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 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 reasonable developer 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 a storage dispatch schedule which maximizes revenues from participation in two ISO New England (“ISO-NE”) markets, energy and the ten-minute spinning reserve (“TMSR”), 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 price timeseries – under two sets of assumptions, reflecting different degrees of knowledge about future prices.

- First, the AGO assumed that storage was optimally dispatched with *perfect foresight* of hourly real-time energy and TMSR prices.
- Second, the AGO assumed that storage was *dispatched* optimally based on known day-ahead energy prices, but *operates* only in the real-time market. Put differently, storage was dispatched in real-time based on the observed prices from that day’s day-ahead market.

The first set of assumptions reflects the upper-bound of revenues from participation in these markets and is unlikely to be realized in practice. The second set of assumptions reflects a readily achievable, albeit simple dispatch scheme. Both approaches are based on dispatch schemes outlined by the ISO-NE External Market Monitor (“EMM”) in their comments in ER20-308.[1] In the EMM comments, the EMM noted the ”limited sophistication” of the second approach and that this method “represents the minimum that an [energy storage resource] developer could reasonably expect to receive in EAS net revenues.”[2]

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

[2] Id.

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 conducted in this analysis, **the AGO proposes alternative energy and TMSR revenue estimates of $4,730,619 ($31.54/kW-year), assuming the FRM sunsets, and $5,375,295 ($35.84/kW-year), assuming the FRM is maintained**. In contrast, CEA estimates average EAS revenue at $22.39/kW-year assuming the FRM is sunset and $32.05/kW-year assuming the FRM is maintained. (The AGO estimate does not include revenues that could be obtained concurrently from other markets, such as CEA's estimate of incremental regulation revenues of $3.43 million, or $22.84/kW-year.)[3]

An energy storage resource dispatched using the AGO's scheme would earn 41 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 and about 12 percent more than the CEA estimate. Both AGO estimates assume that the device is dispatched based on known day-ahead prices but earning revenue in the real-time market. 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 precise pricing information and what it could 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 relies on pricing data directly extracted directly from the CEA battery ORTP model in "Battery_ORTPdispatch_2020.08.25_noFRM.xlsx" workbook.[4]

- 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).

When the battery is dispatched based on *day-ahead* prices, the optimization model also requires *expected* (not observed) real-time TMSR prices. Expectations about TMSR revenues can result in

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[3] See CEA Discount Cash Flow Model, Sheet = "E&AS"

[4] https://www.iso-ne.com/static-assets/documents/2020/08/a4_a_iii_cea_ortp_models_20200806.zip

changes to the periods when a battery may charge or discharge, but not how it is paid. For example, if an operator thinks that there could be a positive TMSR price in some future hour, it may choose to charge the battery earlier so it can provide TMSR in that period, even if that earlier charging costs a little more money. The operator is paid, however, based on the actual price of energy and TMSR; not what it expected to earn. Because there are not day-ahead TMSR prices, the AGO assumes *expected* TMSR prices of \$5/MWh in all hours. Overall ESS dispatch is not particularly sensitive to this assumption, so long as it is non-zero.

When the battery can participate in the FRM and is dispatched based on *day-ahead* prices, the model relies on the FRM TMSR price as the day-ahead TMSR value.

Prices used for Dispatch and Revenue by Model Run

Scenario		Prices used for Dispatch		Prices used for Revenue	
Information	**FRM**	**Energy**	**TMSR**	**Energy**	**TMSR**
Real-Time / Perfect Foresight	With FRM	RT LMP	OnPk: FRM OffPk: RT TMSR	RT LMP	OnPk: FRM OffPk: RT TMSR
	No FRM	RT LMP	RT TMSR	RT LMP	RT TMSR
Day-Ahead	With FRM	DA LMP	OnPk: FRM OffPk: RT TMSR	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* (CEA assumes 258 MWh deliverable)
Round-trip Efficiency	%	86%	*Same as CEA*
One-way Efficiency	%	92%	*Assumed Symmetric;* $92\% = \sqrt{86\%}$
TMSR Capacity	MW-ac	150	*Same as CEA*
Total Study Injection Limit	GWh-ac	3.285	*Same as CEA;* = 365 Days x 3 Years x 300 MWh-ac

- Like CEA, the AGO assumes that the battery has a capacity of 150 MW-ac.

- Unlike CEA, the AGO assumes that the battery can deliver 300 MWh-ac of energy to the grid. While CEA reported that the device had a "net plant capacity" of 300 MWh in June[5] and July,[6] the actual EAS revenue modeling assumes an MWh-ac capacity of 258 MWh.[7]
- 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.
- 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.

2.3 Linear Program Formulation

The linear program itself is derived from prior storage dispatch models employed by AGO staff.[8] 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 energy or TMSR. Note that **P** can be either the day-ahead or real-time prices, depending on input assumptions.

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

Injection & Withdrawal (measured MW-dc)

Energy may be injected into, or withdrawn from, the ESS 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 withdrawals 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.

$$\mathrm{ESS}_{\text{Charge Rate}} = \mathrm{ESS}_{\text{Discharge Rate}} \tag{2}$$

$$0 \leq \mathrm{I}_{\mathrm{t}} \leq \mathrm{ESS}_{\text{Charge Rate}} \tag{3}$$

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[5] CEA / MM presentation at 41. https://www.iso-ne.com/static-assets/documents/2020/06/a7a_cea_presentation_cone_ortp.pptx

[6] CEA / MM presentation at 30. https://www.iso-ne.com/static-assets/documents/2020/07/a5_b_i_cea_mm_presentation_cone_ortp.pptx

[7] See, for example, the Note in the Cell C7 of the "Battery ORTP dispatch with FRM" model, which reads: "150 MW injection, max generation of .86*300 MWh per day."

[8] 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.

$$0 \leq \mathrm{W_t} \leq \mathrm{ESS_{Discharge\ Rate}} \tag{4}$$

$$\sum_{\mathrm{t=0}}^{\mathrm{T}} (\mathrm{I_t}) \leq \text{Total Injection Limit} \tag{5}$$

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 TMSR Sales

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. This requires a set of equations,

$$0 \leq Q_{TMSR,t} \leq \eta SOC_t \tag{9}$$

$$Q_{TMSR,t} \leq \eta W_t - Q_{EA,t} \tag{10}$$

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,

$$\begin{array}{ll} If & (FRM\ Hour_t = OnPeak)\ and\ \left(FRM\ Threshold_t < P_{LMP,t}\right) \\ Then & Q_{TMSR,t} = 150 \end{array} \tag{11}$$

Because the FRM threshold price is relatively high, in most on-peak hours $Q_{TMSR,t}$ equals 150 MW.

If the FRM is sunset, this constraint is 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.

When the model is run assuming perfect information, the endogenous revenue outputs from the model are used for this computation.

When the model is run assuming imperfect information, additional *post hoc* processing is required. The endogenous revenue estimates returned by the model reflect revenues that a battery would have earned by taking efficient day-ahead positions. This is not the operational scheme actually assumed by the AGO (nor the EMM). Instead, the AGO assumes that these prices are simply used for the battery to develop an efficient schedule ($Q_{EA,t}$ and $Q_{TMSR,t}$) for each hour. Actual revenues, therefore, equal the hourly position for energy and TMSR outputted by the model, multiplied by the *real-time* price for each product. 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 could earn $4.73 to $9.22 million per year by selling energy and TMSR, depending on degree of foreknowledge and the existence of the FRM. These results, along with values from CEA and the EMM, are summarized in Table 2.

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

	Revenue (Million, 2025$)		Revenue ($/KW)		Change from CEA	
Source	**w FRM**	**No FRM**	**w FRM**	**No FRM**	**w FRM**	**No FRM**
CEA	$4.81	$3.36	$32.05	$22.39		
AGO						
Perfect Knowledge	$7.61	$7.57	$50.71	$50.46	58%	125%
DAM Knowledge	$5.38	$4.73	$35.84	$31.54	12%	41%
EMM*						
Perfect Knowledge	$8.40		$56.00		75%	150%
DAM Knowledge	$4.50		$30.00		-6%	34%
DAM + CTS	$5.10		$34.00		6%	52%

** EMM revenue estimates computed based on the revenue rate and an assumed 150 MW capacity. EMM did not estimate FRM revenues separate from TMSR and energy sales.*

These AGO estimates align closely to the estimates developed by the EMM in ER20-308. The EMM found that storage could earn about $56/kW-year given perfect information (11 percent higher than the AGO estimate) and about $30/kW given knowledge of day-ahead pricing (5 percent lower than the AGO estimate). The EMM also found that a more sophisticated trading strategy based on the day-ahead LMP and CTS transactions could earn $34/kW-year (8 percent higher than the AGO imperfect information estimate).

In contrast, CEA estimates average EAS revenue from energy and TMSR at $3.39 million per year, assuming the FRM is sunset ($22.39/kW-year) and $4.81 million per year assuming the FRM is maintained ($32.05/kW-year). The former estimate is about 30 percent lower than the equivalent AGO value and 25 percent lower than the EMM's comparable approach. The latter CEA estimate is about 10 percent lower.

5. Conclusions

The AGO disagrees about the reasonableness of the CEA EAS revenue estimates for battery storage resources. Through related, but independent, analyses the EMM and the AGO found that a "reasonably competent" storage operator could achieve net EAS revenues in the range of $30-36/kW-year. The CEA net EAS revenue estimates, by contrast, are 30 percent lower than what this "reasonably competent" storage operator could earn. 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.

Based on the specific modeling conducted in this analysis, **the AGO proposes alternative energy and TMSR revenue estimates of $4,730,619 ($31.54/kW-year), assuming the FRM sunsets, and $5,375,295 ($35.84/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. In addition, additional revenue from other markets, such as regulation, are both possible and expected.