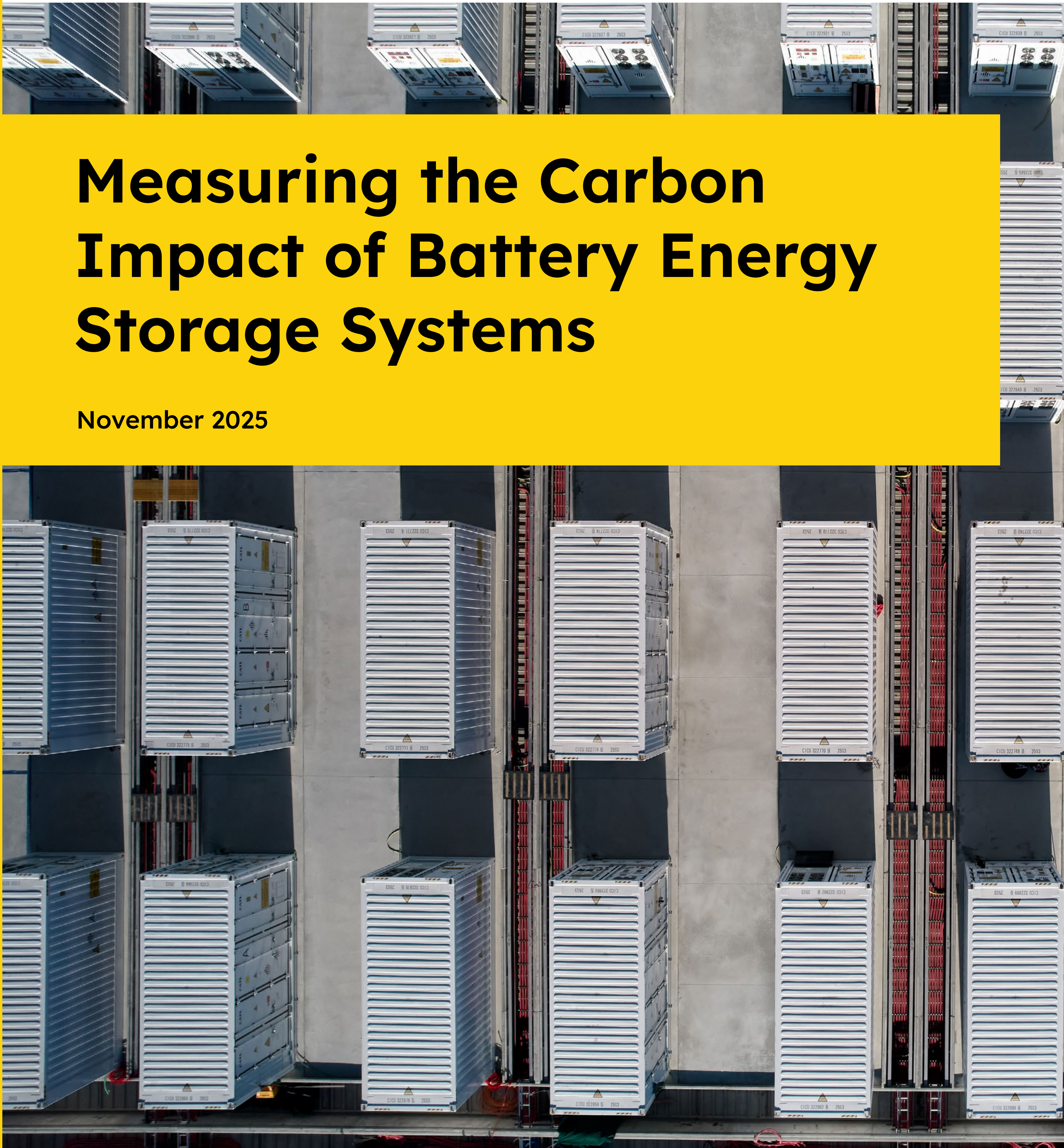
WattTime

Measuring the Carbon Impact of Battery Energy Storage Systems

November 2025



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About WattTime

WattTime is an environmental tech nonprofit that empowers all people, companies, policymakers, and countries to slash emissions and choose cleaner energy. Founded by UC Berkeley researchers, we develop data-driven tools and policies that increase environmental and social good. During the energy transition from a fossil-fueled past to a zero-carbon future, WattTime ‘bends the curve’ of emissions reductions to realize deeper, faster benefits for people and the planet.

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Executive Summary

As the deployment of commercial-scale battery energy storage systems (BESS) accelerates, companies are seeking a common standard for quantifying the system-wide emissions impact that they cause. Companies that operate BESS are also integrating real-time emissions forecasts as signals to optimize the timing of charge/discharge cycles. To the extent that the goal of this strategy is to measure and reduce CO_2 emissions into the atmosphere, both the measurement and control signals must use consequential emissions factors to measure and achieve the desired outcome.

This study assesses an Amazon-enabled BESS in California to demonstrate a practical way of estimating the atmospheric CO_2 emissions caused by a BESS (including the system-wide short- and long-run impacts) using freely and globally available data. This study also showed that a battery can be operated to achieve multiple objectives (revenue and CO_2 avoidance) by very simply combining both objectives into the control signal. It also shows the high cost that can come from using a CO_2 signal that doesn't measure consequential atmospheric emissions impact (e.g., hourly average emissions rates as used in GHG Protocol Corporate Standard Scope 2 reporting).

Estimating the Impact of BESS is Practical

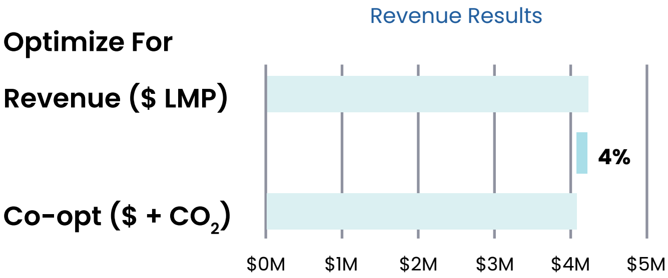
WattTime analyzed an Amazon-enabled BESS in California as a case study to demonstrate a practical method for estimating the consequential emissions impact of a BESS. We used an approach consistent with well-established guidelines and standards for consequential analysis and emissions factors that are freely and globally available. This approach is accessible to any party operating a BESS today.

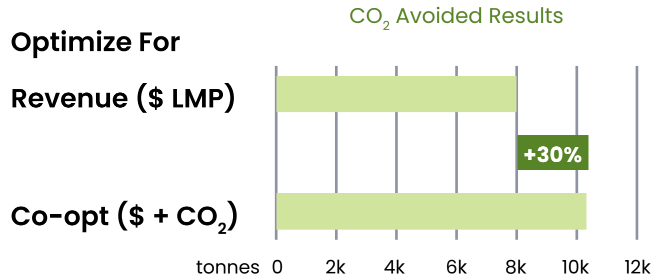
BESS Can Achieve Multiple Objectives

We found that when the BESS had been operated to maximize revenue, it also avoided substantial CO_2 emissions. This outcome would not occur everywhere; it is more likely in places with surplus renewables whose curtailment aligns with negative wholesale prices.

We also analyzed several theoretical scenarios for dispatching the BESS for multiple objectives. We found that there was significant additional potential to avoid CO_2—up to 45% more—by combining emissions and price signals when optimizing the dispatch timing of the BESS (this technique is applicable everywhere, with varying degrees of emissions upside).

Different companies may have different budgets and different ideal outcomes. We demonstrated that the objective outcomes can be balanced by customizing the weight of each. There's a wide range of CO_2 abatement costs, from $45 to $170 per tonne, that achieve better than 85% of the best-case outcomes for both objectives. For example, the BESS could avoid 30% more CO_2 emissions, while only giving up 4% of maximum revenue, at an abatement cost of $68 per tonne.





BESS 3 Victorville, CA 2024, Optimized for	**Revenue** ($, LMP)	**Avoided CO_2** (tCO_2, CMER)	**Forgone Revenue** ($)	**Inc. Avoided CO_2** (tonnes)	**Abatement Cost** ($/tonne)
Revenue $ (Wholesale LMP)	$4,254,166	7,981	-	-	-
$ + CO_2 (LMP + CMER)	$4,091,641	10,383	$162,525 (-4%)	2,402 (+30%)	$68

The Risks of Optimizing to Reduce Hourly Scope 2 Footprint

Many companies produce annual carbon accounting inventory reports using the GHG Protocol Corporate Standard under Scope 2 for electricity, using data of annual granularity. For BESS to be reflected in this inventory, hourly accounting is necessary. However, this shift to hourly Scope 2 accounting using an attributional framework could incentivize BESS optimization using an attributional signal (i.e., average emissions rates). There are significant climate, health, and financial risks to companies using this attributional framework to guide operational strategy or decision-making. To quantify those risks, we analyzed the outcomes for a hypothetical case where the BESS was optimized to minimize a Scope 2 carbon footprint, measured hourly.

Optimizing the BESS to reduce a company's Scope 2 hourly carbon footprint would cost $657 per tonne of CO_2 inventory reduction. **While it would reduce carbon footprint on paper, it would cause an increase in CO_2 in Earth's atmosphere by an estimated 3,509 tonnes.** The real-world impact of such an approach extends beyond GHG emissions. On coal-powered grids this increase in CO_2 emissions would be coupled with an increase in co-pollutants(e.g., particulate) emissions, which are damaging to human health and cause premature death. This shows the high cost that would come with operating a BESS to reduce a company's attributional carbon footprint on paper instead of aiming to reduce atmospheric CO_2.

BESS 3 Victorville, CA 2024	**Revenue** ($, LMP)	**Avoided CO_2** (tCO_2, CMER)	**Scope 2 Improvement** (tCO_2, AOER)	**Forgone Revenue** ($)	**Incremental Avoided CO_2** (tonnes)	**Incremental Scope 2 Inventory Reduction** (tonnes)	**Cost of Scope 2 Incremental Inventory Reduction** ($/tonne)
Revenue $ (LMP opt)	$4,254,166	7,981	-1,387	-	-	-	-
Hourly Scope 2 (AOER)	$ 998,974	4,472	3,564	$3,255,192 (-77%)	-3,509 (-44%)	4,951	$657

Introduction

Battery Energy Storage Systems (BESS) capacity worldwide is growing quickly, with new BESS capacity expected to exceed 400 GWh per year by 2030. This rapid buildout is critical for global decarbonization. “Achieving COP28 targets will hinge on battery deployment increasing sevenfold by 2030” (IEA). However, building BESS capacity does not reduce power sector emissions by default. In fact, BESS can cause emissions increases when operating purely economically or when operated to reduce a company’s Scope 2 emissions inventory. A real-time consequential carbon signal can fix this issue. The choice is not either/or, as a battery can be co-optimized for multiple objectives, including cost, emissions, and others. Put simply, the inclusion of an emissions signal (not a proxy) in battery dispatch logic is critical to ensuring or maximizing emissions reductions.

With the growth of BESS, companies are seeking a common standard for quantifying the system-wide emissions impact of operating them. Companies are also integrating real-time emissions forecasts as signals to optimize the operation of batteries in their portfolio. The framework used for both measurement and control signals should be consistent and indicative of genuine real-world impacts (i.e., consequential) when the goal is to reduce CO_2 emissions into the atmosphere.

This paper is meant to support the development of a practical and impactful measurement guideline based on established standards. First, it reviews the existing and emerging protocols and guidelines relevant to measuring the emissions of energy storage. Then, it presents a BESS case study analysis that demonstrates various aspects of measuring and reducing the carbon impact of a BESS, using a methodology consistent with established protocols.

Review of Measurement Methods

Limitations of Attributional Methods

The current GHG protocol for Scope 2 emissions does not sufficiently reflect BESS carbon impact and provides insufficient guidance for operators. The reasons are at least two-fold: 1) common practice is to use annual factors and annual emissions factors don't differentiate between emissions rate differences at different times of day during charging vs. discharging, and 2) most importantly, the standard uses an attributional (really allocational) framework. An attributional framework uses average emissions factors to allocate emissions from all generators equally to all loads. Attributional frameworks and average emissions factors, by definition, do not represent a causal relationship between actions and impacts, and thus they tend to perform poorly if used for estimating real-world emissions impacts caused by actions that affect electric grids, since that is not their purpose.

As the GHG Protocol has stated, an attributional framework is used for inventory accounting (Scope 2), which is explicitly not meant to measure system-wide impacts. From the GHG Protocol: "Inventory accounting, however, does not quantify impacts of an organization's individual actions. By contrast, project accounting provides a holistic view of the impacts of a specific intervention relative to what would have otherwise occurred, including the system-wide impacts beyond the GHG inventory boundary."

Established Consequential Impact Methodologies

A consequential framework, by design, measures the real-world impacts caused by certain interventions. Established guidelines that use a consequential framework already exist from respected international bodies (GHG Protocol and UNFCCC), and these guidelines can be applied when accounting for the impact of BESS.

The GHG Protocol's Protocol for Project Accounting ("Project Protocol") was first published in 2005 as a standard means for quantifying the system-wide consequential GHG impact of an intervention. This protocol is a complement to the Corporate Standard (which includes Scope 2, published in 2001), since that standard had not included a means for quantifying consequential impact. In addition to providing the means for post-hoc measurement of impact, this protocol allows companies to more effectively plan emissions abatement projects by estimating the emissions impact of potential projects before deploying them.

The GHG Protocol's Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects, first published in 2007, further explained how to estimate the consequential impact of a project affecting the electric grid. These guidelines describe how to use a combination of operating margin (OM) and build margin (BM) emissions rates to more comprehensively quantify the impact of an intervention.

The International Financial Institutions Technical Working Group (IFI TWG) was formed in 2012 as a collaborative effort to harmonize GHG accounting standards and methodologies. The United Nations Framework Convention on Climate Change (UNFCCC) secretariat joined to coordinate the IFI TWG in 2015. The group has maintained a methodology that accounts for the consequential impact of grid-connected projects using a combined margin (CM) factor, which combines OM and BM factors. They've periodically released annual OM and CM factors for every country in the world, which can be found here. These emissions factors are built for estimating the impact of renewable energy and energy efficiency projects. Since they are annual factors, they are insufficient to quantify the impact of any technology that performs temporal energy shifting (e.g., a battery).

The California SGIP energy storage incentive program got off to a rocky start, when during its first year, the storage projects added under the program actually increased electricity emissions, even though the intention was for them to reduce emissions. The problem was that there wasn't a requirement or a means provided for them to explicitly operate to reduce emissions; instead they were operated economically, and a minimum round-trip efficiency was required. These proxies had been insufficient to cause emissions reduction. The CPUC fixed the issue by using consequential emissions factors instead of proxies. They decided that measuring the consequential emissions impact would be required, and projects would be paid more if they reduced emissions. It also provided not only an official measurement signal in real time, but a forecast of that signal. So far, for three years after implementation, the program's batteries have been reducing emissions as a result. This long-running real-world demonstration shows that measuring and optimizing for consequential emissions can be done practically and effectively.

Emerging Consequential Methodologies

The Verra Draft VCS Methodology CN0157 Grid-Connected Energy Storage Systems defines a methodology that quantifies GHG emissions reductions from the operation of both existing and new grid-connected energy storage systems (ESS). Once approved, this will be used to validate total carbon impact in a defined period and issue credits for carbon reductions produced by an ESS. As described in Appendix V of that methodology, it allows the use of OM-type marginal emissions rates, and is thus oriented toward quantifying short-run/operating emissions impacts only.

The GHG Protocol Corporate Standard is undergoing revision, and GHGP is considering how and where to include consequential accounting beyond the Project Protocol. Despite a majority of the Scope 2 Technical Working Group voting in favor of incorporating consequential impact into Scope 2, the Independent Standards Board and GHGP decided to exclude it from consideration in Scope 2, seemingly to avoid mixing attributional and consequential frameworks in the same report. The Actions & Market Instruments TWG will further consider where else it could be included in the GHG Protocol.

A Caution About Using Proxies

Using proxies to measure or incentivize consequential impact leads to uncertain GHG outcomes. At best, fewer emissions are reduced. At worst, emissions can increase. As seen in the California SGIP example above, the most reliable way to achieve a desired outcome is to measure and optimize for that outcome directly.

These are some common proxies that have been used either explicitly with the intention of reducing emissions or with the hope of reducing emissions as a byproduct of pursuing other objectives.

- Price of electricity
- Average emissions rate
- Grid fuel-mix
- Grid demand (peak avoidance)
- Matching carbon-free energy (CFE) to facility load

In some cases using one or more of these proxies could result in real emissions reductions, when they are correlated to some degree with consequential emissions rates. However, if the objective of BESS optimization is to reduce emissions into the atmosphere (i.e., real system-wide consequential emissions), then the explicit use of consequential emissions rates (e.g., a combination of high-quality operating and build margin rates) will, naturally, maximize this intended outcome.

Case Study Overview

This study aims to demonstrate the practicality of measuring emissions reduction from BESS and to understand the full consequential emissions reduction opportunity presented by BESS optimization. WattTime analyzed historical dispatch data from an Amazon-enabled BESS in California and compared the baseline economic dispatch to several alternate dispatch scenarios. We evaluated performance on a number of potential objective metrics, including financial, consequential emissions of multiple types, and attributional emissions (i.e., hourly Scope 2).

Below is a summary of the BESS that is the subject of this case study.

BESS Identifier	**BESS 3**
Location (Grid Region)	Victorville, California (CAISO_SANBERNARDINO)
Start of Operation	31 May 2024
BESS Description	Utility-scale, paired with PV
Dispatch Strategy	Optimization for wholesale market revenues within the constraints of any resource adequacy commitments.
Capacity / Energy	75 MW / 300 MWh (4-hr battery)

After a mid-year startup, the battery operated for seven months in 2024. The charging and discharging dispatch of the battery was executed to maximize revenue while operating in tandem with a 150 MW solar photovoltaic (PV) installation.

The analysis in this case study seeks to answer these questions:

1. What is the effect on grid CO_2 emissions if batteries optimize for maximum revenue?
2. What is the effect on grid CO_2 emissions if batteries optimize for CO_2 reduction?
3. If optimizing for CO_2 reduction, what is the effect on revenue?
4. What are the combined effects of co-optimizing for both revenue and CO_2?

Scenarios for Optimizing Various Objectives

To explore revenue and emissions impacts, we designed a study of optimization scenarios with varying objective signals. A summary of the scenarios we analyzed and compared is below.

Scenario	**Optimized on**	**Date Range**
BESS 3 Actual	Revenue maximization	5/31-12/31/2024
Max Revenue (Baseline)	LMP only (Revenue from energy arbitrage)	1/1-12/31/2024
Avoid CO_2	CMER only (combined margin emissions rate)	1/1-12/31/2024
Revenue + CO_2	LMP + CMER (various weights using $/t$CO_2$)	1/1-12/31/2024
Hourly Scope 2	AOER (hourly average emissions)	1/1-12/31/2024

Appendix A & B include results for additional signals and combinations of the signals above.

BESS 3 Actual - The observed dispatch of the battery when operated to maximize revenue when paired with solar PV. The battery was not in operation for the full year of 2024.

Max Revenue (baseline) - We modeled a standalone version of BESS 3 to establish a baseline for comparison of all other scenarios. This baseline isolates the BESS from any constraints related to being co-located with solar PV, provides a full year of 2024 data to study, and allows us to establish a baseline for revenue performance as if the battery had been optimized solely to maximize revenue from energy arbitrage based on wholesale locational marginal pricing (LMP). This allows us to consistently examine the results of counterfactuals that optimize for other objectives or co-optimize for revenue along with the other objectives. Each additional scenario beyond this baseline was subject to the same constraints as this baseline.

Avoid CO_2 - To determine how much more CO_2 the BESS could avoid, we modeled an additional scenario using the combined margin emissions rate (CMER) as the sole objective, optimizing the dispatch for emissions avoidance only.

Revenue + CO_2 - We also modeled scenarios where emissions and revenue were co-optimized by setting a combined objective as a combination of price (LMP) and emissions (CMER) with various weights between the two objectives.

Hourly Scope 2 - We evaluated the potential outcomes of optimizing battery dispatch to reduce Hourly Scope 2 CO_2 carbon footprint using an hourly average operating emissions rate (AOER) signal.

Methodology

Applicable Emissions Rates for Estimating Consequential Impact

Operating Margin (OM) Emissions Rate - The rate of change in emissions due to existing grid assets changing their operation because of a change in load. Examples include WattTime's Marginal Operating Emissions Rate (MOER), Resurety's Locational Marginal Emissions rates (LME), UNFCCC IFI TWG's OM grid factor, US EPA AVERT's Avoided CO_2 rates, and NREL's Short-run Marginal Emission rate (SRMER).

Build Margin (BM) Emissions Rate - The rate of change in emissions due to structural changes to the grid because of a change in load. An example is Climate Trace's Marginal Build Emissions Rate (MBER), and UNFCCC IFI TWG's BM grid factor.

Combined Margin (CM) Emissions Rate - The full rate of change in emissions due to the combination of operational and structural changes on the grid because of a change in load. Examples include UNFCCC IFI TWG's CM grid factors, a CM rate that combines WattTime's MOER and Climate Trace's MBER, and NREL's Long-run Marginal Emission rate (LRMER).

Since the consequential impact of operating a battery is based on shifting energy from one time to another, a time-varying (e.g. hourly or more granular) emissions rate is needed to estimate its impact.

If measuring and optimizing for the full-system consequential impact in both short- and long-run is desired, the CM emissions rate is the theoretical best match for that objective.[1]

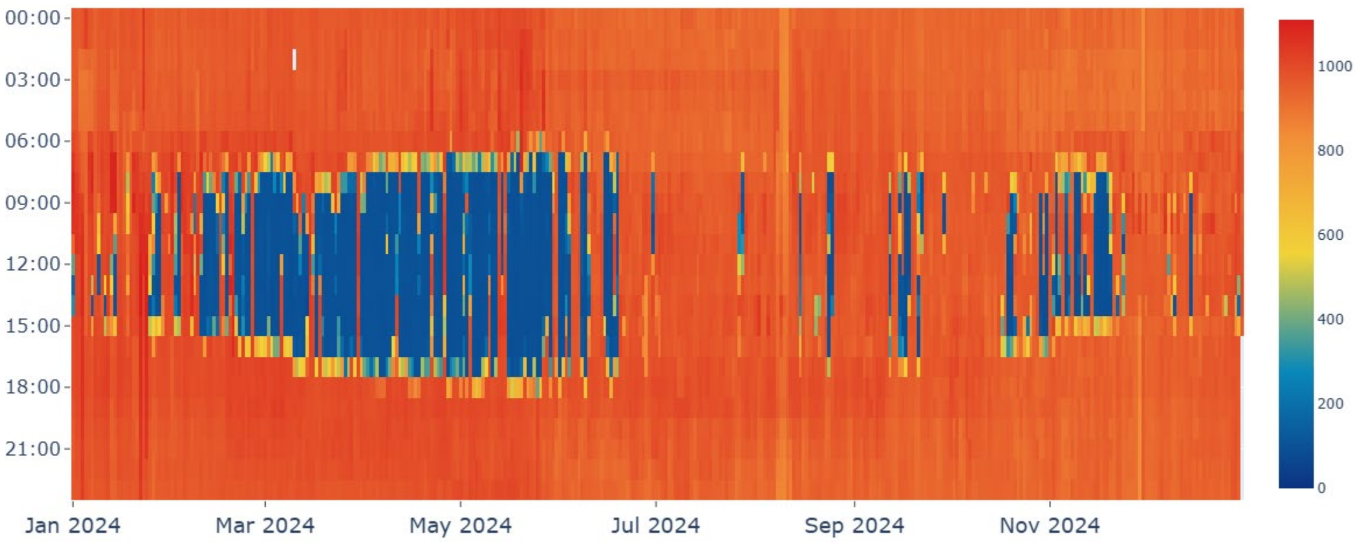
[1] As described by "Assessing the Impact of Voluntary Actions on the Grid: A Consensus Paper from ZEROgrid's Impact Advisory Initiative" https://rmi.org/insight/assessing-the-impact-of-voluntary-actions-on-the-grid/

Visualizing the Emissions and Price Signals

The heatmaps below show each of the marginal emissions rate datasets used in this study and the wholesale market price (LMP). These plots help to quickly visualize the daily and seasonal patterns of variation which are what define the opportunity for BESS. Very low or zero emissions rates (blue) occur when carbon free energy and renewables (in this case mostly solar PV), are on the margin. Renewables are marginal if using more electricity would cause more renewable generation; this occurs when solar PV is being curtailed due to insufficient demand within a grid region bounded by congestion. Low MOERs from solar curtailment in California are seen most often in spring, because solar output is high and temperatures are still low, so air conditioning loads are also relatively low.

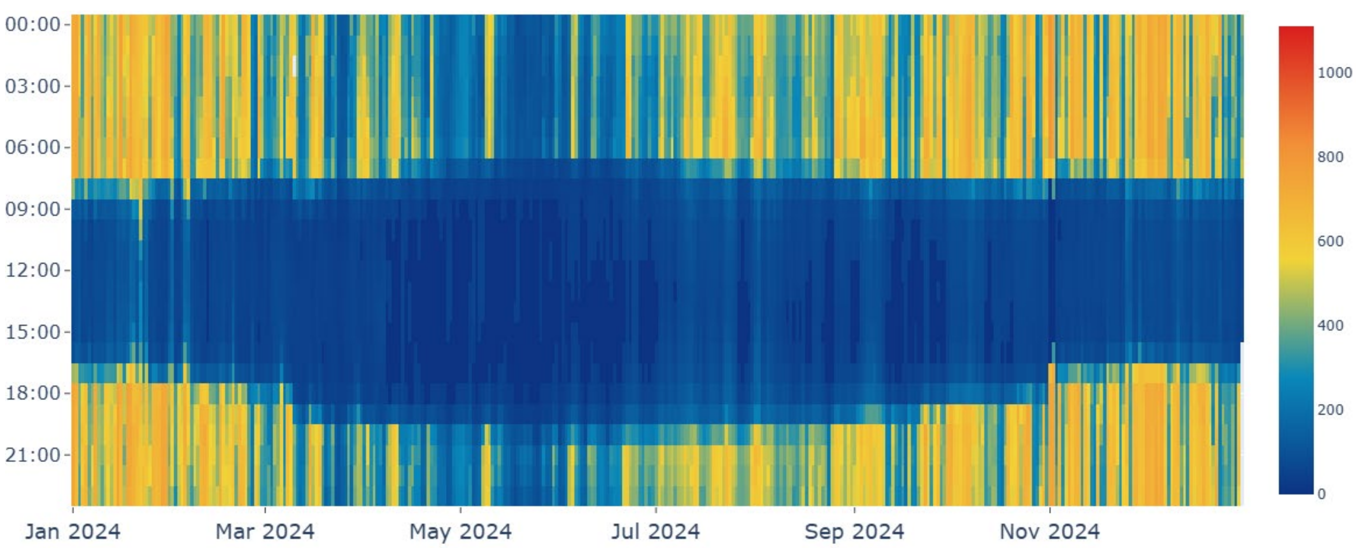
MOER (CO_2 lbs/MWh) - CAISO_SANBERNARDINO

min = 71 / max = 1109 / mean = 837



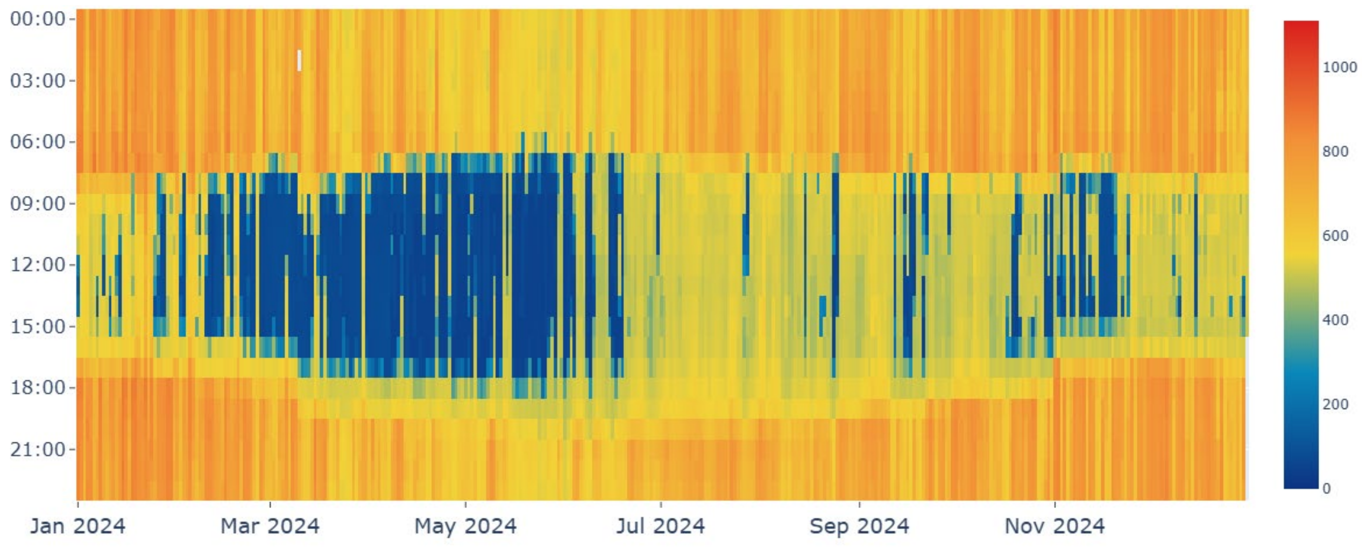
MBER (CO_2 lbs/MWh) - CAISO

min = 0 / max = 800 / mean = 272



CMER (CO_2 lbs/MWh) - CAISO_SANBERNARDINO

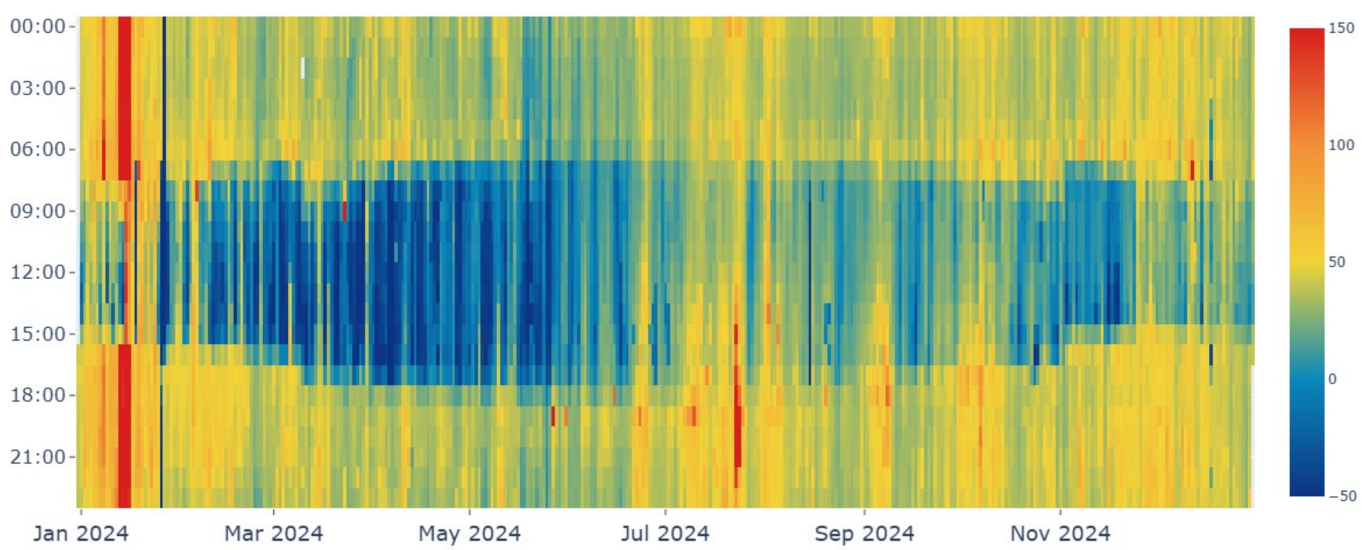
min = 46 / max = 885 / mean = 554



For comparison, here is the heatmap of wholesale LMP for the pricing node (SOUTHBAS_1_N001) used for WattTime's MOER subregion CAISO_SANBERNARDINO. Notice that prices during the day are often negative (especially in spring), due to oversupply on the grid. Negative prices are the market signal to generate less, which leads to renewable curtailment. Though late summer still has high solar production during the day, negative prices occur less often because demand is also high (higher temperatures lead to higher air conditioning load).

LMP ($/MWh) - CAISO_SANBERNARDINO

min = -688 / max = 895 / mean = 30



Estimating the Consequential Impact of BESS

A BESS will avoid emissions if the net result of its charging and discharging activity is that less fossil fuel is burned by electricity generators compared to the counterfactual case (e.g., the BESS didn't exist).

To estimate the consequential impact of the charge and discharge of the battery, we use the following equation, consistent with the GHG Protocol's Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects.

$$\textit{Total Avoided Emissions}_t = CM_t \cdot GEN_t \quad \text{(Equation 1)}$$

Where:

- *Total Avoided Emissions*$_t$ are the emissions avoided because of the project, including operating and build impacts, based on what occurs in period t
- CM_t is the combined margin emissions rate in period t (e.g., tCO_2/MWh)
- GEN_t is the electricity added to the electricity grid by the project in period t (e.g., MWh, and in this case, positive = discharging BESS, negative = charging BESS)

Marginal emissions factors are the emissions rates of the generator(s) affected by the BESS dispatch, and these are used to estimate the consequential impact of the BESS. As defined in the guidelines, we estimate the full consequential impact by combining the build and operational emissions factors to get the combined emissions factor.

$$CM = \omega\, BM + (1-\omega)\, OM \quad \text{(Equation 2)}$$

Where:

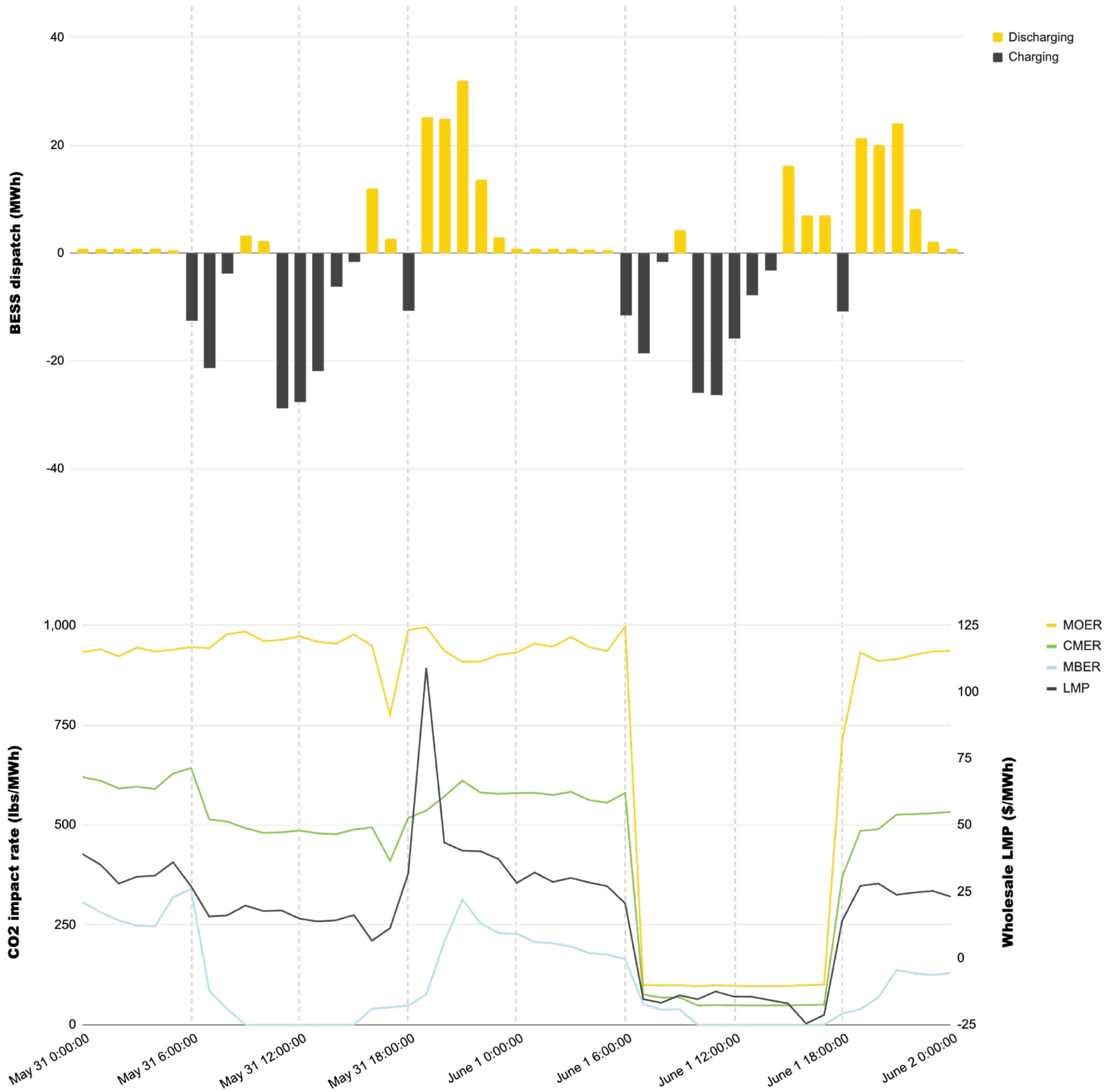
- *BM* is the build margin emissions factor (e.g., tCO_2/MWh)
- *OM* is the operating margin emissions factor (e.g., tCO_2/MWh)
- ω is the weight (between 0 and 1) assigned to the build margin

For this study, for the OM emissions rate, we used WattTime's MOER data, pulled from gridemissionsdata.io (free, historical, hourly). For the BM emissions rate, we used Climate Trace's MBER data, as available for free from https://www.gem.wiki/MBERs. When we combine these rates, we use the label CMER (Combined Margin Emissions Rate) for CM. The guidelines suggest using a static default $\omega = 0.5$ for intermittent and non-firm power when determining a precise expected capacity factor is not practical, which we use in this study.

Measure BESS Emissions and Revenue

The 2024 BESS dispatch data is a historical time series of hourly net energy values. To measure a particular outcome, we take the sum of the product of a) the BESS energy time series and b) the historical time series of that objective's rate (e.g., CO_2 tonnes/MWh). For emissions, we use Equation 1; for revenue, we use Equation 1 but with price in place of CM. Here's a two-day sample of the historical BESS energy data (top) and the measurement signals for the same period (bottom).

2-Day Sample of BESS Energy and Measurement Signals



Estimated Outcomes for BESS 3 during 5/31-12/31/2024

	Energy Generated (MWh)	**Revenue Est.** ($, LMP)	**Avoided Emissions** (tonnes CO_2)
Charging	-17,207	-$306,283	-3,158
Discharging	16,769	$695,217	4,599
Total (Net Result)	-438	$388,934	1,081

Even though the BESS was being dispatched solely to maximize revenue, it also avoided CO_2 emissions. The outcomes in the table describe the impact the battery had compared to a counterfactual where the battery didn't exist. These results demonstrate how the impacts of charging and discharging net out to a total impact that results from shifting load (charging at one time and discharging at a different time). The net energy generated is negative, meaning that energy was consumed, because batteries consume some energy due to round-trip losses. Since the actual historical revenue was not provided, we used wholesale LMP to estimate the revenue of the BESS dispatch via energy arbitrage.

Modeling Energy Flows and Dispatch of BESS

Optimized battery dispatch was modeled using EPRI's DER-VET, which performs a dispatch schedule optimization, solving to maximize objective signals within the defined constraints. This study examined the potential opportunity for maximizing objectives; we modeled dispatch based on perfect foresight, using historical data where day-ahead forecast data would be used in practice.

Constraint	**Value**
Battery Round-trip Efficiency (RTE)	90%
Auxiliary Load (in addition to RT losses)	700 kW
SOC Limits and Target [lower, target, upper]	[30%, 65%, 100%]
Daily Cycle Limit	1
Optimizer Horizon	24 hours

For our modeling of various cases, we target 85% AC round-trip efficiency (inclusive of the standby loss from auxiliary load), consistent with the NREL 2024 Annual Technology Baseline. The resulting RTE for the scenarios did vary, usually 85% +/- 1%, but in the case where the battery is relatively underutilized, the auxiliary load becomes more significant, and RTE approached 80%.

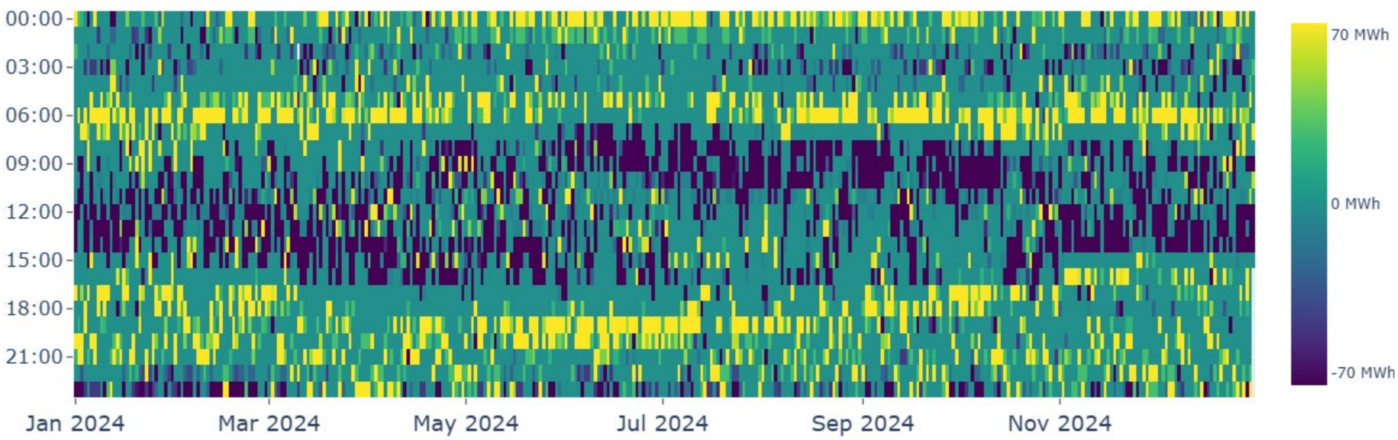
Results

Each scenario's absolute performance (relative to no BESS) is presented first, then a summary of the scenarios is provided for easier comparison.

Optimize to Maximize Revenue (Baseline)

We optimized the BESS within the constraints above, using hourly average historical wholesale LMP as the objective signal.

Signal = Price (LMP), BESS 3 Dispatch Pattern



Scenario "Max Revenue (Baseline)" Outcomes for Bess 3 in 2024 (full year)

	Energy Dispatched (MWh)	**Revenue Est.** ($, LMP)	**Avoided Emissions** (tonnes CO_2)
Charging[2]	-125,373	-$ 943,662	-23,087
Discharging	107,228	$ 5,197,829	31,069
Total (Net Result)	-18,146	$ 4,254,166	7,981

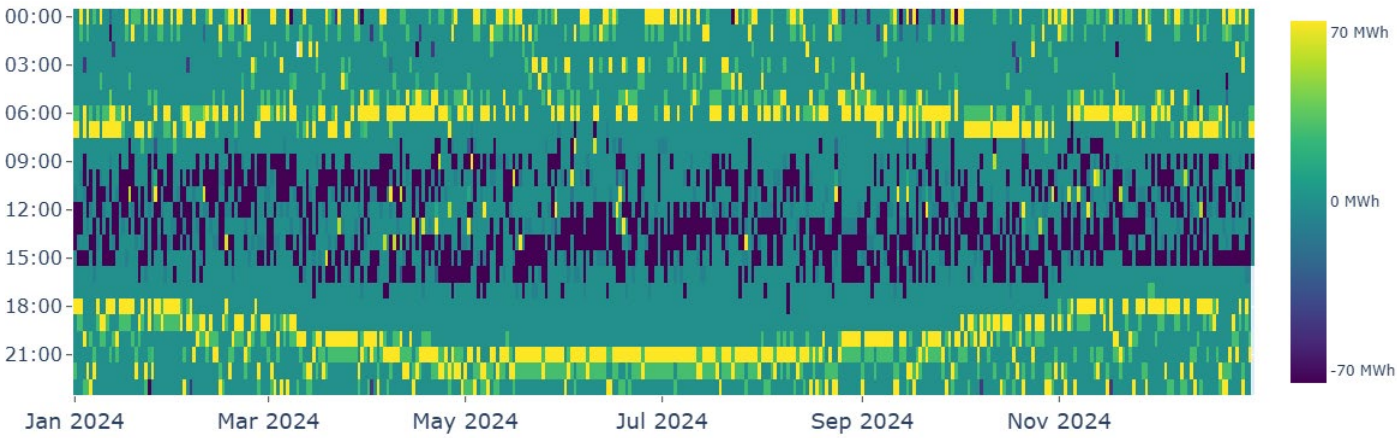
This baseline optimization was unconstrained in ways that the actual BESS was (e.g., the actual BESS only charged with PV), which resulted in far more cycles. With higher utilization, the revenue and avoided emissions performance on a total and normalized basis were higher than the observed performance of BESS 3 in the partial year of operation in 2024. Of course, there may be reasons that pure energy arbitrage might not be practical to pursue, and this baseline wouldn't apply to those scenarios. Nevertheless, LMP-based arbitrage provides a clean price signal to benchmark against.

2
"Charging" includes all energy drawn from the grid (energy to charge the battery and to power auxiliary loads)

Optimize to Avoid CO_2

We optimized the BESS using a combined margin emissions rate (CMER) as the objective signal.

Signal = CO_2 (CMER), BESS 3 Dispatch Pattern



Scenario "Avoid CO_2" Outcomes for Bess 3 in 2024 (full year)

	Energy Dispatched (MWh)	**Revenue Est.** (\$, LMP)	**Avoided Emissions** (tonnes CO_2)
Charging[2]	-97,156	-\$ 680,732	-14,614
Discharging	81,832	\$ 3,549,125	26,157
Total (Net Result)	-15,324	\$ 2,868,393	11,543

45% more CO_2 avoided - Dispatching the battery purely on a CO_2 signal avoided 3,562 tonnes more CO_2 emissions than the baseline. When the battery was optimized for CO_2 instead of revenue, it achieved more avoided CO_2 with a lower utilization (273 cycles vs. 357 cycles in the baseline).

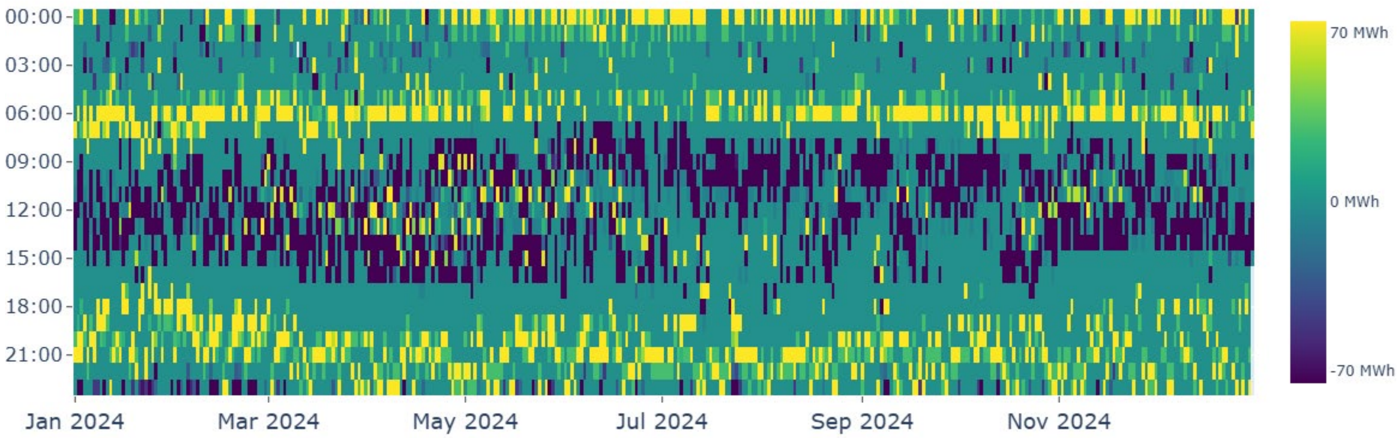
33% lower revenue - CO_2 avoidance was maximized using fewer cycles, but revenue was reduced by \$1.39M. The marginal abatement cost of pure CO_2 optimization is **\$389 per tonne CO2**, compared to the revenue-optimized baseline. Some companies may find this trade-off worthwhile, but we think most would consider it too expensive. Luckily, optimizing either a) purely to maximize revenue or b) purely to avoid emissions are not the only options.

This scenario was optimized on CM and measured with CM, and we also evaluated optimizing on OM and measuring this and the other scenarios using OM. Those results can be found in Appendix A.

Co-Optimize for Both Revenue and CO_2

We combined the LMP and CMER signals into a co-optimization signal for both revenue and CO_2 avoidance objectives. We ran many co-optimization scenarios with varying weights between the price and CO_2 signals. The results below are for a chosen weight of $200 per tonne of CO_2 (this weight does not equal the abatement cost realized, as we show later).

Signal = Price + CO_2 BESS 3 Dispatch Pattern



Scenario "Revenue + CO_2" Outcomes for Bess 3 in 2024 (full year)

	Energy Dispatched (MWh)	**Revenue Est.** ($, LMP)	**Avoided Emissions** (tonnes CO_2)
Charging[2]	-112,431	- $ 385,261	-18,114
Discharging	95,580	$ 4,476,902	28,496
Total (Net Result)	-16,851	$ 4,091,641	10,383

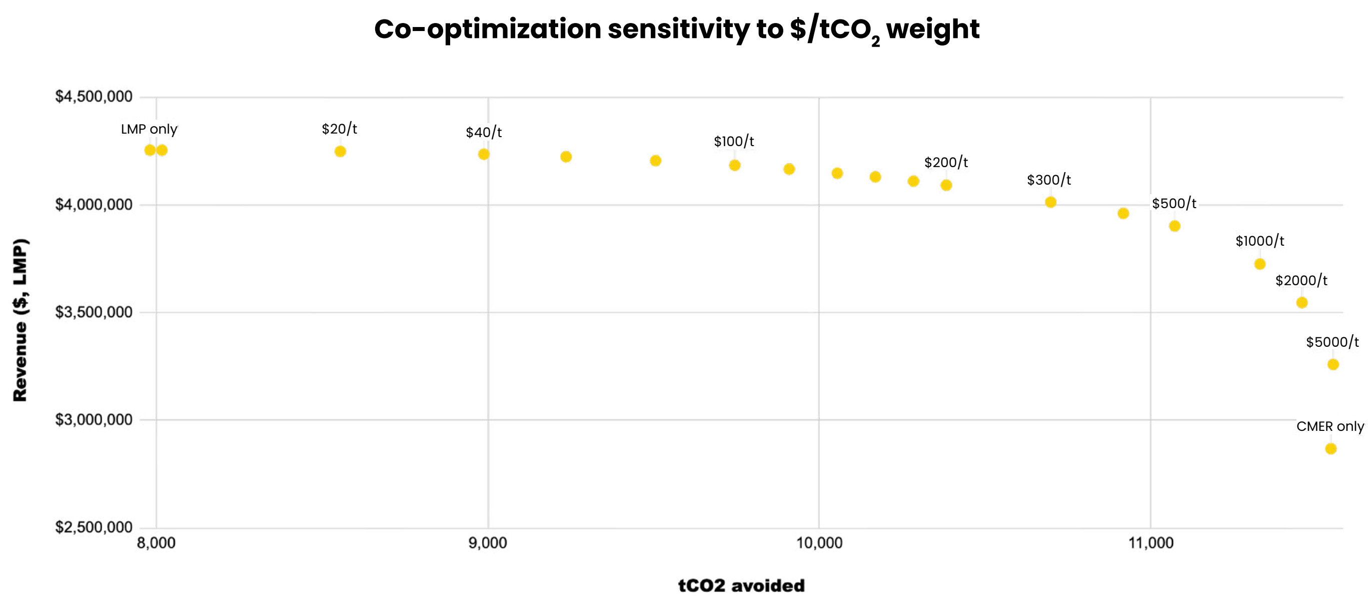
30% more CO_2 avoided - Compared to the baseline, this co-optimization avoided more CO_2 emissions. Compared to the CO_2 only optimization, 90% of the optimal CO_2 avoidance is achieved.

4% revenue reduction - This scenario earned $163k less than the baseline, but still earned 96% of the maximum possible revenue. The marginal abatement cost in this case is **$68 per tonne CO_2**, compared to the revenue-optimized scenario.

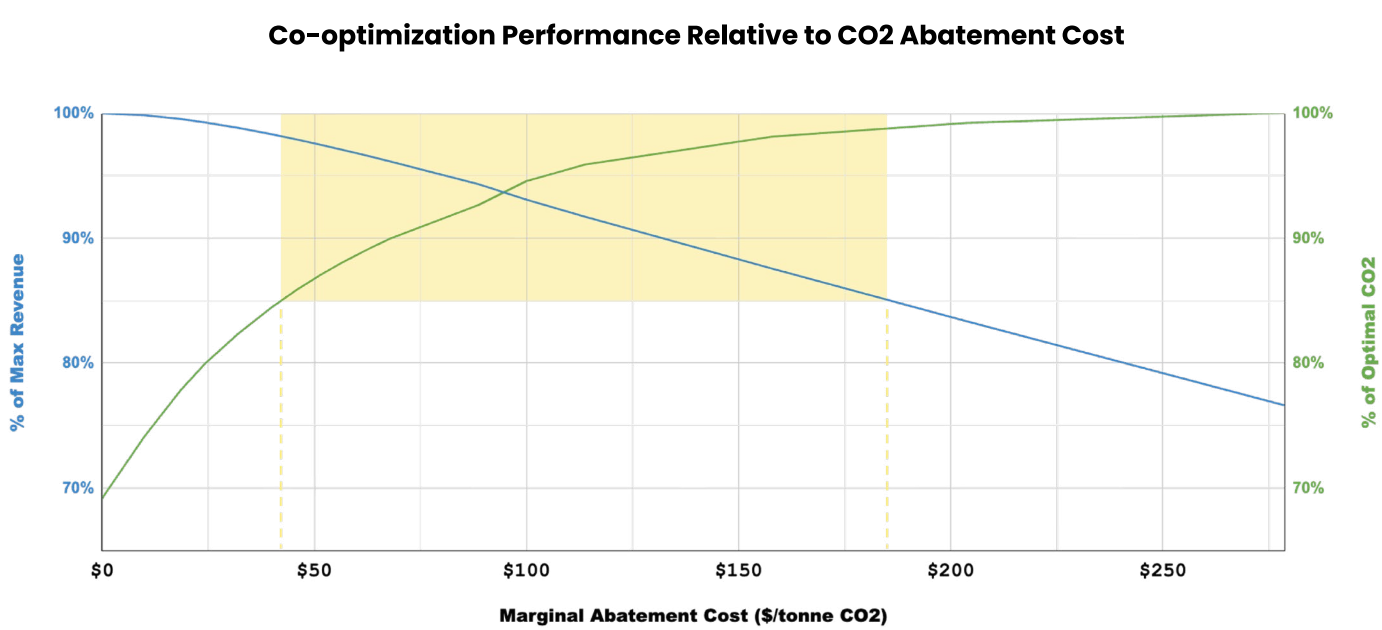
This shows one potential outcome of a co-optimization strategy where the objective weighting gives a higher priority to revenue. This would probably be a win-win for most companies, but still, some companies may be willing to pay more or less than $68 per additional tonne of CO_2 avoided. The next section shows how the results can be dialed in according to preferences and budget.

Co-Optimization Sensitivity

We performed a sensitivity analysis on the weighting factor for co-optimization to characterize the range of trade-offs available for this battery in 2024 ($/t$CO_2$ weight is not equivalent to $/t$CO_2$ abatement cost, more about this in the discussion section).



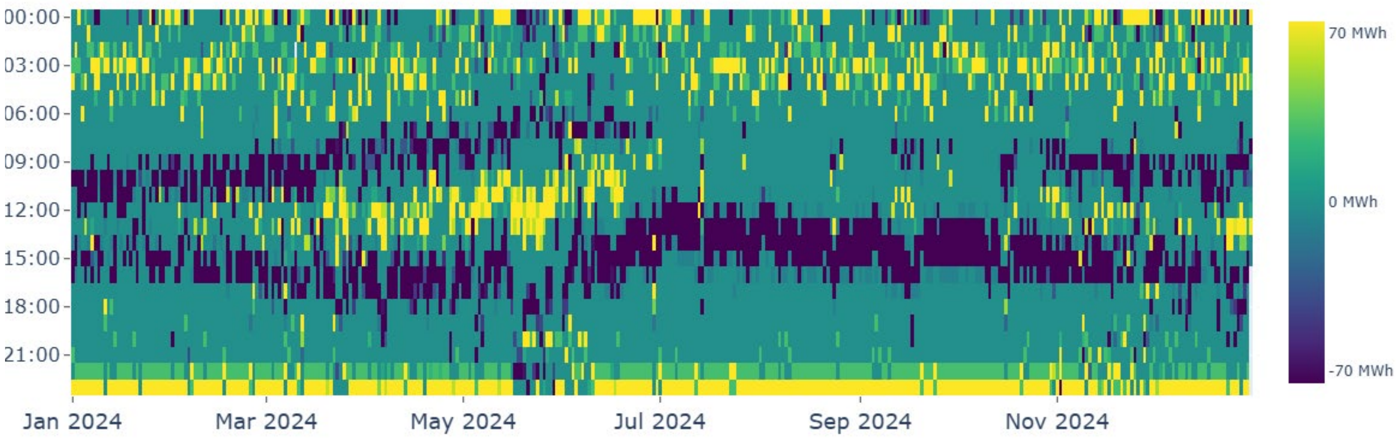
What this sensitivity analysis shows is that there are many weight factors "in the middle" that achieve greater than 85% performance for both objectives, at marginal abatement costs of about $45 up to about $170 per tonne. At a cost of roughly $90/tonne, 93% of both objectives is reached.



Optimize for Hourly Scope 2 Reporting

There have been many cases where optimizing for attributional (e.g., Scope 2) emissions reductions on paper caused higher real emissions. We evaluated that risk for this BESS by analyzing a case optimized for Scope 2 CO_2 footprint reduction, using hourly average emissions (AOER) as the optimization signal. Even though Scope 2's attributional framework is not meant to measure the emissions impact of an intervention (like operating a BESS), a company may wish to know how its Scope 2 annual CO_2 inventory report would be affected by the operation of a BESS. Scope 2 inventories are centered around electricity-consuming facilities, so this would be relevant for BESS co-located with, or in the same grid region as, a company facility. We measured the change in Scope 2 carbon footprint according to the location-based method (LBM) for each scenario using the CAISO hourly AOER (average operating emissions rate). Appendix B shows the hourly Scope 2 outcomes for the other scenarios beyond this one.

Signal = Hourly Avg Emissions (AOER) BESS 3 Dispatch Pattern



Scenario "Hourly Scope 2" Outcomes for Bess 3 in 2024 (full year)

	Energy Dispatched (MWh)	**Revenue Est.** ($, LMP)	**Avoided Emissions** (tonnes CO_2)	**Scope 2 Inventory Reduction** (tCO_2, AOER)
Charging	-109,640	- $ 1,961,765	-21,049	-15,388
Discharging	93,142	$ 2,960,739	25,521	18,952
Total (Net Result)	-16,497	$ 998,974	4,472	3,564

Operating to minimize the Scope 2 footprint earned the lowest revenue of any scenario analyzed and **increased atmospheric emissions impact** relative to the baseline by an estimated 3,509 tonnes, even though on paper it reduced the Scope 2 footprint by 4,951 tonnes. The cost of pursuing Scope 2 footprint reductions in this way would be **$657/tonne-reported.**

Results Summary

The results thus far describe the impact of building and operating a BESS relative to the counterfactual where it didn't exist, which allows direct comparison of various operating strategies compared to the status quo of dispatching purely to earn revenue. That would be the impact of the decision to build a battery.

The results summary here shows the impact of various operating strategies compared to the baseline revenue maximization strategy (with that baseline shown first as a reference), impact relative to the baseline counterfactual. For all performance results, positive numbers mean the metric was improved (negative reduction is an adverse result).

OPTIMIZATION SCENARIO	**Revenue** ($)	**Avoided CO_2** (tonnes)	**Abatement Cost** ($/incremental tonne)	**Scope 2 Reduction** (tonnes CO_2)	**Scope 2 Cost** ($/incremental tonne)
Maximize Revenue [baseline] ($ LMP)	$4,254,166	7,981	$0	-1,387	n/a
Revenue + CO_2 Reduction ($ + CO_2)	$4,091,641	10,383	–	-15	–
diff vs. baseline	-$162,525	2,402	$68	1,372	$118
Avoid CO_2 (CMER)	-$2,868,393	11,543	–	1,408	–
diff vs. baseline	-$1,385,773	3,562	$389	2,795	$496
Hourly Scope 2 (AOER)	$998,974	4,472	–	3,564	–
diff vs. baseline	-$3,255,192	-3,509	n/a*	4,951	$657

* Hourly Scope 2 optimization doesn't abate carbon, it increases carbon. So even though it would come with significant cost, it doesn't have an abatement cost.

Discussion

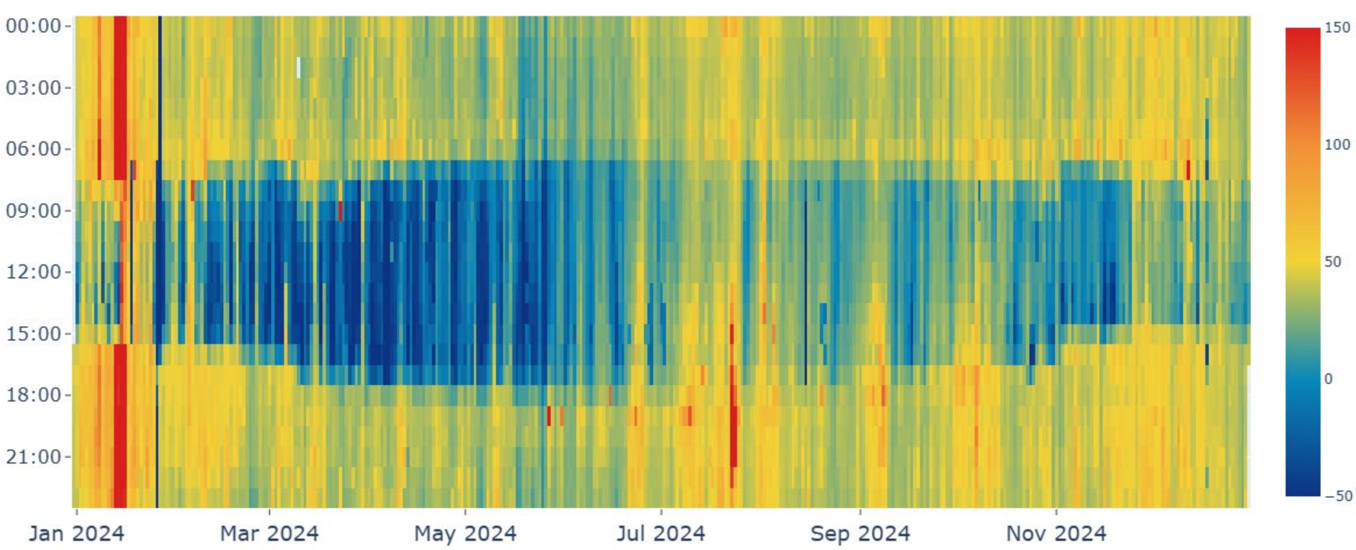
Patterns and Opportunities

The CO_2 reduction and revenue opportunity size will vary in different locations and with different constraints. The grid location and its physical and market properties will determine how variable the signals (e.g., price or CO_2) are. Places with more variable signals, specifically those with variability within the timescale of battery dispatch (a few hours, up to a day), will have greater opportunity, since the arbitrage opportunity (buy low, sell high) needs both high and low values in the window of flexibility.

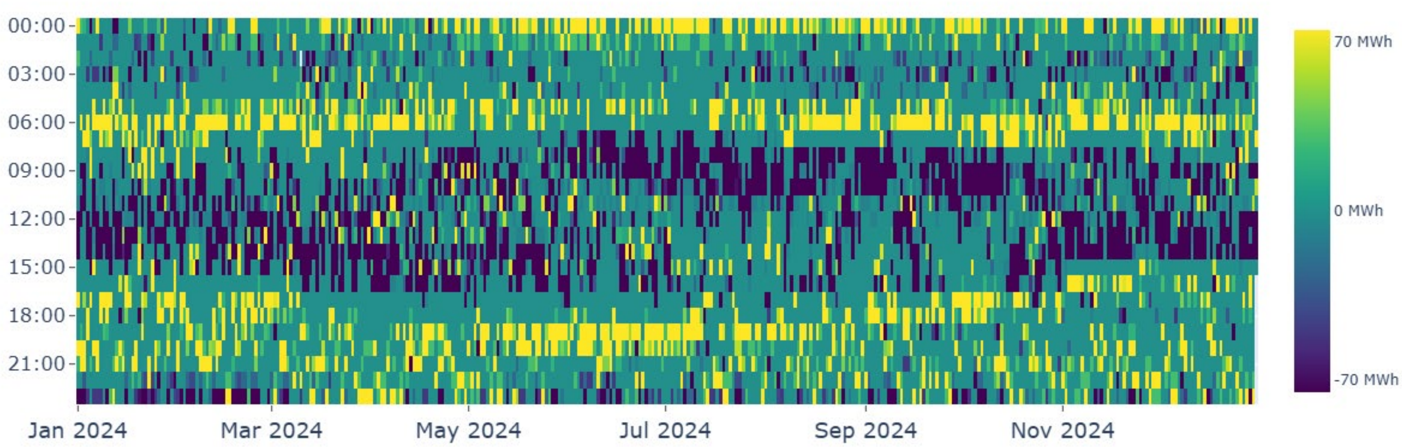
California has strong diurnal variability in both signals of interest (price, CO_2) most days of the year, due to oversupply during the day being met with curtailment of solar PV resources. If you compare the wholesale LMP pattern with the battery dispatch pattern (when optimized on revenue from LMP arbitrage), you see the same diurnal shape.

LMP ($/MWh) - CAISO_SANBERNARDINO

min = 688 / max = 895 / mean = 30



Signal = Price (LMP), BESS 3 Dispatch Pattern



Why doesn't the "status quo" reduce as much CO_2?

The LMP and CMER signals both have a similar diurnal pattern in California, but are not identical. Their strongest correlation occurs when renewable energy is being curtailed. At these times, wholesale LMP tends to be negative, and both the MOER and MBER components of the CMER tend to be zero (can be true in other markets besides CAISO), and for both objectives, this is the best time to charge a battery. This is a major reason why optimizing for revenue, especially in grids that have frequent curtailment, can also lead to CO_2 avoidance as a byproduct. However, even with a relatively strong correlation between price and emissions, if the emissions signal is not included in the objective function, there will always be emissions impact left on the table.

Practicality Considerations

Historical Analysis - With the availability of free, nearly global, historical hourly MOER and MBER data, historical analysis of consequential impact as performed in this case study can be performed by anyone. Anyone with the ability to use Excel can easily implement equations 1 and 2 from this methodology using the free emissions rate time series data and a battery's energy interval data.

Optimizing BESS Dispatch - Implementing a sophisticated optimization algorithm to optimize for avoided emissions while respecting all other constraints is more difficult than historical analysis. However, most commercial- or utility-scale batteries are already dispatched by software that is sophisticated enough to optimize for revenue and is doing so. There is little to no incremental difficulty to optimize for CO_2, on top of optimizing for revenue, since 72-hour forecasts of the MOER are available and updated every 5 minutes in real-time.

Data Granularity - All data used in this case study were of hourly granularity. Wholesale markets often settle on a 5-minute frequency and MOER historical and forecast data are also available at 5-minute frequency, so there is additional intra-hour variability that has been dampened by the use of hourly data here. The 5-minute data will exhibit higher highs and lower lows, potentially both in the same hour, which brings more arbitrage opportunity. This means that the theoretical best performance of both revenue and CO_2 objectives is likely higher than estimated here.

Practical Performance - The scenarios explored in this case study represent the best-case opportunities(granularity aside), which could only result from perfect foresight and perfect software implementation. While these are not practically achievable results, it can be helpful to benchmark the base case results. In practice, the dispatch of a BESS is typically scheduled ahead of time, potentially 32 hours or more in advance when based on day-ahead market forecasts. Generally, the longer the lead time when scheduling, the lower the accuracy of forecasts, and the bigger the gap will be between actual and theoretical performance. Better practical performance will be achieved when using forecast data updated more frequently and when dispatch schedules are updated closer to the time of dispatch.

Co-optimization weighting - One noteworthy finding is that the resulting marginal abatement cost does not equal the price of carbon used as an input to establish the relative weighting between price and carbon emissions. For example, when \$200/tCO_2 was used as the weight, the resulting abatement cost was \$68 per additional tonne avoided (relative to revenue-only optimization). This warrants a caution that if a company aims to capture all the carbon reduction opportunity up to a certain abatement cost threshold, and if they simply use that threshold as the input weight, they will avoid fewer emissions than they targeted. Defining the relationship between the weighting factor and the resulting abatement cost (through a sensitivity analysis like we've done here) will allow a certain abatement cost threshold to be effectively targeted.

Optimizing for Short-run vs. Long-run Impact

Short-run impact is defined by how existing grid assets are operated in response to changes in load, which is estimated by an operating margin (OM) emissions rate. Long-run impact is defined by how grid assets are added or removed (e.g. new generation capacity is built) plus how those new assets are operated in response to changes in load, which is estimated by a combined margin (CM) emissions rate (a combination of operating and build margins). The short-run impact is one piece of the full consequential impact that results from a change on the grid. Long-run impact differs from long-term impact, where long-run impact can be estimated for energy use in a particular hour, and long-term impact aggregates impact of activity over a longer period of time (e.g. years).

Appendix A compares the results of optimizing for short-run and long-run impact. Unsurprisingly, performance is maximized for the metric that is used as the optimization signal. Since short-run/OM is a component of long-run/CM, optimizing on CM still results in good performance on short-run.

Relevance to Generating Carbon Credits

The methodology used in this case study is substantially consistent with the methodology used in the **Verra Draft VCS Methodology** CN0157 **Grid-Connected Energy Storage Systems** ("VCS draft"). The primary difference of note is that in the VCS draft, an Operating Margin emissions rate is specified, whereas here, we've focused on using a Combined Margin emissions rate, of which the OM rate is a part. Also, in the VCS draft, there are very specific rules about additionality and choosing a baseline, which should be referenced when planning the pursuit of carbon credits.

The results of this case study allow estimation of consequential impact in two ways, depending on which intervention is being estimated. The first potential intervention is building a battery, in which case the impact is measured relative to a baseline where the battery didn't exist. The second type of intervention is operating an existing battery differently than the status quo, in which case, the impact is the additional/incremental carbon avoided beyond what is achieved by the status quo (revenue-optimized) battery. This is a simplified explanation, so please refer to the VCS methodology to understand these considerations in more detail.

Relevance to GHG Accounting

The approach used here to account for the consequential impact of BESS is already compliant with the GHG Protocol's Project Protocol and Guidelines, which have been in place for many years. Any company can report on the carbon impact achieved by its BESS projects in its sustainability reports, as a supplement to its Corporate Standard inventory. The GHG Protocol revisions currently in progress may provide further ways to report on avoiding emissions with a BESS.

Conclusion

As demonstrated in this case study analysis, BESS can deliver substantial emissions reductions, especially when optimized explicitly for avoiding emissions. This study showed that a battery can be operated to achieve multiple objectives (revenue and CO_2 avoidance) by very simply combining both objectives into the control signal. It also shows the high cost that can come from using a CO_2 signal that doesn't indicate real atmospheric emissions impact (Hourly Average Emissions as used in GHG Protocol Corporate Standard Scope 2 reporting). Measuring and optimizing for consequential emissions impact is practical and easy to do with freely and globally available data.

How can the real impacts of a battery be measured? Measuring emissions reductions from load-shifting technology like BESS requires the use of time-granular data that indicates the differences in grid carbon intensity between one time and another. The typical annual GHG inventory analysis would not reveal any impact. Also, measuring the real emissions caused or avoided requires the use of consequential emissions factors that are theoretically designed for that. These consequential factors are not only—by definition—the theoretical way to measure impact, they are also a practical way to estimate impact. There are free and globally available datasets offering these factors, and there are well-established standards and guidance describing the relatively simple ways to use them. Estimating consequential emissions impact in this way is the most effective basis for deciding how to operate a battery if one of your objectives is to reduce emissions.

Did maximizing revenue also reduce CO_2 emissions from the grid? The baseline operating strategy for the BESS in California was to discharge to maximize revenue earned from selling energy into the wholesale market. In this case, there is fairly strong alignment between market prices and grid emissions rates, so while the battery maximized revenue, it also avoided substantial CO_2 emissions. This result doesn't apply everywhere and is most representative of electric grids that are deep into their renewable energy transition, which frequently use renewable curtailment as a solution to generation oversupply through a market mechanism (like negative wholesale prices).

How much more CO_2 could the BESS avoid if operated differently? When reducing CO_2 emissions is an explicit goal, the best way to achieve that goal is by incorporating the consequential CO_2 emissions rate into the signal that drives the dispatch of the battery. In this case, if a BESS is optimized for CO_2 alone, it can avoid up to 45% more CO_2 emissions than operating solely for revenue.

What is the opportunity cost (lost revenue) of pursuing more CO_2 reduction? When excluding revenue from the objective signal and only optimizing for emissions reduction, earned revenue would be reduced by 33% in this case, so the carbon avoided came at a cost of $389 per tonne of CO_2. However, this opportunity cost is only indicative of the extreme where revenue is ignored in pursuit of the most environmental benefit, which probably won't be common.

Can both revenue and emissions objectives be satisfied? As demonstrated, by using both objectives in combination to dispatch the BESS, you can achieve strong performance on both objectives. The co-optimization example shown in the study avoided 90% of the best-case CO_2 reduction, while earning 96% of the maximum revenue, at an abatement cost of $68 per additional tonne of CO_2 avoided. Companies can dial in the balance of revenue and emissions benefits according to their preferences and budget.

Areas for further research

The following extensions of this analysis could be performed to broaden the scope of the conclusions drawn by the study.

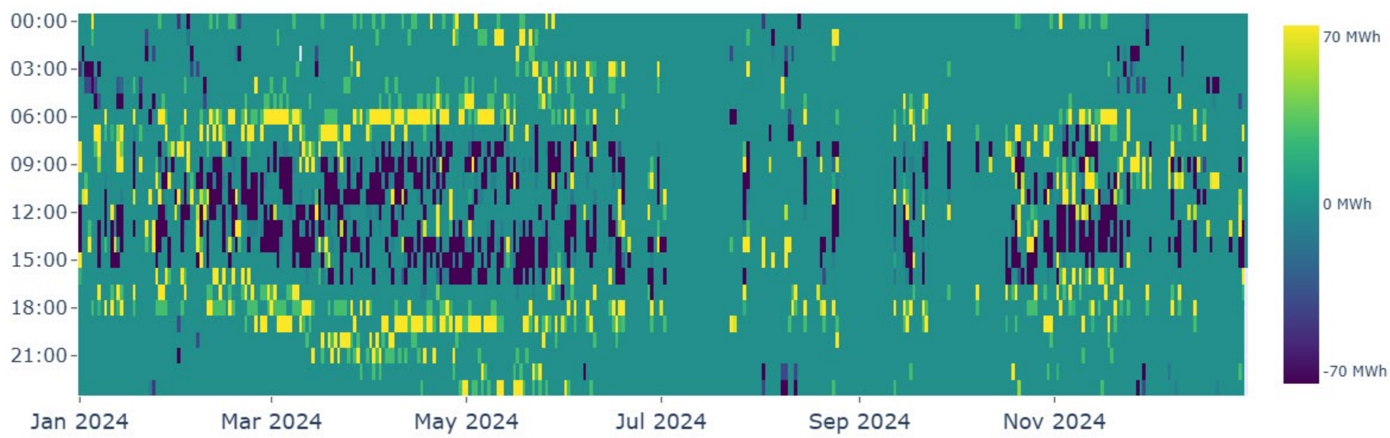
- Expand the geographical scope of the analysis to quantify the co-optimization benefits in other electric grids across the US and the world. This could be done fairly simply by extending the BESS optimization model used in this case study and using price and emissions rates from the other grids.
- Repeat the analysis with increased granularity, down to 5 minutes instead of hourly. This would allow an estimate of the additional benefit that could potentially be gained through more frequent dispatch planning.
- Repeat the analysis using forecast data instead of perfect foresight with historical data. Instead of showing the extent of the opportunity or upper bound of performance, this would estimate the practical performance more likely to be achieved by a real BESS.

APPENDIX A: Results including Operating Margin

The Operating Margin (OM) emissions rate is a component of the Combined Margin (CM) emissions rate. In this case study, we used WattTime's MOER for the OM rate. When we optimized battery dispatch on that OM/MOER signal, it maximized the avoided emissions as measured with the OM/MOER, at the expense of avoided emissions outcomes measured with the CM/CMER rate and further reduced revenue.

Total/Net Results by Optimization Scenario (Signal)	**Energy Discharged** (MWh)	**Revenue Est.** ($, LMP)	**Avoided Emissions, CM** (tCO_2, CMER)	**Avoided Emissions, OM** (tCO_2, MOER)
Maximize Revenue (LMP)	107,228	$ 4,254,166	7,981	7,677
Co-Optimization (LMP + CMER $200/t)	95,580	$ 4,091,641	10,383	8,478
Avoid CO_2 (CMER)	81,832	$ 2,868,393	11,543	9,343
Avoid CO_2, Short-run (MOER)	47,662	$ 2,186,633	6,832	11,769

Signal = CO2 (MOER) BESS 3 Dispatch Pattern



APPENDIX B: Results Including All Scenarios

For all performance results, positive numbers mean the metric was improved (negative reduction is an adverse result).

Absolute Performance (relative to no BESS)

Total/Net Results by Optimization Scenario	**Energy Discharged** (MWh)	**Revenue Est.** ($, LMP)	**Avoided Emissions, Combined** (tCO_2, CMER)	**Avoided Emissions, Operating** (tCO_2, MOER)	**Scope 2 Inventory Reduction** (tCO_2, AOER)
Maximize Revenue (LMP)	107,228	$ 4,254,166	7,981	7,677	-1,387
Revenue + Avoid CO_2 (LMP + CMER $200/t)	95,580	$ 4,091,641	10,383	8,478	-15
Avoid CO_2 (CMER)	81,832	$2,868,393	11,543	9,343	1,408
Avoid CO_2 (MOER)	47,662	$ 2,186,633	6,832	11,769	-1,565
Scope 2 Reduction (AOER)	93,142	$ 998,974	4,472	-2,512	3,564
Revenue + Scope 2 (LMP + AOER $120/t)	98,962	$ 4,157,602	8,988	7,780	30
$ + CO_2 + Scope 2 (LMP+CMER$80+AOER$140)	93,728	$ 4,071,942	10,056	8,367	611

Performance Relative to Baseline

Baseline Scenario (optimized on)	**Revenue**	**Avoided CO_2** (tonnes)	**Avoided CO_2 Abatement Cost**	**Scope 2 Reduction** (tCO2, AOER)
Maximize Revenue (LMP)	$ 4,254,166	7,981	$ 0	-1,387

Scenario (optimized on)	**Revenue Change**	**Incremental Avoided CO_2**	**Abatement Cost of Incremental Avoided CO_2**	**Incremental Scope 2 Reduction**	**Cost of Scope 2 Reduction**
Revenue + CO_2 (LMP + CMER)	-$ 162,525 [-4%]	2,402 [30%]	$ 68 / tonne	1,372 [99%]	$ 118 / tonne
Avoid CO_2 (CMER)	-$1,385,773 [-33%]	3,562 [45%]	$ 389 / tonne	2,795 [202%]	$ 496 / tonne
Avoid CO_2 (MOER)	-$2,067,533 [-49%]	-1,149 [-14%]	n/a	-178 [-13%]	n/a
Hourly Scope 2 (AOER)	-$3,255,192 [-77%]	-3,509 [-44%]	n/a	4,951 [357%]	$ 657 / tonne
$ + Scope 2 (LMP + AOER)	-$ 96,564 [-2%]	1,007 [13%]	$ 96 / tonne	1,417 [102%]	$ 68 / tonne
$ + CO_2 + Scope 2 (LMP+CMER+AOER)	-$ 182,224 [-4%]	2,075 [26%]	$ 88 / tonne	1,998 [144%]	$ 91 / tonne

APPENDIX C: 2024 AOER Heatmap

The pattern of variation in the average operating emissions rate (AOER) for CAISO is shown in the heatmap below for 2024. The AOER was used to compute the hourly Scope 2 carbon footprint in this study. The scale's maximum was kept consistent with the heatmaps for the other emissions rates included in the body of the report.

AOER (CO_2 lbs/MWh) - CAISO

min =0 /max =828 / mean =396