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Assessing Control Strategies for Grid and Customer Benefit with Data from Simulated vs. Field-Deployed Battery Energy Storage Systems

Assessing Control Strategies for Grid and Customer Benefit with Data from Simulated vs. Field-Deployed Battery Energy Storage Systems

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ABSTRACT

As residential battery energy storage systems (BESSs) are being deployed in greater numbers in homes, it is vitally important to understand and analyze BESS operational performance as it relates to residential control system operation modes and the ability to reduce customer and societal costs, support grid harmonization, and meet current and future building code standards. Unfortunately, there is limited research on replicable efficacy of deployed BESSs in real-world homes.

As part of a California Energy Commission (CEC) grant received in 2020, EPRI is quantifying the potential of residential energy storage in achieving California's goals of electrification, efficiency, and enhanced grid reliability through the field installation of <15 kWh commercially available residential BESSs in 15 single-family homes located in three California Climate Zones. Leveraging information gathered from the CEC field installations, this report aims to quantifiably determine the delta from optimal BESS performance vs. actual operation with installed BESSs at customer sites. The report also characterizes present-day BESS operation in comparison to the ideal and identifies strategies for improving its control response in real-world contexts.

Insights gained from this study will identify how BESS control systems can be configured to improve the efficacy of deployed BESS, inform enhancements to BESS control system operations, and determine the potential for BESSs to promote building resilience and reduce greenhouse gas emissions.

Keywords

Battery energy storage system (BESS)
Battery control modes and strategies
Customer resilience
Building standards
Performance evaluation
Single-family homes

CONTENTS

1 Introduction 1

Home Descriptions 1

The Modeling Methodology 2

2 Greenhouse Gas Emissions 3

3 Life-Cycle Cost Analysis 5

4 Evaluation and Analysis of Residential BESS Controls and Operation 9

Throughput Energy and Efficiency 9

State of Charge and Depth of Discharge 10

BESS Utilization 12

EV Charging Challenges 12

Import Excess 15

5 CONCLUSION 17

A DOE Electricity Price Escalation Rates 18

LIST OF FIGURES

Figure 1. Annual GHG emissions across baseline, measured, and modeled scenarios. 3
Figure 2. Mean power draw grouped by grid carbon intensity. 4
Figure 3. Annual LCC and annual electricity consumption of each home. 7
Figure 4. Throughput energy and efficiency for the homes measured operation. 9
Figure 5. Throughput energy and efficiency for the homes modeled operation. 10
Figure 6. Histogram of the homes' state of charge, depicting their distribution over time. 11
Figure 7. State of charge timeseries for the homes on the average day. 11
Figure 8. Measured vs. modeled BESS utilization over the analysis year 12
Figure 9. Average day of loads, generation, and dispatch for Home 1 in December, depicting EV charging patterns. 13
Figure 10. Average day of loads, generation, and dispatch for Home 4 in December, depicting EV charging patterns. 14
Figure 11. Import Excess comparison of measured vs. modeled operation for the calendar year 16

LIST OF TABLES

Table 1. Descriptions of the four out of fifteen homes whose energy operations are being modeled and measured. 1
Table 2. Input assumptions of the LCCA. 6

1 INTRODUCTION

As residential battery energy storage systems (BESSs) are being deployed in greater numbers in homes, it is vitally important to understand and analyze BESS operational performance as it relates to residential control system operation modes and the ability to reduce customer and societal costs, support grid harmonization, and meet current and future building code standards. Unfortunately, there is limited research on replicable efficacy of deployed BESSs in real-world homes.

As part of a California Energy Commission (CEC) grant received in 2020, EPRI is quantifying the potential of residential energy storage in achieving California's goals of electrification, efficiency, and enhanced grid reliability through the field installation of <15 kWh commercially available residential BESSs in 15 single-family homes located in three California Climate Zones. Leveraging information gathered from the CEC field installations, this report aims to quantifiably determine the delta from optimal BESS performance vs. actual operation with installed BESSs at customer sites. The report also characterizes present-day BESS operation in comparison to the ideal and identifies strategies for improving its control response in real-world contexts.

Home Descriptions

The four out of fifteen homes used for this study are located in the Department of Energy Climate Zone 3C, warm marine climate. Each home is different in terms of home size and electrical loads. Home 1 and 3 are larger single-family homes, approximately 2500 sq. ft. installed with 4.32 kW of solar, with electric vehicle charging load. Home 2 and 4 are small townhomes, approximately 1500 sq. ft. installed with 2.32 kW of solar and with no electric vehicle charging load (until December 2023, when Home 4 added an Electric Vehicle to their load).

Table 1. Descriptions of the four out of fifteen homes whose energy operations are being modeled and measured.

Home	Area (approx. sq. ft.)	Solar PV (kW)	BESS Capacity (kWh)	EV charging?
1	2500	4.32	10	Yes
2	1500	2.32	10	No
3	2500	4.32	10	Yes
4	1500	2.32	10	No, until Dec 2023

The Modeling Methodology

For this study we define our three scenarios the following way:

1. **Baseline**: the consumption of the home's loads without a distributed energy resource (DER), no solar or storage.
2. **Measured**: the real-life measured net load of the home, including how the operation of installed solar and storage assets affected the one another and the grid.
3. **Modeled**: the simulated net load of the home, based on the true-to-life baseline consumption, using the naive solar self-consumption control framework described below.

Understanding the difference between *modeled* battery performance and *measured* battery performance, as studied here, requires a thorough understanding of the assumptions made in the model. The modeling methodology used in this study was the principles of *naive solar self-consumption control mode,* defined below:

1. Under naive solar self-consumption, there is no predictive or forward thinking done by the battery control into the battery charging and/or discharging patterns...by control mode the battery simply charges until it exhausts its State of Charge (SOC) headroom, and then discharges until it reaches its SOC floor.
2. Under naive solar self-consumption, photovoltaic (PV) self-consumption is prioritized by the battery operation. Therefore, for a given time interval, the power generated by the PV system is first allocated to addressing the home's base load. If there is remaining headroom (meaning the SOC has not reached 100% yet), any surplus is then stored in the battery. If the SOC has reached 100%, then any remaining generation surplus is exported.

Those two points describe the main operating principles of naive solar self-consumption control mode. This control mode can also be thought of as having the load following operating more combined with solar charging only constraint on the BESS. Under these principles, it is useful to think of naive solar self-consumption control mode as representing a theoretical demand flexibility potential – a best-case performance scenario.

2 GREENHOUSE GAS EMISSIONS

The method used to determine the greenhouse gas emissions (GHG) for this study are calculated using the 8760 hourly electricity loads time the hourly emission based on *Long-run Marginal Emission Rates for Electricity – Workbooks for 2023 Cambium Data*[1] published by National Renewable Energy Lab (NREL). For this study, we adopted the conservative, mid-case scenario for this calculation, representing the central estimates for inputs such as technology costs, fuel prices, and demand growth. No nascent technologies are considered in this scenario, and electric sector policies are considered the same that existed in 2023.

Figure 1 shows the annual greenhouse gas emissions of each home under each scenario (baseline, measured, modeled). In all four homes, measured scenarios with installed solar and battery have a lower annual GHG emissions by 25% to 56% than the baseline scenarios without solar and battery. The modeled scenarios, with optimized solar and battery operations, are estimated to reduce annual GHG emissions within these homes by more than 49% to 73% compared to the baseline.

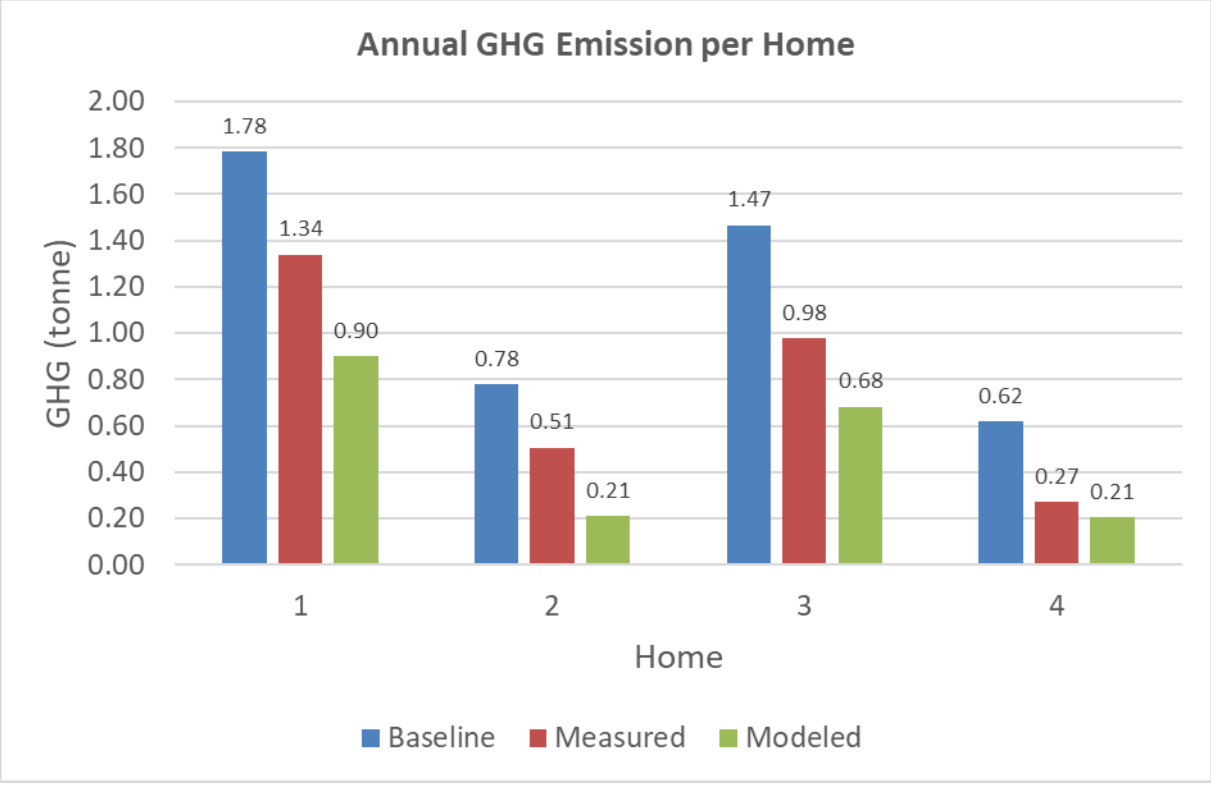


Figure 1. Annual GHG emissions across baseline, measured, and modeled scenarios.

[1] Gagnon, Pieter. 2024: Long-run Marginal Emission Rates for Electricity - Workbooks for 2023 Cambium Data. NREL Data Catalog. Golden, CO: National Renewable Energy Laboratory. https://data.nrel.gov/submissions/230.

Figure 2 shows, for Home 3, the mean hourly energy use grouped by grid carbon intensity for the different scenarios that were explored: baseline, measured, modeled. Overall, both scenarios are successfully avoiding high power draws during periods of high grid carbon intensity. Directionally, the field-deployed and modeled batteries behave the same, but the field-deployed battery seems to exhibit control distinctions – possibly due to SOC reservation limits - that are not fully captured by the model. The trend shown for Home 3 was repeated across all homes.

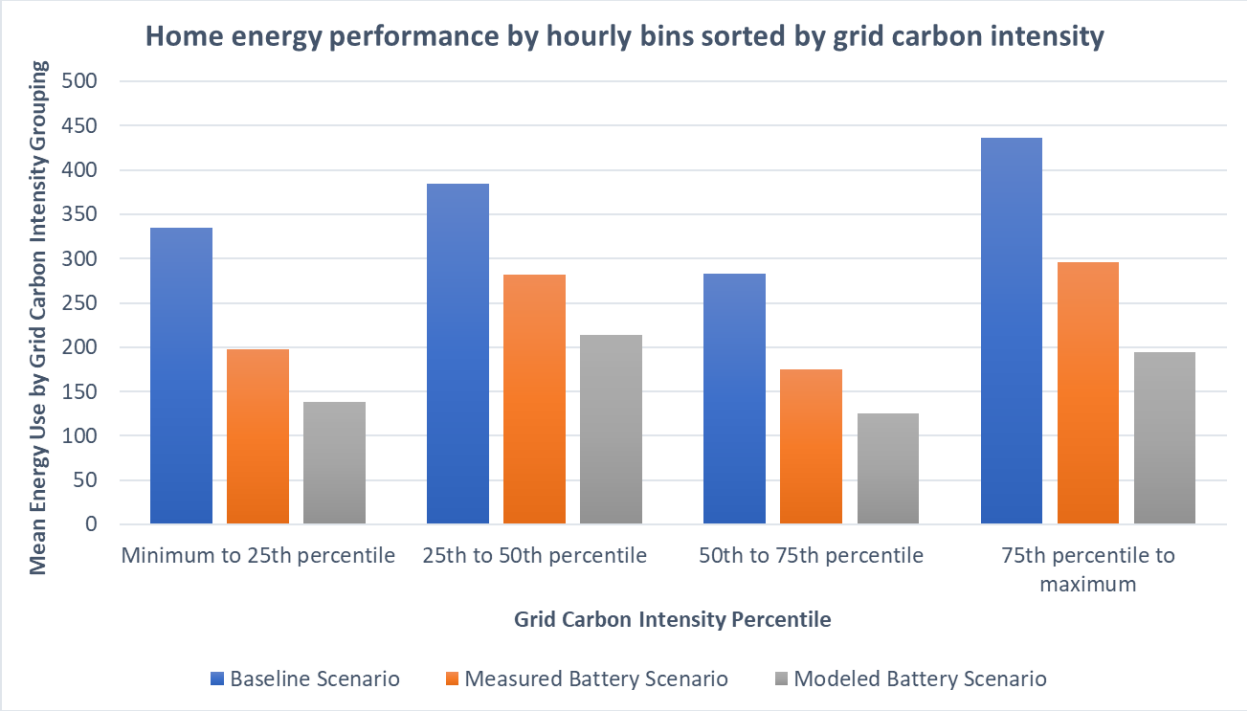


Figure 2. Mean power draw grouped by grid carbon intensity.

3 LIFE-CYCLE COST ANALYSIS

Life-cycle cost analysis (LCCA) assesses the total cost of facility ownership by considering all costs of acquiring, owning, and disposing of a building or a building system. A low life-cycle cost (LCC) is the most straight forward and easy-to-interpret measure of cost effectiveness valuation in a decision-making process. We used the Building Life Cycle Cost (BLCC) tool developed by the National Institute of Standards and Technology (NIST) to compute the LCC of three different scenarios: baseline homes without solar and battery, homes with the modeled solar and battery, and homes with the measured solar and battery performance onsite. For this study, we assumed a 15-year study period of each home, with 2024 being the first year. We adopted end-of-year discounting and conducted current dollar analysis[2] with a nominal discount rate[3] at 4.2%. The LCCA of this project includes two components: energy cost and capital component.

The energy cost is calculated based on the first year's energy consumption and the price per unit of energy consumed. In our case, the only energy considered is electricity, regardless of whether the home is all-electric or not. We collected the hourly electricity consumption onsite before and post the installation of the battery and solar, as well as modeled the theoretical hourly electricity consumption. The energy cost is computed using the actual rate plan each home enrolled. No annual demand charge or annual utility rebate is considered. We adopted the default Department of Energy (DOE) price escalation rates[4] of electricity in California for residential sector for the next 15 years, listed in detail in Appendix A.

The capital component, in this case, includes investment cost, annually recurring operation, maintenance and repair (OM&R) costs, and non-annually recurring OM&R costs. For investment cost, we input the initial procurement cost of the battery and solar in the first year of analysis with an expected life span of 15 years. We assumed zero annual rate of increase and a 4% of initial cost as the residual value[5]. Annually recurring OM&R costs include the amount of OM&R cost in the first year and annual rate of increase[6]. The additional item included in non-annually recurring OM&R costs is the frequency of the OM&R starting from the first year. Battery performance degradation over the 15-year period is not factored into the LCCA.

[2] Current dollars are dollars of uniform purchasing power, including general price inflation or deflation, in which actual prices are stated.

[3] The rate of interest (market interest rate) reflecting the time value of money stemming from both inflation and the real earning power of money over time.

[4] Annual rate of increase for energy, by region, rate type and fuel type, as a real or nominal rate.

[5] The estimated value, net of any disposal costs, of any building or building system removed or replaced during the study period, or remaining at the end of the study period, or recovered through resale or reuse at the end of the study period.

[6] The average annual rate at which the first-year dollar amount of the cost is expected to change throughout the study period.

All assumptions used in this study for LCCA is summarized in Table 2.

Table 2. Input assumptions of the LCCA.

Basic Information	
Location	California
Discounting Convention	End-year discounting
Analysis	Current dollar analysis
Nominal Discount Rate	4.2%[7]
Base Year	2024
Study Period	15 years
Energy Cost	
Fuel	Electricity
Solar Capital Component	
Investment Cost	
Initial Cost	$30,000 for large solar, $22,000 for small solar
Annual Rate of Increase	0%
Expected Life Span	15 years
Residual Value	4% of initial cost
Annually Recurring OM&R	
Amount	$250
Annual Rate of Increase	1.2%
Non-Annually Recurring OM&R	
Frequency	Every 8 years from the first year
Amount	$1,100
Annual Rate of Increase	1.2%
Storage Capital Component	
Investment Cost	
Initial Cost	$20,000
Annual Rate of Increase	0%
Expected Life Span	15 years
Residual Value	7% of initial cost
Annually Recurring OM&R	
Amount	$200
Annual Rate of Increase	1.2%
Non-Annually Recurring OM&R	
Frequency	Every 10 years from the first year
Amount	$1,300
Annual Rate of Increase	1.2%

[7] Annual Supplement to NIST Handbook 135

The results of LCCA of each home is presented in Figure 3. The bars plot the annual value of LCC of each scenario, and the markers plot the annual electricity consumption under each scenario. The annual value of LCC is the time-equivalent value of past, present, or future cash flows expressed as an annually recurring uniform amount over the study period.

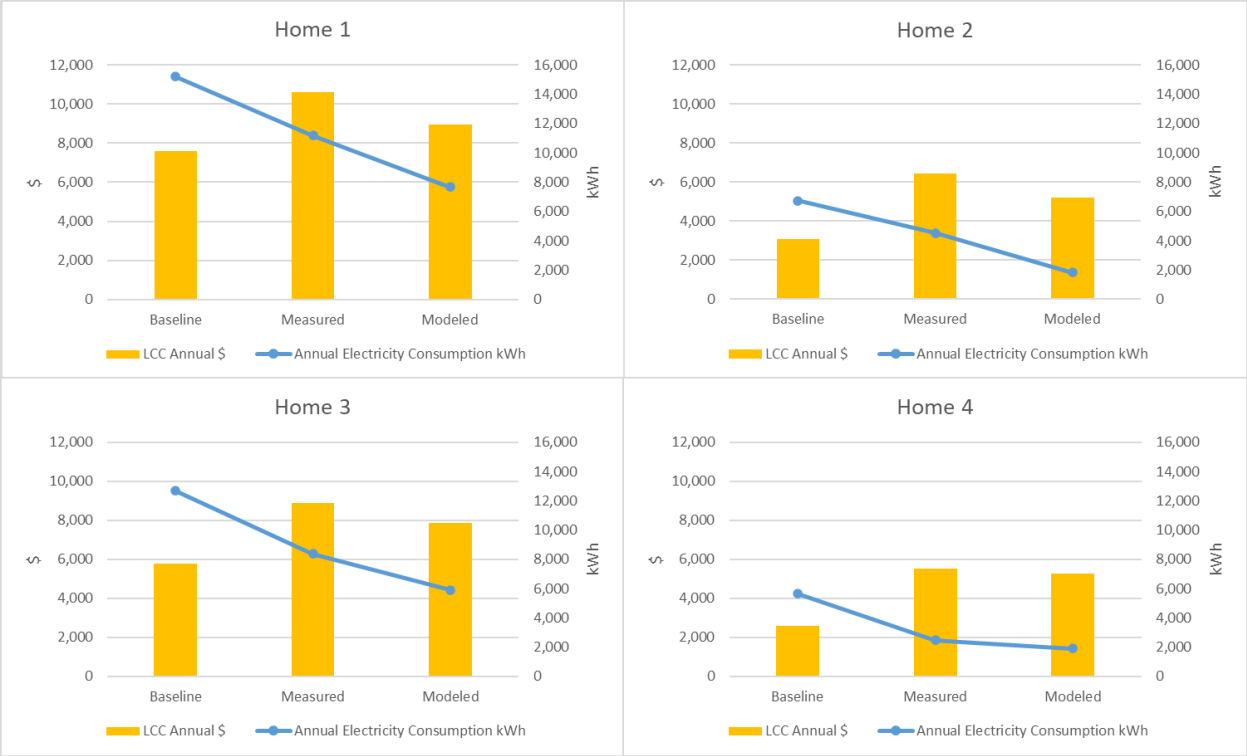


Figure 3. Annual LCC and annual electricity consumption of each home.

While annual electricity consumption dropped significantly from baseline, measured and modeled LCCs are both higher than baseline LCC, indicating that under common residential time-of-use tariff structures, the capital investment will generally outweigh the savings from energy cost. Since the annual electricity consumption is lower for the modeled scenarios than the actual measured scenarios, measured LCC is still higher than modeled LCC in all four homes. This implies that there are some potential energy cost savings not fully realized in the measured scenarios. this potential is limited by the magnitude of the cost delta between off- and on-peak energy prices.

Unlike large commercial and industrial utility customers, the vast majority of residential customers lack: the site load magnitude, access to initial capital, physical space to install enough BESS to achieve economies of scale – which precludes them from participation in ancillary and wholesale markets to enable enough cost savings or electricity revenue earning potential. The largest potential for financial return on investment with the BESS is utilizing peak demand charges which are virtually non-existent in the residential segment. Some utilities have

already begun piloting such peak demand charge rate plans for specific and interested customers, but it's still not prevalent within the industry.

Based on the homeowners surveyed as part of the CEC study, it was determined that these residential customers do not purchase BESS with the main objective of saving money. The primary goal of the surveyed homeowners is to give themselves and their families the peace of mind of having backup power for their home if and when a power scheduled or unscheduled outage occurs. In such case, the increase in cost between the measured or modeled scenarios as compared to the baseline scenario can be viewed as the cost of resilience, or at least how much a particular customer should value having backup power for their home in order for their investment to be worthwhile.

4 EVALUATION AND ANALYSIS OF RESIDENTIAL BESS CONTROLS AND OPERATION

The naive solar self-consumption control mode modeled against the measured, real-world residential battery operation presents several notable observations when compared to one another. The analysis shows how a simple modification - requiring minimal control conditions and absent of any fancy forecasting and A.I. algorithms - can lead to non-negligible impacts to various notable battery performance metrics.

Throughput Energy and Efficiency

The throughput efficiency of an energy storage system is the ratio of energy outputted from the system to energy inputted to the system. Note that this is not the same as round trip efficiency, which is calculated per cycle. However, with a large enough sample size of representative cycles, throughput efficiency is a strong proxy for estimating and characterizing a system's overall round trip efficiency. Overall, the measured throughput efficiencies of these lithium iron phosphate (LFP) batteries over the sample year of 2023 are a bit lower than often reported for others of similar chemistry, hovering around 66% to 82%, but they are not overly concerning. Efficiency calculations are highly dependent on how the BESS has been cycled, its depth and rate of discharge, and many other factors that are often not uniform from day to day.

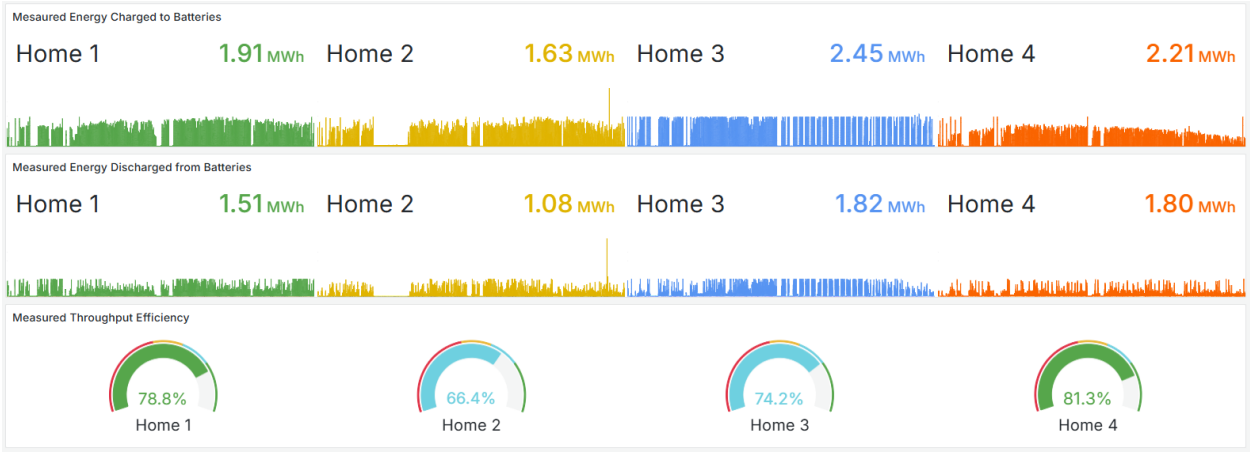


Figure 4. Throughput energy and efficiency for the homes measured operation.

For the modeled case, since we elected to model a theoretically maximal, perfectly efficient battery, the model throughput efficiencies are 100%.

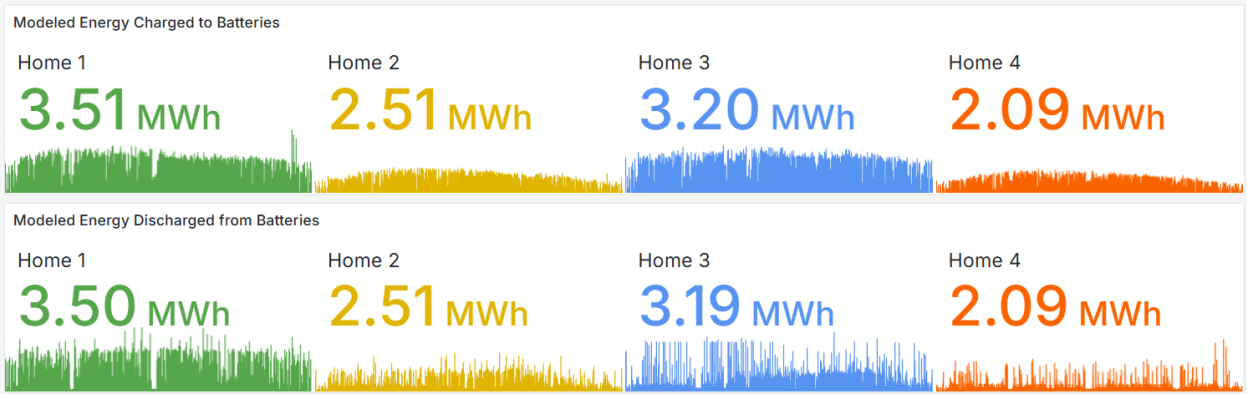


Figure 5. Throughput energy and efficiency for the homes modeled operation.

State of Charge and Depth of Discharge

The histogram and average state of charge (SOC) of a BESS also helps reveal information on how a battery is being used, such as its depth of discharge (DoD), and overall utilization.

The histogram or distribution chart shows how the measured, real-world BESS systems implement an SOC reservation on to save BESS capacity for backup power. Homeowners can choose how low this SOC reservation limit should be, based on their risk appetite, since a lower reservation limit would allow for more of the battery's energy capacity to be used for energy shifting and self-consumption thus providing more cost savings, while decreasing the amount of energy available to serve load in the unlikely event of a power outage.

Typically, this lower SOC limit is set between 10% to 50% and can be adjusted by the homeowner. This range still allows for more than half the battery to be utilized for charging from solar and offsetting purchasing energy from the grid. The SOC limit set by manufacturers often defaults to 30% out-of-the-box. Since this value is in the middle of that range, this setting would commonly allow for 3 to 8 hours of backup power throughout the night when home consumption is generally 1 kW or less, with a battery of 10 to 15 kWh.

Such is the case for Home 3, shown in blue. Home 3 has peaks at the 30% and 100%, meaning that its battery spends most of its time at 30% and 100% SOC, indicating a frequent depth of discharge of around 70%. However, this limit can be set at any level by the homeowner, as Home 1 in green sets this limit at 50%, thus a DoD of 50%. Home 4 in red is seemingly at 20%.

However, in the case of Home 2 in yellow, the peaks at 60% to 70% are likely not due to the SOC reservation limit being set that high, but that the battery is not cycling as deeply due to the load of this home being the smallest of these four.

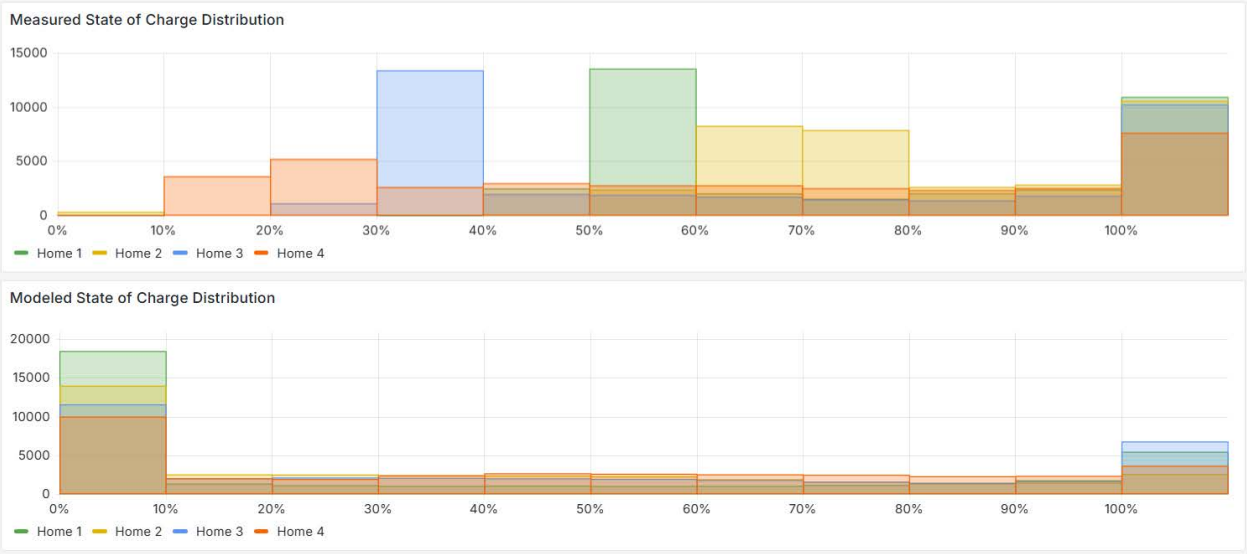


Figure 6. Histogram of the homes' state of charge, depicting their distribution over time.

In the case of the modeled operation, no SOC reservation was used, so the battery energy storage system of each home was free to use the entire usable energy capacity of the battery and cycle down to 0%. It should be noted that while this kind of operation would yield, "getting the most out of it," but practically, the battery should not stay at a low SOC for too long, as cell balancing and startup issues may occur as a result of not being routinely charged up to max state of charge. Moreover, the peak average SOC of the modeled battery maxes out at 60%, meaning that there is often not enough excess solar to get the batteries up to full charge.

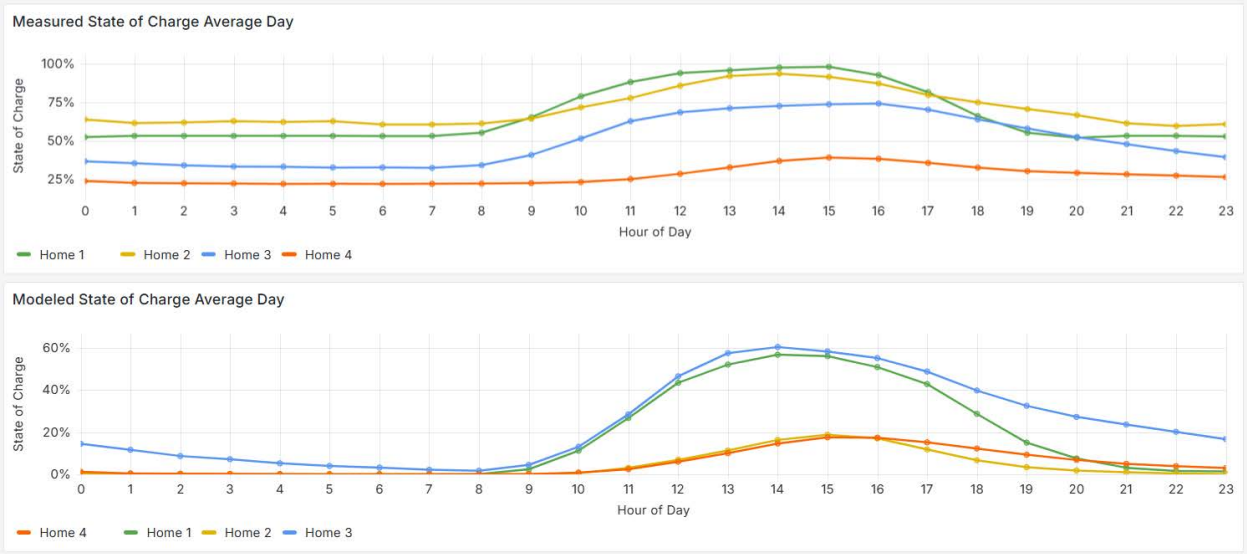


Figure 7. State of charge timeseries for the homes on the average day.

The average day SOC plot further reveals that the peak SOC of the BESS occur later for the modeled systems versus the measured ones. This is because the modeled systems take longer

to charge up under the same solar production assumptions, due to the fact that they are being cycled to lower SOCs. As a result, we see great utilization with the modeled systems.

BESS Utilization

BESS utilization is calculated by dividing the total amount of charged energy to the battery energy capacity and number of days that have elapsed, effectively resulting in a depth of charge per day metric. Higher values of BESS utilization indicate that the battery is being *discharged* more deeply, regularly, and thus can also be *charged* more deeply, regularly. In order for this to occur, the system must be set in a conducive control mode that allow the BESS to cycle, there must be sufficient discharge from the day before, and there must be excess on-site solar generation during the day when the PV panels are producing power and energy.

Generally, greater BESS utilization is preferable, but one must be mindful of what their target SOC reservation limit should be and to not keep the battery as too low of an SOC for too long.

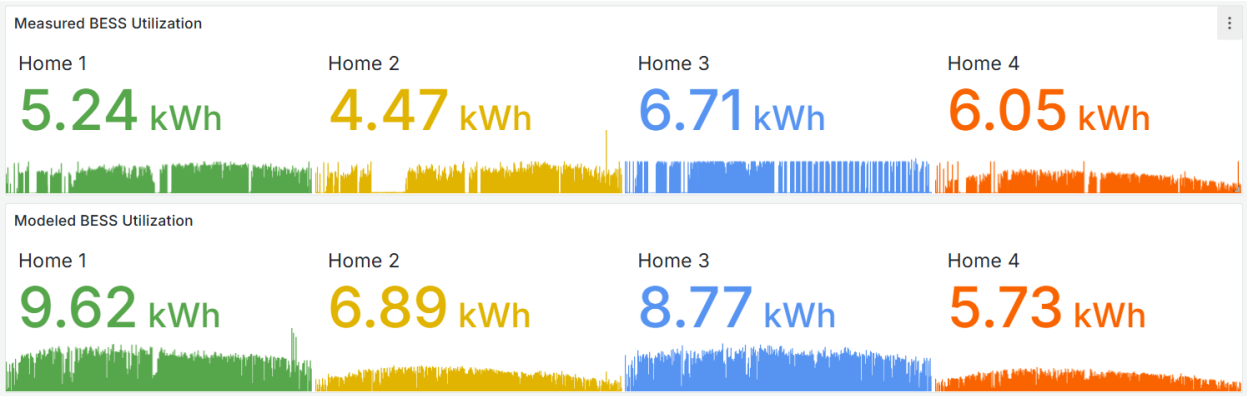


Figure 8. Measured vs. modeled BESS utilization over the analysis year.

Comparing the measured and modeled BESS utilization numbers, we see that for three of the four homes, the modeled operation presents a dispatch pattern with greater BESS utilization value. Strangely, Home 4 does not follow this pattern, likely due to three factors:

1. prior to December, Home 4 had a smaller load,
2. generally coincident with when solar power is being generated, causing most of the solar to go to power loads over being stored in the battery,
3. purchases and begins to charge an electric vehicle (EV) in the last six weeks of the calendar year, thus is the most peculiar home of the bunch.

EV Charging Challenges

The high consumed energy numbers for Homes 1 and 3 (and in December for Home 4) are indicative of homes with electric vehicle charging events. For Home 1, charging occurs from late

evening to midnight. For Home 3, charging is at the very early hours of the morning. For Home 4, charging starts at midnight.

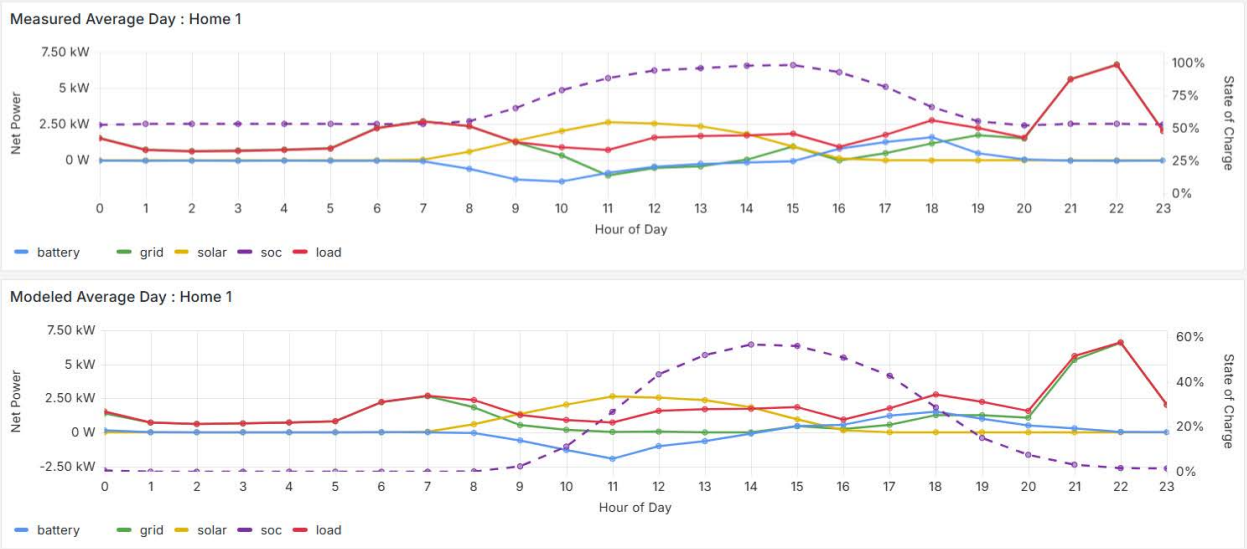


Figure 9. Average day of loads, generation, and dispatch for Home 1 in December, depicting EV charging patterns.

Comparing the measured and modeled operation, certain aspects stand out, especially when during the winter months, like December. Firstly, the modeled BESS routinely goes to 0% SOC, while the measured does not, due to the SOC reservation for backup power. Also, the modeled battery is unable to reach high SOCs often, since there is a lack of solar generation during the day to get the BESS SOC charged all the way back up. As a result, using both the modeled naive solar self-consumption control mode as well as the real-world self-consumption algorithms, the BESS is drained of its usability by the time the EVs begin to charge. Thus, in both cases, the battery is actually unable to assist with charging the EVs or reduce the power and energy demanded from the grid.

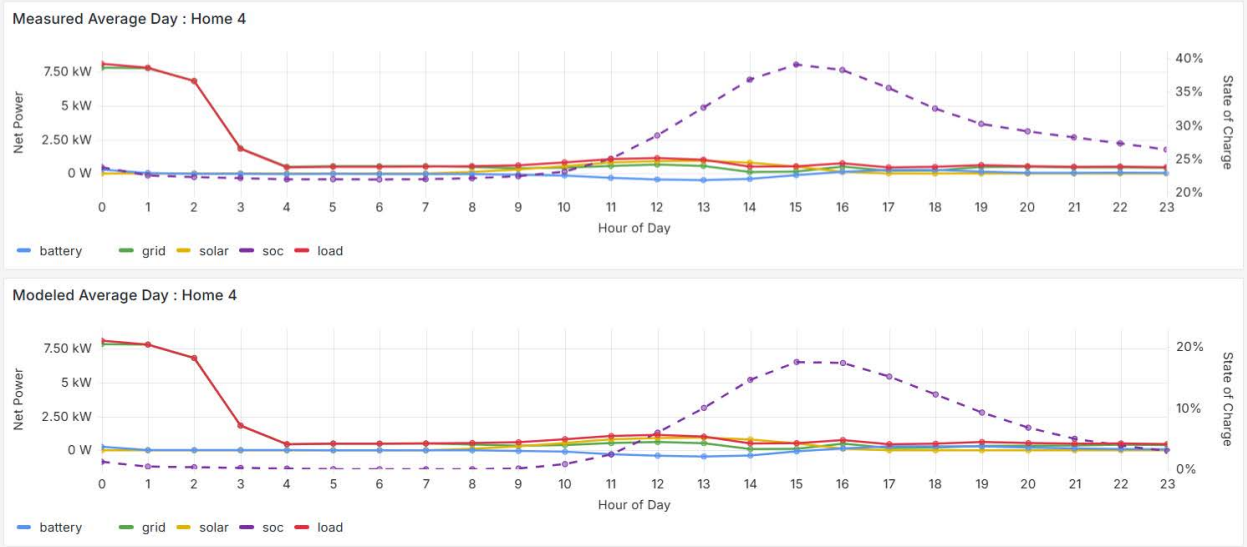


Figure 10. Average day of loads, generation, and dispatch for Home 4 in December, depicting EV charging patterns.

Having the battery wait until the EV to begin charging would create a situation where solar power would contribute to charging the EV via the home's energy storage, though offset in time. In order for this to happen, however, the BESS controller needs to be programmed or learn that an EV charging load is likely to occur later in the night or early morning. The BESS controller would then need to be programmed to stop discharging the battery for other home loads occurring earlier in the evening, essentially enabling another SOC reservation limit. This could be achieved a variety ways:

1. Homeowner manually schedules when the battery should be allowed to discharge, therefore manually aligning the times and control modes changes based on their routine and preferences
2. Battery providers develop a control mode for EV charging that either:
    a. allows users to set the times of the charging, indicating when the BESS controller switches discharge allowance on and off (open-loop control) or
    b. implement algorithms that learn a customer's EV charging routine (or load usage in general), then decides and adjusts discharge allowance based on what it predicts, what actually happens, and other objectives and constraints, like bill savings or SOC reservation for backup (load forecast with closed-loop control)
3. EV manufacturers and BESS providers agree to standard communication schemes that allows for these devices to talk with each other to decide priority of loads, when to charge the EV, at what power level, and for how long. V2X requirements may assist in determining these communication schemes.

Note that all the scenarios noted above will require a more advanced control paradigm or direct management from the end user.

While there is some opportunity for improvement for scheduling and developing better controls algorithms to better align BESS use and EV charging, much of the limitation actually lies in the reality the typically specified stationary residential battery energy storage systems are simply too small (undersized) and not large enough compared to an electric vehicle's battery capacity – often times an EV battery is 4 to 10 times greater in size versus a typically specified residential BESS. This severely limits the amount of excess solar generation can be stored on site.

Though this can technically be overcome by electing to install more batteries at one's home, there are many practical challenges to consider, such as space constraints, cost limitations, safety concerns, and additional utility interconnection requirements for larger BESS.

Import Excess

Import excess is the amount of energy imported from the grid less how much was actually needed to cover the load deficit, which is calculated by subtracting the amount of solar generation/produced energy from the amount of consumed energy on site/how much energy is used by the home. If there is no load deficit, meaning solar energy production was more than used energy, then all the grid imported energy was excess, but nothing more.

The import excess metric does not penalize solar exports as it would create the undesired effect of allowing more on-site energy use to "improve" the metric - which is not a desired result. At the same time, unlike some utility programs and governments policies, the import excess metric does not influence nor directly penalize the homeowners' energy use, allowing that impetus to come from elsewhere. Importantly, improvements could be made by BESS manufacturers formulating smarter, more load-aware battery control modes and algorithms, that wouldn't rely on modifying homeowner behavior and usage patterns to gain BESS performance efficiencies.

The ideal scenario is that every unit of energy produced by the solar panels would be used on-site, but since generation and demand are not coincident, this is virtually impossible. The import excess metric answers the question of 'How much more energy am I using that I am producing?' without having to penalize solar exports. This also leads to the more important question of 'Why am I using more energy than I need to?', so homeowners, building managers, and end users alike can begin to more thoughtfully consider their use patterns and load needs.

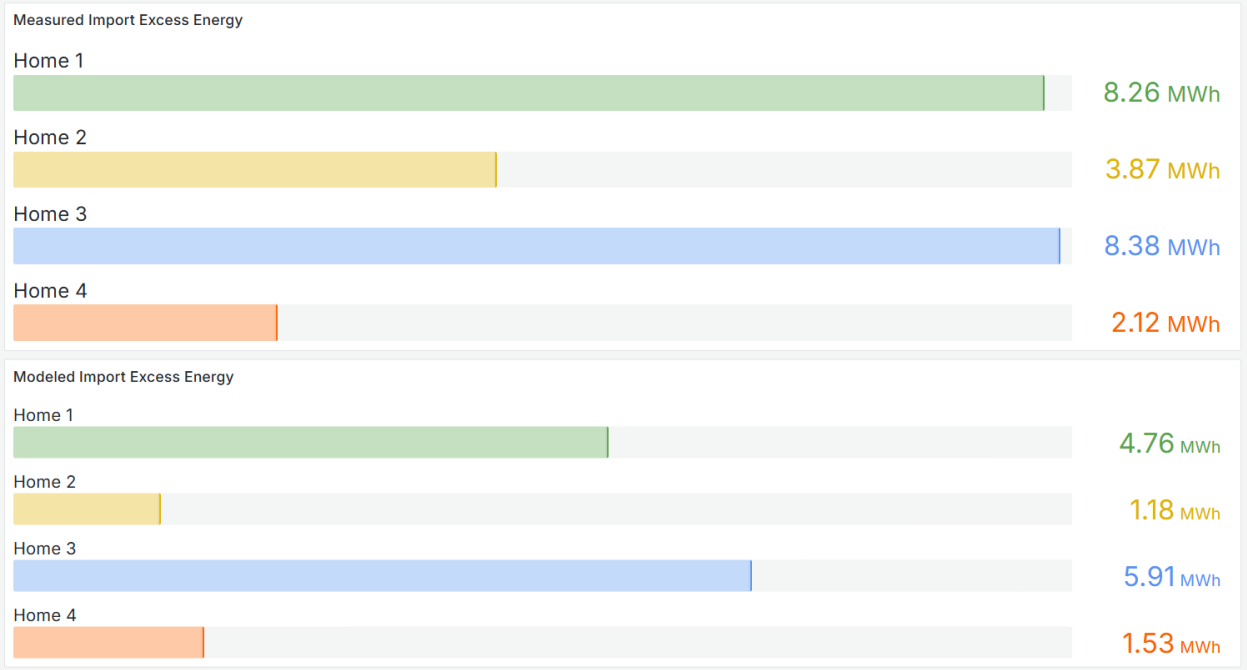


Figure 11. Import Excess comparison of measured vs. modeled operation for the calendar year.

Using the naive solar self-consumption control mode methodology, the modeled results show import excess energy reductions from 28% to 70%. Much of this improvement likely comes from having higher BESS utilization numbers overall: using the battery more means a greater amount home load is being provided by the battery's stored energy rather than from the grid. This may suggest that simple adjustments to make control logic more time- and load-aware may significantly help BESS dispatch and operate in ways more beneficial to the customer and the grid.

5 CONCLUSION

The results of the modeled vs. measured scenario analysis of these four homes quantifies some of the environmental, financial, customer, and grid impacts of paired residential solar PV and battery energy storage systems and control systems. The data reveals various positive outcomes stemming from having DER assets available to be used on site, but also areas of further refinement required in order to better realize operational goals.

The analysis of scope 2 emissions suggests that the measured battery performance is in directional agreement with modeled battery performance. However, measured greenhouse gas reduction tends to fall short of modeled gas reduction, likely due to control strategies meant to extend battery longevity and provide an additional layer of resilience.

Life cycle cost analysis indicated that BESS systems may not necessarily have positive outcomes in single family residential homes. While operating cost savings could be achieved from the deployment of BESS in a residential setting, it appears that capital costs are still too large to outweigh these savings. The conditions that are favorable to BESS economic competitiveness in commercial and industrial settings are not replicated in residential settings. Furthermore, resilience is a significant consideration for single family homeowners, competing against financial motives. Optimizing battery operation for resilience may not be the most financially beneficial way of operating a BESS but provides other non-monetary benefits.

There is opportunity to adjust and/or develop BESS control algorithms to be more open to extending the utilization of the BESS by lowering SOC reservation limits, increase energy throughput by discharging more often without strict consideration of off- and on-peak prices, to then also cycle more often. These opportunities may lead to sustained improvements to various metrics, such as depth of discharge and throughput efficiencies. However, achieving more complex goals - such as time-aligned load dispatch and minimized import excess - requires a more nuanced approach and wholistic understanding of a customer's current and future use cases, loads, and objectives.

As the project continues to progress, this analysis will be refined to model real-world situations more accurately, expanding the learnings on the suite of control modes and approaches provided within the studied BESSs on additional residential BESS sites, aiming to incorporate further data visualizations, calculations, and recommendations.

Overall, the modeled naive solar self-consumption control mode approach suggests potential improvements and considerations to the deployed controls of residential BESS. Nonetheless, for a more impactful and comprehensive outcome, a time-aware, rate-aware, emission-aware, and customer load-aware operational approach is necessary to maximize benefits.

A DOE ELECTRICITY PRICE ESCALATION RATES

Year	Duration	Escalation
2024	1 year	-8.38%
2025		0.11%
2026		1.09%
2027		1.62%
2028		1.49%
2029		2.14%
2030		2.87%
2031		2.97%
2032		2.73%
2033		2.65%
2034		2.67%
2035		2.24%
2036		2.15%
2037		2.03%
2038		1.81%

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