charge for the next interval in the real-time or day-ahead market. This multiplier will be specified in a business practice manual and may be updated as analysis drives updates of actual regulation awards and impacts to state of charge. This multiplier may be different for each hour for regulation up and regulation down.

[1] Business Practice Manual for Market Operations, p 353: https://bpmcm.caiso.com/Pages/BPMDetails.aspx?BPM=Market%20Operations.

3.1 Original ESE Proposal

Implementing the changes that were developed in the energy storage enhancements policy would include updating the state of charge equation from what is outlined in equation 1 above to the definition of what is included in equation 2. Equation 2 links the state of charge for a storage resource with awards for regulation up and regulation down. This has a potential consequence of negative market prices for regulation because of the implications on state of charge.

With the changes applied to the state of charge equation, the model understands that a storage resource bidding $0/MW for regulation down also gets an additional benefit of increased state of charge. The model then understands that state of charge can be sold later in the energy market. This can result in negative market clearing prices, just incentivizing the marginal storage resource to provide these regulation services and sell energy at prices that materialize later in the day. These mechanics for setting prices for regulation down are not as straightforward as typical negative marginal energy prices observed on the grid today because of the intertemporal nature of the relationship between regulation prices at one time and energy prices later.

Because regulation down awards increase state of charge, it is unlikely that the original proposal from energy storage enhancements would result in frequent negative prices for regulation up. In fact, regulation up prices could be higher than without the change because the market would now consider that regulation up awards would reduce state of charge and therefore would reduce the amount fo energy that a storage resource could sell later in the day. Negative regulation down prices would be most likely to materialize in the peak solar hours, when energy prices were also lowest, and negative regulation down prices would be unlikely during peak load hours of the day, because there would be no opportunity to sell the additional energy charged at sufficiently high prices.

In order to implement the original proposal from the energy storage enhancements policy, the ISO may need to either allow for negative regulation prices or limit regulation prices to be zero. The latter could make price verification difficult.

3.2 Envelope Equations

In the day-ahead market enhancements initiative, the ISO developed guardrails for state of charge via the envelope equations applied in the day-ahead market, to account for resource awards for imbalance reserves. Envelope equations estimate a reasonable upper bound and a reasonable lower bound for what state of charge could be if a resource was awarded imbalance reserves during a specific hour. The imbalance reserves would impact the upper and lower limits, as would energy awards, but would not impact the state of charge equation for storage resources. Imbalance reserves are a product developed to anticipate potential differences in demand between the day-ahead forecasts and real-time. Imbalance reserves ‘earmark’ potential energy in the day-ahead timeframe to accommodate for these differences.

The envelope equation outlined in the day-ahead market enhancements proposal is outlined in Equation Set 3. These equations estimate a hypothetical upper bound for storage resources and a hypothetical lower bound for storage resources, and tracks these values over time. These values create an envelope, or boundary, for state of charge. Once the hypothetical state of charge reaches the lower or upper limit of the resource, then the market will schedule the resource to charge or discharge prior to scheduling any additional imbalance reserves that could potentially cause the hypothetical value to exceed the limit.[2]

$$\begin{aligned} SOC_{i,t}^{(u)} &= SOC_{i,t-1}^{(u)} - EN_{i,t}^{(+)} - \eta_i \, EN_{i,t}^{(-)} + \eta_i \, AIRD_t \, IRD_{i,t} \le \overline{SOC}_{i,t} \\ SOC_{i,t}^{(l)} &= SOC_{i,t-1}^{(l)} - EN_{i,t}^{(+)} - \eta_i \, EN_{i,t}^{(-)} - AIRU_t \, IRU_{i,t} \ge \underline{SOC}_{i,t} \end{aligned} \qquad (3)$$

Where:

$SOC_{i,t}^{(u)}$	Upper envelope for state of charge for resource *i* at time *t*
$AIRD_t$	Adjustable multiplier applied to downward imbalance reserves to calculate the upper envelope for state of charge at time *t*
$IRD_{i,t}$	Downward imbalance reserve award for resource *i* at time *t*
$\overline{SOC}_{i,t}$	Upper limit for state of charge for resource *i* at time *t*
$AIRU_t$	Adjustable multiplier applied to upward imbalance reserves to calculate the lower envelope for state of charge at time *t*
$IRU_{i,t}$	Upward imbalance reserve award for resource *i* at time *t*
$\underline{SOC}_{i,t}$	Lower limit for state of charge for resource *i* at time *t*

The envelope equations ensure that the upper envelope is always at or above the modeled state of charge and that the lower envelope is always at or below the modeled state of charge. This implies that if the state of charge is at a resource’s maximum, then the upper envelope will also be at the maximum. The same is true for the lower limit and the minimum. When the values for the upper

[2] The initial values for both the upper and lower state of charge would be the actual initial state of charge in the day-ahead market.

and lower envelopes are both at limits, the state of charge of the resource is uncertain and will prevent further use of the resource.

Several examples of how the envelope equations function can be found in the day-ahead market enhancements paper.[3]

This paper suggests that a possible alternative to previously proposed changes to the state of charge equation could be an expansion of the envelope equations to include regulation up and regulation down. Prior to development of the day-ahead market enhancements policy these envelope equations could simply accommodate regulation up and regulation down awards, as outlined in Equation 4.

$$\begin{aligned} SOC_{i,t}^{(u)} &= SOC_{i,t-1}^{(u)} - EN_{i,t}^{(+)} - \eta_i\, EN_{i,t}^{(-)} + \eta_i\, ARD_t\, RD_{i,t} \leq \overline{SOC}_{i,t} \\ SOC_{i,t}^{(l)} &= SOC_{i,t-1}^{(l)} - EN_{i,t}^{(+)} - \eta_i\, EN_{i,t}^{(-)} - ARU_t\, RU_{i,t} \geq \underline{SOC}_{i,t} \end{aligned} \qquad (4)$$

Where:

ARD_t	Adjustable multiplier applied to regulation down to calculate the upper envelope for state of charge for resource *i* at time *t*
$RD_{i,t}$	Regulation down award for resource *i* at time *t*
ARU_t	Adjustable multiplier applied to regulation up to calculate the lower envelope for state of charge for resource *i* at time *t*
$RU_{i,t}$	Regulation up award for resource *i* at time *t*

It is necessary to determine what the multipliers would be set to prior to implementing these envelope equations. Because the purpose of these functions is to estimate a hypothetical upper and lower bound, the ISO suggests that a 90th or 95th percentile of the amount of an ancillary service award that gets converted to energy could be considered for a starting point. This would provide bounds for state of charge that would capture actual state of charge almost all of the time, and it would exclude very significant outliers.

Implementing the envelope equations in the day-ahead and residual unit commitment markets would take the place of revising the optimization's state of charge equation. Further, there may not be a need to develop real-time envelope equations because ancillary service procurement is rare in real-time. Although, this should also be discussed further.

[3] Day-ahead market enhancements: http://www.caiso.com/InitiativeDocuments/RevisedFinalProposal-Day-AheadMarketEnhancements.pdf.

4 Addendum

4.1 Summary

The Energy Storage Enhancements policy approved by FERC on June 5, 2023 contained a revision to the day ahead market state-of-charge (SOC) constraint. The approved policy allowed the market to optimally schedule both energy and regulation by considering their impacts on the SOC.

During the market simulation and prior to the implementation of this revised constraint, stakeholders observed that the inclusion of regulation in the SOC formulation resulted in the market procuring additional regulation down awards at negative marginal prices. This negative pricing result was the SOC in the day-ahead market temporally linking MWh of "energy" charging resulting from a regulation down award with the potential and future discharge of those same MWh's; functionally the market determined it was efficient to pay for regulation down awards that could be discharged later in the day at a profit.

The ISO delayed implementation of this feature, published a workshop paper, and held a stakeholder meeting to discuss this result with market participants while collectively workshopping next steps. During that workshop Pacific Gas and Electric (PG&E) presented on a proposed modification to the formulation of the SOC constraint. The proposal retained the existing SOC constraint that did not consider the impact of regulation awards on state of charge. When implemented concurrently in the market the two constraints decouple the dispatch of energy and regulation awards. While the $SOC_{i,t}^{AT}$ constraint will continue to ensure that regulation awards are supported in conjunction with energy awards through the day-ahead market optimization, the need to also satisfy the $SOC_{i,t}^{EN}$ constraint will ensure that energy discharge awards are supported absent the potential energy created by regulation awards. This revision removes the pricing linkage between regulation and energy and the potential for negative priced regulation down awards.

$$SOC_{i,t}^{AT} = SOC_{i,t-1}^{AT} - (EN_{i,t}^{(+)} + \eta_i EN_{i,t}^{(-)} + ATRU_t RU_{i,t} - ATRD_t \eta_i RD_{i,t}) \frac{\Delta T}{T_{60}}$$

$$SOC_{i,t}^{EN} = SOC_{i,t-1}^{EN} - (EN_{i,t}^{(+)} + \eta_i EN_{i,t}^{(-)}) \frac{\Delta T}{T_{60}}$$

In response to stakeholder comments supporting the exploration of the solution put forward by PG&E, the ISO developed code to test the revised implementation. Testing indicated the revised formulation eliminated regulation awards clearing at negative prices. The ISO plans to expand the testing of this constraint with stakeholders through market simulation starting October 3, 2023. Pending successful market simulation, the ISO plans to implement the

ESE SOC constraint consistent with existing regulatory timelines. The ISO would like to thank stakeholders, specifically PG&E, for working towards a successful implementation of this element of the ESE policy.

4.2 Results

The ISO has tested the proposed ESE SOC implementation within its Map-Test day-ahead market environment. As expected the proposed implementation of the SOC constraint resulted in a reduction to the quantity of regulation down procured and the elimination of negative marginal prices for regulation down awards. The results show changes for the awards of energy, regulation up and regulation down as well as the prices for these commodities. These results are expected as the consideration of regulation awards within the SOC constraint naturally will result in a different market solution.

Table 1: Awarded commodities of both proposed ESE SOC implementations

	Initial Formulation			Revised Formulation					
HE	**EN**	**RD**	**RU**	**EN**	**RD**	**RU**	**EN Diff**	**RD Diff**	**RU Diff**
1	105.00	206.00	72.00	105.00	139.00	157.00	0.00	-67.00	85.00
2	48.00	321.00	64.00	92.00	137.00	157.00	44.00	-184.00	93.00
3	-65.00	259.00	40.00	-156.00	166.00	101.00	-91.00	-93.00	61.00
4	-49.00	321.00	18.00	-55.00	72.00	146.00	-6.00	-249.00	128.00
5	60.00	273.00	20.00	55.00	141.00	157.00	-5.00	-132.00	137.00
6	33.00	181.00	70.00	10.00	139.00	146.00	-23.00	-42.00	76.00
7	162.00	266.00	0.00	62.00	174.00	123.00	-100.00	-92.00	123.00
8	-9.00	370.00	148.00	0.00	174.00	170.00	9.00	-196.00	22.00
9	-120.00	356.00	70.00	-97.00	321.00	102.00	23.00	-35.00	32.00
10	-38.00	369.00	144.00	-36.00	321.00	174.00	2.00	-48.00	30.00
11	-87.00	370.00	224.00	-91.00	321.00	224.00	-4.00	-49.00	0.00
12	-119.00	370.00	188.00	-110.00	321.00	270.00	9.00	-49.00	82.00
13	-228.00	370.00	187.00	-234.00	349.00	301.00	-6.00	-21.00	114.00
14	-173.00	370.00	185.00	-169.00	294.00	320.00	4.00	-76.00	135.00
15	-89.00	370.00	152.00	-83.00	266.00	320.00	6.00	-104.00	168.00
16	-38.00	370.00	131.00	-40.00	321.00	160.00	-2.00	-49.00	29.00
17	32.00	370.00	83.00	14.00	213.00	101.00	-18.00	-157.00	18.00
18	543.00	154.00	98.00	175.00	6.00	157.00	-368.00	-148.00	59.00
19	138.00	181.00	96.00	90.00	26.00	98.00	-48.00	-155.00	2.00
20	116.00	154.00	83.00	117.00	75.00	98.00	1.00	-79.00	15.00
21	98.00	229.00	130.00	5.00	128.00	130.00	-93.00	-101.00	0.00
22	-16.00	229.00	126.00	1.00	102.00	130.00	17.00	-127.00	4.00
23	-45.00	266.00	96.00	-48.00	75.00	202.00	-3.00	-191.00	106.00
24	7.00	169.00	114.00	-16.00	52.00	202.00	-23.00	-117.00	88.00

Table 2: Quantity and price differentials for regulation down awards

	Initial Formulation	Revised Formulation

HE	MW	RD PRICE	MW	RD PRICE
1	350.00	4.12	350.00	7.14
2	350.00	8.00	350.00	6.33
3	350.00	6.33	350.00	6.33
4	350.00	8.00	350.00	6.33
5	350.00	8.00	350.00	5.15
6	350.00	3.52	350.00	5.91
7	350.00	8.00	350.00	8.56
8	370.00	-3.97	350.00	8.51
9	356.97	0.00	350.00	7.91
10	370.00	0.00	350.00	7.91
11	370.00	0.00	350.00	7.91
12	370.00	-3.16	350.00	7.79
13	370.00	-4.34	350.00	7.93
14	370.00	-4.72	350.00	8.10
15	370.00	-4.99	350.00	8.27
16	370.00	-4.99	350.00	8.29
17	370.00	-5.26	350.00	9.43
18	350.00	6.72	350.00	7.99
19	350.00	6.11	350.00	7.99
20	350.00	6.72	350.00	10.40
21	350.00	8.00	350.00	10.40
22	350.00	8.00	350.00	10.33
23	350.00	8.00	350.00	6.33
24	350.00	6.33	350.00	6.33

Table 3: Quantity and price differentials for regulation up awards

	Initial Formulation		Revised Formulation	
HE	MW	RU PRICE	MW	RU PRICE
1	350.00	3.94	350.00	4.55
2	350.00	5.37	350.00	4.37
3	350.00	4.67	350.00	3.48
4	350.00	5.42	350.00	4.40
5	350.00	4.63	350.00	3.57
6	350.00	4.63	350.00	3.94
7	350.00	4.01	350.00	4.00
8	350.00	6.26	350.00	9.54
9	350.00	4.00	350.00	4.00
10	350.00	6.75	350.00	6.75
11	350.00	6.88	350.00	5.36
12	350.00	6.92	350.00	4.92
13	350.00	5.85	350.00	4.23
14	350.00	6.51	350.00	4.76
15	350.00	4.18	350.00	4.59
16	350.00	3.00	350.00	3.61
17	350.00	4.00	350.00	3.48
18	350.00	4.00	350.00	4.00

19	350.00	4.00	350.00	3.36
20	350.00	4.00	350.00	3.36
21	350.00	3.00	350.00	2.83
22	350.00	3.00	350.00	2.81
23	350.00	4.00	350.00	3.40
24	350.00	4.00	350.00	3.40

Table 4: Quantity and price differentials for energy awards

	Initial Formulation		**Revised Formulation**	
HE	**MW**	**EN PRICE**	**MW**	**EN PRICE**
1	14452.55	87.00	14448.84	88.00
2	14171.17	78.50	14143.17	82.00
3	13974.13	76.80	13974.13	73.77
4	13899.53	79.96	13899.53	76.53
5	14228.03	82.00	14228.03	82.00
6	15042.58	87.37	15058.37	84.98
7	16272.69	90.00	16272.69	90.00
8	17151.96	78.50	17148.96	83.08
9	17336.75	74.08	17336.75	73.92
10	17493.88	80.01	17494.94	80.01
11	17523.77	76.00	17520.73	76.00
12	17317.04	74.90	17317.04	74.90
13	17182.09	69.44	17181.09	69.65
14	17231.65	73.54	17231.65	73.76
15	17316.12	75.98	17316.12	76.00
16	17621.79	79.86	17621.79	79.86
17	17858.06	89.70	17858.06	89.70
18	18683.22	92.02	18648.22	94.55
19	18367.01	91.92	18415.25	91.40
20	18264.31	90.00	18238.31	93.49
21	17723.30	89.70	17710.77	90.00
22	16875.75	89.70	16876.75	88.22
23	15835.40	79.07	15831.48	80.00
24	15226.90	80.77	15226.90	80.77