Revenue for Energy Storage Participating in ISO-NE Energy and Reserves Markets

Alternative ORTP EAS Offset Estimates

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1. Introduction

Accurately modeling energy storage dispatch and market revenues poses unique challenges. The revenues that storage generates from energy and reserves depends on its ability to purchase electricity in low-priced periods and sell electricity or reserves in higher priced periods. Storage dispatch is further complicated by its energy-limited status, which introduces significant cross-product and intertemporal opportunity costs, and by technical characteristics such as its efficiency at charging and discharging. How storage should operate, conceptually, is generally quite different from how deterministic modeling will simulate how storage could operate. Deterministic modeling of energy storage will generally leave money on the table that, in practice, a reasonably competent operator could earn.

The Massachusetts Attorney General's Office (AGO) offers this memorandum outlining a straightforward optimization model to more reasonably estimate energy and ancillary services ("EAS") revenues available to a storage device. More specifically, the model produces an operational schedule for storage that maximizes revenues from participation in three ISO New England ("ISO-NE") markets – energy, ten-minute spinning reserves ("TMSR"), and regulation – while respecting the technical limitations of the storage device.

We employed this optimization model to evaluate the reasonableness of the Concentric Energy Advisors ("CEA") EAS revenue estimate. The AGO ran its optimization model – using CEA-sourced market prices and battery specification – assuming that storage was *scheduled* optimally based on known day-ahead energy prices, but *operated* only in the real-time market. Put differently, the AGO assumes that storage is dispatched in real-time based on the observed prices from the day-ahead market. The AGO dispatch methodology does not require foresight of the market's actual real-time prices nor does it require intra-day updating based on prevailing market conditions. The dispatch strategy reflects a readily achievable, albeit simple dispatch scheme.

The AGO's operational approach is based on a dispatch scheme outlined by the ISO-NE External Market Monitor ("EMM") in their comments in ER20-308.[1] In its comments, the EMM noted the "limited sophistication" of the dispatching of storage based on day-ahead price curves "represents the minimum that an [energy storage resource] developer could reasonably expect to receive in EAS net revenues."[2]

The AGO finds that the CEA revenue estimates for energy storage are unreasonably low assuming the FRM is sunset and somewhat too low assuming the FRM is maintained. Based on the specific modeling

[1] EMM Comments at 6 https://elibrary.ferc.gov/eLibrary/filelist?accession_num=20191112-5337&optimized=false
[2] Id.

conducted in this analysis, **the AGO proposes alternative energy, TMSR, and regulation revenue estimates of $ 8,231,249 ($54.87/kW-year), assuming the FRM sunsets, and $ 8,866,214 ($59.11/kW-year), assuming the FRM is maintained**. In contrast, CEA estimates average EAS revenue from these three markets at $6,856,653 ($45.71/kW-year) assuming the FRM is sunset and $8,288,982 ($55.26/kW-year) assuming the FRM is maintained. An energy storage resource dispatched using the AGO's scheme would earn 20 percent more money – in the same markets – than that same resource under CEA's analysis, assuming the FRM is sunset. Assuming the FRM is maintained, the AGO's dispatch scheme would earn the resource about 7 percent more than the CEA estimate.

The AGO suggests that a more sophisticated developer could earn still more EAS revenues if it employed less rudimentary dispatch logic; there is substantial headroom between what a developer could earn if it had more perfect foresight of real-time prices for energy and reserves, and what it would earn using the AGO's proposed approach.

2. Methodology

The AGO assessed EAS revenues for an energy storage device using a purpose-built linear optimization model. In an effort to comport with CEA's analysis, the AGO relied on CEA assumptions unless otherwise noted. This section summarizes the model's exogenous price data and battery specification, then outlines the linear program itself.

2.1 Prices

Pricing Data

The AGO relied on pricing data directly extracted directly from the CEA battery ORTP model in "Battery_ORTPdispatch_2020.09.30wFRM.xlsx" workbook.[3]

- Day-Ahead LMP: "RI RCPF Adj. day-ahead LMP ($/MWh)" (Column E)
- FRM TMSR Price: "FRM TMSR price ($/MWh)" (Column H)
- Real-time LMP: "RI RCPF Adj real-time LMP ($/MWh)" (Column F)
- Real-time TMSR: "RI real-time RCPF Adj TMSR ($/MWh)" (Column G)
- FRM Hour: "ON or OFF PEAK" (Column D)
- FRM Threshold: "daily threshold price ($/MWh)" (Column C)

These timeseries reflect some 26,280 hours of prices, spanning 2017-2019, for Rhode Island (the assumed location of the storage device).

While the battery formulates its dispatch based on day-ahead prices, the optimization model also requires an estimate of opportunity costs for TMSR so that it can explicitly account for trade-offs between products and across time. [4] The AGO assumes *expected* TMSR prices of $5/MWh in all hours.

[3] https://www.iso-ne.com/static-assets/documents/2020/09/a6_a_iii_cea_ortp_models_20200901.zip

[4] For example, if the device assumes TMSR to be zero in future periods, it might elect to earn a pittance in the energy market, rather than maintain its charge to earn TMSR revenue in some later period.

Regulation revenues were assumed constant at $21.26/hour, a value estimated by CEA and ISO-NE.[5] Because the battery allocates the same share of its capacity to provide regulation in all hours, the dispatch-weighted average regulation price is the same as the simple-average price.

Prices used for Dispatch and Revenue by Model Run

Scenario		Prices used for Battery Operation		Prices used for Revenue	
Information	**FRM**	**Energy**	**TMSR**	**Energy**	**TMSR**
Day-Ahead	With FRM	DA LMP	$5/MWh TMSR Estimate	RT LMP	OnPk: FRM OffPk: RT TMSR
	No FRM	DA LMP	$5/MWh TMSR Estimate	RT LMP	RT TMSR

2.2 Battery Parameterization

The AGO-modeled battery participating in the ISO-NE markets is assumed to have a capacity of 150 MW and can deliver 300 MWh energy at the revenue meter. Details of the battery, and its operational characteristics, are summarized in Table 1.

Table 1: Storage Operational Parameters

Parameter	Units	Value	Notes
Capacity	MW-ac	150	*Same as CEA, Measured at the Revenue Meter*
Stored Energy	MWh-ac	300	*Measured at the Revenue Meter*
Round-trip Efficiency	%	86%	*Same as CEA*
One-way Efficiency	%	92%	*Assumed Symmetric;* $92\% = \sqrt{86\%}$
TMSR Capacity	MW-ac	150	*Same as CEA*
Regulation Capacity	MW-ac	16.5	*Same as CEA*
Total Study Withdrawal Limit	GWh-ac	3.285	*Same as CEA;* = 365 Days x 3 Years x 300 MWh-ac

A few notes:

- Like CEA, the battery is assumed to have an 86% round-trip efficiency, but unlike CEA, the losses on charge and discharge are assumed symmetric (i.e., the battery is ~92% efficient when charging and when discharging). By contrast, CEA assumes that all losses are incurred on discharge.
- The model assumes that the battery can be fully charged and fully discharged in two hours.

[5] See CEA Draft Report at 86.

- Like CEA, the model limits total dispatch to minimize cell degradation. CEA imposes a firm constraint that limits dispatch to a maximum of one cycle per day, while the AGO model limits dispatch to an *average* of one cycle per day.[6] As discussed below, the AGO also factors into its calculations battery aging caused by cycling for regulation.

2.3 Linear Program Formulation

The linear program itself is derived from prior storage dispatch models employed by AGO staff.[7] The linear program was developed using the standard Python 3.8 scientific stack, Pyomo optimization library, and was solved using GLPK.

Objective Function ($)

Objective function of this program seeks to maximize revenues from energy arbitrage and TMSR sales, where **T** is the set of hourly prices, **Q** is the quantity of energy delivered to the meter in each hour, and **P** is the price of each product. Note that for purposes of solving the optimization **P** is the day-ahead price (or expected price in the case of TMSR).

$$max \sum_{t=0}^{T} \left(Q_{EA,t} \times P_{LMP,t} + Q_{TMSR,t} \times P_{TMSR,t} + Q_{Reg,t} \times P_{Reg,t} \right) \quad (1)$$

Injection & Withdrawal (measured MW-dc)

Energy may be **I**njected into, or withdrawn from, the battery at any value between zero and an exogenous charge rate. The battery is assumed to be able to charge and discharge at the same rate, as noted in Eqns 2-4. Separately, total AC **W**ithdrawals from the battery over the course of the study period can be capped using Eqn. 5. This has the effect of limiting overall storage cycling. Mirroring the EMM analysis, the AGO factors regulation cycling into its dispatch limits, and assumes that cycling for regulation has 1/10th of the effect on storage aging as cycling for energy arbitrage.[8]

$$\mathrm{ESS}_{\mathrm{Charge\ Rate}} = \mathrm{ESS}_{\mathrm{Discharge\ Rate}} \quad (2)$$

$$0 \leq \mathrm{I_t} \leq \mathrm{ESS}_{\mathrm{Charge\ Rate}} \quad (3)$$

$$0 \leq \mathrm{W_t} \leq \mathrm{ESS}_{\mathrm{Discharge\ Rate}} \quad (4)$$

$$\eta \sum_{\mathrm{t=0}}^{\mathrm{T}} (\mathrm{W_t}) + 0.1 \sum_{\mathrm{t=0}}^{\mathrm{T}} \left(Q_{Reg,t} \right) \leq \text{ Total Withdrawal Limit} \quad (5)$$

[6] It may be cost effective to cycle multiple times on a day with very volatile prices and never cycle on days with more modest variability in prices.
[7] Cf. B.W.Griffiths (2019) “Reducing emissions from consumer energy storage using retail rate design”. *Energy Policy,* vol. 129, 481-490. https://doi.org/10.1016/j.enpol.2019.01.039.
[8] See EMM Comments at 11.

State of Charge (measured MW-dc)

SOC measures how "full" a battery is at a given point in time. SOC in each period t must equal the SOC at the beginning of the prior period plus injections less withdrawals in that prior period. SOC ranges from zero to the SOC_{max} of about 324 MWh-dc. Note: SOC is measured at the top of each hour.

$$0 \leq SOC_t \leq SOC_{max} \tag{6}$$

$$SOC_t = SOC_{t-1} + I_{t-1} - W_{t-1} \tag{7}$$

Constraints for Energy Arbitrage

The quantity of energy delivered to, or consumed at, the meter for energy arbitrage equals loss-adjusted discharging less loss-adjusted charging. One-way efficiency, η, is assumed symmetric on charging and discharging. Note that injections are negative because they are a cost to the storage owner while withdrawals are positive because they are revenue.

$$Q_{EA,t} = \eta W_t - \frac{I_t}{\eta} \tag{8}$$

Constraints for Regulation

Selling regulation is almost always more profitable than providing a different service. For simplicity, the battery is set to provide regulation at a fixed 16.5 MW in all periods.

$$Q_{Reg,t} = Q_{Reg\ MAX} = 16.5\ MW \tag{9}$$

Constraints for TMSR

The quantity of energy eligible for TMSR must be less than (a) the loss-adjusted quantity of energy currently stored in the battery, (b) less than the maximum discharge rate (MWh-ac/h); and (c) must not be double-counted with EA sales. The same MW of capacity providing TMSR can, however, also be used to provide regulation. This requires a set of equations,

$$0 \leq Q_{TMSR,t} \leq Q_{TMSR,MAX} \tag{10}$$

$$Q_{TMSR,t} \geq Q_{Reg,t} + I/\eta \tag{11}$$

$$Q_{TMSR,t} + W\eta \leq \eta SOC_t \tag{12}$$

$$Q_{TMSR,t} + W\eta \leq Capacity \tag{13}$$

$$Q_{TMSR,t} + I/\eta \leq Capacity \tag{14}$$

Constraint for FRM

The FRM, when present, imposes new constraints on how storage is dispatched. In this simple model, a set of time-conditional constraints are added which require TMSR sales to equal 150 MW in each on-peak hour, so long as the LMP for a given on-peak hour is less than the FRM threshold price for that day. The FRM constraint is thus,

$$\begin{aligned} If \quad & (FRM\ Hour_t = OnPeak)\ and \\ & \left(FRM\ Threshold_t < P_{DA\ LMP,t}\right)\ and \\ & \left(FRM\ Threshold_t < P_{RT\ LMP,t}\right) \\ Then \quad & Q_{EA,t} = 0 \end{aligned} \tag{15}$$

Because the FRM threshold price is relatively high, in almost all on-peak hours $Q_{TMSR,t}$ equals 150 MW and $Q_{EA,t}$ equals zero. To ensure that the FRM resource is paid its full FRM payment during all periods when penalties are not assessed the helper variable $Q_{FRM\ Supplemental,t}$ is added where,

$$\begin{aligned} If \quad & (FRM\ Hour_t = OnPeak)\ and \\ & \left(FRM\ Threshold_t < P_{DA\ LMP,t}\right)\ and \\ & \left(FRM\ Threshold_t < P_{RT\ LMP,t}\right) \\ Then \quad & Q_{TMSR,t} + Q_{FRM\ Supplemental,t} = Q_{TMSR\ MAX} = 150\ MW \end{aligned} \tag{16}$$

This has the effect of providing additional FRM revenue when the battery is cycling for energy during periods when the LMP exceeds the threshold price. $Q_{FRM\ Supplemental,t}$ is paid using the same TMSR/FRM prices as the main $Q_{TMSR,t}$ variable.

If the FRM is sunset, these constraints are disabled.

2.4 Revenue Calculation

Hourly revenue estimates, in nominal dollars, are summed by year, then adjusted into constant 2019$, then 2025$, using CEA-sourced scalers. Like CEA, the AGO then takes the simple average of the three years of data to come up with its EAS net revenue estimate for energy storage. This allows for easy integration of the AGO revenue estimates into the overall CEA ORTP estimates.

Note that the revenue output from the model's objective function reflects the quantity of revenue the device would have earned had it taken day-ahead positions and received a flat $5/MWh for all TMSR sales. This is not what it actually earned in the real-time market.

Instead, actual revenue earned by the storage device requires additional *post hoc* processing to calculate actual real-time revenues based on the "optimal" dispatch. Recall that the linear program returns how the battery's capacity is split between the three products in each hour. Actual revenues, therefore, equal the hourly position for each product outputted by the model, multiplied by the *real-time* price for each product. These actual revenues – based on real-time prices – could be higher or lower than prices assuming day-ahead positions.

3. Data

Along with this memo, the AGO is also releasing its storage optimization model as well as Excel workbooks with model outputs and revenue calculations. As noted, the optimization model itself is implemented in Python 3.8 and offered as a Jupyter Notebook (filetype: ipynb) for portability.

4. Results

After running its analysis, the AGO finds that a 150 MW / 300 MWh storage device, operated with reasonable competence, could earn $8.23 to $8.87 million per year between the energy, reserve, and regulation products. Table 2 compares AGO and CEA revenue estimates, by product.

Table 2: Estimated Annual Average EAS Revenues from Energy & TMSR, by Case & Source

		Revenue (Millions, 2025$)				
Scenario	**Model**	**DA Energy**	**RT Energy**	**Reserves**	**Regulation**	**Total**
No FRM	**AGO**	--	$1.752	$2.965	$3.514	$8.231
	CEA	$0.044	$0.857	$2.496	$3.460	$6.857
With FRM	**AGO**	--	$1.455	$3.897	$3.514	$8.866
	CEA	$0.036	$0.905	$3.887	$3.460	$8.289

AGO revenues are higher for all products except day-ahead energy, where AGO assumes net revenues are zero.

The AGO estimates for energy and reserves align with the estimates developed by the EMM in ER20-308. The EMM found that storage could earn about $30/kW between energy and reserves, given knowledge of day-ahead pricing, compared with the AGO estimates of $35.68/kW and 31.45/kW, with and without the FRM. (The EMM also found that a more sophisticated trading strategy based on the day-ahead LMP and CTS transactions could earn $34/kW-year.[9])

In contrast, CEA estimates average EAS revenue from energy and TMSR at $22.35/kW-year ($3.35 million per year), assuming the FRM is sunset and $31.95/kW-year ($4.79 million per year) assuming the FRM is maintained. The CEA sunset estimate is about 30 percent lower than the equivalent AGO value and 25 percent lower than the EMM's comparable approach. The CEA no sunset estimate is about 10 percent lower.

The AGO revenue estimate for regulation closely aligns with the CEA value, reflecting similar operational strategies for that product. (Both the CEA and AGO values are materially higher than the EMM estimate for regulation, reflecting changes in both strategy and prices.)

[9] EMM Comments at 6; "Approach 3".

Sensitivity of Revenues to Foreknowledge of Real-time Prices

To assess the potential for additional revenue above the AGO's proposed values, the AGO ran a sensitivity where the storage device has perfect foresight of real-time energy and TMSR prices (as opposed to the day-ahead prices assumed in the main analysis). As expected, perfect foresight enables storage to earn significantly more revenue, as Table 3 demonstrates.

Table 3: Value of Perfect Information in AGO Revenue Estimates.

	Revenue (Millions, 2025$)				
Scenario	**DA Energy**	**RT Energy**	**Reserves**	**Regulation**	**Total**
No FRM	$0.000	$1.752	$2.965	$3.514	$8.231
With FRM	$0.000	$1.455	$3.897	$3.514	$8.866
Perfect Dispatch	$0.000	$3.791	$3.112	$3.514	$10.417

Overall, if a resource has perfect foresight, it could earn about $10.4 million per year, about 25% more than the assumed No FRM scheme and about 20% more assuming the FRM is maintained. The $1.5 to $2 million increase in revenue is due almost entirely to improved energy dispatch. While it is very unlikely that a battery operator could earn revenues equal to this theoretical maximum, it does suggest that a more sophisticated storage dispatch strategy could potentially yield significantly more revenue than the values proposed by the AGO based on day-ahead price curves.

5. Conclusions

The AGO disagrees about the reasonableness of the CEA EAS revenue estimates for battery storage resources. A reasonable operator using a battery for energy, reserves, and regulation should be able to earn **$ 8,231,249 ($54.87/kW-year), assuming the FRM sunsets, and $ 8,866,214 ($59.11/kW-year), assuming the FRM is maintained**. In contrast, CEA estimates average EAS revenue from these three markets at $6,856,653 ($45.71/kW-year) assuming the FRM is sunset and $8,288,982 ($55.26/kW-year) assuming the FRM is maintained. The AGO reiterates that this estimate is conservative: the AGO fully expects that more advanced dispatch schemes could yield higher revenues.

EAS revenue estimates for ORTPs should not be based on the rosiest of predictions, but neither should they based on the assumption of bumbling incompetence. The AGO dispatch approach sits squarely between these two extremes and reflects the revenue available to a reasonably competent storage operator.