Benchmarking ERCOT Performance of Stem's Athena® Optimization Platform

Analysis of energy storage systems in 2022

December 2023

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1. Executive Summary

The realm of battery energy storage system (BESS) optimization in merchant markets is both dynamic and challenging. Developing an optimization software product for this market is a complex and nuanced endeavor, demanding not only technical expertise but also a deep understanding of market dynamics and energy storage intricacies. Optimization capabilities play a vital role in determining the economic performance of BESS deployed in merchant markets.

In this paper, Stem shares in-depth backcast analyses and resulting perspectives about the importance of BESS optimization capabilities for maximizing merchant revenue attainment for asset owners in Electric Reliability Council of Texas (ERCOT) and beyond.

Leveraging publicly available data from ERCOT on operational behavior in its wholesale market, Stem selected a sample of six operational BESS assets comprising a mix of zones, project capacities, and incumbent operators. We reconstructed each asset's bidding behavior to analyze actual revenue earned in 2022 by the incumbent asset owners and operators. Concurrently, we conducted backcast simulations comparing actual revenue with the following: (1) performance under a naïve forecasting and optimization trading strategy, (2) potential revenue achievable using Stem's Athena® automated bid optimization platform without any human intervention, and (3) the theoretical maximum revenue achievable with perfect market foresight.

Figure 1 presents the results of each scenario across the six assets. Notable takeaways include:
- Stem's Athena optimization platform in fully automated mode outperformed five of the six assets with respect to actual revenue attainment, averaging 28% overperformance across the six assets.
- On average, Athena's AI-driven optimization successfully captured 75% of the theoretical maximum revenue, as determined by the perfect forecast scenario. In comparison, the average actual revenue realized across the analyzed assets amounted to 61% of this theoretical maximum.
- Highly accurate price forecasts drive enhanced revenue attainment, with Athena's stochastic price forecasts outperforming a naïve persistence-based approach by 53% in revenue.
- Advanced optimization capability unlocks maximal revenue potential. In line with Athena's revenue stack across all six assets, three of the four best performing assets (in terms of actual revenue attainment on a $/kWh basis) captured revenue across a mix of ERCOT market products while the three worst performing assets had revenue concentrated heavily in the Responsive Reserve Service (RRS) product.
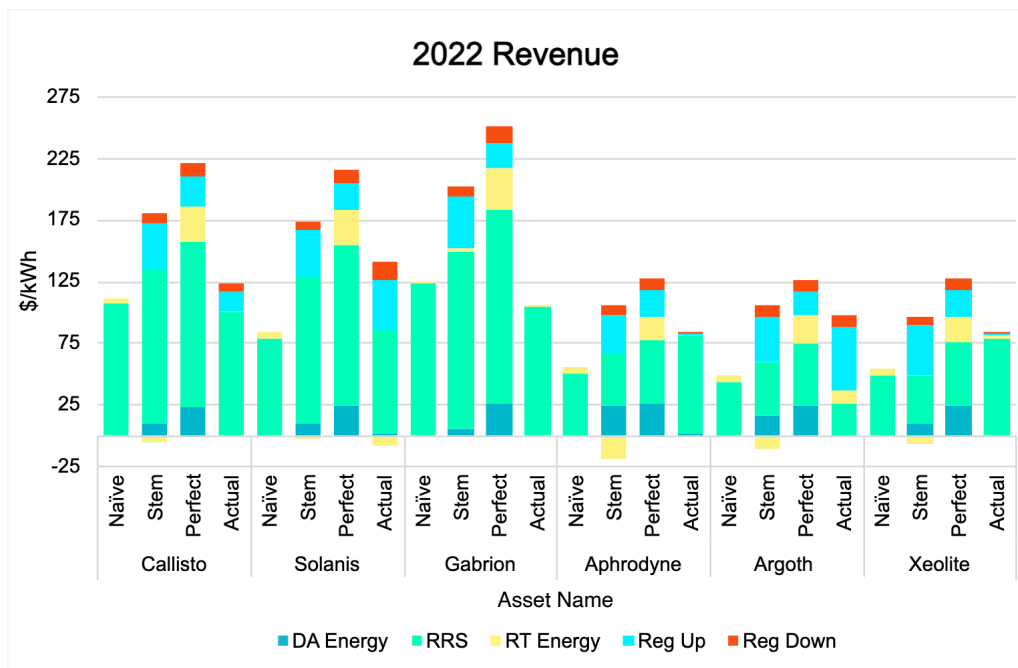

Figure 1: Revenue attainment across four analyzed scenarios

This benchmarking exercise also yielded important insights about optimizing battery operations in a merchant market like ERCOT that our readers and customers can leverage on an ongoing basis:

1. Deriving reliable estimates of utilization rates for different ancillary service products is needed for improved state-of-charge (SOC) management and can enable more optimized trading strategies.
2. Having accurate real-time price forecasts prior to the day-ahead market closing is critical to extracting overall value from all the markets products.
3. Employing human expertise through strategic manual intervention helps boost returns from a software-only optimization approach.
4. Without consistent battery availability, even the best optimization efforts fall short.

Detailed in the appendix, we describe the rigorous methodology used for conducting these simulations, ensuring adherence to ERCOT market rules, and maintaining the integrity of the results. Athena's models used a rolling time-based training approach, incorporating data only up to the point of each forecast, ensuring real-time accuracy and avoiding prospective bias.

Our goal is to offer transparency regarding our analytical process, thereby reinforcing our commitment to reliability in managing BESS optimization for merchant markets. We invite stakeholders and interested parties to engage with us for a deeper exploration of the insights presented in this paper.

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2. Introduction

Throughout 2022, ERCOT witnessed substantial growth in battery storage, a trajectory that is expected to persist. This expansion is fueled by the increasing integration of renewable energy in the state and the imperative for reliable, efficient grid management. Batteries play a vital role in stabilizing the grid by balancing the intermittency of renewable energy sources and mitigating grid strain during times of peak demand.

This report presents a detailed retrospective analysis of battery storage economic performance during 2022 within the ERCOT market, deriving insights from a range of simulations. Importantly, this analysis focuses on a distinct period within an ever-changing energy landscape, where market rules and pricing are continuously evolving. As such, while the findings provide valuable learnings, they are specific to 2022 data. For best practices in designing future BESS, we direct interested readers to our white paper that discusses the relative value of one- and two-hour duration systems in the ERCOT market.

Central to our analysis is Athena's bidding engine and proprietary stochastic price forecasts, the combination of which enables Athena to derive optimal merchant market bidding strategies. We demonstrate the ability of Athena to optimize energy storage in ERCOT across a variety of simulated operational scenarios. This paper offers a comparative analysis of Athena's performance relative to alternative operational strategies, highlighting its ability to refine decision-making, optimize bidding strategies, and adeptly manage the complexities of operating energy storage assets in a dynamic market environment like ERCOT.

Leveraging the power of Athena's forecasts and automated bidding engine, Stem offers customers both managed and self-service wholesale market bid optimization solutions. As part of our managed offering, Stem's experts manage Athena's day-to-day bidding of battery storage assets on our customer's behalf. Alternatively, our Athena® PowerBidder™ Pro application gives asset owners, traders, and tolling offtakers direct management of Athena's bidding, providing unmatched control and customization of their bidding strategies. Because our analysis focuses on a theoretical scenario where Athena is in fully automated mode, it likely understates the total potential value for these assets when either Stem or the customer leverages its human experts to enhance performance beyond a software-only approach.

3. Benchmarking Athena Optimization Performance in ERCOT

In this section, Stem provides the detailed methodology we employed to complete the benchmarking exercise and key results from the benchmarking analysis.

3.1 Methodological Overview

Stem selected six standalone storage assets for analysis based on the following criteria, ensuring a robust comparison across multiple operational scenarios within the ERCOT market:

- Started commercial operations prior to January 2022 to provide a reliable performance baseline.
- Geographically dispersed across various ERCOT zones to reflect locational diversity.
- Incorporated BESS with capacities ranging from 10 MW to 100 MW, with varying durations of one or two hours to illustrate performance across different energy capacities and operational flexibilities.
- Managed by a variety of incumbent operators to present an array of management strategies and operational practices.

Table 1 details the six assets we included in our analysis. We use pseudonyms to preserve preserve asset anonymity.

1-Hour Assets	2-Hour Assets
Callisto	Xeolite
Solanis	Argoth
Gabrion	Aphrodyne

Table 1: Asset pseudonyms

Stem utilized our Athena simulation platform to analyze how different operating strategies, including hypothetical ones such as naïve operations, would have fared in 2022 relative to the actual operations of the chosen assets achieved by the incumbent operator. By analyzing each strategy along with its respective revenues earned, we gained valuable insights into the relative levels of performance of each strategy. These strategies are categorized in the following table.

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Naïve Operations	This hypothetical approach combines elementary forecasting with basic optimization to form a straightforward bidding strategy. The forecasting component uses a persistence model, assuming current market prices are the best predictor of near-term trends. Optimization is limited to bids and offers for real-time energy and RRS, reflecting a simplified operational strategy that is representative of the actual revenue profiles for some of the assets analyzed within this sample.
Stem Operations	Utilizing Athena's advanced forecasting and optimization technologies, this strategy is engineered to maximize merchant revenue attainment. It adheres to ERCOT market rules[1] and respects operational and warranty constraints. It includes comprehensive optimization across all available market products[2], including day-ahead energy, real-time energy, RRS, regulation up, and regulation down, reflecting an asset's potential performance if Athena fully managed bidding strategies without any human intervention. This strategy does not assume foreknowledge of market prices, and instead utilizes our proprietary stochastic price forecasts to inform optimal behavior of the battery asset's operations.
Perfect Forecast	This mirrors the Stem strategy but uses actual cleared market prices and production data, removing uncertainty associated with forecasting. It serves as a benchmark for the theoretical maximum revenue achievable with complete foresight into market prices.
Actual	Reflects the revenue achieved by the incumbent operator, as reconstructed by Stem using public ERCOT data.

Table 2: Simulated strategies

The appendix includes a more detailed description of the benchmarking process Stem employed to derive the results highlighted in this section.

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[1] In December 2022, ERCOT revised the ancillary service (AS) SOC requirements in the Business Practice Manual (BPM). The updated guidelines stipulate that an energy storage resource must maintain sufficient discharge (or charge) capacity to fulfill its AS obligations, assuming full utilization. However, the actual utilization rate for AS varies by product, averaging around 20% for regulation services and significantly lower for reserves.

Due to the lack of clarity on how incumbent operators adhered to this requirement before the BPM update, our simulations adopt a balanced approach. We stipulate that, in real time, assets must have enough discharge (or charge) capacity to cover at least 50% of the asset's regulation or reserve obligations. This approach reflects a middle ground, considering the varied interpretations and implementations prior to the BPM revision.

Significantly, as echoed by other market participants, enforcing a requirement for energy storage resources to reserve capacity for full AS coverage notably diminishes revenue potential, especially for assets with a one-hour duration. This observation is critical in understanding the operational and financial implications of the revised AS SOC guidelines.

[2] Stem excluded selecting assets that provided non-spinning reserves in 2022 and excluded provision of non-spin from our simulations due to the moratorium which was in place for qualifying energy storage resources for non-spin pending the implementation of the duration requirements in NPRR1096.

3.2 Benchmarking Results

To facilitate a balanced analysis across various asset sizes, Stem employed two metrics: (1) revenue per kilowatt ($/kW) and (2) revenue per kilowatt-hour ($/kWh).

The $/kW metric is key for evaluating not only the physical interconnection costs of BESS, such as transformers and switchgear, but also extends to evaluating key contractual and regulatory aspects. This metric is commonly used in offtake agreements for BESS projects, where payments to the asset owner are often based on a defined level of power capacity. Beyond these direct costs, the $/kW metric also encapsulates various soft and opportunity costs associated with interconnection studies, permitting, and meeting regulatory requirements. Notably, while these costs are significant and growing, they generally do not scale linearly with the increase in energy capacity of the system. This highlights a strategic advantage in expanding energy duration without proportional increase in the above-mentioned costs.

Meanwhile, the $/kWh metric becomes increasingly important in capturing the costs related to the energy capacity of the system. This is particularly pertinent in ERCOT, where market trends like the saturation of ancillary service markets, introduction of new market products that require sustenance of the power capacity for certain durations, evolving grid dynamics, and an increased focus on reliability are shifting the market towards storage systems with longer energy durations. In addition to these market drivers, the decreasing costs of lithium-ion batteries, closely tied to the $/kWh metric, enhance the economic viability of expanding energy capacity. Overall, BESS with larger energy capacities are projected to become more valuable and prevalent in ERCOT.

Figure 2 captures how the perceived 'best' performing asset varies based on the comparison metric. The left side of the figure compares revenue attainment in $/kW terms while the right side of the figure compares revenue in $/kWh terms.[3]

Argoth was the top performing asset on a $/kW basis, earning approximately $195/kW, or roughly 18% more than the second-best performing asset (Xeolite). Argoth also outperformed the worst performing asset (Gabrion) by a margin of nearly $91/kW, with nearly 86% greater revenue. In contrast, Solanis was the top performing asset on a $/kWh basis, earning approximately $132/kWh, or roughly 7% more than the second-best performing asset (Callisto). Solanis also outperformed the worst performing asset (Aphrodyne) by a margin of $49/kWh, with nearly 60% greater revenue.

The most evident trend from analyzing actual revenue is that when comparing results on a $/kWh basis, the top performing assets all earned meaningful revenue outside of RRS. Although RRS was a lucrative market product in 2022, the top performing assets enhanced their revenue by effectively optimizing for additional market products, including regulation services.

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[3] Stem's review of Gabrion's publicly available Current Operating Plan (COP) submission data indicated that the asset operated at a derated capacity for most of 2022. To ensure a realistic comparison in our simulations, we adjusted the assumed capacity levels to approximate Gabrion's actual operational capacity observed throughout the year.
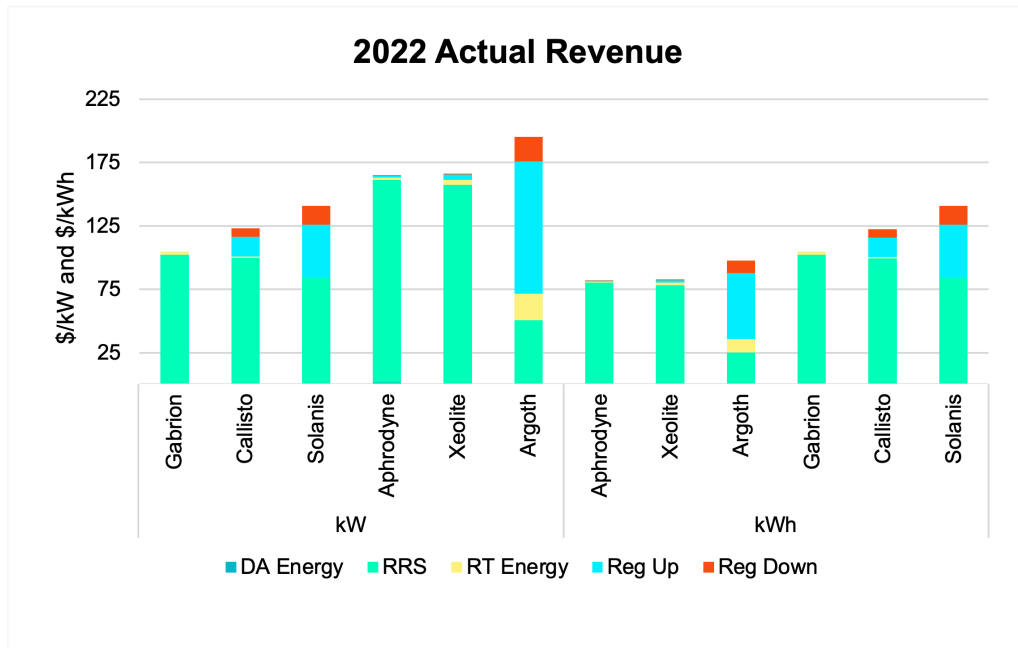
Figure 2: 2022 actual revenue attainment on a capacity ($/kW) and energy ($/kWh) basis

Figure 3 presents side-by-side results for all four scenarios outlined above: (1) a naïve trading strategy, (2) Stem's operating strategy, (3) perfect forecast, and (4) actual earned revenue. These results illuminate three key takeaways:

- Stem's Athena platform outperformed five of the six assets with respect to actual revenue attainment, ranging from 5% over Aphrodyne to 90% over Gabrion, averaging 35% across the five assets. Stem's performance trailed Argoth by 4%[4], in large part due to negative net revenue emanating from charging in the real-time energy market.

- On average, Stem's Athena platform captured 75% of the theoretical maximum revenue attainable as measured by the perfect forecast scenario, ranging from 68% for Aphrodyne to 80% for Gabrion. Stem's percent-of-perfect performance was best for assets where there were limited or no losses attributable to charging in the real-time energy market.

- Revenues under perfect forecast are never achievable given the uncertainty inherent in operating batteries, but the perfect forecast results highlight the finding that optimizing across all market products yields better results. Stem's operational strategy excels in this regard as Athena would have earned revenue from all five ERCOT market products for each of the six assets. It should be noted that actual day-ahead energy revenue attainment for three of the assets was zero and de minimis for the other three assets as managed by the incumbent operator. Athena's ability to capture revenue across all market products, including the day-ahead energy market, positions Stem to deliver outstanding results for our customers.

[4] Although in Figure 3 the total height of the Stem stacked bar exceeds Argoth's actual performance, the yellow bar below the x-axis in Stem's stacked bar represents a net loss associated with Athena's real-time energy performance. As such, Athena's net performance relative to Argoth's actual revenue is lower by 4%.
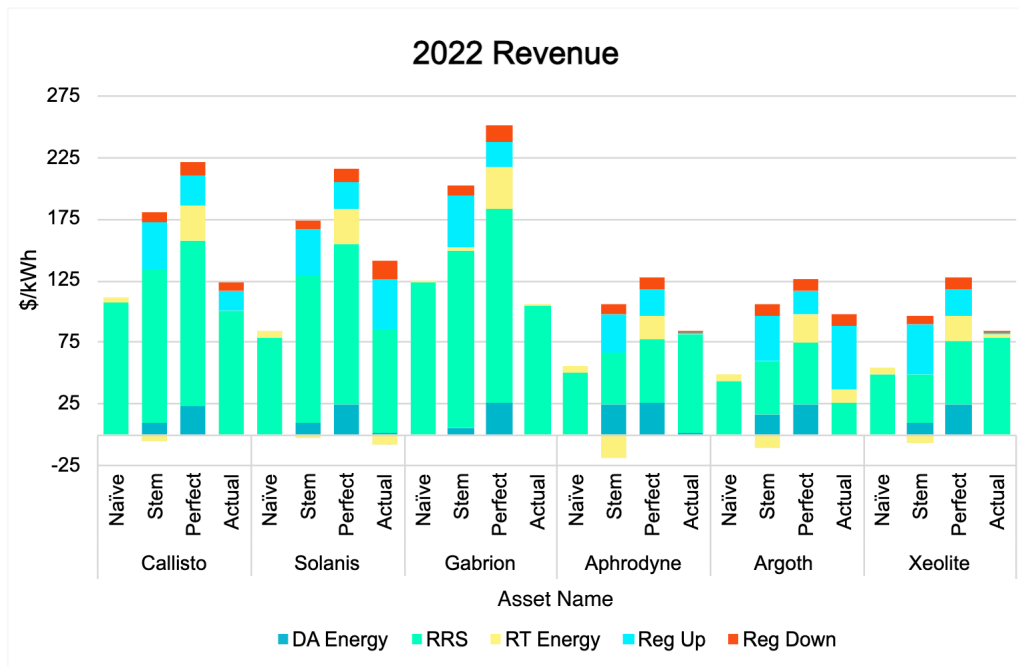
Figure 3: 2022 revenue attainment across the four strategies ($/kWh)

Underpinning Stem's strong performance is Athena's (1) industry-leading proprietary price forecasts and (2) advanced optimization capabilities.

3.2.1 The Value of Advanced Price Forecasting

A robust price forecasting capability is a key driver of revenue attainment during merchant operations and a core reason why Stem outperforms other operators.

The benchmarking results demonstrate the importance of Athena's advanced price forecasting on revenue attainment, particularly when comparing the results of Athena's operation to the naïve trading strategy. As shown in Figure 3, Stem achieved an average 53% improvement in revenue over the naïve trading strategy. While there is some degree of correlation between market prices on consecutive days, this more simplified forecasting approach fails to fully capture true market dynamics where new market information is immediately reflected in short-term market prices, leading to lost revenue opportunities that may ultimately jeopardize a project's financial viability.

With ERCOT being an energy-only market with high price volatility, the economic performance of battery storage assets hinges on their ability to capitalize on periods of high price fluctuations. Advanced forecasting capabilities are thus not just beneficial, but essential.

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Athena's stochastic price forecasts enable our partners to effectively manage risk, allowing for risk assessment of revenue opportunities. Notable observations based on a sample of historical prices and forecasts for the ERCOT North zone from May 11th to 17th, 2022 are presented below. Athena's forecasts exhibit high efficacy in anticipating market conditions by:

- identifying the time intervals of large price movements or spikes (this ability is instrumental in extracting value more effectively from the market);
- predicting the potential level or magnitude of prices by incorporating a stochastic capability; and
- avoiding false positives by learning from the conditions that lead to market volatility.
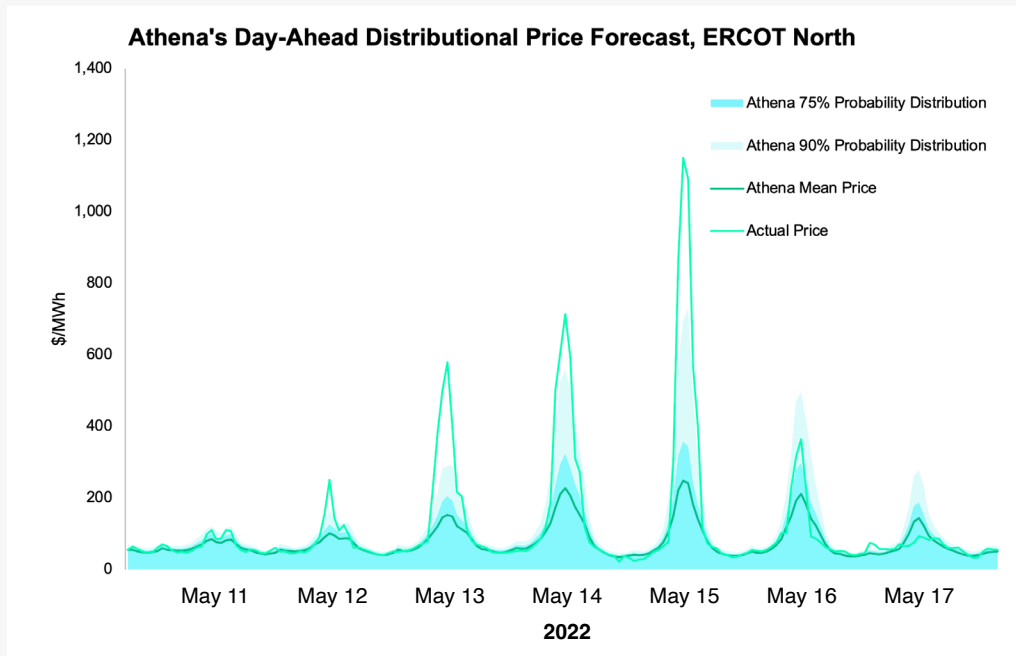

Figure 4: Athena's stochastic day-ahead energy price forecast for ERCOT North, May 11-17, 2022

Figure 4 represents a simplified rendering of our forecasts in two important regards. First, while Athena updates its forecast on at least an hourly cadence, this figure stitches multiple forecasts into a single continuous distribution for ease of viewability. Second, Athena generates stochastic—rather than deterministic—forecasts, but the figure represents this simplistically by showing just the mean, 75th percentile, and 90th percentile curves.

Further highlighting Athena's advantage, a comparison of the mean absolute error between our proprietary ERCOT North 2022 price forecasts and those of an industry competitor revealed a 20-40% improvement in accuracy across various ERCOT market products.

Figure 5 depicts for each asset how Stem's revenue attainment progressed throughout the year compared to actual revenue, as ranked by the amount of daily revenue accrued (i.e., 100 on the y-axis implies 100% of actual revenue attained by the incumbent in 2022). In terms of revenue attainment during the top 20 highest revenue days—which is a proxy for high-volatility days[5]—Athena's performance was comparable to three assets (Xeolite, Argoth, and Aprodyne) and significantly better than three assets (Gabrion, Callisto, and Solanis). Athena's advanced price forecasting enables this strong performance on the highest volatility days, positioning our customers to earn significant revenues.

A notable observation from Figure 5 is the concentration of a substantial portion of annual revenue within a limited number of days. On average, 42% of Athena's annual revenue across the six assets is derived from the top 20 highest revenue days. This means that performance during a few days can have an outsized impact on overall asset economics. However, it also indicates that realizing consistent revenue throughout the year requires effective strategies even during periods of less pronounced price volatility. Athena's proprietary forecasts play a crucial role in both these regards, enabling us to implement trading strategies that optimize revenue attainment.
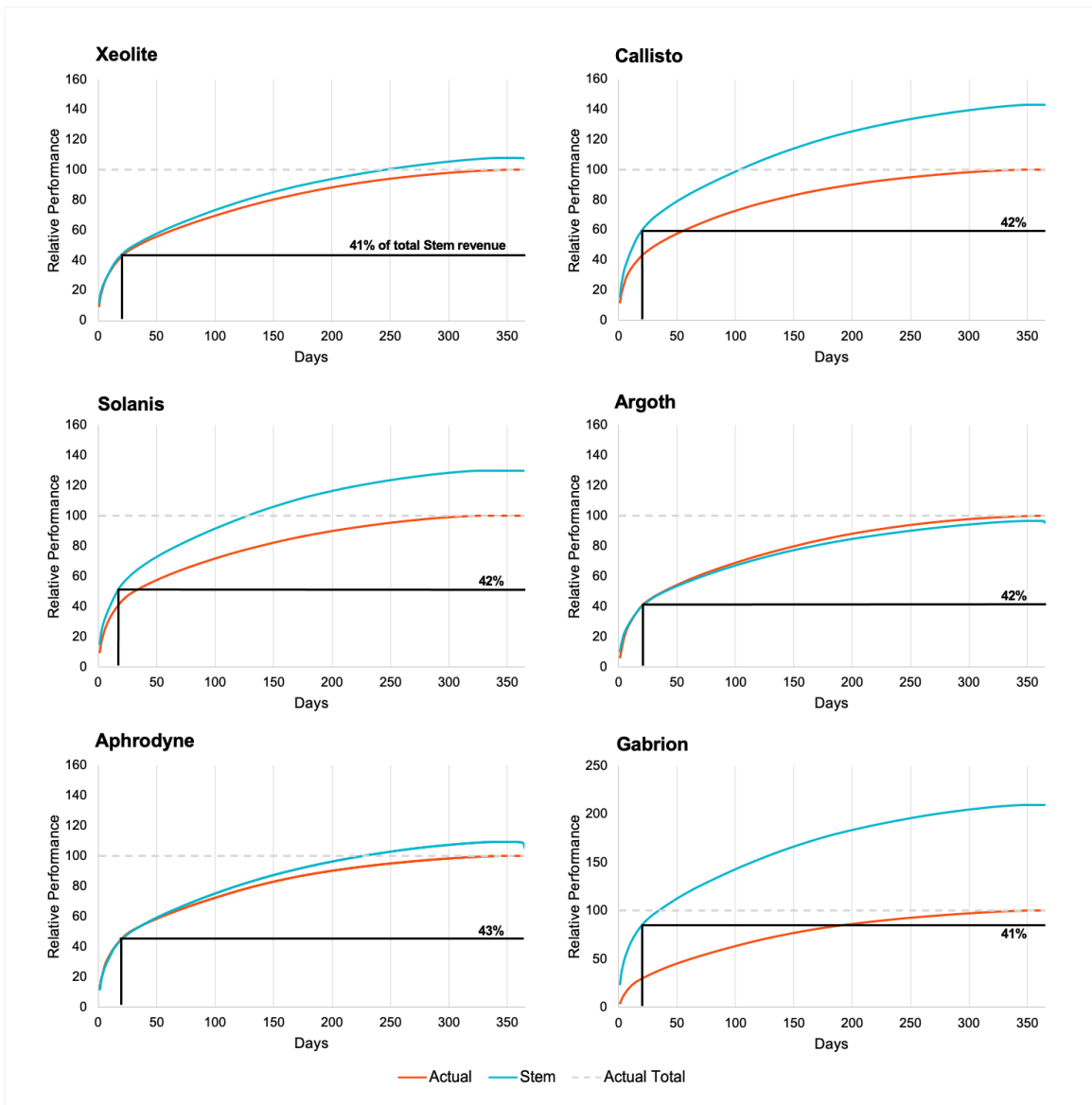

Figure 5: 2022 revenue attainment, ranked by daily revenue levels

[5] With battery storage revenue being a function of both price volatility and absolute price levels, we use top revenue days as a proxy to capture the effects of both trends.

3.2.2 Advanced Optimization Enables Revenue Uplift

Successfully managing the economic and operational tradeoffs for a BESS project is an exceedingly complex task. The technical and economic factors that drive final dispatch ultimately result in thousands of individual variables and constraints that must be respected by an operating system. An advanced, AI-enabled solution like Athena is vital to maximizing total project value, minimizing degradation and down-time, and ensuring compliance with key project requirements by automatically generating bidding strategies that optimize across both (1) day-ahead and real-time markets and (2) different energy and ancillary service market products.

While variability in revenue attainment between assets (as displayed in Figure 2) is in part driven by differences in physical asset location (i.e., exposure to different day-ahead and real-time energy prices caused by varying congestion profiles based on geographic dispersion), the underlying operational strategy is a key determinant of the asset's revenue attainment potential. Athena's advanced optimization capabilities not only enable us to capture revenue across all market products but also allow for a more dynamic mix of products in the operational strategy over time as the underlying prices of those products evolve.

As previously demonstrated in Figure 3, the revenue profiles of the naïve trading strategy are heavily skewed towards RRS, which resembles the return profiles for the Gabrion, Aphrodyne, and Xeolite assets (Table 3). While RRS-heavy optimization strategies fared well in 2022, the revenue these three assets earned only represented 48%, 62%, and 63% of the top performing asset's (Solanis) revenue on a $/kWh basis, respectively.

Market Product	Aphrodyne	Xeolite	Argoth	Gabrion	Callisto	Solanis
Day-Ahead Energy	1%	0%	0%	0%	0%	0%
Real-Time Energy	1%	2%	11%	2%	1%	-7%
RRS	97%	95%	26%	98%	81%	64%
Regulation Up	1%	2%	53%	0%	13%	32%
Regulation Down	0%	0%	10%	0%	5%	11%
Total Revenue ($/kWh)	82.2	82.8	97.7	105.9	122.5	131.6

Table 3: Actual revenue breakdown by market product

Furthermore, advanced optimization capabilities help operators adapt to the shifting revenue potentials of various market products over time. For example, RRS is unlikely to yield the same revenue levels moving forward as it did in 2022 because of fundamental market changes like (1) additional battery capacity saturating the ERCOT ancillary services market and (2) the introduction of new products like ERCOT Contingency Reserve Service (ECRS) that change the relative procurement and subsequent pricing of RRS. This is a key advantage of our Athena platform: as revenue earning opportunities shift between market products over time as the result of market design changes, introduction of new market products and services, regulatory evolution, and macroeconomic factors, Athena continuously adapts its bidding strategy to maximize revenue attainment.

Although not fully representative of battery storage potential, one simple benchmark for gauging the economic opportunity available for battery storage is the energy arbitrage value that exists in a market. This energy arbitrage value is often represented by the top-bottom (TB) metric for "x" hours, or TBx. This represents the price differential between the top and bottom hour(s) of the day-ahead or real-time energy market based on actual cleared prices rather than what the asset achieves.

Table 4 compares for all six assets the possible revenue from capturing 100% of the day-ahead TBx value (with the hours matching the duration of the battery asset) compared to the overall revenue Athena captures by optimizing across all energy and ancillary service products. These results validate the highly improved returns achievable from employing an advanced optimization strategy.

1-Hour Assets	TB1 Value ($/kWh)	Stem Revenue ($/kW and $/kWh)	
Callisto	48.44	175.03	
Gabrion	46.52	219.38	
Solanis	49.91	170.99	
2-Hour Assets	TB2 Value ($/kWh)	Stem Revenue ($/kW)	Stem Revenue ($/kWh)
Xeolite	45.26	174.46	88.93
Aphrodyne	45.92	172.56	86.47
Argoth	46.36	195.44	93.54

Table 4: Athena's strong performance relative to day-ahead TBx value

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4. Key Takeaways

While the benchmarking exercise was inherently retrospective, it provided important insights about optimizing battery operations in a merchant market like ERCOT moving forward. Four takeaways worth highlighting are:

1. Deriving reliable estimates of utilization rates for different ancillary service products is needed for improved SOC management and can enable more optimized trading strategies.
2. Having accurate real-time price forecasts prior to the day-ahead market closing is critical to extracting overall value from both the day-ahead and real-time markets.
3. Ensuring robust battery availability is critical for the effectiveness of sophisticated optimization strategies.
4. Employing human expertise through strategic manual intervention helps boost returns from a software-only optimization approach.

While this analysis featured fully automated operations, Stem's firsthand experience in different BESS management settings has demonstrated the value of operational augmentation by hardware and market experts

4.1 Reliable Ancillary Service Utilization Estimates

As highlighted in section 3.2.2, optimization across energy and ancillary service products for maximizing revenue is important. Critical to executing these optimized trading strategies is the precision of Effective Usage Rate (EUR) estimates for capacity-based ancillary services like RRS and regulation. These services are awarded on a day-ahead basis for a specific capacity amount (MW) and vary in their actual dispatch during the operating day, ranging from the full scheduled amount to no dispatch at all, thereby determining the EUR. An illustrative example of EUR calculations is as follows.

Capacity Award for Hour (MW)	Total Dispatched Energy During Hour (MWh)	Effective Usage Rate (%)
1	0.25	25
5	2	40
10	10	100
10	0	0

Table 5: Illustrative Effective Usage Rate Calculations

Accurate EUR predictions are vital as they inform decisions around SOC management and the optimization with other market products. This is particularly pertinent in ERCOT with the anticipated implementation of NPRR 1186[6], mandating hourly SOC checks to ensure batteries can meet their awarded commitments, with financial penalties for shortfalls. Realistic EUR estimates can mitigate this risk by providing clearer expectations of hourly SOC expenditure, which, in turn, impacts the ability to fulfill other commitments. Appropriate EUR assumptions enable operators to balance between conservative and aggressive trading strategies, avoiding unnecessary conservatism that aims merely to evade penalties.

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[6] https://www.ercot.com/mktrules/issues/NPRR1186

Athena's performance in ERCOT is partly driven by our adept handling and accurate estimation of EURs. With NPRR 1186 likely ushering in stricter SOC management requirements, our focus on refining EUR predictions becomes even more important. We believe that EUR forecasting, combined with robust strategies to manage with variable ancillary service utilization rates will be a key differentiator between top and average performers in the ERCOT market, playing a crucial role in both risk management and the optimization of asset profitability.

4.2 Accurate Real-Time Energy Price Forecasts

Accurate day-ahead forecasting of real-time prices is also important for devising optimal trading strategies, especially those that attempt to extract value from both the day-ahead and real-time markets. Although real-time price forecasts are essential for capitalizing on emerging volatility during the operating day, it is the day-ahead prediction of these prices that informs critical decisions regarding battery commitment in the day-ahead energy and AS markets. Operators need to assess the anticipated value in the real-time market and, based on their confidence in capturing this value, devise a trading strategy that balances day-ahead and real-time market participation effectively.

Figure 6 illustrates how the service component of AS revenues is a function of both real-time prices and EURs, underscoring the importance of having accurate forecasts of both prior to the day-ahead market bid submission window closing. During periods of low real-time price volatility—as shown in the left side of the graph—the EUR is the main driver of AS service revenue, with changes in the EUR corresponding to changes in AS service revenue. However, the right side of the graph illuminates how the scale of AS service revenue fluctuations are more pronounced when real-time price volatility increases. While the shape of the AS service revenue curve is still closely linked to prevailing EURs, it is the real-time price that has an outsized effect on the total amount of AS service revenue. Consequently, inaccurate real-time price forecasts on a day-ahead basis will lead to suboptimal bidding strategies.
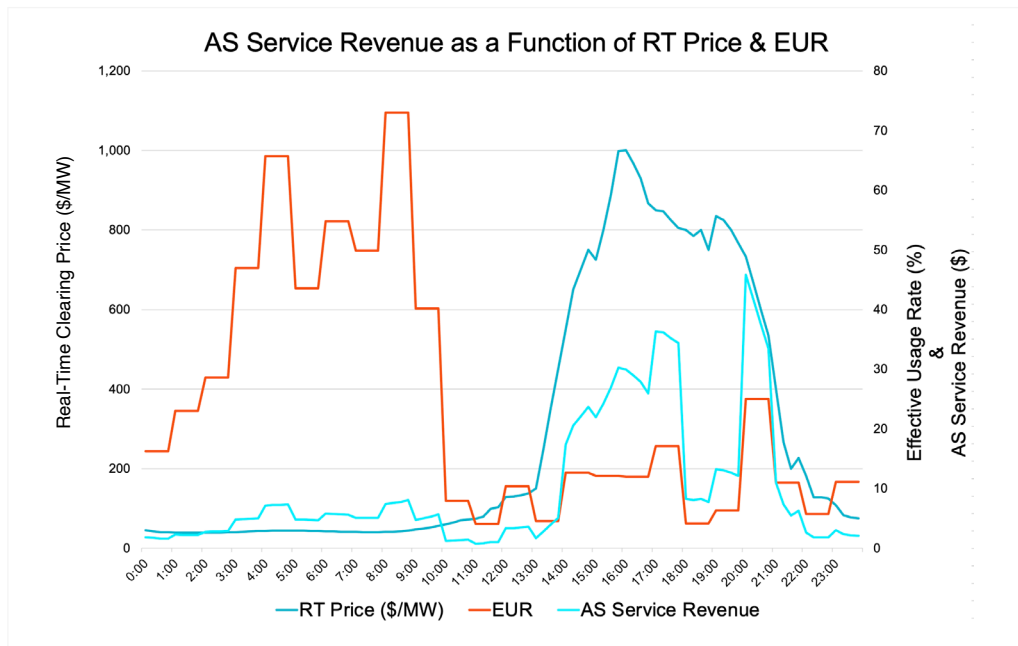

Figure 6: AS service revenue as a function of RT prices and EURs

Recognizing our significance in maximizing revenue, Stem has made the day-ahead projection of real-time prices a focal point of ongoing enhancement efforts. We are continually enhancing Athena's proprietary forecasting model to more accurately account for the variables that influence real-time price dynamics a day in advance and position Athena to identify the optimal split and timing of market participation that maximizes revenue.

4.3 Impact of Asset Availability on Performance

As demonstrated throughout this paper, advanced optimization capabilities are crucial in driving enhanced project returns. However, even if an operator is positioned to develop well-informed trading strategies, it is all for naught if the physical battery storage asset is not available to participate in the market during an attractively priced time interval. The performance of the Gabrion asset described above epitomizes this takeaway; its derated availability throughout 2022 resulted in simulated revenue attainment of 25% less than what would have been achievable had the asset been fully available throughout the year.
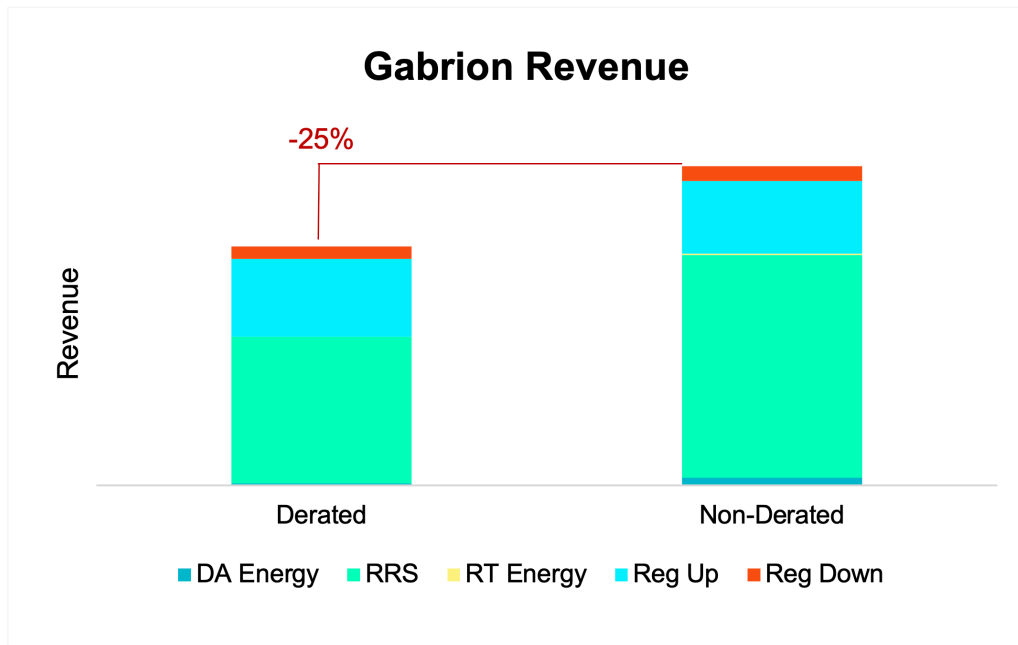

Figure 8: Gabrion derated and non-derated revenue

An asset's performance is both a function of the overall availability throughout the asset's lifetime as well as the timing of the asset's unavailability when it does occur. As demonstrated in section 3.2.1, the hours when an asset is operational are a critical driver of its bottom line. Stem has spent over a decade building out a proprietary system that provides timely situational awareness into asset health and a critical path to issue detection and resolution for all assets, systems, and sites. Having built deep working relationships with original equipment manufacturers (OEMs), Stem can manage field work effectively and ensure faster remediation, helping assets stay online at times when we project a significant revenue earning opportunity. With our Remote Operations Center (ROC), customers can reduce project operational risk, lower services costs, mitigate outage impacts, and increase overall system economics.

Separately, with respect to overall availability, asset owners must not make battery hardware investment decisions based solely on upfront price, but rather on an informed analysis of total cost of ownership over the asset's lifetime. Through our experience working directly with Tier 1 OEMs for over a decade to procure battery hardware solutions on our customers' behalf, we have seen firsthand how these industry-leading hardware solutions are more effective than Tier 2 and 3 OEM solutions at maximizing uptime over the project's useful life, giving asset owners more opportunities to capture revenue.

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Stem provides customers with the option to directly manage their trading strategies via the Athena PowerBidder Pro application. This application provides a user-friendly web interface integrated with our bidding engine, offering users transparency in optimized bids and offers, robust risk management tools, and comprehensive project and portfolio-level insights. With Athena PowerBidder Pro, customers can harness the power of Athena's automation and analytics while maintaining direct control over asset performance. This self-service model, much like our managed service, underscores the enhanced outcomes achievable through the combination of AI capabilities and user engagement.

4.4 Value of Human Expertise Coupled with AI

The backcasting results showcase the potential revenue attainable by Stem's AI-driven Athena platform. However, it is important to note that a managed optimization service complements the advanced AI-powered bidding engine. This hybrid approach maximizes returns, improves efficiency, and reduces risk by combining technological precision with human judgment, particularly valuable in unprecedented situations. For instance, during unexpected events like Winter Storm Uri, a team of human experts can augment Athena's automated operations (both in terms of bid optimization and Remote Operations Center capabilities, as described above), accounting for market conditions and scenarios that automated processes alone might not fully capture.
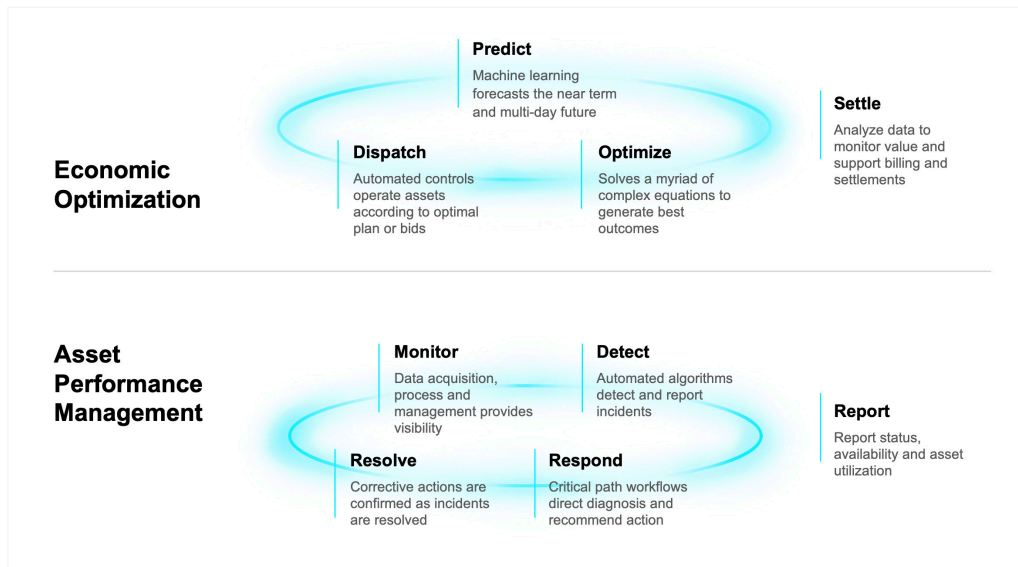

Figure 7: Illustrative rendering of Stem's battery storage management approach

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Appendix: Stem's Benchmarking Process Overview

Overall Process

Our analysis of the ERCOT market was driven by two technical capabilities that are core to powering Athena's market participation capabilities: (1) market analysis and revenue reconstruction and (2) wholesale market battery storage simulations.

With respect to (1), Stem's market experts used available data, including ERCOT's 60-Day Security Constrained Economic Dispatch (SCED) Disclosure Reports, to analyze the market participation behavior of operating energy storage resources. This analysis encompassed a thorough examination of uptime and performance metrics. Building upon this market participation analysis, we reconstructed the realized revenue, which is presented as the "Actual" revenue benchmark in our results in section 3.2. To facilitate a more direct and meaningful comparison, uptime data is integrated within Athena's simulated revenues.

With respect to (2), Stem's Athena simulation platform, which is designed to perform digital-twin simulations of Athena's energy resource optimization and control algorithms, was utilized to perform this analysis. The platform is meticulously engineered and includes the following critical components:

- **Proprietary Forecasting and Optimization Algorithms:** Athena is equipped with advanced stochastic forecasting and optimization algorithms, curated to enable optimal wholesale trading strategies. Our aim is to not only maximize profits but also ensure stringent compliance with battery operational constraints, warranty restrictions, and market regulations.
- **ERCOT Market Simulation:** The platform includes a detailed simulation of ERCOT's energy and ancillary service market-making and economic dispatch activities, including clearing the market and simulating the Automatic Generation Control (AGC) signal that the market operator would send to the storage asset. The behavior of this simulation is informed and enriched by Stem's extensive experience and deep expertise in energy markets.
- **Energy Resource Simulation:** We integrated a high-fidelity energy resource simulation into the platform that uses the high frequency AGC signal (referenced above) and a digital battery model to simulate the BESS's behavior on a rapid cadence. This enables us to accurately capture discrete system dynamics, embodying Stem's market-leading experience monitoring and operating a diverse portfolio of standalone and hybrid energy storage projects.

The integrity of our analysis and the results derived from the Athena simulation platform are of paramount importance. We have implemented rigorous procedures and adhered to best practices to ensure that our findings are accurate, reliable, and defensible, including back-testing with historical data and employing rolling cross-validation. Stem sourced all market data directly from ERCOT and employed a stringent validation process to ensure accuracy and consistency. Separately, the design of the Athena simulation platform is grounded in robustness and reliability. Each scenario was crafted and parameterized to capture the complexity and dynamics of the ERCOT market. We ensured that the model assumptions, constraints, and boundary conditions were realistic and based on empirical data, enhancing the credibility of our simulations.

The entire simulation platform is parametrized to rigorously test different optimization strategies, market behaviors, and operational characteristics of energy resources. This meticulous approach ensures the ongoing refinement and enhancement of Athena's algorithmic performance, guaranteeing robustness to the changing grid dynamics and market rules.

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Naïve Forecasting Definition

For day-ahead (DA) markets, the forecasting process follows the DA clearing schedule to track known prices. Prior to the DA market clearing on the current day, the forecast for future days is populated with the DA prices for the current day, applied on an interval-by-interval basis. After the DA market clears on the current day, the forecast seamlessly transitions to include the newly cleared DA prices for upcoming intervals. However, for intervals that fall within the current day, the forecast consistently uses the cleared prices from the current day, ensuring accuracy and alignment with market conditions.

For real-time (RT) markets, the naïve forecast derives from historical prices, assigning the most recent value from each time interval to its corresponding future interval. For example, when forecasting begins at 10:00 AM, all 10:00 AM intervals in the forecast adopt the price from 10:00 AM of the previous day. For intervals already completed on the current day, such as 9:00 AM, the forecast uses the price from 9:00 AM of the same day.

About Stem, Inc.

Stem (NYSE: STEM) is a global leader in AI-driven clean energy solutions and services.

Stem (NYSE: STEM) provides clean energy solutions and services that maximize the economic, environmental, and resiliency value of energy assets and portfolios. Stem's leading AI-driven enterprise software platform, Athena® enables organizations to deploy and unlock value from clean energy assets at scale. Powerful applications, including AlsoEnergy's PowerTrack, simplify and optimize asset management and connect an ecosystem of owners, developers, assets, and markets. Stem also offers integrated partner solutions that improve returns across energy projects, including storage, solar, and EV fleet charging.

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