Supercharging Battery Economics, Shrinking Emissions

Exploring the Risks and Rewards of Carbon Contracts for ERCOT Energy Storage in 2023

JUNE 2024

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ACKNOWLEDGMENTS

We thank the following reviewers of this study: Adam Reeve & Sarah Sofia (REsurety); Nat Steinsultz & Henry Richardson (WattTime); Connor Waldoch, Max Kanter, & Andrew Gelston (Grid Status); Brandt Vermillion & Neil Weaver (Modo Energy); Dr. Eric Hittinger (Rochester Institute of Technology).

ABSTRACT

In 2023, Texas experienced a sustained summer heatwave that resulted in unprecedented electricity demand. The Electricity Reliability Council of Texas (ERCOT) also introduced a new ancillary product to support grid reliability: the ERCOT Contingency Reserve Service (ECRS). While these market developments translated into a banner year for the financial performance of energy storage assets operating in ERCOT, those energy storage assets continued a concerning trend of inducing electricity emissions.[1] In theory, energy storage coupled with abundant renewable energy is the key to reliable and carbon-free energy on-demand. Leveraging Marginal Emissions Rates (MERs) and operational data, this study finds that operating energy storage assets in ERCOT may inadvertently *increase* emissions; however, this study also considers carbon contracts as a mechanism to enhance both the financial viability and carbon abatement potential of energy storage. Whereas renewable energy projects benefit from the issuance of renewable energy credits (RECs) and other revenue stabilization structures such as power purchase agreements (PPAs), energy storage assets have few means of monetizing their environmental attributes. Based on our findings, carbon contracts deployed across the energy storage fleet could improve economics while simultaneously reducing emissions. Lastly, we discuss the implications of carbon contracts for energy storage owners and potential offtakers and highlight industry-wide momentum behind this approach.

INTENDED AUDIENCE

This study is of particular interest for corporate sustainability professionals, renewable energy developers, energy storage owner/operators, capital providers, public- and investor-owned utilities, and municipalities looking to procure energy storage. As demonstrated in renewable energy, corporate sustainability action can play a significant role in accelerating the deployment of grid-scale technologies with the proper mechanisms (e.g., renewable energy certificates, power purchase agreements, etc.). However, the carbon contract considered in this study is the first carbon-denominated environmental attribute for energy storage. Similar mechanisms are also being contemplated by various state bodies, such as the New Jersey Board of Public Utilities' Performance Based Incentive, which is reviewing a proposal to rate-base energy storage compensation for avoided emissions.[2] Therefore, energy storage owner/operators and corporate sustainability professionals should pay close attention to this nascent space and future opportunities to participate.

1 Induced emissions are indirect emissions caused by the activity of a market participant on the grid. While energy storage does not produce any direct (Scope 1) emissions due to a lack of fossil fuel combustion, it can indirectly increase emissions through its operating activity. For instance, an energy storage asset that charges when emissive generation is on the margin may signal demand that results in increased fossil fuel generation.

2 "Notice In the Matter of the New Jersey Energy Storage Incentive Program." Docket No. QO22080540, New Jersey Board of Public Utilities, 29 Sept. 2022.

BACKGROUND

Importance of Energy Storage

The 'intermittent' nature of renewable energy poses significant reliability challenges to the electricity grid. The U.S. Energy Information Administration (EIA) estimates that wind and solar generation curtailments in markets such as Texas could increase to 13% and 19%, respectively, by 2035.[3] For comparison, ERCOT curtailed 5% and 9% of wind and solar generation, respectively, in 2022. Therefore, the grid has a growing need for flexible, 'dispatchable,' on-demand generation to fill the gaps. Energy storage offers a clean alternative: storing excess renewable energy and shifting it to meet peak demand. Without adequate energy storage, the grid manages mismatches in generation and load by turning up natural gas plants to cover shortfalls and curtailing excess renewable energy to trim surpluses.

To date, efforts to decarbonize the power grid have mainly focused on deploying more wind and solar energy. Recently, we have observed capital investments shift towards more energy storage development. Looking to 2024, the EIA projects 62.8 gigawatts (GW) of utility-scale generation capacity to be added, 96% of which is expected to be clean energy.[4] Energy storage constitutes 23% (14.3 GW) of these projected additions, which would represent a near-doubling of the 15.5 GW existing US energy storage capacity as of 2023. In addition, Texas is poised to overtake California in energy storage deployments in 2024 with an estimated 6.4 GW of new additions, approximately 45% of all projected additions nationwide. Looking beyond 2024, energy storage will be crucial to full grid decarbonization. To reach net zero by 2050, the National Renewable Energy Laboratory (NREL) estimates the U.S. needs to build 200-400 gigawatts (GW) of grid-scale energy storage,[5] requiring over one trillion dollars of investment.

Measuring A Battery's Emissions

Energy storage can provide a complementary role to renewable energy by balancing the grid between shortfalls and surpluses of renewable energy; however, energy storage can also change the way other power plants operate, thereby inadvertently increasing or decreasing overall systemwide emissions. While energy storage is generally presumed to reduce emissions, we have taken a more systematic approach to quantifying the carbon emissions impact of energy storage operations using Marginal Emissions Rates (MER). Timing, location, grid physics, and market economics all influence the MER at each grid node. Every megawatt-hour (MWh) of energy injected into the grid displaces another MWh of electricity that would have otherwise been produced. This is because, in each moment, the total supply of electricity production must exactly match the demand for electricity. Assuming no changes in load, each incremental MWh generated must be met by an equivalent reduction in generation elsewhere in the system. The generator or group of generators whose production was displaced by that incremental injection of energy is referred to as the "marginal generator(s)". MER estimation methods attempt to quantify the emissions impact of those marginal generators being re-dispatched in response to incremental generation.

Quantifying MERs is the result of over a decade of academic research, which is now operationalized by for-profit startups like REsurety and Singularity as well as non-profit WattTime. In addition, multiple electricity grid Independent System Operators (ISO) including PJM, NYISO, ISONE, and MISO either already provide MER data or have signaled their intentions to provide MER data in the near future. The EIA is also developing an online database to track hourly emissions across electricity grids, as directed by Sections 40412 and 40419 of the Federal Bipartisan Infrastructure Law.[6] While there are varying approaches to quantifying MERs, ex-post MERs have a high degree of accuracy with less than 6% error from expected simulated values.[7] Other research performed by groups such as VERACI-T – a working group supported by leading global organizations – has similarly validated MERs with rigorous real-world tests.[8] Given MERs allow users to accurately determine the short run emissions effects from specific actions, a groundswell of support has emerged within the corporate sustainability ecosystem. Last year, several leading sustainability-minded corporations launched the Emissions First Partnership to promote the use of MERs to more efficiently allocate procurement resources to maximize grid decarbonization at the lowest costs.[9]

Ex-post MERs have a high degree of accuracy with less than 6% error from expected simulated values

For our study, we leveraged REsurety's Locational Marginal Emissions (LME) dataset, which represents the emissions impact of the marginal generators being re-dispatched in response to incremental generation. REsurety uses grid data reported by ERCOT to identify the specific marginal generator(s) for

3 Warady, Debra, et al. As Texas Wind and Solar Capacity Increase, Energy Curtailments Are Also Likely to Rise, U.S. Energy Information Administration (EIA), 13 July 2023.

4 Ray, Suparna. Solar and Battery Storage to Make up 81% of New U.S. Electric-Generating Capacity in 2024, U.S. Energy Information Administration (EIA), 15 Feb. 2024.

5 NREL Storage Futures Study, April 2022

6 Yeatts, Leigh, and Sam Pearl Schwartz. "Energy Customers Want Transparent, Precise, Reliable Emissions Data." CEBA, 10 Mar. 2023.

7 Elenes, Alejandro GN, et al. "How Well Do Emission Factors Approximate Emission Changes From Electricity System Models?." Environmental Science & Technology 56.20 (2022): 14701-14712.

8 Koebrich, Sam, et al. "Towards Objective Evaluation of the Accuracy of Marginal Emissions Factors." 13 Nov. 2023. Available at SSRN 4631565.

9 Oster, Jake, et al. "Princeton's Zero Lab Has It Wrong on Corporate Renewable Energy Procurement and Emissions." Utility Drive, 25 Oct. 2023

each electrical node at every fifteen-minute interval and then calculates the LME given the economic and physical constraints on the grid. Like Locational Marginal Prices (LMP) used in wholesale energy markets, LMEs focus on the marginal energy delivered at a particular node at a particular point in time. LMEs are thus particularly effective for calculating avoided emissions attributable to energy storage operations under a consequential emissions framework. In addition, LMEs provide a practical framework for measuring a 'carbon arbitrage,' whereby an energy storage asset may charge (i.e., buy) from low-LME power and discharge (i.e., sell) during a prevalence of high-LME power. In doing so, an energy storage asset may displace an emissive energy resource with clean energy, which results in quantifiable avoided emissions equivalent to the difference in LMEs between charge and discharge.[10]

Comparing 2023 & 2022

Since 2022, there were two significant market dynamics that affected financial and environmental performance in 2023: a record-setting summer heat wave and the introduction of a new ancillary product called ERCOT Contingency Reserve Service (ECRS). According to data from the National Oceanic and Atmospheric Administration (NOAA), Texas experienced its second hottest summer on record in 2023 with an average summer temperature of 85.3 degrees fahrenheit, only narrowly behind 2011's average summer temperature of 86.8 degrees. In addition, cities like Austin experienced a record-breaking forty-five consecutive 100-degree-days. The Texas heat, combined with increased industrial load, resulted in unprecedented electricity demand; ERCOT shattered the previous load record of 80,038 megawatt-hours (MWh) from July 2022 with 85,464 MWh of load on August 10, 2023.

ERCOT's introduction of ECRS also provided a substantial revenue uplift. While other existing ancillary services were designed to balance supply and demand to manage grid frequency in the normal course of grid operations (frequency regulation) or recover from a generator tripping offline unexpectedly (spinning reserves), ECRS was implemented as a supplemental reserve service to address forecasting errors in renewable energy production and/or replace deployed reserves. As discussed further in this study, the confluence of these two factors contributed to a banner year for energy storage profits (tied to greater reliance on ancillary service revenues) accompanied by higher level of induced carbon emissions.

STUDY DESIGN

Scope

We limited the geographic scope of our study to the Texas power grid, operated by the Electricity Reliability Council of Texas (ERCOT), for three reasons. First, Texas has the highest renewable energy deployments as measured in nameplate capacity of any state, with over 59.12 GW of renewable energy capacity – 18.47 GW of solar capacity and 40.65 GW of wind capacity – as of 2023.[11] Second, Texas already has the second-most grid-scale energy storage of any state with over 3.9 GW online as of December 2023,[12] and an additional 145 GW in the interconnection queue awaiting commercialization. As previously mentioned, the EIA projects Texas is poised to overtake California in energy storage deployments in 2024 with an estimated 6.4 GW of new additions. Third, ERCOT is the only deregulated power market with merit-order dispatch that makes operating asset data publicly available, which is integral to our analysis of realized, ex-post outcomes and to our simulation of other possible outcomes.

Texas may overtake California in energy storage deployments in 2024

Sample Size

We limited our sample size to only energy storage assets that had complete operational data for 2023 and were actively functioning for at least 60% of the time. By excluding assets that came online partially throughout the year, we avoided skewing results with incomplete project data that either includes or omits peak seasons, such as the summer or winter. We evaluated sixty-five operating assets (see Figure 1) that represent 2,316 MW of nameplate capacity in 2023.[13] This is a substantial increase in sample size from our 2022 study where we evaluated twenty-four assets with a combined 765 MW of nameplate capacity. Approximately two-thirds of these additions came in North Zone and West Zone with 543.5 MW and 499.8 MW, respectively. Unless otherwise specified, 2023 results correspond to the new sample of sixty-five assets and 2022 results correspond to the original twenty-four assets featured in our prior study.

10 Note: this analysis intentionally does not consider the emissions impact of energy storage associated with structural changes to the grid, (i.e., how energy storage might influence the interconnection queue, other projects being built, etc.) seeing as this is impossible to quantify on a retrospective consequential basis with a reasonable degree of confidence. Therefore, operational emissions (i.e., how the operations of batteries influences the dispatch of other projects) are the focus of this analysis on account that they are much more readily quantified with confidence.

11 Climate Central, 2024, A Decade of Growth in Solar and Wind Power: Trends Across the U.S

12 Vermillion, Brandt. *ERCOT: What Did Battery Energy Storage Revenues Look like in 2023?* Modo Energy, 15 Mar. 2024

13 Sample includes the following 65 projects: Azure Sky, Bat Cave, Triple Butte, Blue Summit, BRP Alvin, BRP Angleton, BRP Brazoria, BRP Dickinson, BRP Heights, BRP Loop 463, BRP Lopeno, BRP Magnolia, BRP Odessa SW, BRP Pueblo I, BRP Pueblo II, BRP Ranchtown, BRP Sweeny, BRP Zapata I, BRP Zapata II, Byrd Ranch, Castle Gap, Catarina, Cedarvale, Chisholm Grid, Commerce Street, Coyote Springs, Crossett Power U1 & U2, Decordova U1-4, Endurance Park, Eunice, Faulkner, Flat Top, Flower Valley I, Flower Valley II, Gambit, Georgetown South (Rabbit Hills), Hoefsroad, Holcomb, Inadale, Lily, Lonestar, Madero Grid U1 & U2, Noble U1 & U2, North Columbia (Roughneck), North Fork, Notrees, Port Lavaca, Pyote TNP (Swoose), Pyron, Rattlesnake, Republic Road, Saddleback, Silicon Hill U1 & U2, Snyder, Swoose II, Toyah Power Station, Westover, Worsham

Sample Size Includes All ERCOT Regions

Map of Sixty-Five Operating Batteries Evaluated in Study

Figure 1

Calculation

To calculate the real time emissions impact of battery behavior, we combined both hourly datasets from January 1, 2023 to December 31, 2023 using the equation below:

$$C = \sum_{t=0}^{n} MW_{dis_t} * LME_t - MW_{chg_t} * LME_t$$

Where

$C = Total\ carbon\ impact\ over\ period$
$t = Hourly\ time\ intervals$
$MW_{dis_t} = Megawatt\ hours\ discharged\ at\ time\ t$
$MW_{chg_t} = Megawatt\ hours\ charged\ at\ time\ t$
$LME_t = Locational\ marginal\ emissions\ at\ time\ t$

Caveats

In this study, only short-run emissions impacts from energy storage operations were considered. Albeit important, life-cycle emissions – including embodied emissions from raw materials, manufacturing, and transportation as well as eventual retirement and disposal – are not impacted directly by battery operations and were excluded. Long-term structural grid changes due to energy storage paired with renewable energy were also excluded due to challenges quantifying under a consequential framework.

Within energy storage operations, the carbon impact of providing reserves in the ancillary market is excluded but is acknowledged as a gap in carbon accounting. In Regional Transmission Organizations (RTOs) except ERCOT, ancillary services are co-optimized with energy in the real-time market, and the impact of providing a marginal MW of reserves can be either carbon emissive or abating. Full data transparency of ancillary service offers in a co-optimized real time market makes it possible for LME data providers to estimate the carbon impact of reserves, but ERCOT is not expected to implement real-time co-optimization until summer 2026 at the earliest. The current carbon impact of providing reserves is uncertain and requires further investigation, but as energy storage replaces fossil fuel resources as the primary supplier in reserve markets, the carbon impact becomes less significant.

Methodology

As discussed further in the *Implications* section of this study, carbon contracts fit within a consequential framework, which is subject to rigorous tests for additionality.[14] Additionality is a term used to characterize emissions reductions that would not have occurred via another means (e.g., public policy, current market rules, etc.) absent the intervention. In this case, the carbon contract must be the 'make or break' in effectuating at least some subset of emissions reductions. Under the Verra draft methodology proposed by the Energy Storage Solutions Consortium (ESSC), existing energy storage assets may qualify as additional using an activity method additionality test. Absent a carbon contract, an energy storage asset would continue operating to maximize revenue irrespective of emissions impacts; however, given a carbon contract, an energy storage asset may opt to incur opportunity costs in other services to abate carbon that translates into higher net overall revenue. Therefore, to calculate the avoided emissions attributable to a carbon contract, the ESSC sets forth an approach called 'dynamic baselining' whereby an asset is baselined against its carbon-agnostic counterfactual dispatch and credited for any delta in emissions impact due to a change in its eventual operating mode.

For example, assume a revenue-maximizing energy storage asset enters a carbon contract with an offtaker, changes its operational behavior to account for the carbon signal, and consequently abates 10 tonnes of carbon dioxide equivalent (CO2e). If the asset would have otherwise induced 7 tonnes CO2e without a carbon contract, then the asset would be credited for 17 tonnes CO2e of avoided emissions: the delta between its baseline operations without a carbon contract (i.e., an increase of 7 tonnes CO2e) and its realized operations with a carbon contract (i.e., a decrease of 10 tonnes CO2e). Alternatively, assume another energy storage asset already abated 10 tonnes CO2e without a carbon contract and abates 18 tonnes CO2e with a carbon contract in place. This asset would only be credited for

14 Brander, Matthew. 2021. "The most important GHG accounting concept you have never heard of: the attributional-consequential distinction." Seattle, WA. Greenhouse Gas Management Institute, April 2021.

the incremental additional 8 tonnes CO2e of abatement. Note: the asset isn't compensated for the original 10 tonnes CO2e of abatement, thereby preventing compensation for incidental emissions reductions that would've happened irrespective of the carbon contract's existence, which isn't deemed 'additional.'

Since energy storage already operates in the absence of carbon contracts, we used realized emissions impacts as the basis for our baseline calculations in this study. We then simulated deviations in dispatch based on a perfect knowledge co-optimization for energy arbitrage, ancillary services (where qualified to provide such service), and carbon arbitrage, which is hindsight-adjusted for illustrative purposes.[15] Based on these simulated results, we quantified the incremental carbon abatement attributable to a carbon contract as well as the incremental revenue uplift net of opportunity costs theoretically achieved by an existing energy storage asset. Throughout this paper, raw results will be denoted as "perfect-knowledge" and results modified by an adjustment factor will be denoted as "hindsight-adjusted."

RESULTS

Existing Financial Performance

Based on our evaluation of existing asset operations, energy storage had a banner year for financial performance but induced more grid emissions in the process. Across the sixty-five operating assets featured in our sample, the average realized revenues across energy and ancillary services were equivalent to $16.51/kw-month. Unsurprisingly, energy storage revenues are driven by volatility that is highly seasonal. Approximately 61% of total revenues occurred in peak months (i.e., January, February, July, and August). With the exception of non-spin reserves, more than half of all other revenue streams are realized in the peak months. However, most of this revenue is even further concentrated in a select number of market events spanning a few days. In 2023, the top five revenue-days accounted for 28% of all fleetwide revenues. For perspective, that's 1.3% of the year delivering over one-quarter of annual revenues. The top ten and twenty revenue-days constitute 45% and 61% of annual revenues, respectively. Figure 2 shows the concentration of revenue with incremental revenues across different time intervals. The revenue concentration is particularly noteworthy.

The top five revenue-days delivered <u>more</u> revenue to energy storage than the bottom 315 revenue-days

Needless to say, energy storage economics rely heavily on extreme weather events to deliver market volatility, including pricing at the cap, and in return higher revenues. Consequently, energy storage developers and operators prioritize both physical designs and operating strategies that focus on high-revenue

High Concentration of Battery Revenues In A Limited Number of Days Raises Stakes
Percentage of Total Annual Revenue Achieved Within Top # Revenue-Days

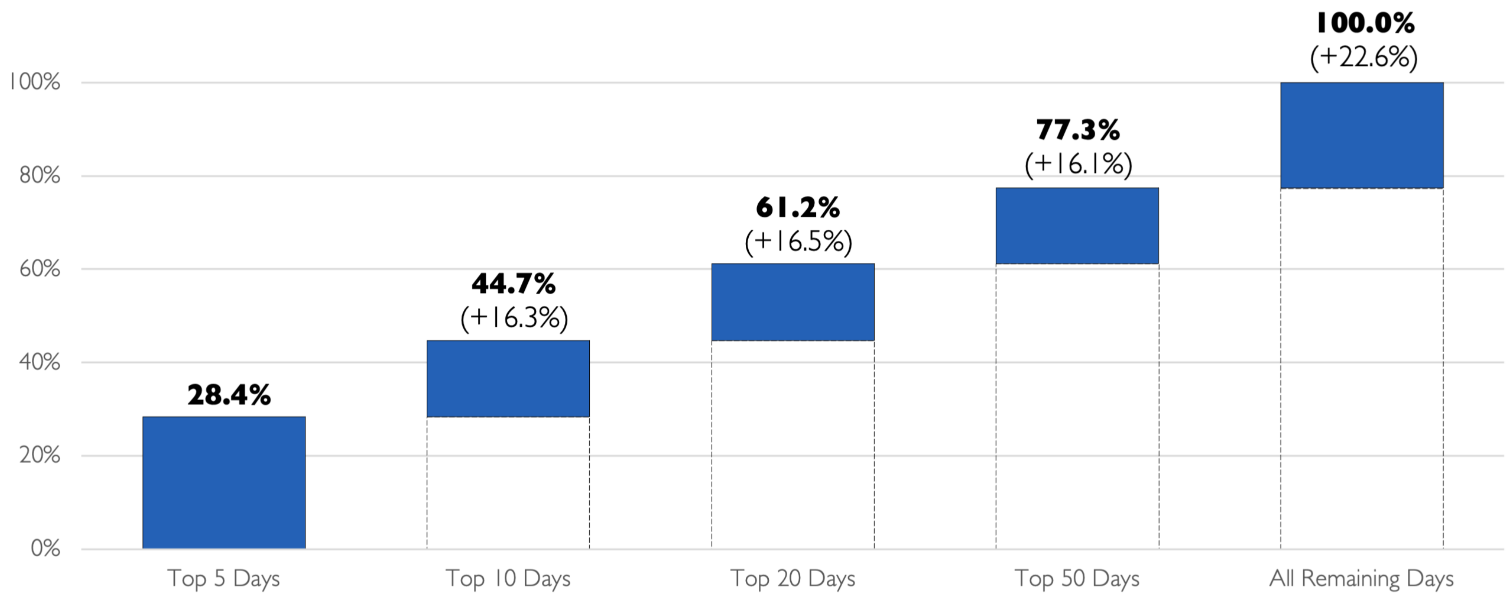

Figure 2

15 To estimate the carbon reductions resulting from a change in operational behavior to optimize to emissions reductions at $100/tonne CO2e, we applied an adjustment factor to a "perfect knowledge" optimization model. The perfect knowledge emissions abatement is equal to the emissions impact in a perfect knowledge model with a $100/tonne CO2e minus the emissions impact in a perfect knowledge model with a $0/ton CO2 e carbon price. This abatement is then multiplied by an adjustment factor equal to the demonstrated energy and ancillary revenue in the period divided by the perfect knowledge energy and ancillary revenue in the same period. We note the upper bound of the opportunity with the perfect knowledge model throughout this paper. It is worth noting that more work is required to validate the carbon impact using forecasts for prices and emissions factors, and that this estimation of knowledge capture is included for illustrative purposes only.

Ancillary Services Comprise a Larger Share of Energy Storage Revenue Year-over-Year

Percentage of Total ERCOT Fleetwide Revenue By Service Provided

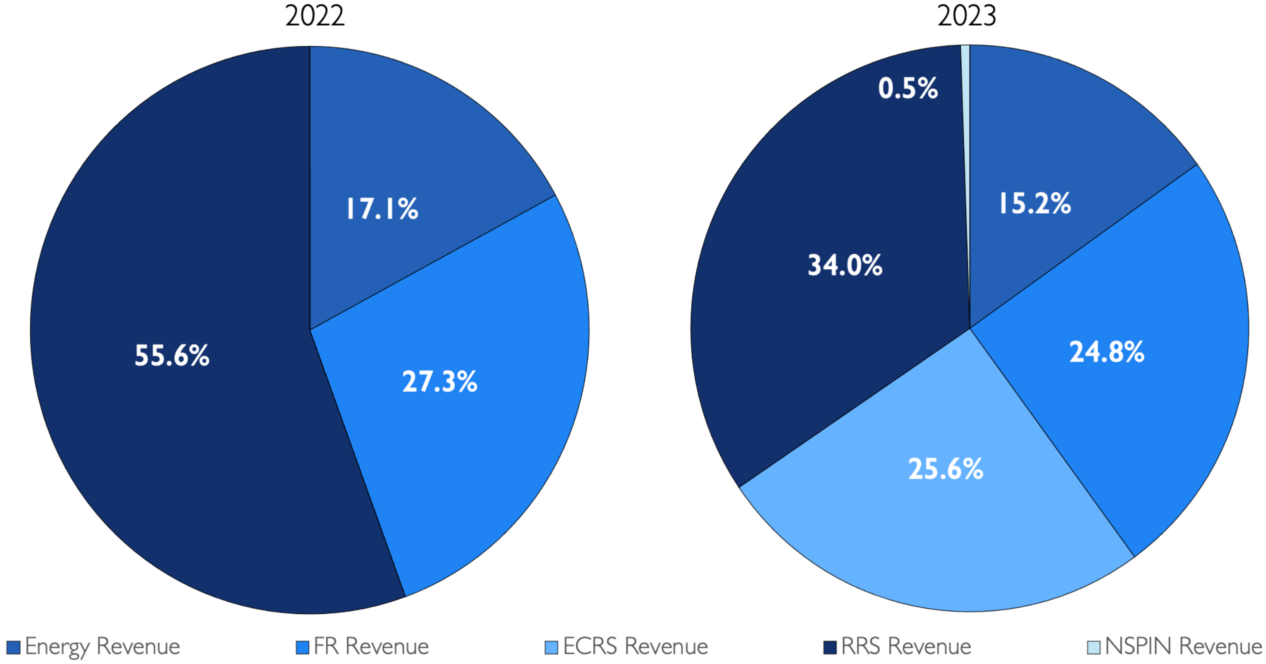

Figure 3

days rather than regular energy shifting. In contrast, CAISO's capacity mechanism requires a four-hour duration and a must offer obligation, which results in significantly more regular energy arbitrage. If we were to hypothetically remove the top ten revenue-days to account for milder weather, average revenues would decline from $16.51/kw-month to $8.95/kw-month. While extreme weather events have increased in frequency, the ability of energy storage to consistently capitalize on resulting volatility is uncertain. The concentration of top revenue events places a heightened weight on operational uptime and increases the risk of unplanned outages imperiling financial returns. In addition, it's unclear to what extent increased energy storage deployments will begin to cannibalize the ability to profit from future market volatility.

Ancillary Services Continue to Face Downward Pressures Year-over-Year

Total # Hours Priced Less Than $4/MWh

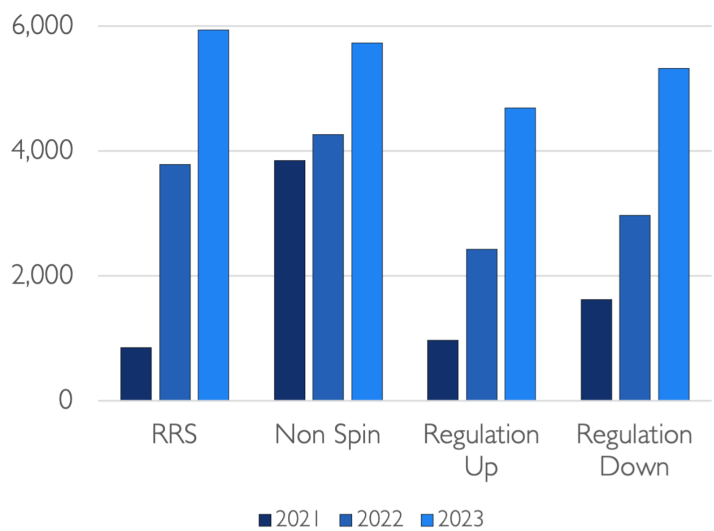

Figure 4

Beyond discrete episodes of market volatility, ancillary services also continue to buttress energy storage profitability. In 2023, ECRS accounted for approximately 25% of total revenue generated. Compared to 2022, ancillary service revenues as a percentage of total revenues increased from 83% to 85% in 2023 as shown in Figure 3. However, there are already initial signs of market saturation as energy storage assets increasingly begin to set price for ancillary services. While the total value from ancillary services captured by energy storage went up from 2022 to 2023, this value became increasingly concentrated. In fact, the percentage of hourly price intervals in RRS, Non-Spinning Reserves, and Frequency Regulation that cleared less than $4/MWh has increased substantially over the past three years as shown in Figure 4. This indicates that ancillary services are increasingly being provided by lower-cost resources, which are putting downward pressure on pricing outside of extreme weather-induced volatility. While energy storage is able to financially capitalize on extreme volatility and ancillary services at present, these advantages may soon become vulnerabilities as more energy storage capacity is added and markets saturate, underscoring the need for alternative revenue streams.

Existing Environmental Performance

Consistent with our findings from 2022, we found the ERCOT energy storage fleet, in aggregate, caused a net *increase* of carbon emissions. Total energy storage fleetwide emissions increased from 21,293 tonnes CO2e in 2022 to 74,737 tonnes CO2e in 2023. In addition, only five of the sixty-five batteries were net abators in 2023 as shown in Figure 5.[16]

92%

Number of ERCOT batteries that <u>increased</u> emissions in 2023

We found that almost all of the twenty-four batteries from our 2022 study were also more emissive. Although initially surprising, there are several explanations for why most energy storage assets are net emitters: 1) power & emissions correlation; 2) round-trip efficiency losses; 3) participation in ancillary services.

Power & Emissions Correlation

The average monthly correlation between LMPs and LMEs for operating energy storage assets for 2023 was 0.46,[17] which is up from 0.38 in 2022 but suggests that energy storage assets participating in energy arbitrage may not abate carbon emissions by default. If LMPs and LMEs were in fact highly correlated, this would suggest that energy storage assets participating in energy arbitrage may incidentally reduce emissions; however, even an energy storage asset co-located with a solar facility like Castle Gap, which happened to be the most abating asset in our 2022 study, saw its correlation between LMPs and LMEs weaken year-over-year from 0.60 in 2022 to 0.50 in 2023. While one may intuit that there's some positive relationship between energy prices and emissions, there are several nuances that weaken the overall correlation. For example, intraday fuel switching (e.g., coal-to-gas) can result in similarly priced assets in merit-order dispatch having widely different marginal emissions rates. In addition, we find that the correlation decreases during the summer of 2023 possibly due to scarcity events where unplanned outages and transmission constraints can frequently change the 'marginal' source of electricity available to a node as well as the price. While higher-priced and higher-emitting generators might initially respond to these scarcity events, this relationship can break down due to the prices being unbounded while the emissions from marginal generators have a finite set of possibilities. Lastly, some components of energy prices paid to generators are calculated at the grid level instead of the nodal level. Based on some initial correlation analysis, we consistently see similar levels of weak energy-to-emissions correlation across other deregulated power markets, which suggests this phenomenon isn't exclusive to the ERCOT market. As shown in Figure 6, a weak positive correlation between financial performance and carbon emissions further suggests that current market mechanisms do not adequately align incentives to account for emissions reductions.

Round-Trip Losses

Energy storage is inherently a net load on the electricity grid due to round-trip efficiency (RTE) losses. RTE is a measurement of the energy retained between charge and discharge. For instance,

Most Operating Batteries In ERCOT Inadvertently Increase Emissions

Average Monthly Carbon Impact Measured in Tonnes CO2e Per Megawatt-Month By Energy Storage Asset

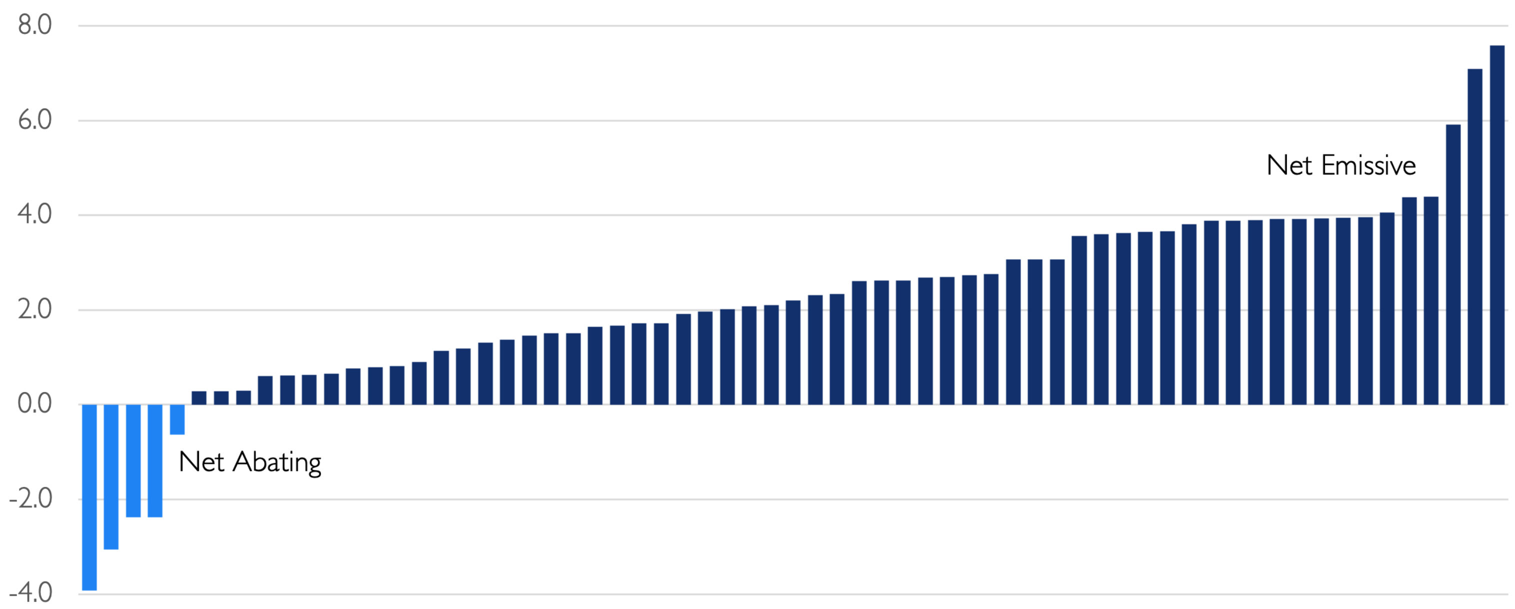

Figure 5

16 Note: Negative values indicate an emissions reduction and positive values indicate an emissions increase.

17 Since we see a non-linear relationship between price and LME (violating assumptions for Pearson correlation), we used a Spearman correlation, which is used to measure the relationship between two variables in a monotonic function. To calculate a fleetwide average, we measured the correlation for the year at each node and then took the average across all nodes.

lithium-ion batteries have a RTE of 80-90%, which means some energy (i.e., 10-20%) is lost during transmission and storage. Researchers from NREL have identified 86% as a representative RTE for lithium-ion battery technology.[18] Consequently, only 0.86 MW is available to discharge for every 1.0 MW charged, with the 0.14 MW of consumed energy lost as heat, incurring a Scope II emissions inventory. Different technology types also have substantially different RTEs. For instance, compressed air energy storage and long-duration iron air technology have a lower RTE than lithium ion techology, which results in more energy consumed across charge/discharge cycles.

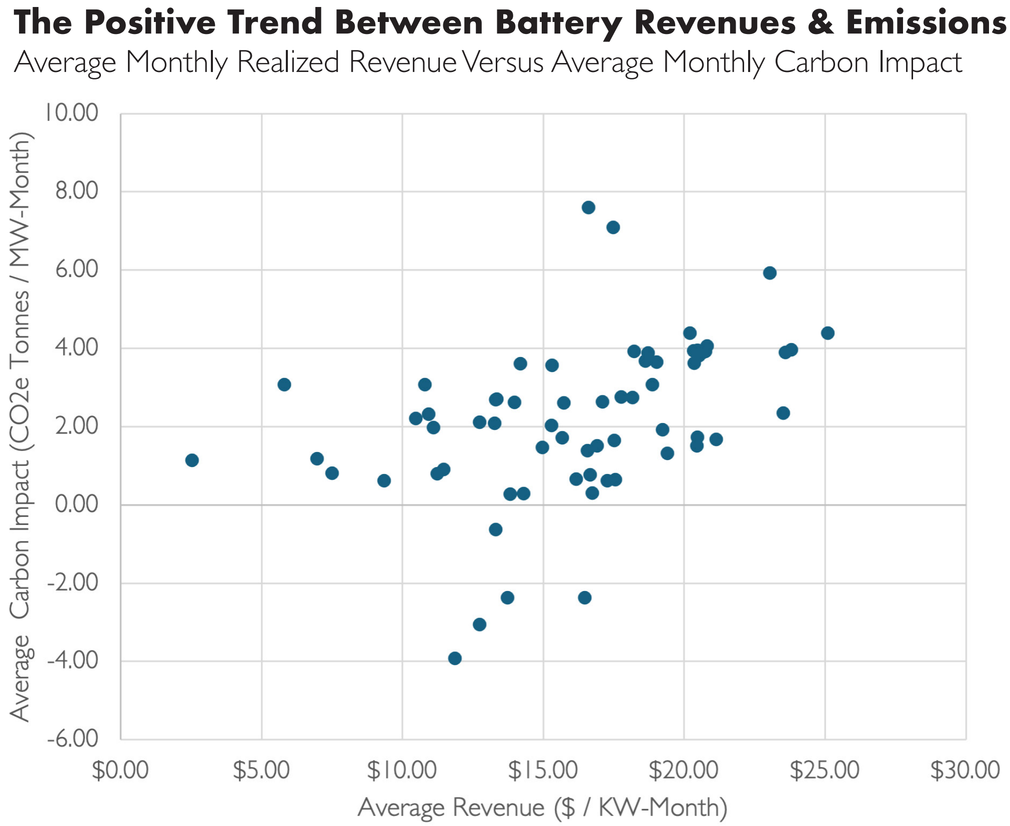

Figure 6

Ancillary Services

Energy storage assets participating in ancillary services typically induce carbon emissions. Because ancillary services are system-wide, energy storage assets in pursuit of ancillary revenues may behave in ways that don't correspond to localized conditions on the grid. For instance, energy storage assets that sell Responsive Reserve Service (RRS) may not cycle often and may charge uneconomically in the real time market to maintain a required state of charge (SOC) that satisfies their ancillary obligation. In addition, energy storage assets pursuing a Frequency Regulation (FR) deployment signal frequently charge and discharge when marginal emissions are high, incurring efficiency losses with corresponding emissions inventories. Following this reasoning, it is unsurprising that the ERCOT fleet induced more emissions, given the grid comprised a greater proportion of thermal generation to satisfy unprecedented load driven by extreme weather, round-trip efficiency losses are relatively unchanged (if not worse year-over-year for existing assets) and ancillary services comprised a greater share of the revenue pie.

Potential Financial Performance

Whereas energy storage revenues carry significant concentration risk in peak months and ancillary services, carbon contracts could provide diversification and stable revenues. Carbon arbitrage is far less seasonal on account that the spread in marginal emissions between renewable energy generation and fossil fuel energy generation is virtually 'open' year-round, resulting in a new revenue stream that is significantly less volatile. At a carbon price of $100/tonne, approximately 74% of the fleetwide average incremental carbon revenue is generated in shoulder months as shown in Figure 7 compared to 40% generated in shoulder months across all other revenue streams.

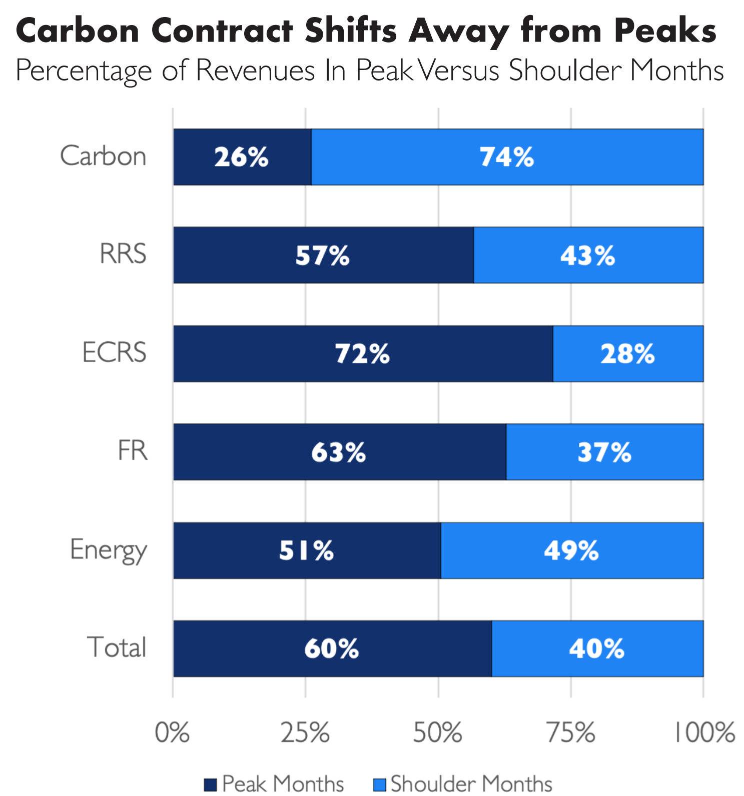

Figure 7

18 Mongird, Kendall, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, Vincent Sprenkle, and Richard Baxter. "2020 Grid Energy Storage Technology Cost and Performance Assessment." Washington, D.C.: U. S. Department of Energy, December 2020.

Comparison of Incremental Revenue vs Opportunity Costs

Average Fleetwide Monthly Revenue Impacts Per Kilowatt-Month

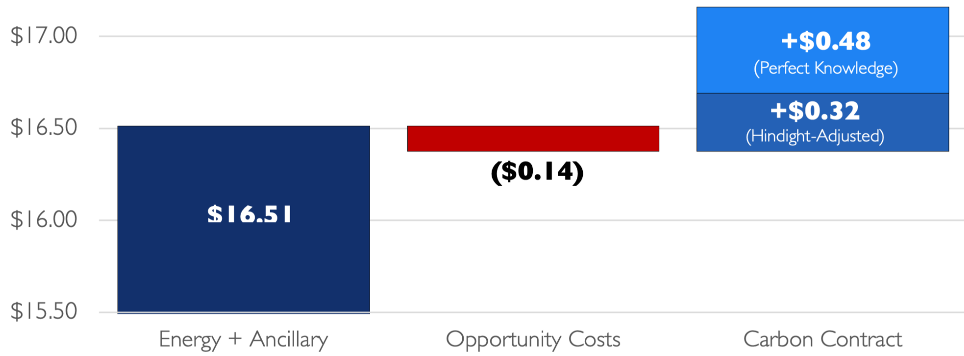

Figure 8

In an energy storage asset's optimization, the carbon price provides a relative weight on carbon arbitrage versus other revenue-generating services, such as energy arbitrage and ancillary services. Given there is weak correlation between marginal emissions rates and energy prices, carbon abatement may incur an opportunity cost in the form of foregone energy and ancillary revenues. At any given carbon price, an energy storage asset may participate in carbon abatement, incurring opportunity costs in energy arbitrage and ancillary services in the process in pursuit of greater overall net revenues. In Figure 8, the energy storage fleet averaged $16.51/kw-month in revenue; however, a carbon price of $100/tonne could have induced an average opportunity cost of $0.14/kw-month in lost energy and ancillary market revenue to fetch $0.32/kw-month in increased carbon market revenue, netting $0.18/kw-month, after conservatively adjusting for estimated knowledge capture. An additional $0.48/kw-month of revenue uplift is available under a perfect knowledge modeling approach, some of which may become possible to achieve as forecasting improves.

As the carbon price increases, the energy storage asset may increasingly pursue carbon arbitrage insofar as it results in greater overall revenues. As carbon price increases in Figure 9, modest declines in energy and ancillary revenues are more than offset by growing carbon revenues. After accounting for opportunity costs and adjusting for estimated knowledge capture, the incremental revenue uplift attributable to carbon contracts in 2023 ranges between $0.08/kw-month in August and $0.28/kw-month in November and averages $0.18/kw-month. However, as emissions forecasting improves, the average incremental revenue uplift could reach $0.66/kw-month and exceed $1.00/kw-month in shoulder months as shown in Figure 10 using 2023 data.

As emissions forecasting improves, the average incremental revenue could reach $0.66/kw-month

It's worth noting that incremental carbon revenue is lower in

A Carbon Contract Drives Incremental Battery Revenues Net of Opportunity Costs

Average Fleetwide Monthly Revenue Per Kilowatt-Month Plus Incremental Carbon Revenue at Various Carbon Prices

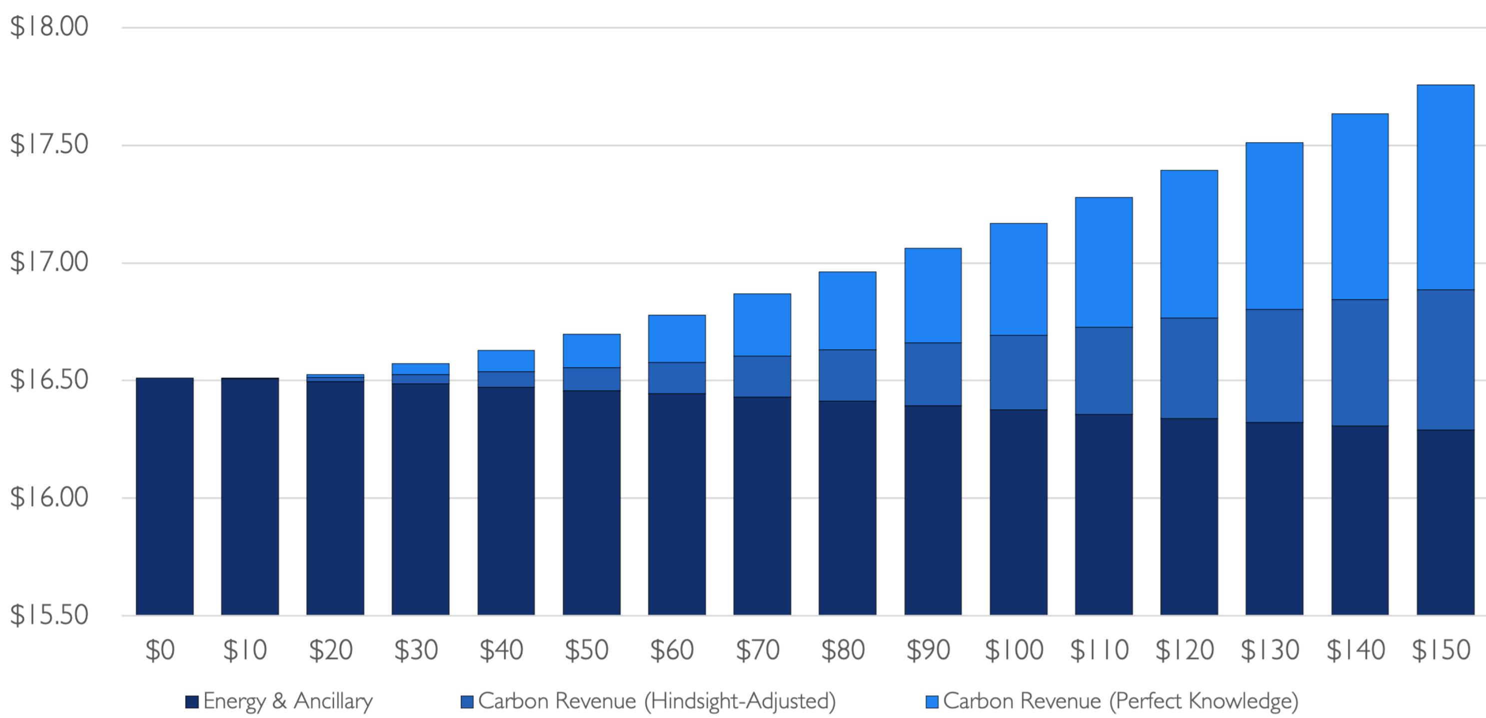

Figure 9

Emissions Forecast Improvements May Unlock More Upside in Carbon Revenues

Average Fleetwide Incremental Monthly Carbon Revenue Per Kilowatt-Month

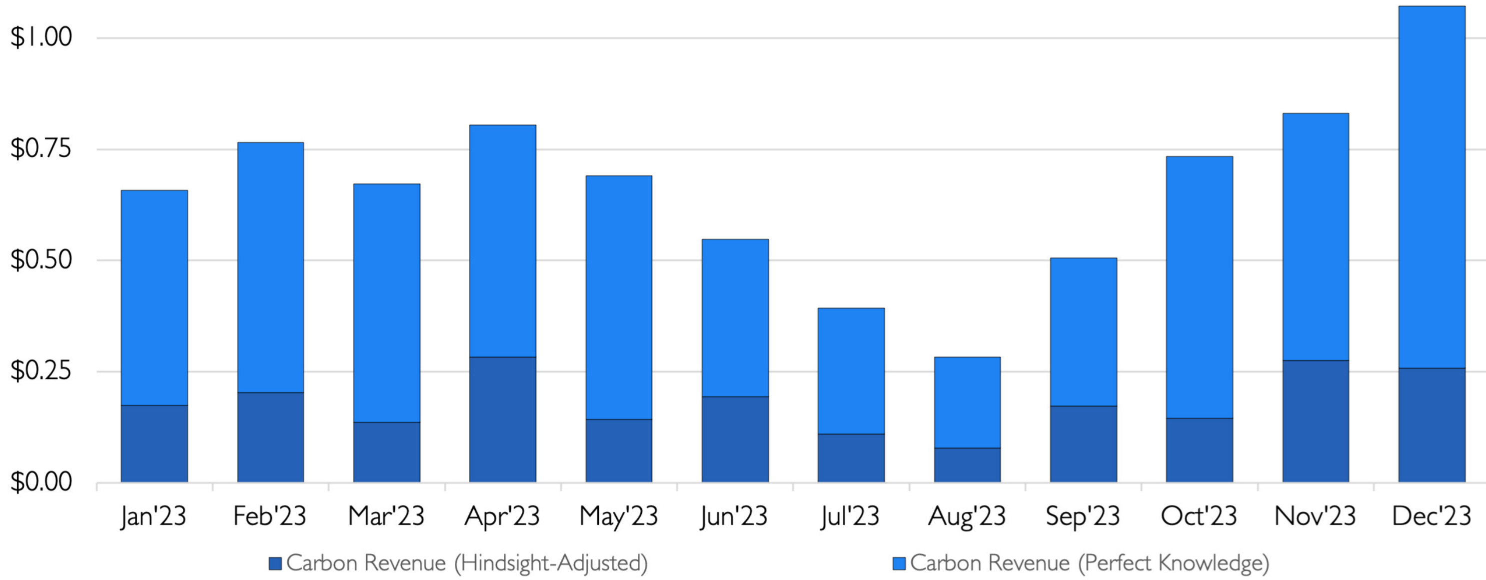

Figure 10

summer months on account that carbon abatement incurs a higher relative opportunity cost in energy and ancillary markets compared to other months, especially when accounting for the record-setting load accompanied by sustained summer heat in ERCOT during 2023.

While this analysis employs fleetwide averages, we found significant variation in both the financial and environmental opportunity within the ERCOT fleet as shown in Figure 11. Using the perfect knowledge model, we see significant differences in the revenue uplift opportunity between the 25th and 75th percentiles. For prospective corporate offtakers and participating projects, this suggests that not all assets are equally well-suited for a carbon contract and there is significant value to project selection for both parties involved.

As the carbon price increases, the energy storage asset may increasingly pursue carbon arbitrage

Carbon contracts can lift revenues in both peak and shoulder months without sacrificing the upside of scarcity events. In addition to merchant upside, an energy storage asset owner/operator participating in an as-generated carbon contract also retains operational flexibility, which is an advantage relative to traditional hedges, tolls, and 24/7 carbon-free energy constructs, which require hourly temporal matching of energy and load.

A Carbon Contract Potential Differs Widely Across Projects

Distribution of Hindsight-Adjusted Incremental Carbon Revenue Uplift

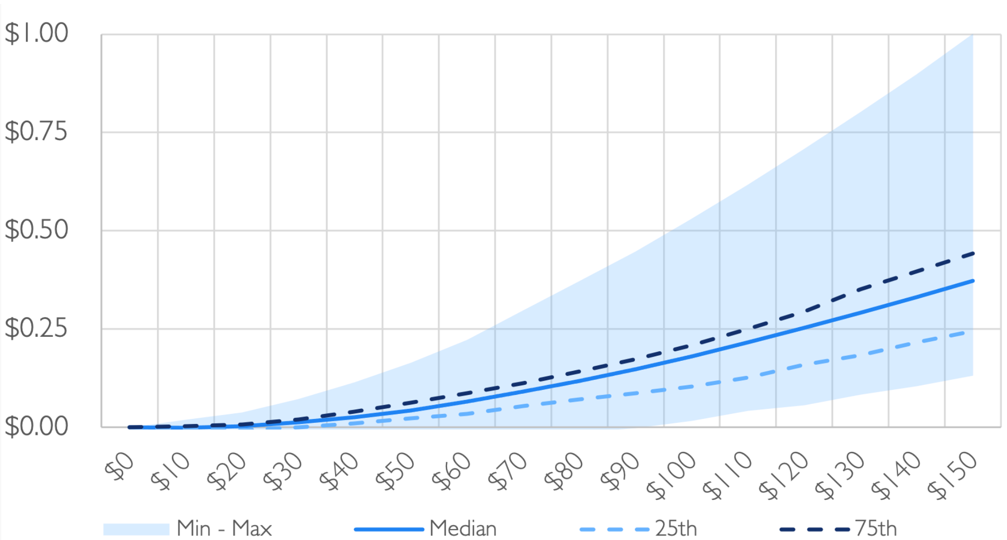

Figure 11

Potential Environmental Performance

Beyond improving energy storage economics, a carbon contract is also a compelling way to drive environmental impact. Across the ERCOT fleet, we found a $100/tonne carbon price could have resulted in 86,442 tonnes of avoided emissions using our knowledge capture estimation method, with a total opportunity of 218,400 tonnes in a perfect knowledge model. In addition, our simulation results suggest energy storage

Carbon Contracts Shake-Up Carbon Leaderboard & Improve Emissions Impact

Average Monthly Hindsight-Adjusted Carbon Impact Measured in Tonnes CO2e Per Megawatt-Month

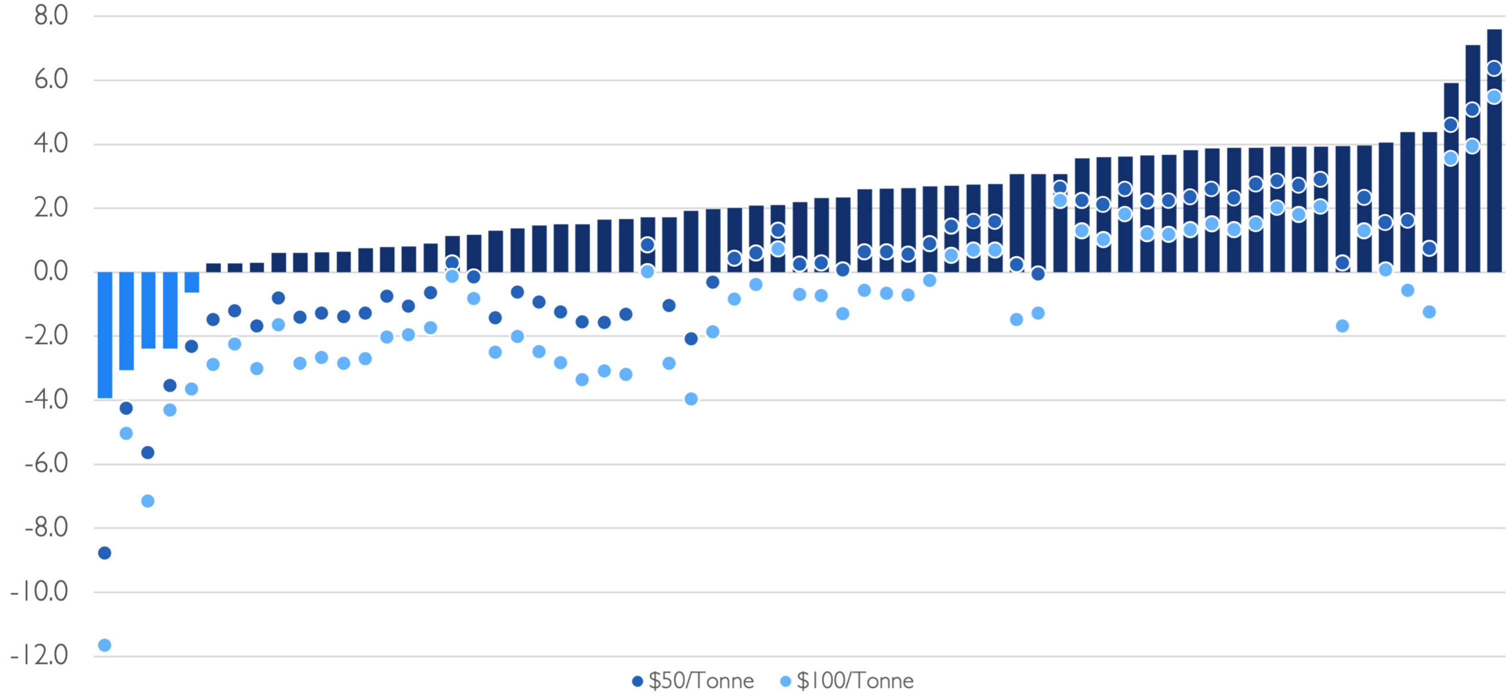

Figure 12

assets aren't pursuing carbon arbitrage at the exclusion of participating in energy and ancillary services.

Given its fungible characteristics, a carbon contract could be aggregated across an energy storage fleet to enable a larger, system-wide impact. In Figure 12, we show the hindsight-adjusted carbon leaderboard with the change in carbon impact plotted at carbon prices of $50/tonne and $100/tonne, which demonstrates that projects have varying levels of responsiveness to a carbon price. For instance, the most abating assets could potentially double or triple their carbon impact with a carbon contract in place whereas the most emissive assets may significantly curb their carbon footprints and induce fewer emissions.[19]

As shown in Figure 13, the carbon price provides a lever to generate greater avoided emissions from energy storage assets. As the carbon price is increased, we expect energy storage assets to more heavily weight carbon abatement, resulting in greater incremental avoided emissions; however, there is an asymptotic relationship between carbon price and avoided emissions, whereby an energy storage asset has a finite limit to its total abatement capacity. Put in context with the entire ERCOT fleet, some assets may present substantially different 'elasticities of supply.' For instance, an average asset may achieve 3.16 tonnes CO2e/MW-month of abatement at $100/tonne, whereas the 25th percentile asset may require a carbon price of $175/tonne to achieve similar levels of incremental carbon abatement. When a robust carbon market develops for energy storage, then greenfield developers may begin to consider alternative technologies (e.g., long-duration), design modifications,

Rising Carbon Price Boosts Volume With Diminishing Returns

Average Carbon Abatement Measured in Tonnes CO2e Per Megawatt-Month

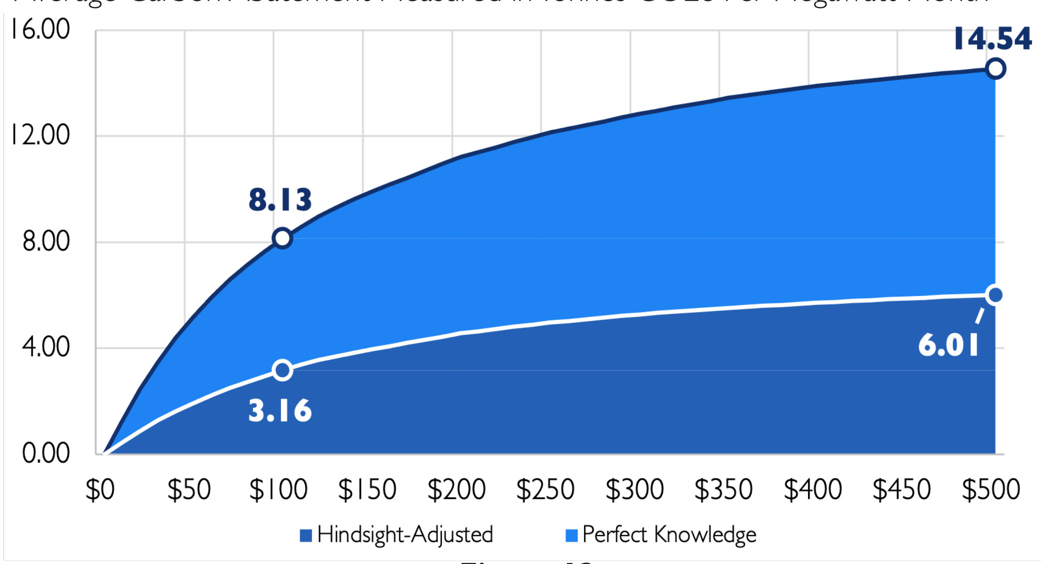

Figure 13

19 For simulated operations, we assumed an energy storage asset sold an ancillary service if it sold that product in more than 5% of intervals in 2023. If it sold the product for less than 5% of intervals, we did not include the product as an opportunity cost in the optimization model because it is not considered core to the operating strategy of the asset.

and alternative project sites that result in greater emissions reductions and more carbon revenues.

For simplicity, this study has frequently referenced a carbon price of $100/tonne; however, using the ERCOT fleetwide average, a $100/tonne carbon price only reflects approximately 50% of the possible carbon abatement potential achievable at a $500/tonne carbon price as shown in Figure 13. Therefore, more price discovery must be done to determine the carbon market's willingness-to-pay for this type of avoidance offsets from an engineered solution (i.e., energy storage).

Access to Low-LME Power Boosts Carbon Abatement

Frequency of Hourly LMEs Measured in Kilograms of CO2e Per Megawatt-Hour

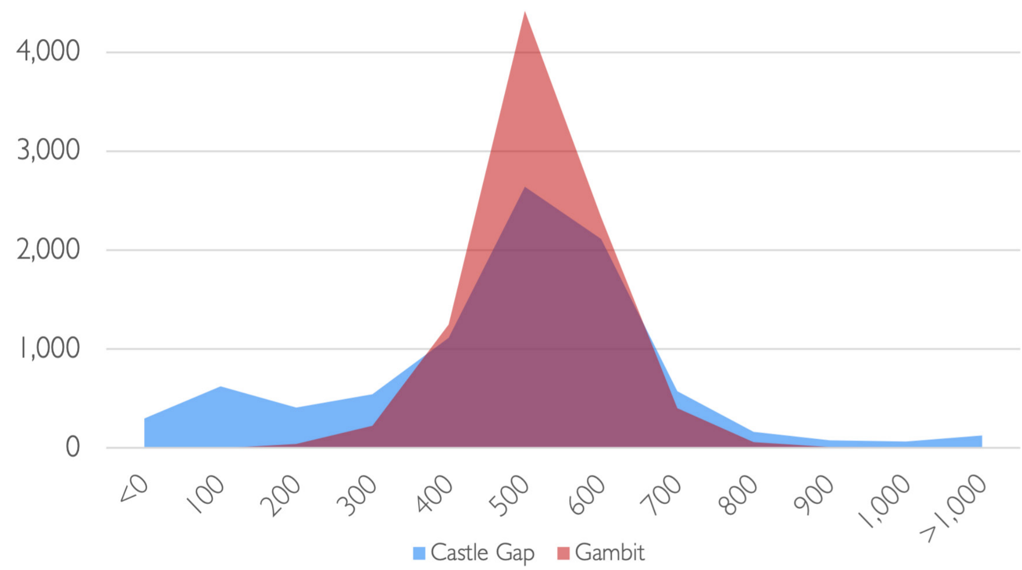

Figure 14

As of 2023, the total size of hindsight-adjusted avoided emissions from energy storage assets in ERCOT at a carbon price of $100/tonne is 86,442 tonnes CO2e. That said, the total opportunity for energy storage assets to abate emissions measured with perfect knowledge is substantially larger (218,400 tonnes CO2e) and can be accessed via improvements in MER and price forecasting. Additionally, corporate demand could easily outstrip supply, especially if the SBTI permits use of environmental attribute certificates (EACs) and carbon offsets to address Scope 3 emissions. Basic economic principles would suggest that when demand exceeds supply, the price should increase to induce more supply to come online, and our elasticity of supply analysis suggests that some assets may be better suited to generate incremental volumes than others.

When a robust carbon market develops, greenfield developers may begin to consider alternative technologies, design modifications, and alternative sites that result in greater emissions reductions

Comparing results across 2022 and 2023, we found that energy storage assets were more emissive yet were more responsive to a carbon price. Across the board, energy storage assets appear more responsive to carbon prices in terms of incremental carbon abatement and incremental revenue uplift. At a carbon price of $100/tonne, the average hindsight-adjusted incremental carbon abatement across the ERCOT fleet increased from 2.19 tonnes CO2e/MW-month in 2022 to 3.16 tonnes CO2e/MW-month in 2023. At the 95th percentile, incremental abatement is 5.48 tonnes CO2e/MW-month in 2023 compared with 4.20 tonnes CO2e/MW-month in 2022.

While our 2023 sample size did increase threefold, these results broadly hold for projects online prior to 2022. Comparing year-over-year changes for the 2022 sample, the average hindsight-adjusted incremental carbon abatement across the ERCOT fleet increased from 2.70 tonnes CO2e/MW-month in 2022 to 3.56 tonnes CO2e/MW-month in 2023. The most likely cause is the increased prevalence of low-priced ancillary intervals in 2023 compared to 2022. As more low-cost suppliers of ancillary service megawatt-hours (i.e. energy storage assets) enter the market, we see more intervals where these low-cost suppliers set price, resulting in price suppression in the ancillary service market. This results in a lower opportunity cost of providing energy arbitrage to pursue carbon abatement, which causes increased abatement potential at the same carbon price of $100/tonne. It's worth noting, however, that this increased carbon abatement potential may not scale linearly with ancillary price suppression. Currently, the sale of ancillary services remains a favorable strategy to energy arbitrage for most assets, however if ancillary service prices fall to the point that energy arbitrage becomes the favorable strategy, the incremental carbon abatement potential may decrease from current levels.

Another factor that may influence the carbon abatement potential of an asset at a given carbon price is the distribution of MERs at its node. Figure 14 compares the frequency of hourly LMEs for two energy storage assets, Castle Gap and Gambit, which are located in ERCOT West and Houston, respectively. Typically, access to low carbon power is the limiting constraint on an energy storage asset's abatement potential. Therefore, increased frequency of low MERs increases abatement at a given carbon price as seen in Castle Gap above. Over time, we expect a symmetrical bimodal distribution of MERs to become more pronounced and further improve an energy storage asset's abatement potential. In contrast, Gambit demonstrates how energy storage assets located near load centers with limited availability of low-MER energy have fewer carbon abatement opportunities, especially when accounting for roundtrip efficiency losses. Plotting incremental carbon impact versus incremental revenue uplift in Figure 15, we also see that most assets that are highly responsive to a carbon contract in terms of incremental emissions reductions tend to be in ERCOT West, which has a prevalence of renewable energy buildout, lack of local load, and more transmission constraints relative to other zones such as Houston or North. Surprisingly, access to low carbon power (defined as the percentage of intervals below 50kg/MWh at a given node) decreased in 2023 for roughly 80% of the ERCOT fleet, while the percentage of intervals above 500kg/MWh increased year-over-year for every single node. This change in MER distribution may have contributed to a greater abatement potential at $100/tonne CO2e by increasing the delta between MER during periods of charging and periods of discharging.

Location Matters for Maximizing Carbon Abatement

Average Incremental Carbon Revenue Versus Average Carbon Impact by Zone

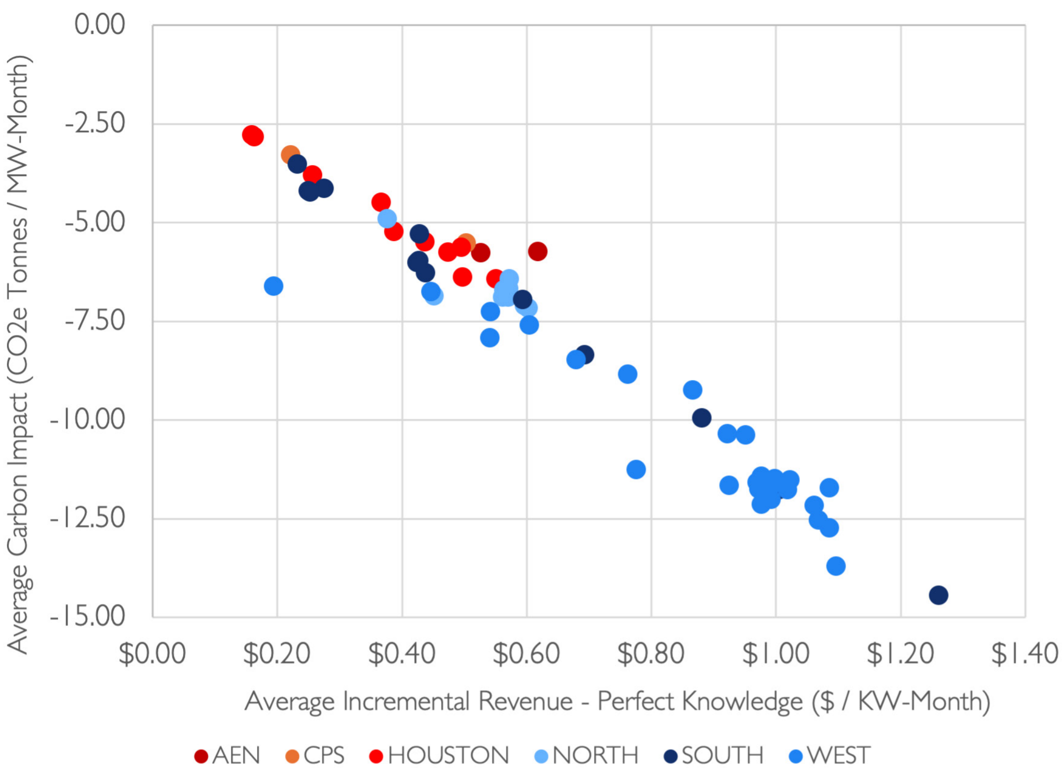

Figure 15

In conclusion, as more energy storage assets are deployed and the fleet grows, we should expect energy storage assets to start setting the price for ancillary services. While we may see the ancillary service market opportunity shrink, we're seeing the carbon arbitrage opportunity grow year-over-year, which may provide an attractive economic off-ramp for existing assets to consider in 2025 and beyond.

IMPLICATIONS

The Role of Carbon Contracts

A carbon-denominated contract is a compelling mechanism for both energy storage owners and potential offtakers. Energy storage assets are unique in that they have the potential to selectively and flexibly provide a variety of grid services based on granular price signals within certain market rule restrictions. For example, an energy storage asset may provide frequency regulation in one interval, responsive reserve service in the following, and energy in the next. Based on conversations with several market participants, energy storage owners prefer potential offtake structures that maintain operational flexibility and preserve upside in merchant revenues. Energy storage owners prefer to maintain operational flexibility to pursue whichever combination of services maximizes revenue. The ability to respond to price signals also ensures that the electricity grid receives whichever services are deemed most valuable.

The ability to respond to price signals ensures that the electricity grid receives whichever services are deemed most valuable

In contrast to alternative structures that require ceding operational control or operating within strict hours, a carbon contract is an elegant way to price carbon arbitrage services that are then accounted for in the overall asset optimization. Consequently, an energy storage owner may choose to pursue carbon arbitrage and incur opportunity costs in energy and ancillary services only insofar as it results in greater net revenues than pursuing energy and ancillary services alone. While there are not any standard carbon contract terms for energy storage yet, 'as-delivered' terms potentially provide even greater operational flexibility to energy storage owners as compared with minimum volume requirements. Conceptually, as the carbon price increases, the energy storage asset's revenue-maximizing strategy converges on its emissions-minimizing strategy; however, there are practical limitations in both the willingness-to-pay in carbon markets and the incremental carbon abatement.

Carbon contracts pose several advantages for potential offtakers as well. Given carbon contracts are denominated in tonnes of CO2e, they are inherently more fungible across market boundaries than energy and REC products. Fungibility unlocks greater market liquidity, improved price discovery, and better asset diversification, which translate into lower market risks for offtakers relative to other products. In addition to low market risk, carbon contracts also provide offtakers with substantially more robust additionality claims. Because the Greenhouse Gas Protocol is primarily an attributional emissions framework used to report and reconcile emissions across supply chains, current environmental attributes within power markets are not subject to additionality tests that require counterfactual claims.[20] In contrast, carbon contracts require project proponents to prove an activity to avoid or remove emissions is additional under a consequential framework. These tests also affect how projects are baselined and eventually credited for avoided emissions. Absent revenue from a carbon contract, we've demonstrated an energy storage asset would have either induced emissions in pursuit of revenue maximization or incurred an uncompensated opportunity cost to reduce emissions. Therefore, corporate buyers stand to make more robust additionality claims of their procurements. Lastly, carbon contracts enable corporates to allocate capital into the most cost-efficient means of decarbonization.

A carbon contract is an elegant way to price carbon arbitrage services that are then accounted for in the overall asset optimization

Industry-Wide Participation

Carbon contracts for energy storage are not merely an abstract concept. Launched in 2022 by Meta, REsurety, and Broad Reach Power (now Engie North America),[21] the Energy Storage Solutions Consortium (ESSC) is an industry-wide initiative that now boasts over eighty-four member companies representing over $10 trillion dollars in market value and a groundswell of support among sustainability-minded corporations, energy storage developers and operators, capital providers, and service providers.[22] As a member of the ESSC Steering Committee, Tierra Climate is spearheading the development of a new methodology with Verra, the largest carbon registry in the world, which upon completion would issue carbon offsets to utility-scale front-of-the-meter energy storage assets for proven avoided emissions.[23]

CONCLUSION

Undoubtedly, energy storage is critical to the eventual transition to a reliable and carbon-free energy future. Yet, based on our evaluation of in ERCOT, we found that sixty-one of the sixty-five operating energy storage assets inadvertently increased carbon emissions through daily operations following current market signals. Wholesale power markets were not designed to value or compensate energy assets for the carbon content of their power, and energy storage faces unique challenges in paving a profitable path to decarbonization. Fortunately, our study shows that carbon contracts might be quite effective in improving the economics and environmental impact of energy storage. For energy storage asset owners, carbon contracts enable value-stacking that preserves operational flexibility to pursue the prevailing revenue-maximizing strategy as well as the merchant upside accompanying extreme weather events. For sustainability-minded corporate buyers, carbon contracts offer an elegant, high-fidelity solution to decarbonize electricity and improve grid resiliency, which cannot be accomplished through renewable energy purchases alone. Therefore, this approach has drawn the support of sophisticated industry players represented in the ESSC and may become a reality as soon as 2025.

Disclaimer

20 Brander, Matthew, Michael Gillenwater, and Francisco Ascui. "Creative accounting: A critical perspective on the market-based method for reporting purchased electricity (scope 2) emissions." Energy Policy 112 (2018): 29-33.

21 REsurety. "Leading Global Organizations Launch New Consortium to Assess Climate Benefits of Energy Storage." REsurety, 25 Jan. 2024

22 To learn more about the ESSC and membership, please visit the following website: **ess-consortium.org**

23 Please note: all opinions shared in this study are expressly Tierra Climate's and may not represent the views held by other members of the ESSC.

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