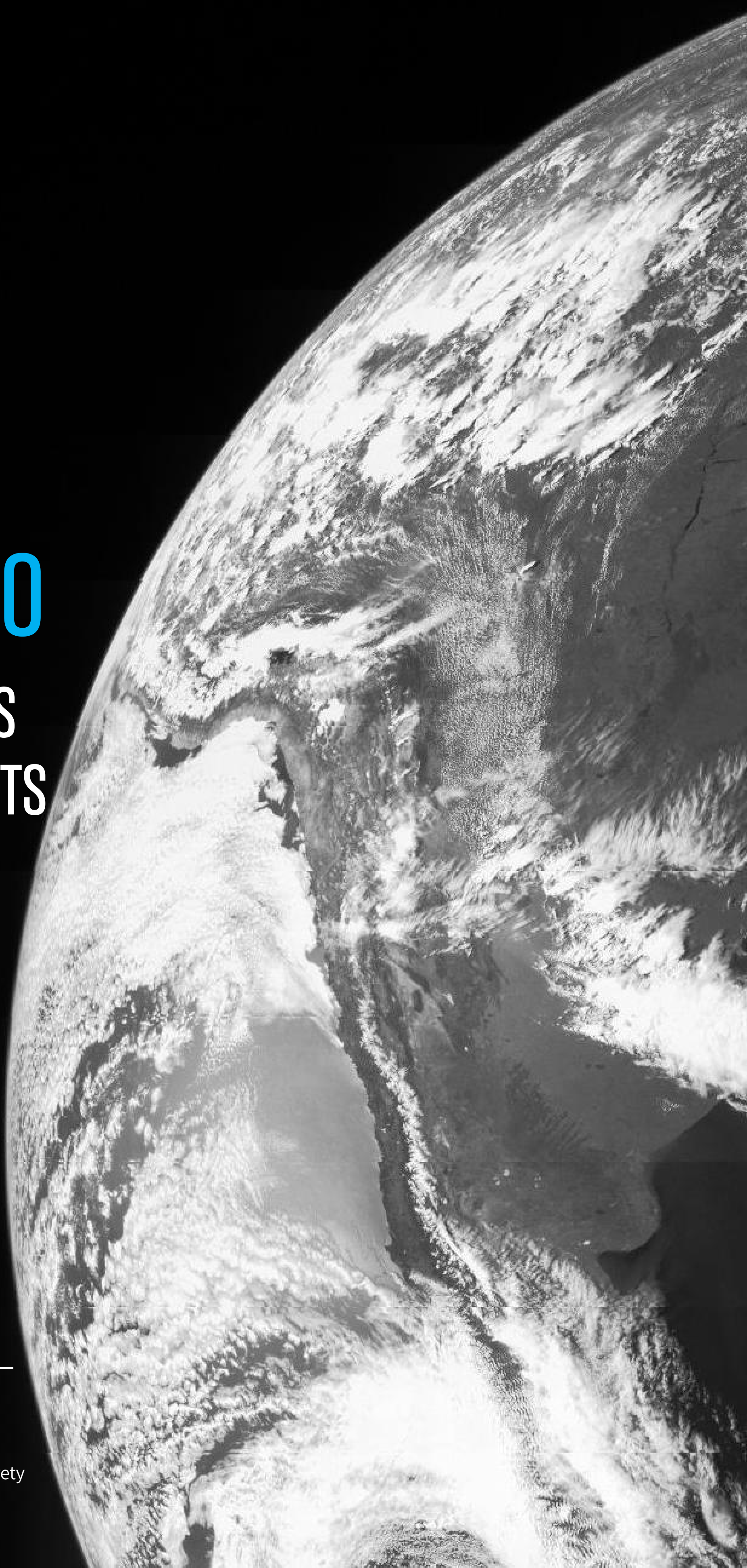
CHARGING TOWARDS ZERO

HARNESSING BATTERIES AND CARBON CONTRACTS TO ACCELERATE GRID DECARBONIZATION



IN PARTNERSHIP WITH

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INTRODUCTION

Energy storage is crucial to decarbonizing the electricity grid, and batteries have become a leading technology to store power at a utility-scale. The National Renewable Energy Laboratory (NREL) estimates the U.S. needs to build 200-400 gigawatts (GW) of grid-scale storage by 2050 to reach Net Zero[1], requiring over one trillion dollars of investment. However, grid-scale batteries have received relatively little investment compared to other technologies to date. Bloomberg New Energy Finance (BNEF) reports that batteries, including research and development, accounted for just 1.4% of total energy transition investments in 2022.[2]

Additionally, there are market challenges that prevent batteries from reaching their decarbonization potential. In fact, most batteries operating in Texas to maximize power market revenues across energy and ancillary services actually increase carbon emissions, rather than reduce them. Both economic and environmental problems can be solved with voluntary carbon markets. A pay-for-performance contract for carbon abatement ("carbon contract") incentivizes behavior switching that can flip a battery from net carbon emitting to net carbon abating, while increasing revenues up to 30%, as demonstrated by our findings.

Whereas renewable energy projects benefit from the issuance of renewable energy credits (RECs) and other revenue stabilization structures such as power purchase agreements (PPAs), batteries have no means of monetizing their environmental attributes. Moreover, corporate purchasers of power have no incentive to contract with storage projects, as the buyers get no carbon accounting benefit from the transaction. This paper examines the economic and carbon impact of compensating batteries for carbon reduction using detailed electricity emissions data and a carbon contract.

Carbon contracts with grid-scale batteries will be critical to stabilize battery cashflows, improve battery economics, and attract lower cost financing to battery projects to transition the power grid to 100% clean energy. In addition, carbon contracts provide sustainability-minded corporate buyers an elegant solution to meet sustainability targets and decarbonize the electricity grid, which cannot be accomplished through renewable energy purchases alone.

INTENDED AUDIENCE

This paper is of particular interest for corporate sustainability professionals, renewable energy developers, grid-scale battery owner/operators, tax equity advisors, utilities, and municipalities looking to procure energy storage. Corporate sustainability action could play a significant role in accelerating the deployment of grid-scale batteries through a carbon contract mechanism. Battery owner/operators and corporate sustainability professionals should pay close attention to this nascent space and opportunities to participate.

1 NREL Storage Futures Study, April 2022

2 Bloomberg New Energy Finance 'Energy Transition Investment Trends' (January 2023)

About Tierra Climate

Tierra Climate is an innovative technology company that is unlocking the decarbonization potential of grid-scale batteries and accelerating the green energy transition. Through a first-of-its-kind carbon offset product, batteries can now monetize their environmental attributes and deliver improved revenue certainty. Through a data-driven approach, Tierra Climate can manage project measurement, verification, and reporting (MVR) requirements at lower costs than comparable carbon project developers. For environmentally conscious companies, Tierra Climate offers a new category of sustainability solutions with a clear line-of-sight to physical assets that is empirically measured, and more cost-effectively verified. For more information, please visit **tierraclimate.com** or contact us at **info@tierraclimate.com**.

About REsurety

REsurety is a mission-driven organization dedicated to accelerating the world's transition to a zero-carbon future. REsurety provides software and services to support both the financial and sustainability goals of clean energy buyers, sellers, and investors. REsurety's software offers data-driven insights at various stages of the project lifecycle from initial exploration to portfolio management and services that leverage the company's domain expertise and deliver solutions tailored to the unique needs of customers. For more information, visit resurety.com or contact us at info@resurety.com.

Acknowledgments

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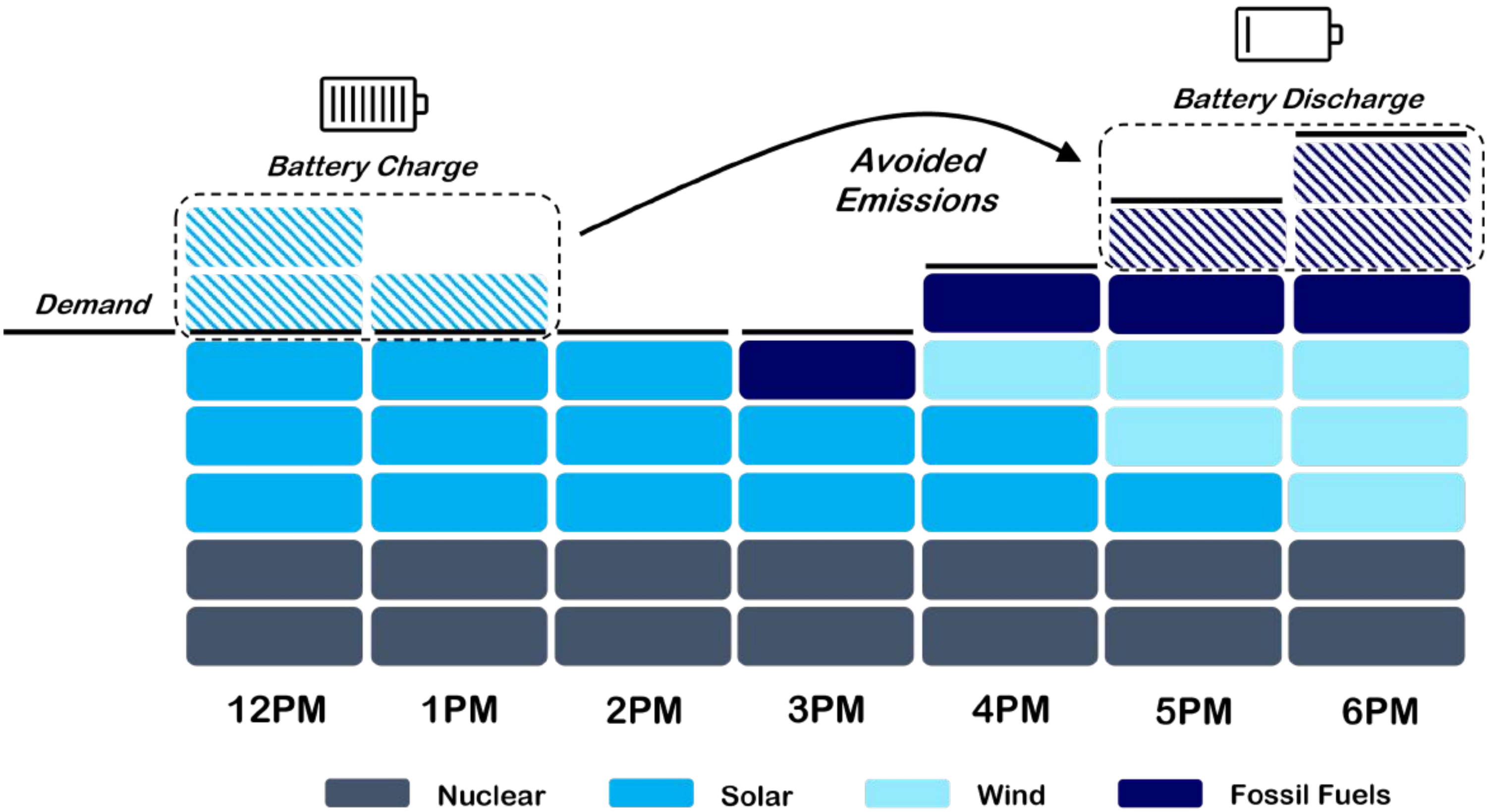
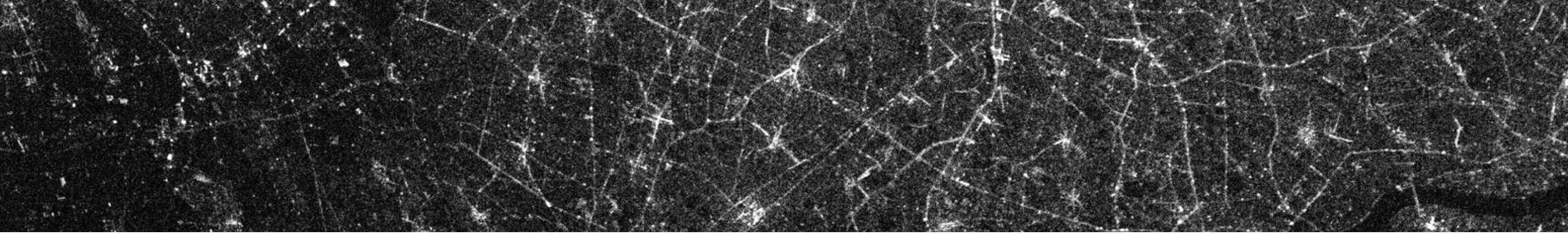
BACKGROUND

Why Batteries?

Electricity has historically lacked widespread and cost-effective storage, requiring power to be produced and consumed near-simultaneously. To date, efforts to decarbonize the power grid have mainly focused on deploying more wind and solar energy, but the 'intermittent' nature of renewable energy poses significant challenges to the electricity grid. As renewable energy expands in its share of electricity supply, the grid becomes more reliant on weather conditions like wind-speeds and solar-irradiance. Therefore, the grid has a growing need for flexible, dispatchable, on-demand generation to fill the gaps. Currently, fossil-fueled generation fulfills this role, but batteries can serve as a cleaner substitute. Grid-scale batteries can charge when excess renewable energy is available and discharge when energy is most needed, reducing the need to curtail renewable production, and displacing fossil fuel generated electricity altogether. **Without energy storage, the grid will inevitably rely on fossil fuels for dispatchable power, regardless of renewable capacity deployment.**



This chart shows the grid conditions under which a battery may reduce curtailment of renewable energy and shift that energy later in the day to reduce reliance on fossil fueled generation. The shaded light blue blocks represent curtailed solar power, which would otherwise be wasted energy. The battery stores this solar power and shifts it later in the day to displace the shaded dark blue blocks, or power that would have otherwise been generated by fossil fuels.



Measuring a Battery's Impact on the Grid

The carbon impact of a battery can be quantified using Locational Marginal Emissions (LME) rates. The LME is a simple metric used to assess the carbon intensity of power at specific locations and times on the grid.[3] Like wholesale electricity market Locational Marginal Prices (LMP), LMEs quantify emissions by identifying the marginal generators dispatched to meet incremental demand. Timing, location, grid physics, and market economics influence the LME value at each grid node. Quantifying marginal carbon emissions on the electricity grid is the result of over a decade of academic research, now operationalized by companies like REsurety, Singularity, WattTime, and others. Furthermore, several Independent System Operators (ISOs) including PJM and ISONE provide or have signaled their intentions to provide emissions data as well. To reduce emissions on the power grid, batteries must charge during periods when LMEs are low and discharge during periods when LMEs are sufficiently high to make up for efficiency losses. For example, a battery with an 85% round trip energy efficiency (RTEF) must discharge when LMEs are at least 18% higher than the LMEs during charging. The difference between the LME at time of discharge and LME at the time of charge after accounting for RTEF corresponds to tons of induced carbon abated (or emitted). For more information on LMEs and quantifying storage emissions, see peer-reviewed literature such as: *How Well Do Emission Factors Approximate Emission Changes from Electricity System Models?*[4] and *Tradeoffs Between Revenue and Emissions in Energy Storage Operation*.[5]

LMEs quantify emissions by identifying the marginal generators dispatched to meet incremental demand. Timing, location, grid physics, and market economics influence the LME value at each grid node.

Carbon Offsets

A pay-for-performance contract for carbon abatement could convey a new class of carbon offsets sourced from grid-scale batteries. A carbon offset is a financial instrument that represents the reduction of one metric ton of CO2 (or an equivalent amount of other greenhouse gases). Buyers of carbon offsets can “retire” them to apply the associated emissions reduction towards their own greenhouse gas reduction targets. Examples of projects that generate carbon offsets include reforestation, avoided deforestation, and carbon capture and sequestration. Although no methodology currently exists to mint and verify carbon offsets from grid-scale batteries, progress is being made: a contract of this nature was executed bilaterally in 2022 between Meta and Broad Reach Power as a proof of concept,[6] and a multi-stakeholder group known as the Energy Storage Solutions Consortium is currently working to create a certified storage carbon offset product.[7]

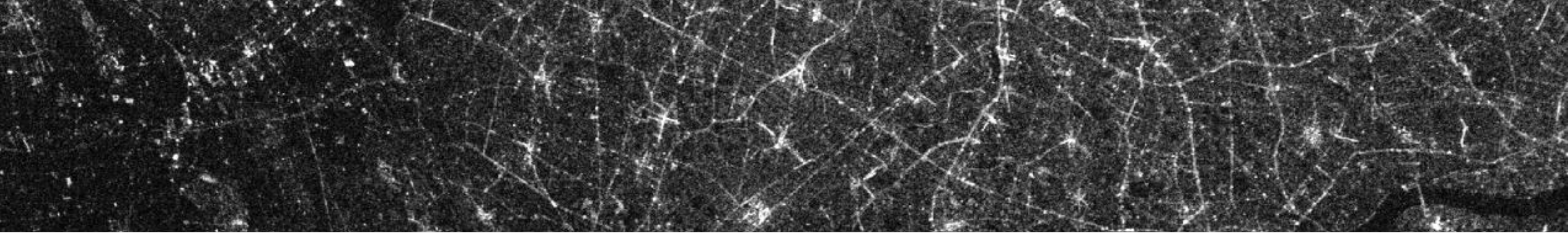
3 Locational Marginal Emissions measure the amount of system carbon emissions equivalent (CO2e) displaced by 1 MWh of clean energy injected into (or induced by 1 MWh of load with drawn from) the grid at a specific location and a specific point in time.

4 Elenes, Alejandro G. N., Eric Williams, Eric Hittinger, and Naga Srujana Goteti. “How Well Do Emission Factors Approximate Emission Changes from Electricity System Models?” Environmental science & technology 56, no. 20 (2022): 14701–14712.

5 Arciniegas, Laura M., and Eric Hittinger. “Tradeoffs Between Revenue and Emissions in Energy Storage Operation.” Energy (Oxford) 143 (2018): 1–11.

6 https://broadreachpower.com/leading-global-organizations-launch-new-consortium-to-assess-climate-benefits-of-energy-storage/

7 https://www.businesswire.com/news/home/20220914005330/en/Leading-Global-Organizations-Launch-New-Consortium-to-Assess-Climate-Benefits-of-Energy-Storage



STUDY

This study quantifies the current carbon emissions impact of grid-scale batteries operating in Texas, as well as the economic and environmental feasibility of a pay-for-performance contract for carbon abatement ("carbon contract") from grid-scale batteries using LME and grid data as the calculating mechanism.

Scope

We focused the geographic scope of our whitepaper to the Texas power grid, operated by the Electricity Reliability Council of Texas (ERCOT), for several reasons. First, ERCOT has high renewable energy penetration with over 53 GW of existing renewable energy capacity.[8] Second, Texas already has the second-most operational grid-scale batteries of any state with over 1 GW operational as of February 2023, and an additional 12 GW in the interconnection queue awaiting commercialization.[9] Third, ERCOT is a highly transparent deregulated power market with ample publicly available operational data.

We also limited our sample size to grid-scale batteries that had complete operational data for the entirety of 2022 and were actively functioning at least 60% of the time. This avoids skewing results with incomplete project data that either partially includes or omits peak seasons, such as the summer or winter. Consequently, our results represent twenty-four out of more than 60 operating batteries in ERCOT. We did not include any distributed or "behind-the-meter" battery projects.

Lastly, only grid emissions associated with battery operations are evaluated in the scope of this paper. Life-cycle emissions, including raw materials extraction, manufacturing, transportation, and decommissioning are not considered.

Context

ERCOT batteries generate revenue in two ways: energy services and ancillary services. Providing energy services involves capturing differences in energy prices (i.e., energy arbitrage) by charging during low price periods and discharging during high price periods. Ancillary services, including Responsive Reserve Service (RRS), Frequency Regulation (FR), and Non-Spinning Reserves (NSR), help maintain grid frequency at 60 hertz. Projects providing these services receive compensation for reserving capacity and for the energy provided when deployed. FR is deployed constantly, RRS and NSR are deployed less often. In 2022, ERCOT batteries included in this study provided RRS in 75% of hours, FR in 39% of hours, and NSR in only 1.5% of hours.[10]

Design and Methodology

We leveraged REsurety's Locational Marginal Emissions (LME) dataset and publicly available operational data from ERCOT released on a rolling 60-day delay. To calculate the real time emissions impact of battery behavior, we combined both hourly datasets from January 1, 2022 to December 31, 2022 using the equation below:

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

where

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

8 Seasonal Assessment of Resource Adequacy for the ERCOT Region (SARA), Summer 2023

9 There are over 96 GW of storage projects in the queue, but only 12 GW have started Full Interconnection Studies (ERCOT GIS Report May 2023)

10 Excluding hours in which battery projects are not "out" or "on test".

Caveats

Locational Marginal Emissions evaluate the induced emissions associated with energy market activities. This includes energy charged or discharged from ancillary service deployment, but not the effects of reserving power for ancillary service or capacity markets, which may also impact carbon emissions and aren't accounted for in the analysis.

Units

Carbon results are generally presented in CO2 tons equivalent per megawatt-month (tons/MW-month) and revenue results are generally presented in dollars per kilowatt-month ($/KW-month) to allow for direct comparison of batteries of different sizes. MW and KW in these units refer to installed nameplate capacity.

RESULTS: EXISTING OPERATIONS

Under the real time emissions methodology, we find that most battery projects are net emitters of carbon through their normal operations. In 2022, only five of the twenty-four operational ERCOT batteries evaluated reduced electricity grid carbon emissions. There are several factors contributing to this result:

Power & Emissions Correlation

The correlation between LMEs and real time energy prices is relatively low, 0.15[11], indicating that batteries operating solely based on energy prices do not automatically minimize carbon impact. This low correlation can be explained by factors like coal-to-gas switching and non-linear relationships between emissions factors and price due to engineering constraints within thermal power plants.

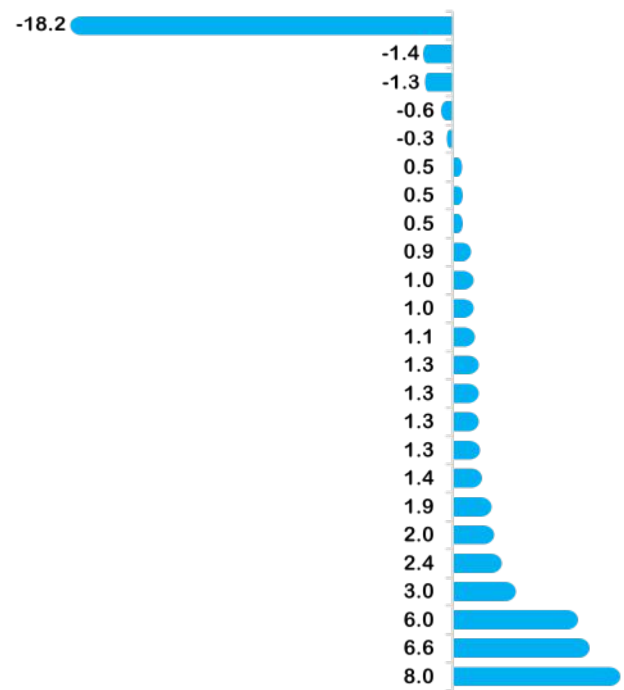
Round-Trip Efficiency Losses

Lithium-ion batteries have an energy efficiency of 80-85%[12] because some energy is lost as heat due to internal resistance during storage. This means that only 0.80 to 0.85 MWh is discharged for every 1 MWh charged. Carbon emissions typically increase when the carbon arbitrage opportunity at a battery's node is not wide enough to make up for energy losses during a charge/discharge cycle. This phenomenon is amplified when selling FR because the battery is bleeding energy from efficiency losses while constantly charging and discharging in response to the FR deployment signal.

Emissionally Suboptimal Charging

Grid scale batteries selling Responsive Reserve Service do not cycle often and may charge uneconomically in the real time market to maintain the required state of charge (SOC) that satisfies their ancillary obligation.

Carbon Leader Board



CO2 Tons/MW-month Emitted (Abated)

Only 5 out of 24 batteries are abating carbon, and only Castle Gap did so meaningfully.

Of the five net-abating batteries, Luminant's Castle Gap battery project – a four-hour duration lithium-ion battery with 9.9 MW (42 MWh) nameplate capacity paired with a 180 MW solar project – is far-and-away the most effective carbon abator. Because Castle Gap does not sell ancillary services, typically cycles once per day in the real time energy market, and has a relatively high correlation between its LMP and LME (0.19), it abates approximately 18 tons per MW-month.

> In 2022, only five of the twenty-four operational ERCOT batteries evaluated reduced electricity grid carbon emissions.

11 This correlation includes all 24 batteries included in this study across 2022. Power and emissions data are more highly correlated when middle thermal power supply stack is excluded. The correlation of power and emissions excluding LMEs between 50 and 600 is 0.44.

12 https://www.eia.gov/todayinenergy/detail.php?id=46756#:~:text=Round%2Dtrip%20efficiency%20is%20the,lost%20in%20the%20storage%20process

In contrast, the largest net emitter of carbon according to real time emissions methodology is Plus Power's 100 MW (175 MWh) Gambit Battery, located about 40 miles outside of Houston. Gambit sold Frequency Regulation in 62% of hours and Responsive Reserve Service in 58% of hours[13] and has a negative correlation (-0.04) between its LMP and LME, resulting in an average emissions rate of 8 tons per MW-month.

Beyond just carbon impacts, batteries face challenges to their primary sources of income: energy services and ancillary services. Energy service revenues are seasonal and dependent on unpredictable extreme weather events, making budgeting and financing difficult. For the group of twenty-four ERCOT batteries included in this study,

42%

of annual revenue came in the top twenty revenue days of the year, and 15% came in the top three days, driven by a summer heatwave and winter storm.

Adding to the challenge of volatile energy revenues is the fact that ancillary services markets, the other driver of battery revenues, are under pressure. Ancillary markets are showing signs of saturation from low-cost providers and as a result, price suppression. Without ancillary revenue boosting revenues in shoulder months, batteries rely on unpredictable energy volatility to breakeven. A carbon contract could improve revenues in shoulder months, stabilize cash flows, and put more battery projects in the black. For more detail on battery economics and trends, see the appendix.

13 A battery cannot sell the same capacity into both Responsive Reserve Service and Frequency Regulation markets, but it can split capacity between the two.

RESULTS: POTENTIAL OPERATIONS

Approach

Batteries operate to maximize revenues, but batteries participating in wholesale markets are not compensated for carbon abatement and operators therefore do not currently factor carbon emissions into their operational behavior. Absent a carbon contract, a battery project that optimizes exclusively to minimize carbon emissions reduces its revenue potential because it is foregoing revenue in the energy and ancillary markets. However, introducing a carbon offset contract could incentivize carbon abatement while maintaining or potentially increasing revenue. A higher carbon price relative to energy and ancillary service prices encourages batteries to optimize dispatch for emissions reduction.

To test this hypothesis, we created a revenue optimization model for batteries using real-time energy prices, ancillary prices, LMEs and theoretical carbon prices at an hourly granularity. This model assesses the effect of a carbon signal on battery operations and carbon reduction potential. The optimization process involves calculating the carbon impact of maximizing revenue from energy and ancillary services, which is referred to as the "baseline impact", or the emissions impact of a battery operating in the status quo. Then, the model redispatches the asset to maximize total revenue while considering compensation for emissions reductions. The baseline carbon impact is determined by:

$$C_b = \sum_{t=0}^{n} MW_{dis_{t_e}} \times LME_t - MW_{chg_{t_e}} \times LME_t$$

where

C_b = *Baseline carbon impact over period*
$MW_{dis_{t_e}}$ = *Megawatt hours discharged at time t optimized to LMP and ancillary prices*
$MW_{chg_{t_e}}$ = *Megawatt hours charged at time t optimized to LMP and ancillary prices*
LME_t = *Locational marginal emissions at time t*

The dispatch is then recalculated by maximizing revenue accounting for carbon reductions at a given carbon price:

$$maximize([C - C_b] \times P_c + rev_{e_c} + rev_{a_c})$$

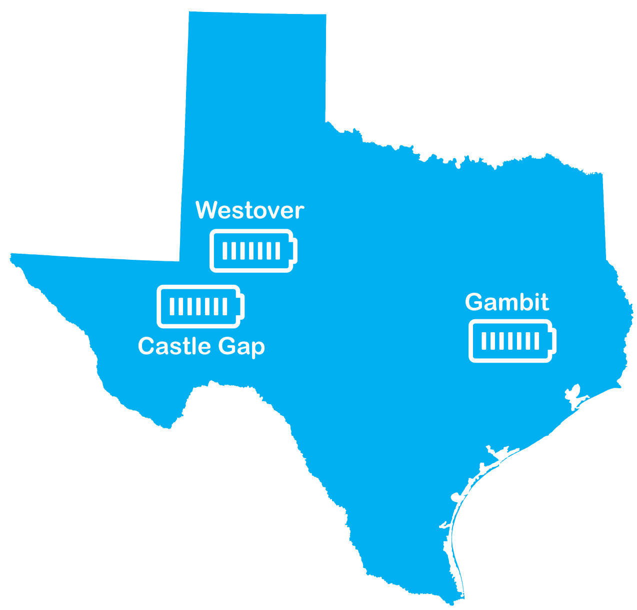
where

C = *Carbon impact from redispatch*
C_b = *Baseline carbon impact*
P_c = *Carbon price*
rev_{e_c} = *Energy revenue from new carbon dispatch*
rev_{a_c} = *Ancillary revenue from new carbon dispatch*

We deployed this model from January 1, 2022 through December 31, 2022 with "omniscience" or "perfect knowledge," meaning the project optimizes all services to prices known ahead of time. Realized performance factors are expected to be much less than 100% due to forecasting errors, and model results are scaled by an omniscience factor to account for these errors.[14]

CASE STUDY RESULTS

We profiled three operational battery projects in ERCOT: Gambit, Westover, and Castle Gap.



Location of three ERCOT batteries profiled

A carbon contract can reduce the impact of emissive batteries, flip assets from net-emitting to net-abating, or increase the abatement impact of batteries already operating as net reducers, depending on a battery's geographic location and physical constraints.

14 Typical omniscience factors for operational ERCOT batteries range between 50-65%

Case Study #1: Reducing Gambit's Carbon Footprint

Plus Power's Gambit Battery is a 100 MW (175 MWh) battery in Angleton, Texas, 40 miles outside of Houston. In 2022, Gambit sold FR in 62% of hours and RRS in 58% of hours and was the most profitable battery in ERCOT in 2022, making $16.75/KW-month. However, Gambit was also the most carbon emissive battery on the grid, emitting 8.0 tons/MW-month for a total of ~9,600 tons in 2022. Gambit achieved 60% omniscience performance factor.[15]

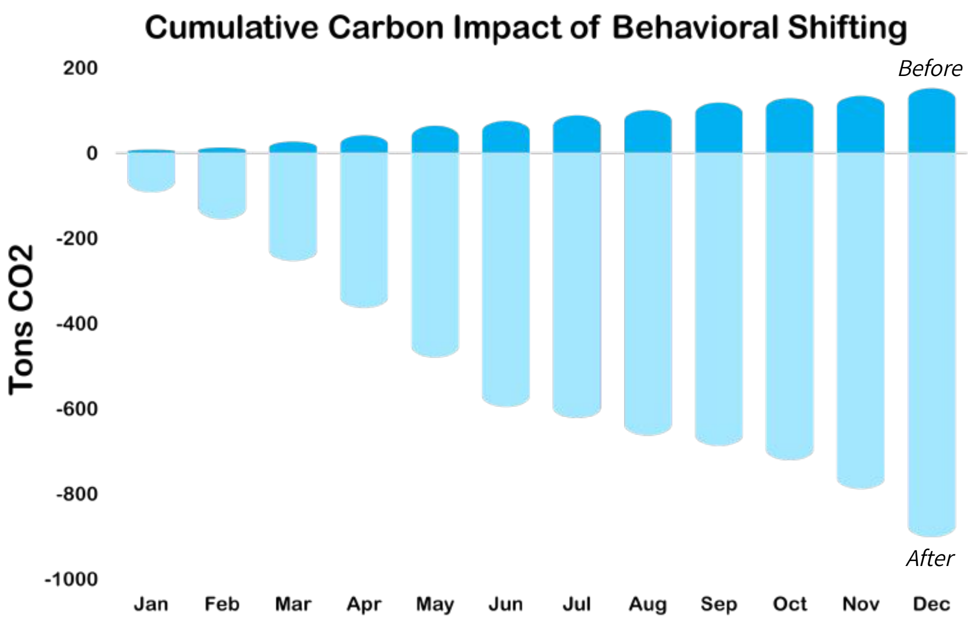
At a $100/ton carbon price, Gambit shifts its operating behavior to lower carbon emissions from 8.0 tons/MW-month to 3.5 tons/MW-month, for a total 4.5 tons/MW-month reduction.[16] Although at this price Gambit is still a net emitter of carbon, a carbon signal cuts emissions by more than half to ~4,200 tons annually.

The carbon arbitrage opportunity at Gambit's physical location is limited because LMEs at the project rarely drop below 0.2 tons/MWh, which constrains the project's ability to charge from low carbon power. Gambit demonstrates that some assets are not optimally sited for carbon abatement at current levels of renewable energy penetration and may have a high opportunity cost of switching from lucrative (and emissive) ancillary service activity, but a carbon price is nevertheless effective in lowering the carbon footprint of such an asset.

A carbon signal cuts emissions by more than half to ~4,200 tons annually

Case Study #2: Flipping Westover from Emitting to Abating

Perfect Power's Westover Battery is a 9.9 MW (20 MWh) battery outside of Odessa, Texas. In 2022, Westover sold Responsive Reserve Service in 96% of operational hours and Frequency Regulation in 3% of operational hours. Since Westover did not sell a meaningful quantity of Frequency Regulation in 2022, we did not include Frequency Regulation revenue in the optimization model and focused on the tradeoffs between RRS and energy services instead. Westover made on average $14.09/KW-month and achieved a 57% omniscience performance factor, with 25% of its annual revenue coming from the single month of July.



Westover's actual carbon impact was emissive, but the introduction of a carbon contract priced at $100/ton induces behavioral switching that flips the asset to net abating

Westover averaged 1.3 tons/MW-month in carbon emissions, totaling ~150 tons of carbon in 2022. However, we found that at a sufficient carbon price-point, this project could change its operations and flip from a net emitting asset to a net abating asset. At a carbon price of $100/ton, Westover flipped from its baseline of net-emitting 1.3 tons/MW-month to net-abating 7.6 tons/MW-month, for a total 8.9 tons/MW-month change.[17]

This equates to an annual impact of approximately 1,053 tons per year of carbon reductions and an incremental revenue of $0.72/KW-month, just from switching operational behavior. In contrast to Gambit, Westover is located near renewable energy projects that frequently result in very low LMEs at Westover's node, which increases the carbon impact of switching behavior at the same $100 carbon price.

[15] The perfect knowledge model optimized to RRS, FR, and real time energy. The model was supplied the frequency FR deployment signal and was constrained to cycle less than or equal to 365 times per year in accordance with equipment warranties.

[16] The perfect knowledge model shows a capability of 7.1 tons/MW-month, which is discounted by a monthly scaling factor equal to the project's actual revenues divided by revenues achieved from the perfect knowledge model.

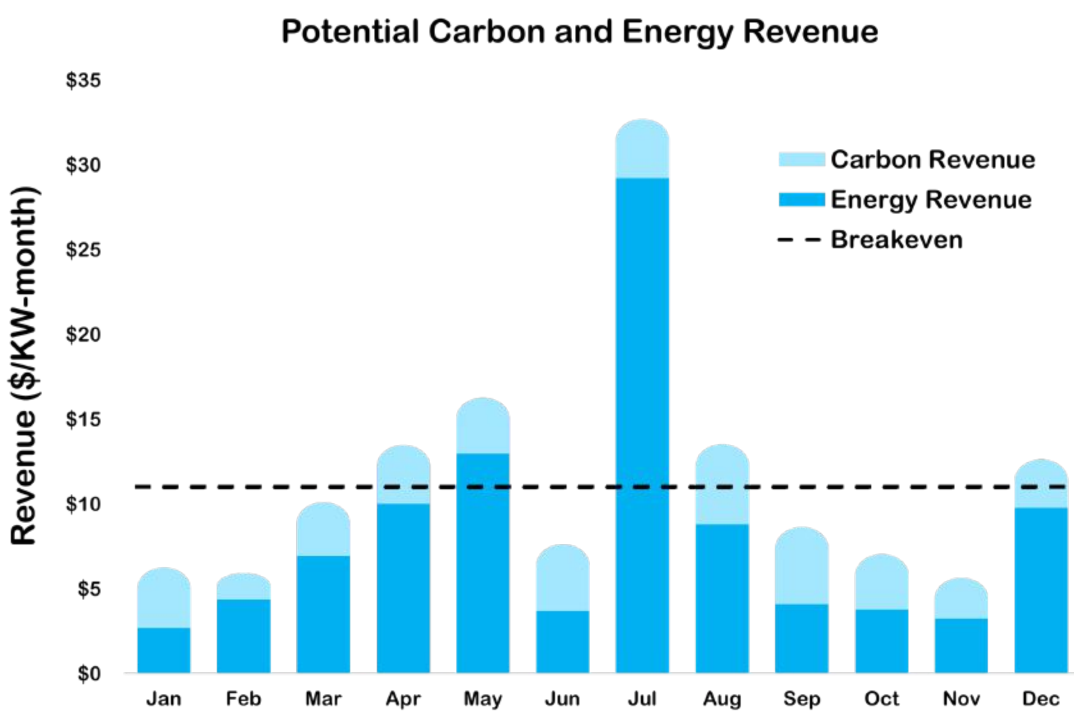
[17] Baseline emissions are the actual emissions produced by the project in 2022. The perfect knowledge model shows an abatement capability of 16.5 tons/MW-month, which is discounted by a monthly scaling factor equal to the project's actual revenues divided by revenues achieved from a perfect knowledge model participating in Responsive Reserve Service and Real Time Energy Markets. The model is constrained to cycle less than or equal to 365 times per year in accordance with equipment warranties.

Case Study #3: Expanding Castle Gap's Abatement Capabilities

Luminant's Castle Gap is a 9.9MW (42 MWh) battery paired with 180 MW Upton Solar facility in Upton County, Texas. The project is configured to charge from either grid energy or behind-the-meter solar energy. Since Castle Gap does not sell any ancillary services, we did not include ancillary revenue as an opportunity cost for the project, instead focusing purely on tradeoffs between energy arbitrage and carbon abatement. A project exclusively selling energy services makes less revenue than a project selling both energy and ancillary services but abates significantly more carbon.

In 2022, Castle Gap made $8.81/KW-month[18] in revenue, with ~28% of its total annual revenue coming from the single month of July. In addition, Castle Gap achieved a 50% omniscience performance factor.[19] Without a carbon contract, Castle Gap abated on average 18.0 tons/MW-month, totaling ~2,134 tons in 2022. However, our model shows with a carbon price of $100/ton, Castle Gap could have abated 35.0 tons/MW-month[20] in 2022, for a total of 4,166 tons of carbon abated annually, nearly doubling the carbon impact of the project operating without a carbon signal. Whereas Castle Gap's actual revenues in 2022 were insufficient to clear the breakeven hurdle, a carbon price of $100/ton could increase the project's revenues by 32%, or $2.84/KW-month moving the needle to a financially viable project.[21] Taking a closer look at monthly revenues, it is worth noting:

67% of carbon revenues are produced within non-peak months, enabling batteries to improve project revenues during months that don't carry seasonal energy premiums.



Castle Gap has a 20% revenue shortfall to its breakeven on energy revenue alone, but a carbon offset contract priced at $100/ton boosts revenues to meet the breakeven at 106% and shores up revenues in the non-peak months.[22]

[18] Energy charged during the day while the solar facility was producing has a cost to the battery that is equivalent to the LMP at the node, but that charging cost is not reflected in the battery's revenues because it is charging "behind the meter", which is not accounted for in ERCOT reports. This leads to an overstatement of the project's revenues that are "stolen" from the adjacent solar facility.

[19] The perfect knowledge model is solely optimizing real time energy purchases and sales, not including any ancillary services

[20] The perfect knowledge model shows a capability of 65 tons/MW-month, which is discounted by a monthly scaling factor equal to the project's actual revenues divided by revenues achieved from a perfect knowledge model participating in real time energy markets. The discount factor accounts for downtime and price forecasting error. The model is constrained to cycle less than or equal to 365 times per year in accordance with equipment warranties.

[21] Carbon revenues assume the project is compensated for all carbon abated by the battery, not just the incremental carbon abated beyond the base case. This is justified if the project is not financially viable without the carbon payments. Financial hurdle rates depend on costs of materials, labor, project specifications, cost of capital, geographic location, and incentives/tax advantages. Hurdle rates can range from $10/kw-month to $15/kw-month.

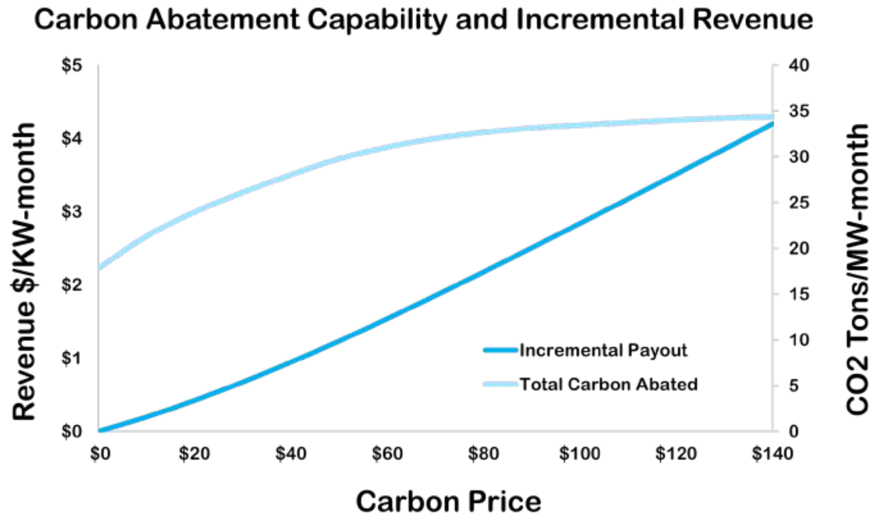
[22] March-June, September-December

IMPLICATIONS

Changes in Operating Behavior

At any carbon price above zero, the battery is incentivized to incrementally increase carbon abatement activity. The figure at right shows that as the price of carbon increases, both the quantity of carbon abated and the carbon payment to the operator increase. This comes at the cost of slightly lower energy market revenues. Beyond $100/ton, there are diminishing returns to increasing carbon price on the volume of carbon abatement that can be generated from grid-scale batteries operating in wholesale energy and ancillary markets. This paper has focused on a carbon price of $100/ton, which is within historical ranges of Low Carbon Fuel Standard prices in California and European Union Carbon Permit prices, but carbon benefits can be extracted from batteries at lower carbon prices, to varying degrees of impact.

Additionally, projects that more commonly cycle to capture energy arbitrage revenues have a lower opportunity cost of behavior switching than those that participate exclusively in ancillary services and can abate more carbon at the same carbon price.

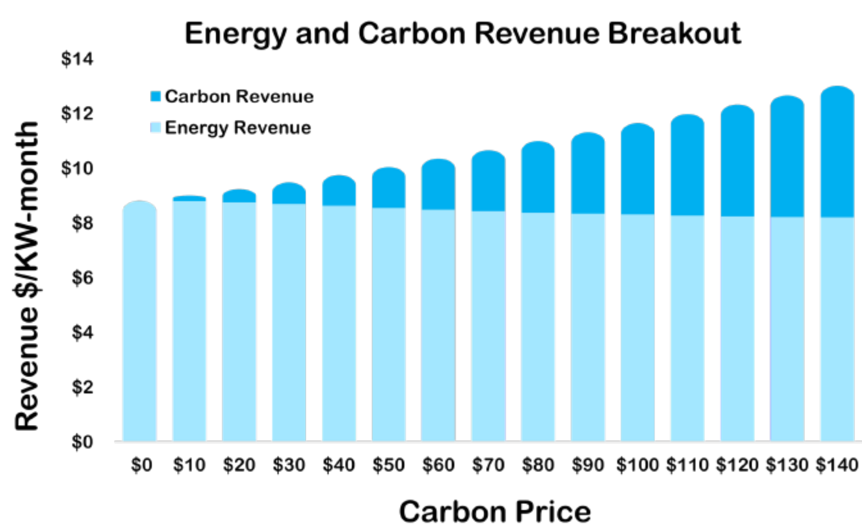


The incremental payout to a Castle Gap increases linearly with the carbon price, but the volume of carbon abated shows diminishing returns past $100/ton. Lower carbon prices incentivize additional decarbonization activity but at a lower volume.

There are diminishing returns to increasing carbon price on the volume of carbon abatement that can be generated from grid-scale batteries operating in wholesale energy & ancillary markets.

Importance of Location

The distribution of LMEs over time significantly impacts a battery's potential to abate carbon on the power grid. Therefore, batteries with access to lower LMEs – high renewable energy penetration, transmission constraints, or frequent renewable energy curtailments – have a greater potential to reduce emissions. Due to their physical locations and proximity to renewable generation, Castle Gap and Westover experience more intervals with low LMEs, which increase carbon offset opportunities. In contrast, Gambit is located near a load center and experiences higher LME floors. Therefore, not all batteries are similarly well-suited to abate carbon due to location's effect on LMEs.



Castle Gap sacrifices a small portion of energy revenue when being compensated for carbon abatement through a pay-for-performance carbon contract but receives incremental revenue from abated carbon.

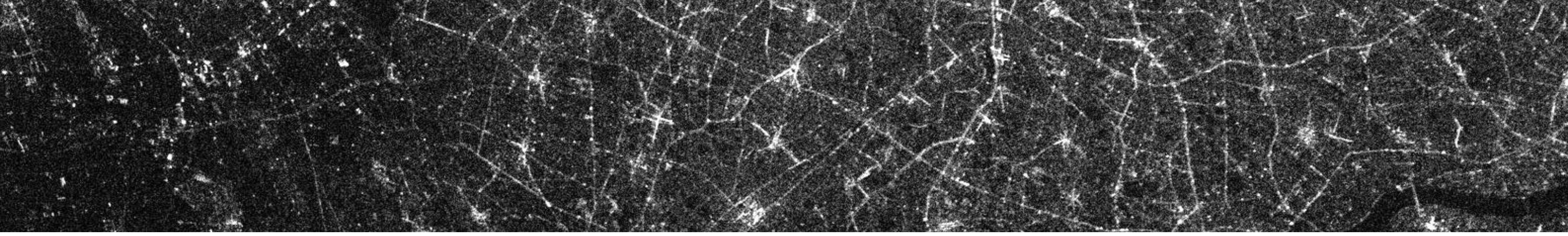
CONCLUSION

Wholesale power markets were not designed to value or compensate energy assets for the carbon impact of their power. As a result, batteries face unique challenges in paving a profitable path to decarbonization, as demonstrated by our examination of the operating battery fleet in ERCOT. Battery revenues rely on volatile energy revenues tied to extreme weather events or ancillary services that face market saturation. Batteries participating in ancillary markets increase emissions on the grid to remain profitable. Yet absent a constructive ancillary service market, energy revenues don't support the widespread investment of low-cost capital into batteries, and energy price signals alone cannot unlock a battery's full potential to reduce carbon emissions on the power grid.

Fortunately, our analysis suggests that carbon contracts could resolve these issues by rewarding carbon abatement activity and simultaneously improving project economics. In addition, a carbon contract potentially accomplishes two different layers of additionality for batteries. For existing operating batteries that are net-emitters, a carbon contract provides compensation for the economic tradeoffs associated with shifts in operational behavior that abate more carbon. For newbuild batteries that struggle to reach the breakeven hurdle, a carbon contract provides a pathway to economic viability. Furthermore, a carbon contract tied to a battery may sufficiently stabilize cashflows to attract low-cost financing and enable operators to place emissions guarantees on their assets that secure tax-equity partners and lead to more successful offtake structures with utilities.

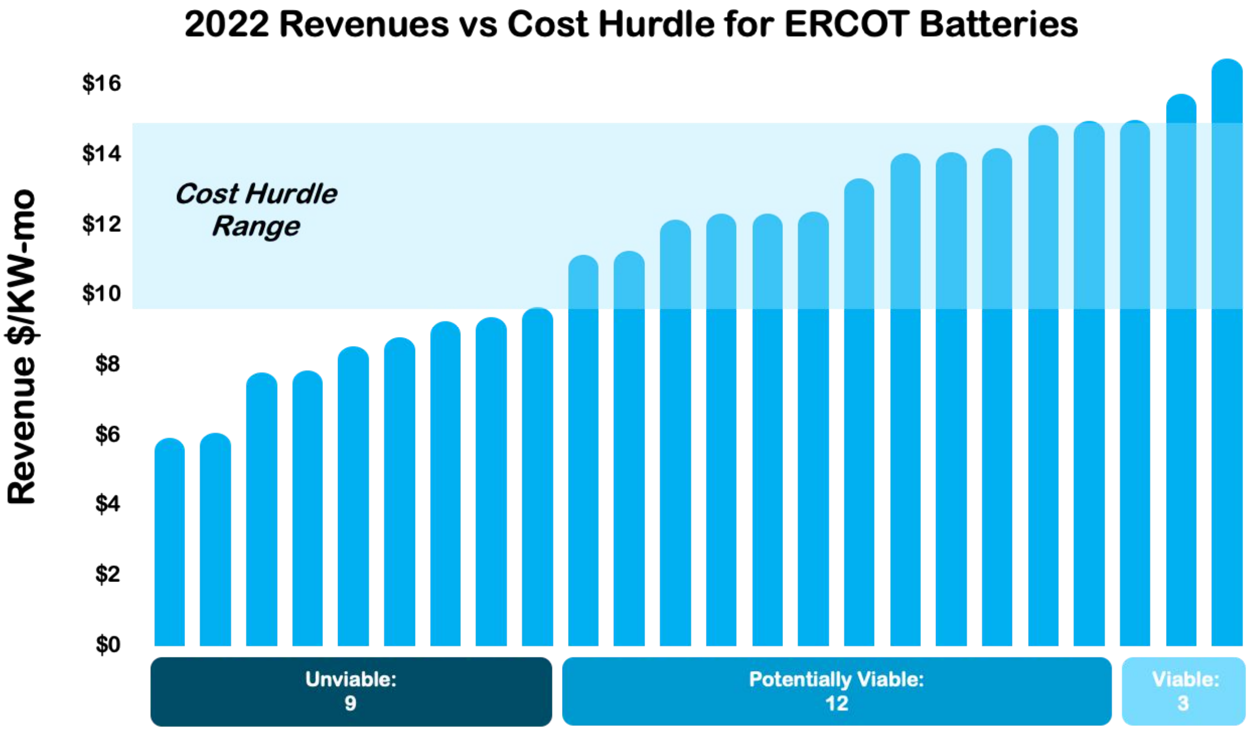
For companies looking to support the power grid's transition to Net Zero, a carbon offset tied to measured environmental performance poses an elegant alternative to outright investments in battery projects. A verified carbon offset sourced from batteries can help companies achieve their sustainability goals while unlocking a pathway to a net zero future and a more resilient grid.[23]

[23] In RegionalTransmission Operators outside of ERCOT, batteries are eligible for revenue from capacity payments, whereby energy assets are compensated for having megawatts *available* for sale into energy markets. RTOs with capacity payments have much lower energy price caps, reducing volatility and revenue available in energy arbitrage activities. In markets lacking regulatory support for energy storage, capacity revenue combined with energy revenue has proven insufficient to support widescale battery development.



APPENDIX

Battery revenues depend on market volatility, operational uptime, the type of products sold, and the accuracy of price forecasts for said products. We assessed the current state of battery economics and found that most projects fail to surpass assumed cost hurdles. Across the twenty-four batteries evaluated, only three projects were deemed economically 'viable,' twelve projects were deemed 'potentially viable,' and nine projects were deemed 'unviable.'[24]



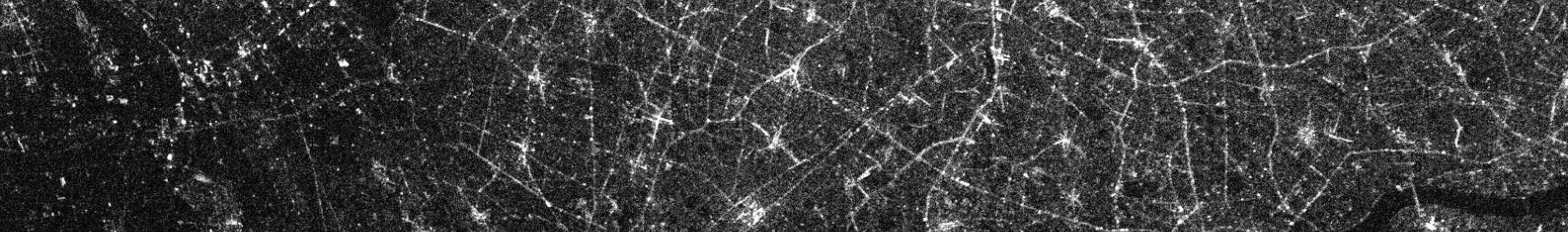
Results include batteries in ERCOT with at least twelve months of operational data for 2022 and 60% uptime.

In 2022, two major weather events contributed to power market volatility that drove energy revenues: a prolonged heatwave in July and Winter Storm Elliot in December. Outside of extremely volatile weather events that drive energy revenues, batteries currently make their remaining revenues from ancillary services. Ancillary revenues, however, are unlikely to provide a long-term support to battery economics. In 2022, the highest revenue-generating batteries were those that sold high volumes of Frequency Regulation, but battery additions threaten to quickly saturate ancillary services and cannibalize revenues. Compared to the scale of the ERCOT energy market, which is forecasted to reach over 82 GW of demand in 2023[25], Frequency Regulation (~1GW) and Responsive Reserve Service (~3GW) are relatively small. In 2022, the operational capacity of battery storage increased by 1,200 MW, leading to a significant decline in ancillary service prices that negatively impacted battery revenues.[26] This trend is particularly evident in recent shoulder months (excluding December's winter storm) with Responsive Reserve Service prices declining by 67% from September 2022 to April 2023 compared to the same months in the previous year.

24 Economic viability was assessed as a project having realized revenues that exceeded its projected fiscal breakeven. Breakeven cost hurdles were assumed to fall within a range of $10-$15/kw-month, which depend on cost of capital, land costs, duration, etc.

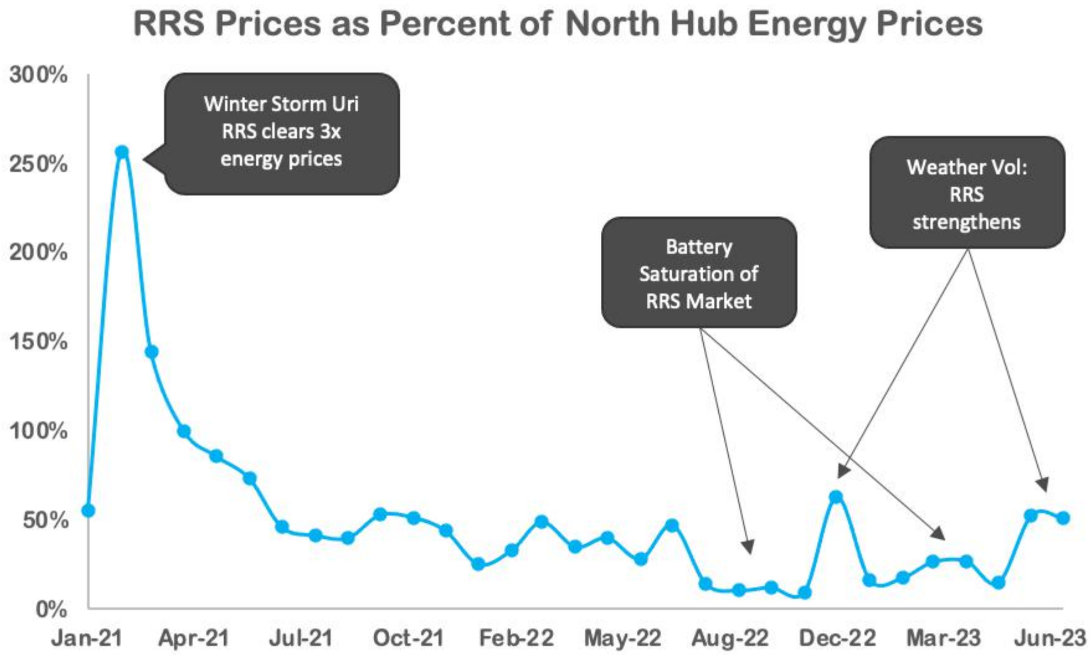
25 ERCOT 2023 Summer Seasonal Assessment of Resource Adequacy: https://www.ercot.com/files/docs/2023/05/05/SARA_Summer2023_Revised.pdf

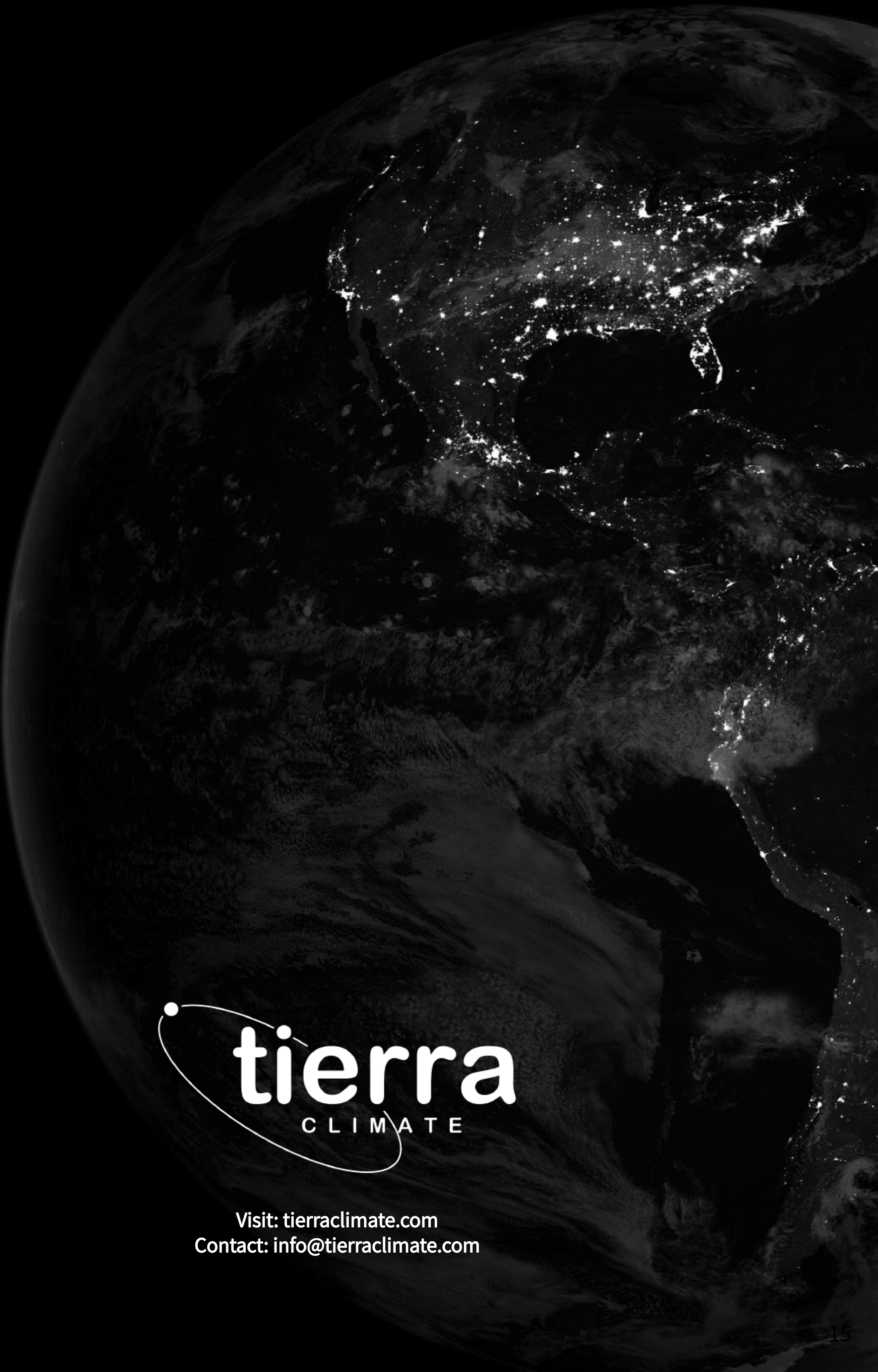
26 This effect became evident approximately August, 2022 following the completion of a 250 MW/250 MWhr facility that has primary sold RRS.



APPENDIX (CONTINUED)

RRS prices have historically been correlated with gas prices, which also collapsed over this period. However, RRS as a percentage of energy prices (a metric which neutralizes the impact of gas prices) also declined by 55%, indicating that the marginal supplier of RRS is shifting from thermal resources to batteries in many intervals.





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