Savings in Action: Lessons Learned from a Vermont Community with Solar Plus Storage

Indu Manogaran, Amanda Farthing, Jeff Maguire, and Kenny Gruchalla

National Renewable Energy Laboratory

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List of Acronyms

AVERT	AVoided Emissions and geneRation Tool
BAU	Business-as-Usual scenario
CO_2	carbon dioxide
EPA	U.S. Environmental Protection Agency
FCM	Forward Capacity Market
GEB	grid-interactive efficient buildings
GMP	Green Mountain Power
ISO-NE	New England Independent System Operator
LCC	life cycle cost
LMP	locational marginal price
NREL	National Renewable Energy Laboratory
S+S	solar plus storage
PV	photovoltaics
RNS	Regional Network Service

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Executive Summary

As the United States works to meet emissions reduction goals and modernize power sector operations, residential buildings—which account for 21% of total U.S. electricity consumption (Energy Information Agency, 2023)—will play a key role. While the bulk power system is becoming increasingly renewable, residential sector efficiency improvements, on-site renewable generation, storage, and other grid-interactive efficient buildings (GEB) technologies will all contribute substantially toward achieving climate goals while maintaining reliable grid operations. The value provided by residential buildings is distributed across multiple stakeholders, including homeowners and occupants, utilities, grid operators, distributed energy resource aggregators, and society at large. However, different value streams are relevant to each stakeholder, resulting in technology valuations and deployments that often lack a holistic quantification of impacts or an equitable distribution of benefits.

To quantify the values provided to different stakeholders from the combination of solar, storage, and GEB technologies, a large multiyear project called Nova Analysis, led by the National Renewable Energy Laboratory (NREL) with funding from the U.S. Department of Energy's Solar Energy Technologies Office, was launched. The Nova Analysis project considers a slate of value streams for residential buildings that are important to multiple stakeholders. The project is focused on developing a suite of metrics to assess building capabilities that can deliver on those value streams, with a particular focus on homes that include solar plus storage (S+S). By calculating these additional metrics, the true value of deploying solar and storage in residential buildings for all stakeholders can be shown rather than the typical focus on benefits direct to the occupant.

In this report, we analyze field data from a deployment of S+S in a community of highly efficient homes in Vermont—the McKnight Lane community. We use this data to quantify value streams of the existing S+S across stakeholders and use modeled results to show how additional value could be derived from these systems. As an additional unique contribution of this report, we demonstrate how these value streams can be visualized and communicated across stakeholders using a novel scorecard.

Based on a literature review of previous work and the value attributed by the stakeholder groups to various value streams, we identify a set of metrics relevant to measuring the value of S+S and which were the best fit for McKnight Lane (Table ES-1).

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Table ES-1. List of metrics evaluated by stakeholder group

Primary Stakeholder	Metric Name
Occupants	Annual Bill Savings [$]
	Grid Independence (or Cover Factor Demand) [%]
	Outage Resilience [hours]
Utility	Grid Peak Shaving [unitless]
	Average Grid Cost Reduction [$/kWh]
	Annual Regional Network Service (RNS) Cost Savings [$]
Society	Emissions Reduction [metric ton CO_2]

To identify the existing and potential benefits from S+S systems for the McKnight Lane homes, we modeled five scenarios using REopt®—a mixed-integer model that determines the cost-optimal deployment of distributed energy technologies while adhering to operational constraints. Each of the five scenarios represent a specific combination of the sizing of the S+S system and the battery dispatch objective as summarized in Table ES-2.

Table ES-2. List and brief decriptions of scenarios evaluated categorized by primary purpose

Category	Scenario Name	Description
To Identify Current Benefits	Baseload Scenario	Modeled the actual (gross) home loads without S+S
	Business-as-Usual (BAU) Scenario	Modeled the existing S+S sizes and actual home loads, PV generation, and battery dispatch (no dispatch optimization)
To Identify Additional Potential Benefits	Sized S+S Scenario	To optimize the S+S sizing as well as battery dispatch for customer and utility benefit; Modeled using the actual home loads and PV production
	Optimal Battery Dispatch Scenario	To optimize the battery dispatch for customer and utility benefit; Modeled using the actual home loads, actual PV generation
	Climate Costs Scenario	To optimize the battery dispatch for customer, utility, and societal benefit; Modeled using the actual home loads, actual PV generation

For the subset of the homes evaluated, the REopt results and metric values were analyzed. We discussed how the strategies adopted in each scenario (i.e., various battery dispatch and S+S sizing strategies) affect the metrics selected, some of the attributable causes, and to what extent adopting these strategies would help improve the metric values.

The findings from this report highlight and validate the significant value provided by solar photovoltaics (PV) and storage installed in the McKnight Lane community. We find that the McKnight Lane homes, when compared against equivalent homes without S+S, exhibit substantial benefits including an 85% reduction in annual energy bills, 148 hours of resilience from outages, $4,035 in Regional Network Service (RNS) savings over the 10-year lifetime of the batteries, and a reduction of 32 metric tons of CO_2 per year across all 14 homes.

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Additionally, we find that the batteries provide significant system benefits, especially when installed in conjunction with solar. Apart from the resilience benefit identified above (solar-only homes would see no resilience unless the home was specifically wired for islanded operation), the utility sees higher RNS savings and grid peak shaving benefits with S+S compared to a hypothetical scenario where McKnight Lane homes only installed solar PVs.

In addition to the existing benefits from the business as usual case, which represents what is currently installed in the field and the default battery control logic, the REopt models and metrics calculated allowed us to capture nuances in how the potential dispatch strategies holistically affect the stakeholder benefits. For instance, the strategy of dispatching the battery for the purpose of minimizing climate emissions provided high benefits across all stakeholder groups. However, the strategy of dispatching battery for customer and utility benefits (without intrinsic consideration of climate costs) gave mixed benefits, with the amount of battery capacity utilization driving these benefits. Through the comparison of benefits across stakeholder groups and across the scenarios evaluated, we find that a moderate frequency of battery dispatch and alignment of battery dispatch to the grid emissions factors maximizes the utility savings while not reducing the benefits for other stakeholders.

Identifying and then calculating the key metrics for each stakeholder as listed in Table 6 allows us to understand the various value streams, benefits, and the impact of economic and system drivers for S+S systems. To facilitate the understanding of various value streams, benefits, and the impact of economic and system drivers for S+S systems, we developed a novel scorecard concept that presents the results in a graphic format. Figure ES-1 summarizes the scorecards for various REopt scenarios modeled.

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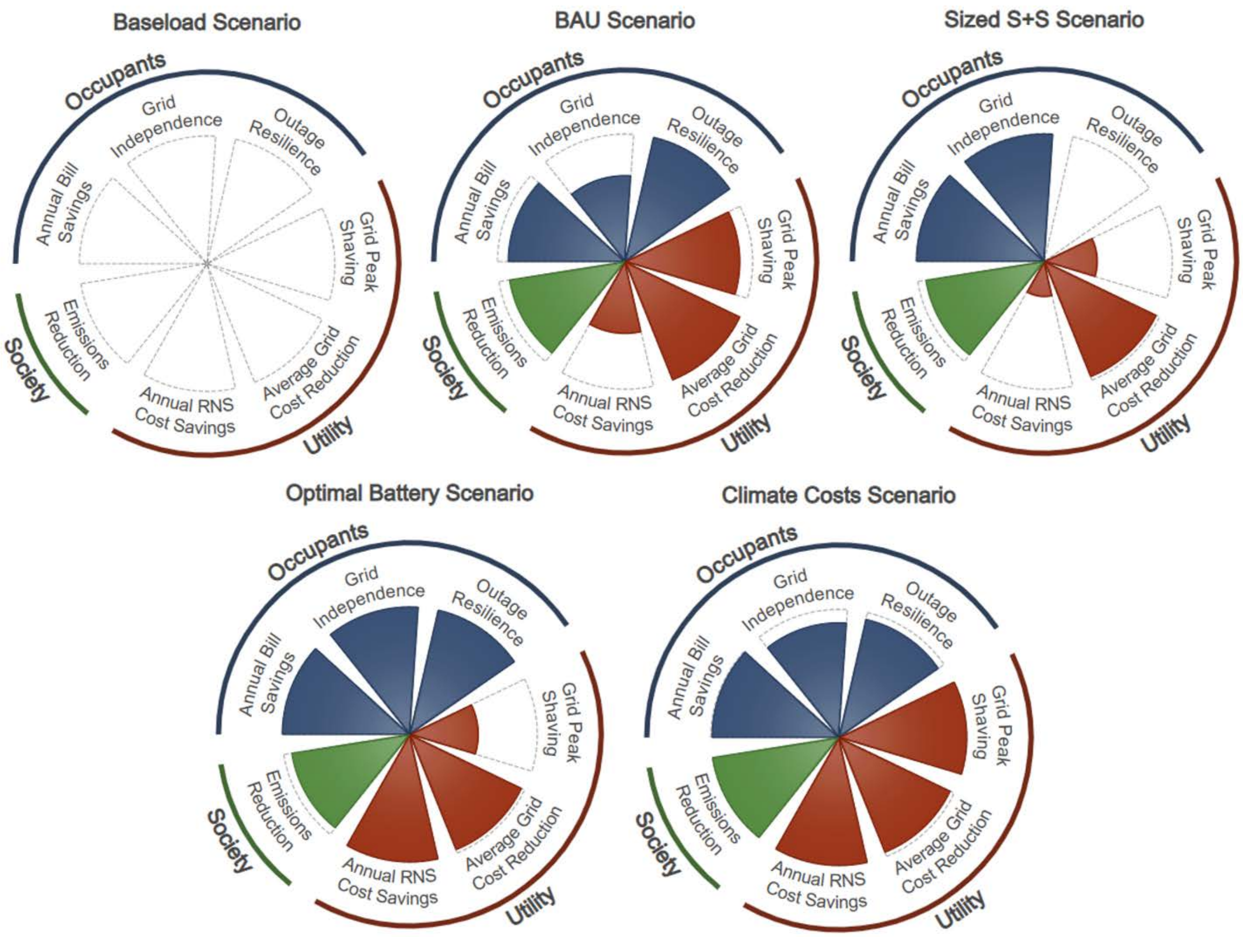

Figure ES-1. Scorecards for all scenarios visualizing various drivers and impacts of strategies adopted in various scenarios

In addition to identifying and communicating the drivers and impacts of various operation strategies for the McKnight Lane community, these scorecards also provide valuable insights for future projects. By comparing the scorecards of the modeled scenarios to the business as usual (BAU) scenario, we are able to identify additional nuances regarding competing priorities and scenario-specific areas that require equitable distribution of benefits. To the extent that the analysis framework can be applied and reproduced in other project sites, it is essential to weigh these drivers and resulting effects accordingly while deciding on an appropriate and equitable battery dispatch strategy and S+S sizing.

In conclusion, for the McKnight Lane community, the current benefits experienced by the occupants, utility and grid, and society at large are considerable. While there is slight room for improvement in this scenario, the BAU case still provides substantial benefit across multiple metrics and stakeholders.

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1 Introduction and Background

As the United States works to meet emissions reduction goals and modernize power sector operations, residential buildings—which account for 21% of total U.S. electricity consumption (Energy Information Agency, 2023)—will play a key role. While the bulk power system is becoming increasingly renewable, residential sector efficiency improvements, on-site renewable generation, storage, and other grid-interactive efficient buildings (GEB) technologies will all contribute substantially toward achieving climate goals while maintaining reliable grid operations. The value provided by residential buildings is distributed across multiple stakeholders, including homeowners and occupants, utilities, grid operators, distributed energy resource aggregators, and society at large. However, different value streams are relevant to each stakeholder, resulting in technology valuations and deployments that often lack a holistic quantification of impacts or and equitable distribution of benefits.

To quantify the values provided to different stakeholders from the combination of solar, storage, and GEB technologies, a large multiyear project called Nova Analysis, led by the National Renewable Energy Laboratory (NREL) with funding from the U.S. Department of Energy's Solar Energy Technologies Office, was launched. This project is a successor to a prior project with a similar focus on calculating metrics for homes with energy efficiency, solar, and storage (Shah, et al., 2020). The Nova Analysis project considers a slate of value streams for residential buildings that are important to homeowners (e.g., bill management, resilience), utilities and grid operators (e.g., peak load management, renewable integration), and society (e.g., emissions reductions). The project is focused on developing a suite of metrics to assess building capabilities that can deliver on those value streams, with a particular focus on solar plus storage (S+S).

The Nova Analysis project has three distinct phases: metrics development, field validation (Metrics@Home), and simulation of GEB technologies and efficiency investments across the U.S. in a national-scale analysis. This project is part of the "Metrics@Home" component of the larger Nova Analysis project, which uses measured field data from homes with solar, storage, and GEB technologies. As part of Metrics@Home, a prior analysis was performed, focused on a community of new construction homes in and around Prescott, Arizona (O'Shaughnessey, 2022). The study looked at data for over 100 homes within the community and determined that the unique rate structure for these homes played a substantial role in the value the DERs provided, eroding value to the homeowner while providing substantial value to the grid. Comparing the measured performance to simulation results also revealed several opportunities to further reduce both emissions and occupant costs through alterations in battery dispatch strategies.

In this report, we analyze field data from a deployment of S+S in a community of highly efficient homes in Vermont. We use this data to quantify value streams of the existing S+S across stakeholders and use modeled results to show how additional value could be derived from these systems. As a unique contribution of this report, we demonstrate how GEB value streams can be visualized and communicated across stakeholders using a novel scorecard.

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2 McKnight Lane Case Study

2.1 Study Site

This study uses data from 14 modular all electric homes in the McKnight Lane Redevelopment Project located in Waltham, Vermont (Samantha Donalds, 2018). The housing project was developed by Addison County Community Trust—a nonprofit affordable housing trust—and the affordable housing developers Cathedral Square. All units were fully occupied by November 2016. The McKnight Lane community includes 14 duplex net-zero energy-efficient rental units, of which 12 are two-bedroom units and two are three-bedroom units. The two-bedroom and three-bedroom houses have approximate floor areas of 925 and 980 square feet, respectively. Each home is equipped with a 6-kW rooftop solar photovoltaic (PV) system and a 4-kW/6-kWh sonnen battery storage system, with the exception of one home that has a 4-kW/8-kWh battery.[1] The solar systems are owned by Addison County Community Trust, and the batteries are owned and operated by McKnight Lane's utility provider, Green Mountain Power (GMP).

One aim of installing solar on the McKnight Lane homes was to provide the low-income tenants with a 100% reduction in annual energy bills. All 14 homes are individually metered under GMP's commercial small general service rate schedule, Rate 6 (Green Mountain Power, 2023). The electricity usage for each billing period is charged at a fixed rate of \$0.641/day and a flat energy rate of \$0.17945/kWh. The rate has no other charges. These high energy charges are offset by the on-site solar generation and by taking advantage of GMP's net-metering program. GMP incentivizes solar generation through its self-generation and net-metering tariff (Green Mountain Power, 2023), which compensates the excess solar generation that is exported to the grid. Each kWh of generation from solar in excess of monthly household consumption that is exported to the grid (i.e., the net solar generation) is compensated at a retail residential rate (Rate 1) of \$0.17650/kWh. Additionally, the tariff provides credits for all *gross* generation from renewable energy systems with installed capacity less than 15 kW at a rate of \$0.053/kWh (Green Mountain Power, 2023).

The batteries were installed in the McKnight Lane homes to serve two primary functions. First, the batteries provide resilience to the McKnight Lane tenants during grid outages. In case of an outage, the S+S systems automatically disconnect from the grid and serve the critical home loads for the duration of the outage. In addition to resilience, the batteries are utilized by GMP to reduce electricity market charges incurred during the grid's monthly and annual peak demands. As a market participant in the New England Independent System Operator (ISO-NE), GMP is subject to transmission and capacity charges in the form of Regional Network Service (RNS) and Forward Capacity Market (FCM) charges, respectively. Therefore, to reduce these demand charges, GMP remotely dispatches the batteries to shave the utility's monthly and annual peaks. These peaks are utility costs that would not be passed onto the homeowner. This represents a rather unique situation as the batteries were not bought directly by the homeowner but funded by several organizations including the utility, which then controls the battery to help smooth utility loads while also providing resilience benefits to the occupants.

[1] All datasets used to perform the modeling and analysis in this study were obtained from the two-bedroom houses

2.2 Site Data and Assumptions

To model and assess the value of S+S to the McKnight Lane homes, we collected home characteristics, timeseries data for loads and S+S system operations, and ISO-NE capacity and transmission charge data.

GMP provided timeseries data for the McKnight homes from 2017 to 2021 for household consumption, PV generation, battery charge and discharge, feed-in to the grid (exports from PV and battery), and electricity consumed from the grid. Of the 70 annual datasets provided (one dataset for each of the 14 homes from each of the 5 years), we down-selected to eight datasets for analysis based on data completeness and data accuracy.[2] Key information for the selected datasets including usage, imports, and exports[3] are listed in Table 1.

Table 1. Details of the McKnight Lane homes evaluated in this study. All energy values (kWh) are annual.

Dataset No.	Home ID	Year	Energy Use (kWh)	PV Output (kWh)	From Grid (kWh)	Grid Exports (kWh)	Battery Utilization (kWh)[1]
1	Home 1	2017	3,452	5,507	2,579	4,469	706
2	Home 1	2018	5,777	6,853	4,178	5,061	2,642
3	Home 2	2019	4,277	5,322	4,196	5,054	2,497
4	Home 3	2017	3,716	5,466	3,096	4,667	844
5	Home 4	2019	4,901	5,624	4,978	5,440	4,047
6	Home 5	2018	4,877	5,258	4,553	4,736	2,629
7	Home 5	2019	4,714	5,105	NA[2]	NA[2]	3,914
8	Home 6	2018	4,958	4,931	4,517	4,298	2,666

[1]Calculated as sum of hourly charge and hourly discharge

[2]Not included because a substantial number of hourly grid energy use and export values were not available for this dataset

Two of the eight datasets evaluated were from the same home but from two consecutive years (Datasets 1 and 2 are from the same home (Home 1) for years 2017 and 2018, respectively, and Datasets 6 and 7 are from the same home (Home 5) for years 2018 and 2019, respectively). Analysis of datasets from the same homes during different years could provide insight into how occupant loads can vary considerably year-over-year, thereby impacting the household metrics. Because this study does not analyze the occupant behavioral changes as causal factors, unless specified, each of these eight datasets is assumed to be from a unique home with distinct occupants and occupant behaviors.

In addition to the timeseries data, GMP provided the RNS monthly peak hours and corresponding charges (Table 2). We used the monthly peak event hours and the corresponding $/kW RNS charges to calculate GMP's RNS savings from demand reduction through battery

[2] We selected houses with data for at least 8,759 hours of the year (i.e., without missing data for more than one hour of the year). The missing data, if any, was filled in with the average of values from the n-1 and n+1 timesteps. We additionally screened the datasets to eliminate those with consistent outliers or unrealistic values.

[3] At any hour, energy balance using the data provided was validated such that: Home use – PV Generation + Battery Charge – Battery Discharge = Grid Demand – Grid Feed-in.

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dispatch. RNS charges between January 2017 and May 2018 were not available and were therefore estimated based on the 2018 and 2019 data provided by GMP.

Table 2. Monthly transmissions charges through ISO-New England's RNS. Per kW charges are applied to the utility's peak load over the hour period specified.

2017 Monthly RNS Charges			2018 Monthly RNS Charges			2019 Monthly RNS Charges		
Peak Day	Hour	$/kW-month	Peak Day	Hour	$/kW-month	Peak Day	Hour	$/kW-month
1/9/2017	18	$9.28[1]	1/2/2018	18	$9.40[1]	1/21/2019	18	$9.52
2/9/2017	19	$9.28[1]	2/2/2018	19	$9.40[1]	2/12/2019	18	$9.52
3/4/2017	19	$9.28[1]	3/19/2018	8	$9.40[1]	3/7/2019	19	$9.52
4/4/2017	20	$9.28[1]	4/16/2018	12	$9.40[1]	4/8/2019	20	$9.52
5/18/2017	20	$9.28[1]	5/31/2018	21	$9.40[1]	5/28/2019	19	$9.52
6/19/2017	15	$9.40[1]	6/30/2018	21	$9.52	6/27/2019	21	$9.64
7/19/2017	21	$9.40[1]	7/2/2018	20	$9.52	7/20/2019	21	$9.64
8/22/2017	18	$9.40[1]	8/28/2018	20	$9.52	8/19/2019	19	$9.64
9/26/2017	20	$9.40[1]	9/5/2018	20	$9.52	9/23/2019	19	$9.64
10/9/2017	19	$9.40[1]	10/25/2018	19	$9.52	10/17/2019	19	$9.64
11/10/2017	18	$9.40[1]	11/14/2018	18	$9.52	11/13/2019	18	$9.64
12/29/2017	18	$9.40[1]	12/18/2018	18	$9.52	12/19/2019	8	$9.64

[1]Assumed based on the values provided for 2018 and 2019

FCM charges ($/kW-year) and annual system peak hours and corresponding charges were provided for the years 2017 to 2019 (Table 3). This annual peak demand charge was not modeled in this analysis because of a lack of information around the baselining approach and contract details used to determine compensation. However, GMP may observe reduced FCM charges by dispatching the batteries during the annual system peaks. Additionally, because the system peaks occur during the summer months, the PV systems may be generating power during the system peak hours, thereby possibly further reducing GMP's FCM charges.

Table 3. Annual Forward Capacity Market (FCM) charges

Peak Day	Hour	$/kW-month
6/13/2017	17	$114.60
8/29/2018	17	$84.36
7/30/2019	18	$63.60

For wholesale grid costs required to calculate some of the metrics, we use ISO-NE's 2017–2019 hourly real-time locational marginal price (LMP) data for the Vermont load zone (annual averages shown in Table 4).

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Table 4. Average real-time location marginal price (LMP) for the Vermont load zone in ISO-NE. Hourly LMPs were used to calculate grid costs of home loads in this study.

Year	Average LMP [$/MWh]
2017	$33.03
2018	$42.84
2019	$30.05

3 Evaluation of Metrics

The objective of this study was to quantify in the form of metrics that can quantify the current and potential benefits of S+S systems for the McKnight Lane households These metrics try to quantify the benefits to all stakeholders, not just occupants, to give a more holistic view of the value provided by S+S systems for each of the different value streams identified here. Put another way, each value stream has an associated specific quantifiable metric associated with it. To calculate these metrics, we first model the existing homes, and subsequently model scenarios that represent specific performance objectives (such as optimizing battery dispatch and minimizing emissions). We then use the results from these scenarios to evaluate a suite of metrics that quantify the value streams of interest to the McKnight Lane stakeholders. The flowchart presented in Figure 1 provides the step-by-step process adopted to calculate high-impact metrics for the McKnight Lane community.

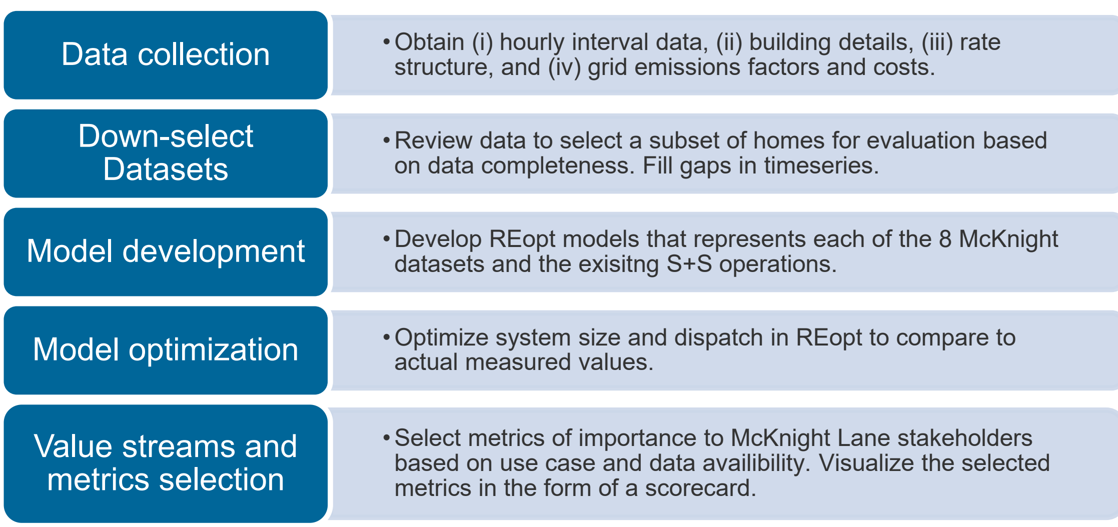

Figure 1. Analysis framework for evaluating stakeholder-specific metrics

Section 3.1 describes the modeling approach and details how the REopt® tool was used to perform scenario analysis. Section 3.2 defines the metrics calculated using REopt results and introduces the scorecard, which presents the key metrics in the form of accessible graphics to holistically capture the energy techno-economics of each household and scenario. Section 3.3 describes the unique project financing of these S+S systems and how we assume S+S economic benefits are allocated for the purpose of calculating metrics.

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3.1 Modeling Approach

We use REopt to model home energy consumption and evaluate potential S+S deployment scenarios, as described in the following sections.

3.1.1 REopt Modeling

In this study, we use REopt to model the actual and optimized S+S systems on each of the datasets in Table 1. REopt is a mixed-integer model that determines the cost-optimal deployment of distributed energy technologies while adhering to operational constraints (Cutler, et al., 2017). The REopt optimization identifies the system sizes and dispatch strategies that minimize the life cycle cost (LCC) of energy for a particular site.

This LCC includes capital, operations and maintenance, and energy costs over the financial life of a project. In our evaluation of McKnight Lane S+S systems, we additionally include RNS charges in the life cycle cost objective, modeled as coincident peak charges per kW, applied at the monthly timesteps listed in Table 2. REopt also allows users to include social equity costs such as carbon costs in the objective function, thereby minimizing both private energy costs and social costs. We utilize this capability to explore how monetizing life cycle CO_2 costs would impact system economics and emissions outcomes (described further in Section 3.1.2).

To the extent possible, we tailor the REopt model inputs to the McKnight home and S+S characteristics. Therefore, across all modeled scenarios, we use the measure hourly PV production series[4] for each home along with the actual rate structure. We similarly use actual gross home loads for most modeled scenarios. Other economic and technology assumptions used in the REopt models are detailed in Appendix A.

3.1.2 Scenarios Evaluated

We model five scenarios, each representing a specific combination of the sizing of the S+S system and the battery dispatch objective.

The five scenarios can be classified into two categories based on the purpose of the evaluation:

- **Current Benefits:** Used to identify benefits of the actual S+S installation experienced by the McKnight Lane stakeholders (results in Section 4.1). This is the "business as usual (BAU)" scenario

- **Additional Benefits**: Used to identify additional benefits that can be realized by optimizing the sizing and/or dispatch of S+S (results in Section 4.2). This corresponds to all other scenarios, with multiple possibilities depending on what is driving the battery controls.

In several scenarios we optimize the dispatch of battery storage. In each of these scenarios, the systems are dispatched to minimize both customer costs (through reduced energy bills) and

[4] PV production factors were calculated from the existing solar generation profiles provided for each home by dividing hourly PV output by system size (6 kW). Production factors obtained from PVWatts (NSRDB TMY3) were not used in this analysis to preserve the real-time conditions and to accurately reflect the actual on-site production.

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utility costs (through reduced RNS charges during event hours[5]). In the Climate Costs scenario, we additionally include climate costs of carbon dioxide (CO_2) emissions from grid-purchased electricity within the model's objective function. We assume this cost is \$51/t CO_2 based on the U.S. Government's Interagency Working Group estimates and use marginal emissions rates from the U.S. Environmental Protection Agency's (EPA's) AVoided Emissions and geneRation Tool, or AVERT (Environmental Protection Agency, 2023). The possible dispatch objectives and associated stakeholders are visualized in Figure 2 and included in Table 5 under "Battery Dispatch."

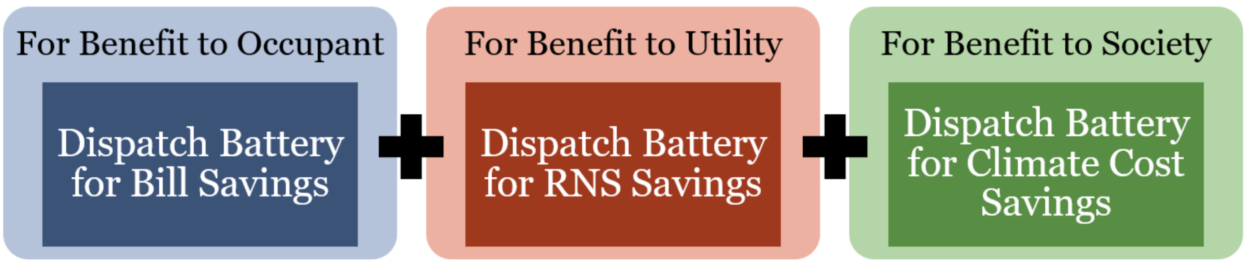

Figure 2. Three value streams for which the modeled McKnight Lane batteries can be dispatched, and the corresponding stakeholder to which the benefit is allocated. These buckets correspond to the labels listed in Table 5 under "Battery Dispatch."

The Baseload scenarios are used as baselines against which other scenarios are compared to determine existing value streams and additional value that could be realized with optimized dispatch and/or sizing. For example, the Business-as-Usual (BAU) scenario's emissions reduction, which is a relative metric, is calculated as the difference between Baseload emissions and BAU emissions.

[5] Typically, the project economics considered in REopt's objective function do not include the costs to utilities, such as RNS charges or wholesale grid costs (LMP). While we do include GMP's RNS charges at monthly peaks as coincident peak costs to customers (and in turn assign these benefits to the utility provider), LMP was not factored into the REopt optimization. LMPs were, however, used to calculate the metrics after REopt modeling and to identify the benefits provided by S+S and the other optimization strategies in the "Additional Benefits" scenarios.

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Table 5. Scenarios explored in this report. Scenarios vary in home loads used (actual vs. modeled), S+S system sizing, and objective function used to determine battery dispatch.

1. Baseload Scenario – Home load only (without S+S)

Home Loads	S+S Sizes	Battery Dispatch
True Loads	N/A, no S+S	N/A

Description: Actual (gross) home loads without S+S. This scenario serves as a baseline against which relative costs and benefits of existing and optimized S+S scenarios can be compared.

2. Business-as-Usual (BAU) Scenario – Existing S+S sizes and dispatch

Home Loads	S+S Sizes	Battery Dispatch
True Loads	Existing system sizes	Actual dispatch

Description: This scenario is used to identify value streams of the existing S+S systems, as compared to the *Baseload* scenario. We model existing S+S sizes and actual hourly home loads, PV generation, and battery dispatch.

3. Sized S+S Scenario – Optimal S+S sizes and dispatch

Home Loads	S+S Sizes	Battery Dispatch
True Loads	REopt sized system	For customer and utility benefit

Description: This scenario is used to identify additional value that could be realized by optimally sizing and dispatching (using REopt) the solar PV and battery systems to minimize customer and utility costs. We model actual hourly home loads and use the actual PV generation production series (hourly kW output per kW installed). We optimize the battery dispatch.

4. Optimal Battery Dispatch Scenario – Existing S+S sizes, optimal S+S dispatch

Home Loads	S+S Sizes	Battery Dispatch
True Loads	Existing system sizes	For customer and utility benefit

Description: This scenario is used to identify additional value that could be realized by optimally dispatching (using REopt) the battery to minimize customer and utility costs. We model existing S+S sizes, actual hourly home loads, and PV generation, and optimize the battery dispatch.

5. Climate Costs Scenario – Existing S+S sizes, optimal S+S dispatch (climate costs included)

Home Loads	S+S Sizes	Battery Dispatch
True Loads	Existing system sizes	For customer, utility, and societal benefit

Description: This scenario is used to identify additional value that could be realized by optimally dispatching (using REopt) the battery to minimize customer, utility, and societal (climate) costs. We model existing S+S sizes, actual hourly home loads, and PV generation, and optimize the battery dispatch.

3.2 Metrics Evaluated

In this section, we identify a set of metrics that capture the various value streams and stakeholder perspectives relevant to measuring the value of S+S on the McKnight Lane homes. This identification process includes a literature review of previous work (Shah, et al., 2020), which establishes the existing landscape of metrics related to zero energy buildings, demand flexibility, bulk power reliability, resilience, value of distributed resources, and other related topics. From the comprehensive suite of existing metrics, we select metrics that are relevant to the key McKnight Lane stakeholders, which are the occupant, utility, and society at large. The occupant is assumed to value their energy usage, the cost of energy and upgrades, and energy resilience. The utility encompasses the retail energy provider, distribution system operator, and wholesale energy provider, and is assumed to value the wholesale energy cost, peak demand contribution, and incurred transmission charges. The societal stakeholder is assumed to value the reduction of carbon emissions. In addition to these stakeholder-specific considerations, we select metrics that could be calculated from the measured field data to ensure that the study methodology—including the calculation of metrics—could be replicated in future field studies. This value attribution filtered down the list of metrics to ones that were best fit for measuring the value of S+S for McKnight Lane.

Next, metrics were filtered based on their ability to be accurately calculated using the available datasets identified in Section 2. Some metrics were removed from the framework because of lack of data or because of the unique circumstances of McKnight Lane (Section 3.3). In particular, this framework does not consider the value of S+S on the distribution system, including impacts on congestion, hosting capacity, or reliability. Additionally, this framework does not consider metrics such as net present value, which are affected by the McKnight Lane project being funded by several partners. Since the McKnight Lane community is low income, high efficiency housing funded by several organizations not including the occupant, it makes it difficult to assign to whom the net present value ought to apply, which led to it being omitted here.

With these considerations, we develop a final list of metrics applicable to the McKnight Lane community. Table 6 defines the final metrics considered in this study, identifies the stakeholder to whom each metric is most relevant, and indicates whether the metric is absolute (no baseline) or relative (requires a baseline).

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Table 6. Names, descriptions, and primary stakeholder for metrics analyzed in this study

Primary Stakeholder	Metric Name	Description	Relative or Absolute
Occupants	**Annual Bill Savings [$]**	Annual utility bill savings from given building upgrade. Includes reduction in energy bill costs and any benefits from exports and renewable energy incentives.	Relative
	Grid Independence (or Cover Factor Demand) [%]	How well the demand is covered by on-site generation. Calculated as $(1 - \frac{grid\ [kWh]}{home\ [kWh]} * 100\%)$, where grid is annual grid purchases and home is the home's gross load. When this metric is 100%, all demand can be met by local generation. Grid independence is also sometimes called cover factor demand. This metric is correlated with bill savings.	Absolute
	Outage Resilience [hours]	Average number of hours that the system can sustain critical loads in case of an outage—determined by modeling an outage at each hour of the year and averaging the hours of outage sustained at each of these 8,760 outages. We assume 100% of the home loads are critical as only whole home power was measured.	Absolute
Utility	**Grid Peak Shaving [unitless]**	Grid peak shaving is the difference in grid peak contribution between a given scenario and a baseline. Grid peak contribution evaluates the degree to which a building load is coincident during the top 5% of hours in which the grid system is peaking (evaluating simultaneity of the peaks) and is commonly applied to evaluating firm capacity requirements of the grid. Grid peak contribution is calculated as the ratio of the building's net load during the 5% of top peak grid hours to its net load during the building's 10 highest peak hours.	Relative
	Average Grid Cost Reduction [$/kWh]	Average grid cost reduction is the difference in average grid cost between a given scenario and a baseline. Average grid cost is the average wholesale cost of serving the home's gross electric load over one year. It is calculated by multiplying building net load by locational marginal grid costs (LMP) and dividing this total cost by the annual gross home load.	Relative
	Annual Regional Network Service (RNS) Cost Savings [$]	Annual RNS cost savings is the difference in annual RNS costs attributable to the home between a given scenario and a baseline. RNS costs are calculated as RNS charges multiplied by the home load during the monthly peak hours (see Table 2). This metric is applicable to the McKnight Lane systems given that GMP participates in ISO-NE markets.	Relative

Primary Stakeholder	Metric Name	Description	Relative or Absolute
Society	**Emissions Reduction [metric ton CO_2]**	Emissions reduction is the difference in annual CO_2 emissions between a given scenario and a baseline. Annual CO_2 emissions are calculated as hourly grid purchases times the hourly marginal emissions rate of the grid, summed over the year. We use hourly marginal emissions factors from EPA's AVERT (EPA, 2020) for the Northeast region as described in (Anderson K. , et al., 2023)	Relative

The results from the REopt runs for the five scenarios for each of the eight datasets were used to calculate metrics that quantify the value streams within the various stakeholder perspectives. Some metrics are presented as an absolute value (i.e., without comparing against a baseline value), while other metrics are calculated as a change from the baseline scenario. Some metrics apply to multiple stakeholders, in which case we attribute a metric to the stakeholder with the presumed highest interest. These presumptions were based on the project team's judgement and include assigning emissions reduction to society instead of occupants or the utility and cover factor demand to the occupant rather than utility.

While averaging these metrics across all eight datasets—which span three years—we may lose the effect of the weather-year, occupant behaviors, and changes in battery dispatch strategies on the metrics. If the difference in years has a major significance in how the metric values are affected, and if averaging the metrics across the datasets does not explicitly show those effects, we will discuss those factors in further detail in Section 4.

3.2.1 Visual Metrics Scorecard

Calculating the key metrics for each stakeholder as listed in Table 6 allows us to understand the various value streams, benefits, and the impact of economic and system drivers for S+S systems. However, these metric values may be dependent on several variables, and some metrics may not hold any intrinsic value except by demonstrating how they change with changes in drivers. In addition, it may be challenging to identify the maximum achievable values for these metrics because they depend on a confluence of factors, including project location, occupant loads, occupant behaviors, and uncertainly in grid operations. For example, while *Grid Independence* can achieve a theoretical maximum of 100%, unless a project site has microgrid capabilities or the S+S is highly oversized compared to the project loads, reaching a 100% grid independence is nearly impossible. We need to contextualize these metric values to be bound by what could practically be possible to achieve.

To facilitate comparisons across scenarios in Table 5 and metrics in Table 6, we developed a visual scorecard in the form of a petal plot. An example of this visual is shown in Figure 3. The metric values for each scenario use averages across the eight McKnight Lane datasets listed in Table 1. For relative metrics (as indicated in Table 6), the Baseload scenario (actual homes without S+S) is used as the baseline.

Each petal outline on the plot extends from the minimum to maximum average metric value across the scenarios. Each metric is then normalized based on the respective min-max values

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across scenarios to determine the size of the petal for that metric and scenario. Therefore, the petal size indicates the relative value of each metric as compared to other scenarios.

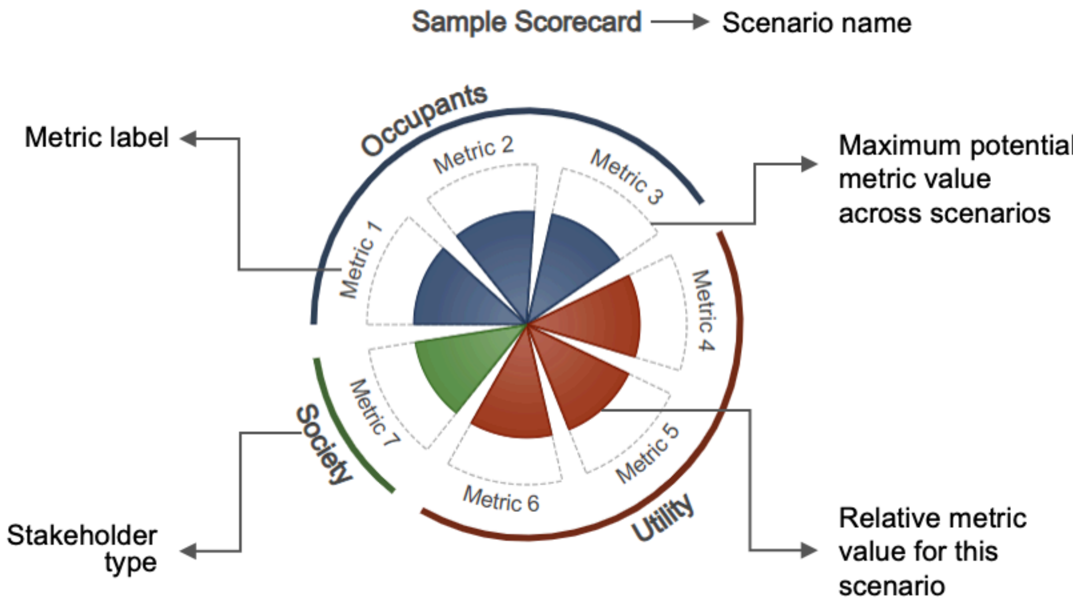

Figure 3. Example petal plot developed for comparison of metrics across scenarios

For all metrics, a bigger petal size is better. If a petal reaches the maximum extent of the outline, this indicates that this scenario results in the best possible outcome (i.e., maximum achievable potential) for the given metric as compared to all other scenarios. Given the number of metrics of interest and the differing stakeholders, there is not a single scenario where all metrics reach the maximum extent. Some of these metrics have competing underlying factors and, depending on the strategies adopted within the scenarios evaluated, what's beneficial for one factor or stakeholder may be detrimental to another metric or stakeholder. The scorecards, therefore, serve as an accessible graphic to visualize these dependencies across scenarios.

3.3 Project Financing and Occupant Economic Metrics

The ownership model of a GEB project dictates how the financial cost metrics are allocated to each of the primary stakeholders. In the case of typical single-family homes with S+S systems, the homeowner owns and operates the system, either directly or through a third party. The homeowner incurs the capital and O&M costs for S+S, and benefits from any federal, state, or local tax incentives. The homeowner then recoups the S+S costs through utility bill savings—from reduced energy and demand charges, export benefits, and production incentives, depending on how the tariffs are structured.

The McKnight Lane homes have key differences compared to a typical single-family home S+S ownership model. The funding for the McKnight Lane project was secured through several partners including Clean Energy Group, Clean Energy States Alliance, Efficiency Vermont, Green Mountain Power, and sonnen (Clean Energy Group, 2023). As a result, the upfront costs for S+S were borne by several external stakeholders, with GMP being the only stakeholder that can earn returns by discharging the batteries to reduce its peak demands and grid costs. Furthermore, the bill savings that are generally received by individual homeowners are, in this

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case, received by the McKnight Lane property manager who passes the savings to the occupants in the form of reduced rent. Therefore, the value streams and metrics meaningful to the occupants, may be valuable to the property owner and manager as well. We assume in this study that the occupants, owners, and managers are of the same stakeholder group given that their interests are in alignment.

In selecting the subset of metrics that provide a holistic representation of the benefits from distributed energy resources, we considered the unique circumstances of McKnight Lane. Metrics for installing S+S such as net present value—typically a crucial economic metric for occupants in decision-making—were not included in the subset of metrics because neither the McKnight Lane occupants nor the property owners were directly liable for the capital expenses of installing S+S. Instead, we represent the economic benefits to occupants in the form of annual bill savings. This implicitly assumes that the entirety of the bill savings is passed down to the occupants in the form of subsidized rent. Future work may consider alternate ways to deal with such complicated financial scenarios.

4 Analysis of System Economics and Performance

We calculate the metrics described in Section 3.2 for each McKnight Lane dataset, under each of the scenarios described in Table 5. In the following sections, we report average metrics across the homes for logical groupings of scenarios and provide observations regarding the drivers behind the metric values and variability across homes and years. Table 7 summarizes the metric values calculated for each scenario, which will be used to develop scorecards in the following sections. We see that all metrics values for the Baseload scenario are zero, making it the relative baseline for the other scenarios. The "PETAL MIN" and "PETAL MAX" rows show the minimum and maximum values observed for each metric across the scenarios. These ranges are used to normalize the respective metrics in determining the petal lengths within a scenario's scorecard.

Table 7. Metric values calculated for each scenario and the minimum and maximum values used to generate the scorecard graphics

	Occupants			Utility			Society
Scenario	Annual Bill Savings ($)	Grid Independence (%)	Resilience (hours)	Grid Peak Shaving	Average Marginal Grid Cost ($/kWh)	Annual RNS Savings ($)	Emissions Reduction (tCO_2)
Baseload	$-	0%	0	0	$-	$-	0
BAU	$ 899	14.2%	148	0.249	$ 0.0345	$ 28.82	2.28
Sized S+S	$ 1,069	30.9%	0	0.053	$ 0.0326	$ 6.90	2.38
Optimal Battery	$ 1,070	31.1%	148	0.089	$ 0.0327	$ 90.43	2.38
Climate Costs	$ 1,052	25%	133	0.307	$ 0.0322	$ 90.43	2.71
PETAL MAX	$ 1,070	31.1%	148	0.307	$ 0.0345	$ 90.43	2.71
PETAL MIN	$-	0%	0	0	$-	$-	0

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In the subsequent sections, we discuss in detail how the strategies adopted in each scenario (i.e., various battery dispatch and S+S sizing strategies) affect these metrics, some of the attributable causes, and to what extent adopting these strategies would help improve the metric values.

4.1 Benefits of Existing S+S Systems

The existing McKnight Lane S+S systems produced significant benefits to multiple stakeholders in the form of bill savings, reductions in utility peak demands, and reductions in carbon emissions. To quantify these benefits, we compare metrics for the actual homes with S+S (BAU scenario) to a baseline home without S+S (Baseload scenario). We discuss the drivers of the economic, system, and societal benefits to gain insight into how the McKnight Lane community could achieve additional savings. Furthermore, we present the scorecard for the BAU scenario, which encapsulates the relative benefits experienced by the McKnight Lane community compared to the maximum value that can be attained by each of the metrics.

4.1.1 Reduction in Energy Bills

The McKnight Lane homes receive substantial benefits from the decrease in energy bills due to S+S. We estimate that on average, between the years 2017 and 2019, households saw an annual utility bill of $158—around $13 a month—after S+S installation, an 85% reduction compared to a baseline annual bill of $1,057—$88 per month—without S+S. These savings are primarily due to the export benefits from GMP's net-metering tariff, which provides customers with monthly credits for excess solar energy exported to the grid. In addition to export benefits, the customers also receive compensation for all gross generation from solar. The reduction in grid energy consumption due to S+S dispatch constituted the remainder of the annual bill savings (Figure 4).

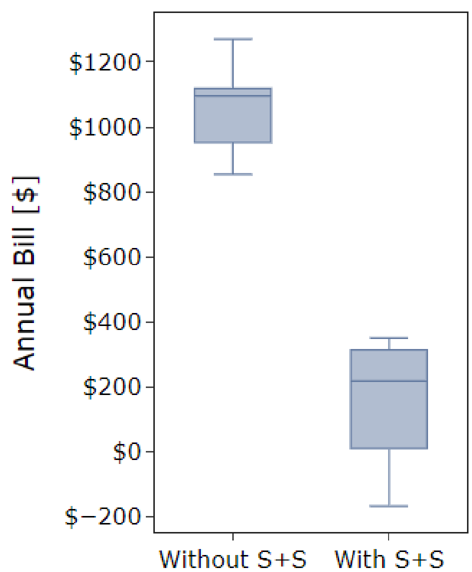

Figure 4. Box plot of average annual bills across eight datasets for McKnight Lane homes without S+S (left) and with S+S (right)

The observed bill savings are not uniform across all datasets and vary seasonally and with occupant loads. Figure 5 shows the variation in energy consumption and solar generation for the eight datasets analyzed. The pattern of monthly loads indicates that the energy consumption from November to February was higher compared to May to August. This is due to considerable

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heating loads in winter (met with an efficient heat pump as these are all electric homes) and significantly lower cooling loads in summer, congruent with both the International Energy Conservation Code climate zone 6A for Vermont and with typical occupant behaviors. Conversely, solar generation is high during summer and low during winter. This combination of load and solar trends results in higher energy bill reductions during summer compared to winter.

Depending on the size of PV, solar generation, and energy consumption over the month, the dwelling may receive bill credits, as illustrated in Figure 6(b). Actual monthly bills for all eight datasets were negative during the summer months of May to July, when the solar export benefits exceeded utility energy charges, with the savings averaging 165% from the baseline utility bills in Figure 6(a). Comparatively, the bill savings from S+S from November to February were relatively low—12% savings on average—due to low solar insolation and snow cover and, therefore, low net export credits.

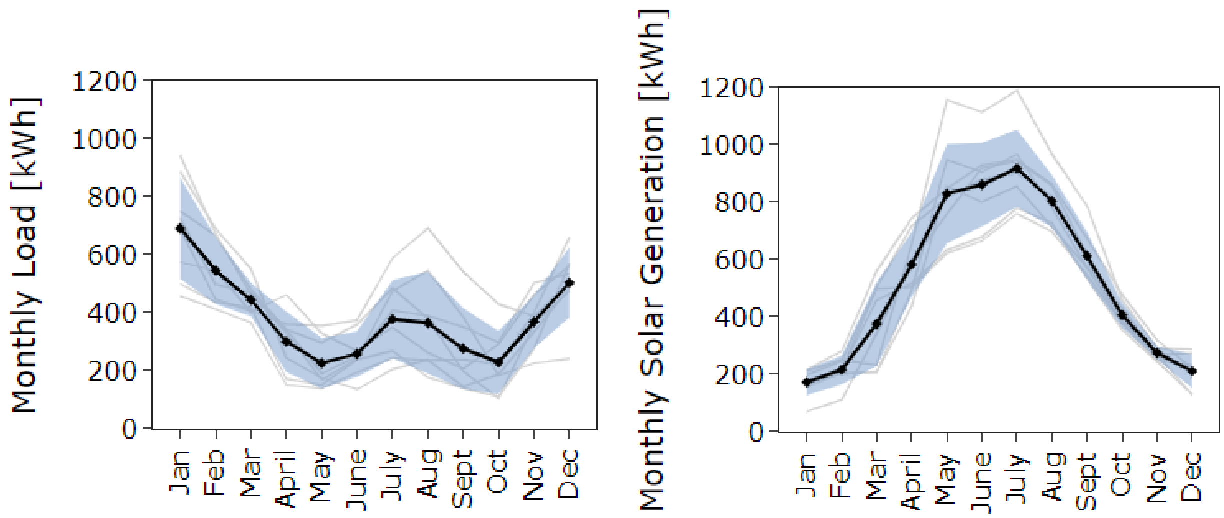

Figure 5. (a) Monthly total electric load (left) and (b) Solar generation (right) for McKnight Lane Homes. Gray lines represent individual home values, the black line represents the average across the eight datasets, and the light blue shaded area extends to one standard deviation above and below the mean.

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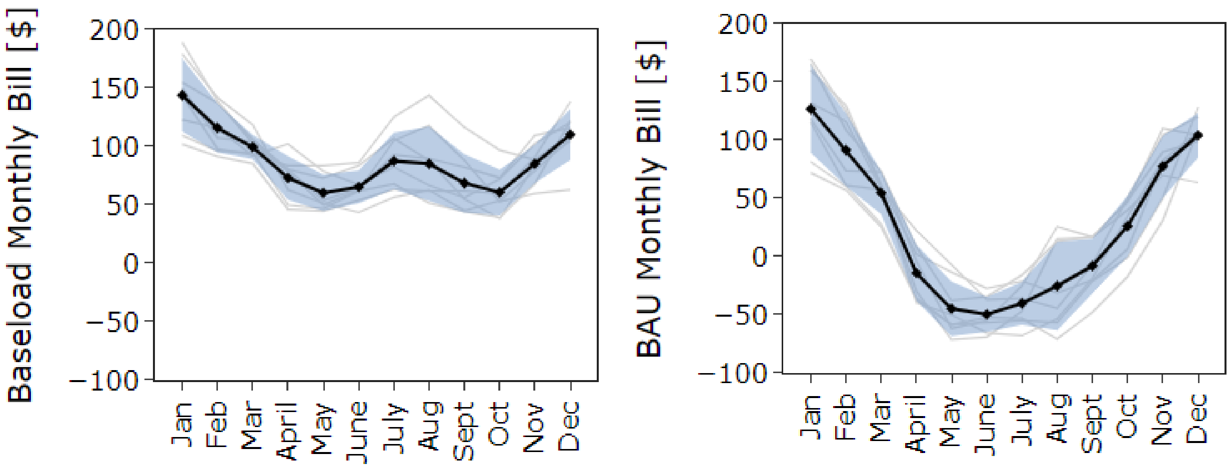

Figure 6. (a) Baseload scenario (homes without S+S) electric bills (left) and (b) electric bills for homes with existing S+S (BAU scenario) (right) for McKnight Lane Homes. Gray lines represent individual home values, the black line represents the average across the eight datasets, and the light blue shaded area extends to one standard deviation above and below the mean.

The outliers to this pattern of low loads and high solar (and vice versa) are Datasets 2 and 6, where occupant loads during summer were higher than winter loads. This could potentially be attributed to the unusually high summer temperatures in 2018 compared to normal temperatures, especially during the month of August. Net Energy and Peak Load data from ISO-NE (ISO New England, 2023) shows that August 2018 experienced 194.4 cooling degree days (tCDD[6]) compared to tCDDs of 78.6 and 98.4 in August 2017 and 2019, respectively. It is also possible that these loads are wholly occupant-driven; homeowners could have kept their homes at lower temperatures or had much higher than average appliance and miscellaneous electric load usage. It is difficult to determine which of these is the primary driver based solely on net consumption, but it is likely that both factors contributed to the outlier energy use to some extent.

While monthly peak demand reduction is not valued for McKnight Lane given that GMP Rate 8 does not have a demand charge, the current battery dispatch strategy adopted by GMP does decrease the homes' monthly peaks by discharging during the daily peak hours (Figure 7(b)).

[6] tCDD is the Monthly Temperature Humidity Index (THI) Cooling Degree Days, with base temperature of 65°F.

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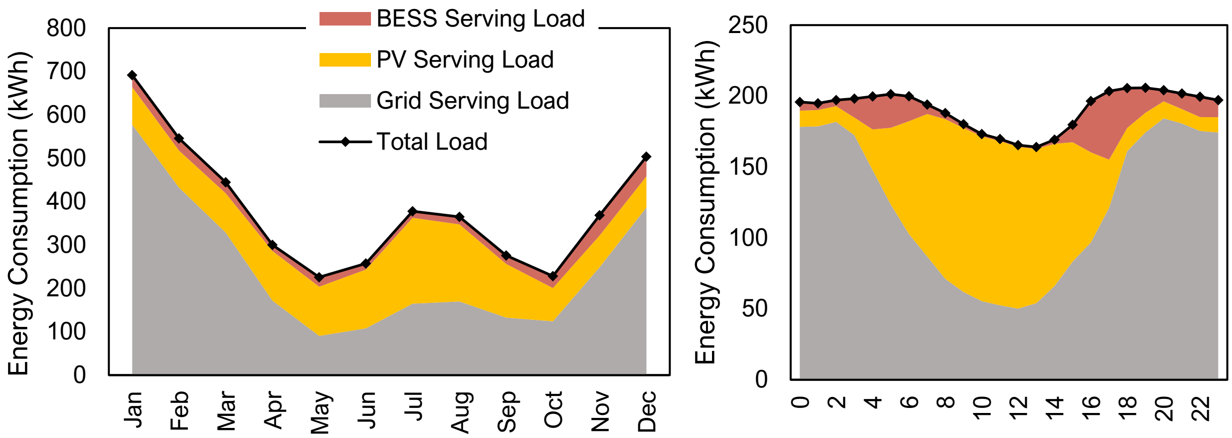

Figure 7. Total home energy consumption from grid, solar PV, and battery for an average McKnight Lane home, shown by (a) month (left) and (b) hour of day (right)

4.1.2 Resilience Benefits

Our analysis shows that the McKnight Lane batteries provide an average of 148 hours of resilience across the datasets for the 6 kWh battery installed in these homes as there are days where the solar system can fully charge the battery daily due to low loads. Resilience benefit is quantified as the average hours of sustained load for an outage occurring at any time of year. Notably, this means that an outage is assumed to be equally likely every hour of the year. However, the resilience metric is calculated considering 100% of the home loads as critical; these values can be regarded as the lower limit. In practice, during an outage, occupants can prioritize necessary loads (e.g., HVAC, refrigeration) and defer noncritical activities (e.g., clothes washing, dishwashing). However, only whole home power was available from this field study, making it difficult to split out critical from non critical loads. Figure 8 shows the average resilience hours, ranging from 58 hours for Dataset 8 (2018) to 458 hours for Dataset 1 (2017). This large range is due to several factors, including differences in the annual energy consumption by the occupants (which could vary by year even for the same home, such as in 2017), hourly battery dispatch, and solar production by year and building.

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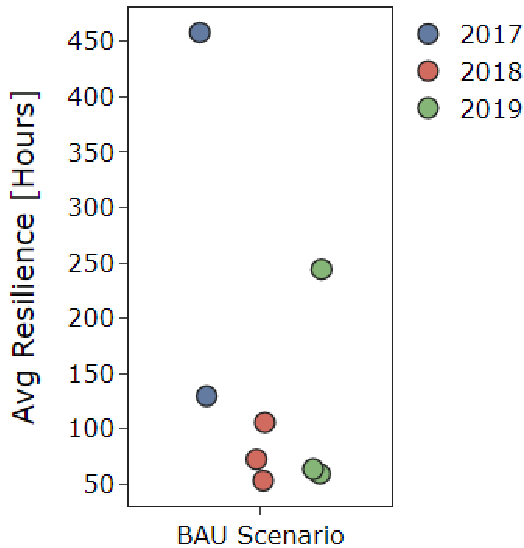

Figure 8. Resilience hours across eight datasets for McKnight Lane homes with existing S+S sizes and dispatch (BAU scenario)

4.1.3 Grid Benefits

The McKnight Lane S+S systems provide value to the utility, GMP, by reducing monthly RNS transmission charges (shown in Table 2), reducing grid costs through energy arbitrage, and reducing FCM charges. In this analysis, we quantify the monetary benefit of the former two value streams.

Our analysis of eight datasets (Table 1) shows the average annual RNS charge attributable to these homes *without* S+S is $90.43, compared to $61.61 *with* S+S (Figure 9(a)). This amounts to an average RNS savings for the utility of $28.82 per household per year. This is substantial savings per household, but small compared to the overall utility costs for RNS events.

Extrapolating these average savings to the 14 homes in the McKnight community, we find that the S+S systems provide RNS savings of approximately $403 per year ($34 per month[7]) and $4,035 over the anticipated 10-year lifetime of the batteries.

GMP achieves RNS savings by dispatching batteries during the anticipated regional peak load (during which hourly RNS charges are calculated). As shown in Table 2, most of these peak hours occur between 6 and 8 p.m. However, as shown in Figure 7, the batteries dispatch most between 4 and 6 p.m. This discrepancy may be attributable to the uncertainty inherent in load forecasting and illustrates the challenge in dispatching to consistently reduce monthly peaks. In Section 4.2.2, we illustrate the additional savings that would be incurred with perfect foresight into monthly peak hours and load.

S+S systems can also lower wholesale grid costs. To calculate the total grid cost of the homes' electricity consumption, we multiply hourly wholesale grid costs by each home's hourly net

[7] These monthly RNS savings are approximately 90% lower than those estimated by a Clean Energy Group report, which reported $350 to $400 per month savings and a payback period of 10–11 years for GMP's contribution to the purchase of the battery systems.

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load. We subsequently calculate average grid cost to serve the homes' native loads as total grid costs divided by the homes' gross (rather than net) load.

The average annual grid cost for the systems without S+S is \$0.045/kWh, compared to \$0.010/kWh with S+S (Figure 9(b)), for an average savings of 3.5 cents per kWh of gross load and an average annual grid cost savings of \$157 per home. Across the 14 homes in the McKnight Lane community, this amounts to an estimated \$2,199 savings per year from reduced grid costs.

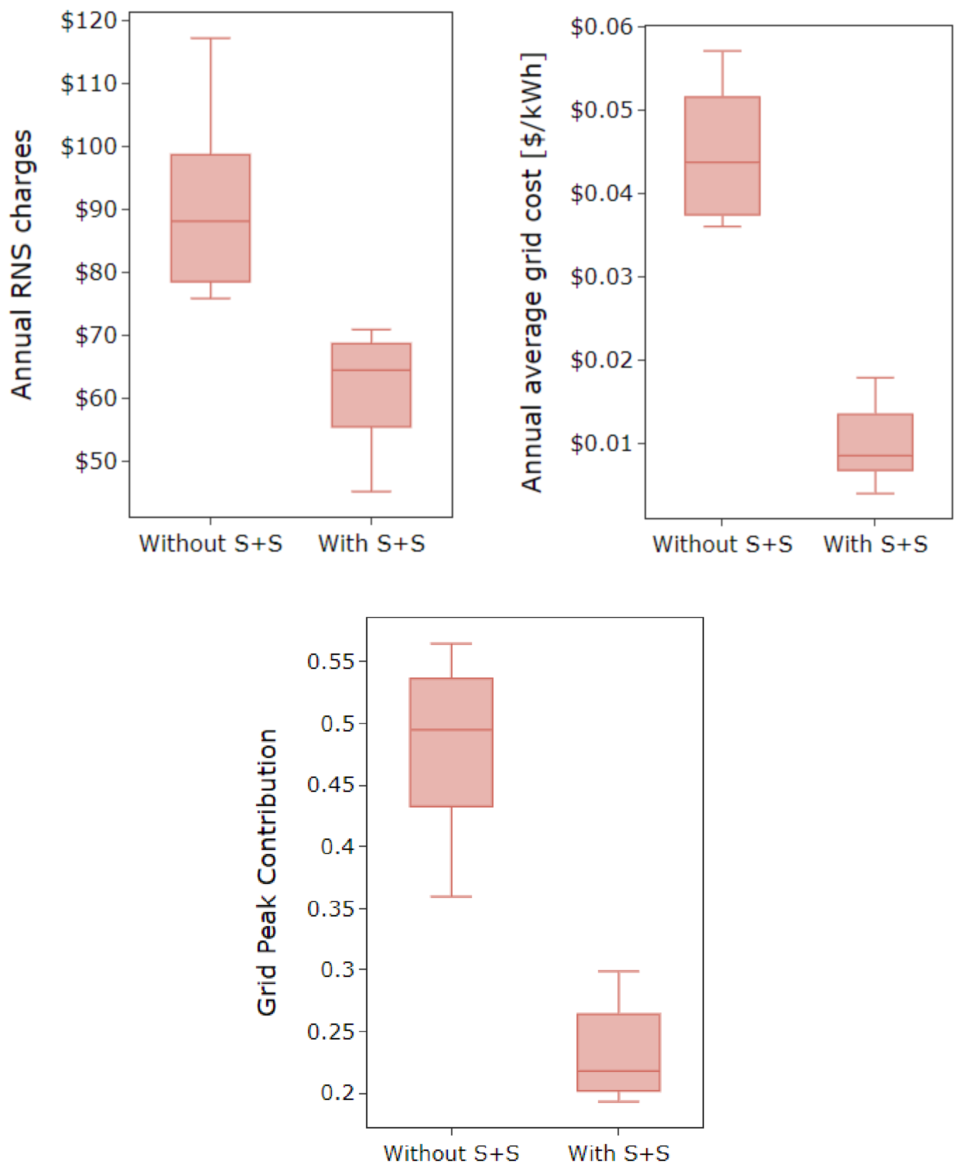

Figure 9. Box plot of (a) average annual RNS transmission charges (left) and (b) average annual grid cost (calculated using real-time locational marginal prices for Vermont) (right) and (c) grid peak contribution across eight datasets for McKnight Lane homes without and with S+S.

In addition to these utility and grid cost savings, S+S also lowers the grid peak contribution of an average McKnight Lane home. Grid peak contribution evaluates the degree to which a building load peaks as the grid peaks, identified using the LMPs for the respective year of the datasets

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(see Table 6 for the detailed description of this metric). Reducing this coincidence benefits the grid operator because it reduces the firm capacity requirements of the grid during its peak hours. S+S in the McKnight Lane homes reduces the grid peak contribution (Figure 9(c)) by 52% on average through peak shaving and load shifting, thereby reducing the building loads during the top grid peak hours. The degree to which solar and storage independently contribute to grid peak shaving is discussed in Section 4.2.1.

4.1.4 Emissions Reduction

The existing S+S systems (BAU scenario) reduce CO_2 emissions from grid-purchased electricity by an average of 2.3 metric tons per year compared to the McKnight Lane homes without S+S (Baseload scenario). Applying the average savings across the 14 homes in the McKnight Lane community, this amounts to an estimated savings of 32.2 metric tons of CO_2 per year from the implementation of S+S. Assuming a social cost of \$51/t CO_2 [8] this equates to savings of \$1,642 per year for the 14 homes, or \$41,000 over the anticipated 25-year lifetime of the S+S systems.

Figure 10 shows the trends in battery dispatch (charge and discharge) compared to the AVERT hourly average marginal emissions factors for the Northeast region. For battery dispatch, values above 0 kW indicate net battery charging at that hour, and values below 0 kW indicate net battery discharge during that hour. As is evident from the figure, the current dispatch strategy adopted by GMP is in close alignment with the grid emissions factors: where marginal emissions factors are low (12−5 a.m.), the battery gets charged, and where the marginal emissions factors are high (3−8 p.m.), the battery discharges to the homes or exports to the grid. This alignment is one of the contributing factors to the estimated emissions reductions in conjunction with the decrease in grid purchases due to on-site solar generation.

[8] This is the social cost of CO_2 recommended by the U.S. Interagency Working Group on Social Cost of Greenhouse Gases for year 2020 using a 3% discount rate and average values across models and socioeconomic emissions scenarios. (White House, 2023)

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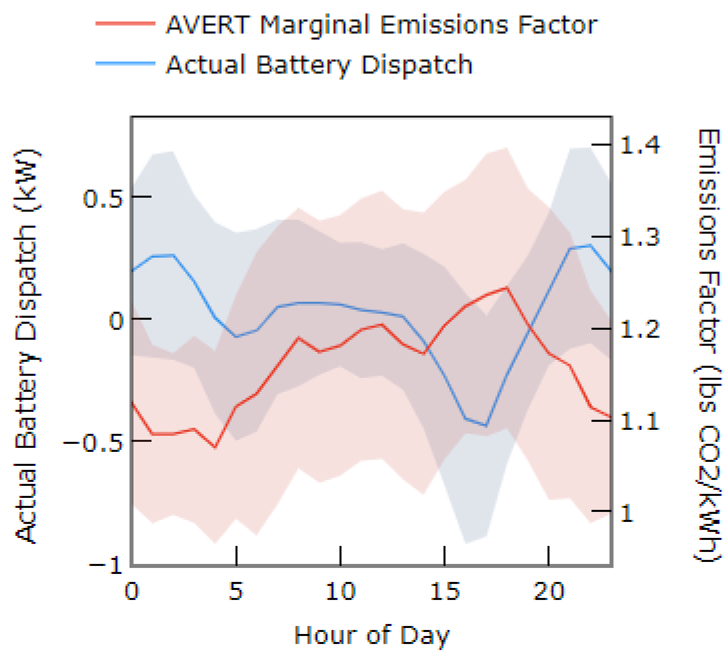

Figure 10. Hourly average battery charging and discharging trends compared to the hourly average AVERT Northeast marginal grid emissions factors.

4.1.5 Existing Benefits Compared to Maximum Achievable Potential

Based on Sections 4.1.1–4.1.4, we can conclude that the exisitng S+S system and the current battery dispatch strategy provide significant economic, system, and emissions reduction benefits. The scorecard for the BAU scenario provides a further understanding of the relative value of the exstitng S+S operation compared to the maximum potential benefits that could be achieved by the system. Because the Baseload scenario, which has no S+S, is used as the baseline for the relative metrics and provides no resilience or grid independence, the petal lengths for the Baseload scenario scorecard are zero, as shown in Figure 11.

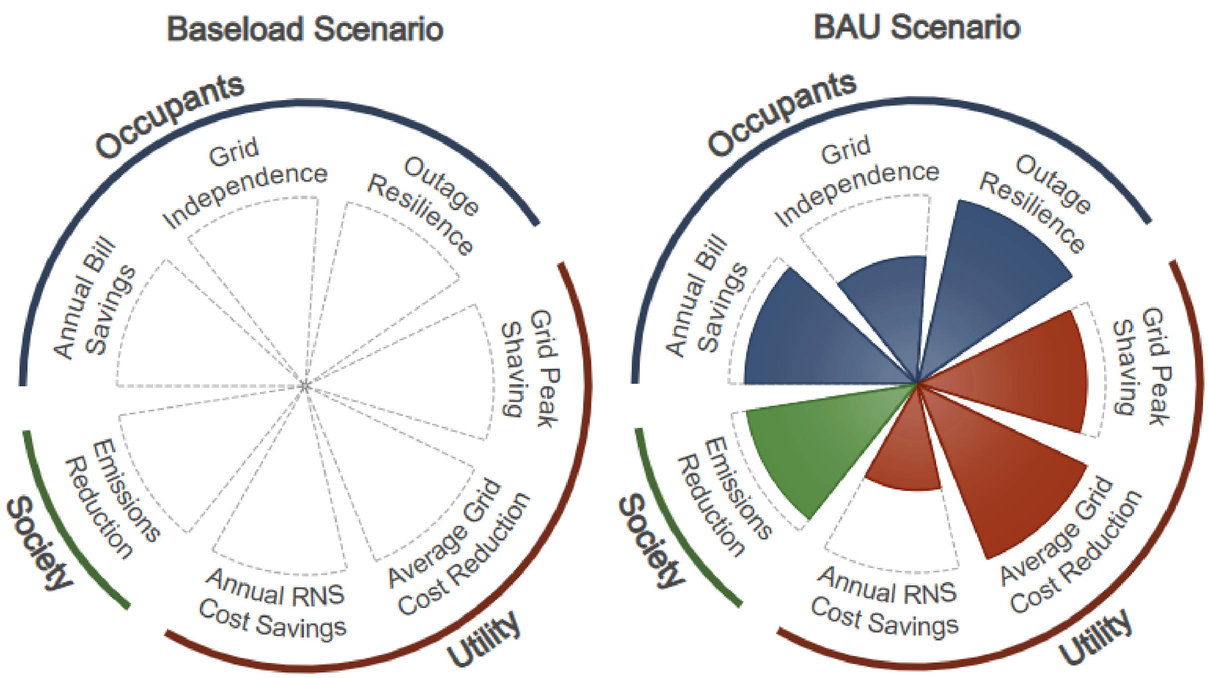

Figure 11. Scorecard for homes without S+S (Baseload scenario; left) and with S+S (BAU scenario; right)

Figure 11 shows how each of the seven metrics perform compared to their respective maximum achievable potential across scenarios. The occupant, utility, and societal metrics reach 77%, 71%, and 84% of the maximum potential. Therefore, the existing S+S systems and the current dispatch strategy provide an average McKnight Lane home with 77% of the maximum potential benefit that can be achieved using these systems. Note that in actuality, it is often not feasible to achieve 100% of the potential benefit determined by REopt, given that REopt has perfect foresight into future energy prices, load, and solar generation when determining the optimal sizing and dispatch strategy. However, this theoretical maximum benefit is useful for assessing the relative performance of real-world S+S and informing where advanced dispatch algorithms could achieve additional value. It is difficult to quantify how much of the theoretical maximum can be achieved in practice since this is generally very location specific and depends on the amount of notice given for some of the drivers, along with the ability and willingness of the occupants to shift loads in response to these drivers.

Further, this figure provides additional context for the comparison between battery dispatch and marginal emissions shown in Figure 10. The existing battery dispatch strategy employed by GMP already provides high emissions reduction (see the "emissions reduction" petal) because of the alignment of battery charging with low marginal grid emissions and battery discharging with high marginal grid emissions.

In the following sections, we will discuss how the metrics and corresponding petals increase or decrease as the system sizes and battery dispatch are optimized.

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4.2 Potential Value Streams Beyond the Existing S+S System

In the following sections, we use modeled results to explore additional value that could be realized by optimizing the S+S dispatch and/or sizing to achieve desired outcomes (Scenarios 3–5).

4.2.1 Isolating Battery Benefits

In the Sized S+S scenario, we allow REopt to size S+S to minimize the life cycle cost of the project. The life cycle cost calculation includes S+S capital and O&M costs, customer energy costs, and the utility's RNS charges. The results reveal that batteries are not cost-optimal for McKnight Lane., i.e., the customer bill savings and utility RNS savings from batteries are not sufficient to offset the capital costs. This is largely due to the utility rate not having a demand rate component, which eliminates an additional value stream that could offset the battery capital costs enough to make the battery cost-optimal. Additionally, we have not considered additional potential utility value streams within the life cycle cost calculation, including offset wholesale costs and annual FCM charges.

It should be noted that, as discussed in Section 3.3, McKnight Lane capital expenses for batteries were heavily subsidized by third parties (parties that are not stakeholders in this study) through grants and were not borne by the occupant. However, in the Sized S+S scenario, we consider capital costs for installing the S+S system as an LCC component even though we do not attribute this cost to any of the three stakeholders. This approach was adopted in order to get an accurate cost-optimal sizing for S+S.

Although we do not find batteries to be cost-optimal for customer savings and reduced RNS charges, they provide significant system benefits, especially when installed in conjunction with solar in comparison to only installing solar. We can identify the metrics that are affected by adding batteries by comparing the scorecards for the Sized S+S scenario (with no battery) to the BAU scenario (which includes S+S). Note that having solar alone does not provide resilience benefits unless the home is specifically wired for islanded operation, which these homes were not.

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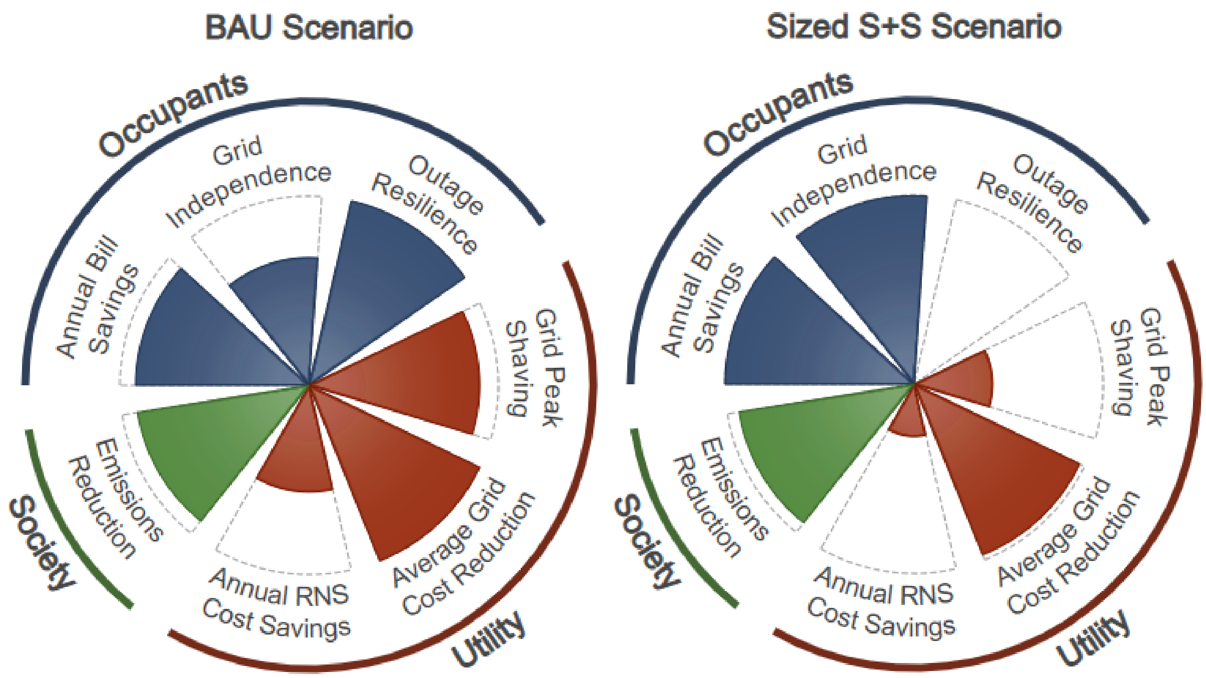

Figure 12. Scorecards for existing S+S sizes (BAU scenario; left) and for optimal S+S sizes (Sized S+S scenario; right). The Sized S+S scenario represents households with only solar PV, as storage was not cost-optimal.

Figure 12 shows the difference in metric values between benefits from S+S compared to benefits from only solar benefits for the McKnight Lane homes. Within the occupant stakeholder group, having solar alone provides the highest possible bill savings and grid independence across all scenarios. This is because the solar production and net metering credits from solar exports are fully applicable to home loads instead of having some portion of the generation used by the battery to charge. Scenarios with alternate compensation to net metering are not included in this report, but do exist in a large number of jurisdictions. However, having only solar provides no resilience compared to 148 hours of resilience with batteries (BAU scenario). Because this benefit is only realized in the event of an outage, depending on the occupant's preference, they may forego the resilience benefits to receive \$89/month in bill savings compared to \$75/month with S+S (assuming these benefits are directly passed down to the tenants).

The batteries in the BAU scenario also slightly increase grid emissions (S+S saw 1.4 metric tons of additional CO_2 emissions per year across all 14 homes compared to solar only). Batteries generally—on a net-annual basis—do not save energy, but rather increase energy use due to inefficiencies with the benefit of being able to shift the timing of energy use.

Utility metrics are where we observe the highest impact if batteries are not present. Unlike solar generation, batteries can be used by the utility to remotely dispatch for the benefit of the grid. GMP's existing dispatch strategy provides them 71% of the maximum possible benefits that can be obtained from the grid. This reduces to 40% with only solar. While this benefit is not insignificant, the utility would be disadvantaged with \$307 in annual RNS savings (which is 76% less than the existing RNS savings (Section 4.1.3)). This is in addition to a 79% reduction in grid peak shaving benefits compared to the BAU scenario. The reduction in grid costs is affected to a

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lesser extent if batteries are not present, signifying that the average grid cost reduction is driven more by solar generation than battery dispatch.

The variations in the metrics between the BAU and Sized S+S scenarios illustrate competing benefits between the occupant stakeholder group and the utility stakeholder group. Having only solar (Sized S+S scenario) favors the occupants, while having S+S favors the utility and the grid. To the extent that these results are applicable to other projects,[9] it is essential to weigh these effects accordingly when determining appropriate S+S sizing.

4.2.2 Benefits from Optimal Battery Dispatch

In REopt, optimal battery dispatch is determined by minimizing any relevant energy costs (e.g., demand, time-of-use, and/or coincident peak charges) by using the battery to shift loads to lower-cost times.[10] Typically, the project economics considered in REopt's objective function do not include the costs to utilities such as the RNS charges or wholesale grid costs. However, we modeled GMP's RNS charges at monthly peaks as coincident peak costs to customers. This allowed REopt to minimize the home loads during these RNS peaks. Because McKnight Lane doesn't have a customer demand charge, the only incentive for the model to dispatch battery is to reduce the home loads during the grid's monthly peaks, thereby reducing GMP's RNS charges stemming from McKnight Lane.

An additional consideration is REopt's perfect foresight about when the monthly system peaks occur. In reality, utilities do not know exactly when the grid peaks will occur and may only have an approximate forecast. To increase the likelihood of dispatching the battery *during* the peak hours, GMP increased the frequency of battery dispatch *around* the peak hours as observed in Figure 13(a). Of further note is the change in GMP's dispatch strategy for the battery from offsetting RNS and FCM charges in 2017 (Figure 13 (a)) to include energy arbitrage starting in mid-2018 (Figure 13(b) and (c)). The figure also shows the optimal dispatch compared to the actual dispatch where we observe REopt dispatching battery exactly during the monthly peaks. One limitation in this modeling is that REopt does not allow battery systems to export to the grid, as the McKnight Lane batteries do to reduce charges to the utility. Therefore, the magnitude of REopt's battery dispatch during monthly peaks is capped by the home load during that hour (as opposed to the actual dispatch magnitude being capped by the battery capacity of 4 kW).

[9] Applicability of these results to other projects depends on several factors, which may include: (i) project financing, (ii) electricity rates and tariff structure, (iii) climate zone, and (iv) grid composition and emissions factors.
[10] An additional driving factor for battery dispatch is climate costs if carbon emissions are valued at a $/metric ton rate. This driver is not applicable for the Optimal Battery Dispatch scenario, but is discussed in more detail in the Climate Costs scenario (Section 4.2.3).

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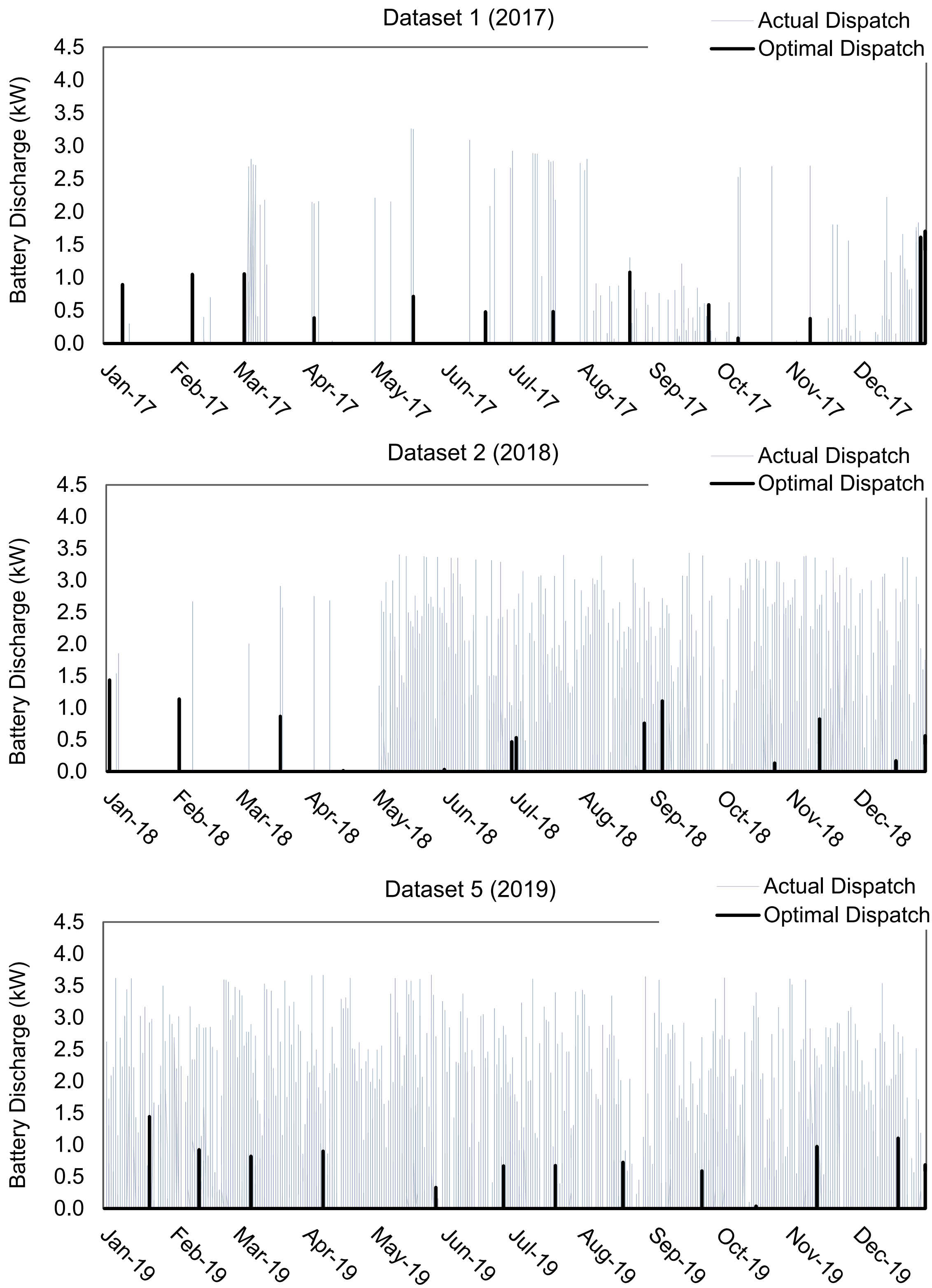

Figure 13. Actual battery dispatch vs. optimal battery dispatch for two datasets in (a) 2017 (b) 2018 and (c) 2019

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To quantify the benefits for all stakeholders of optimizing battery dispatch, we compare the scorecard for the existing benefits to each stakeholder group (BAU scenario) against the scorecard metrics generated using the scenario with optimal battery dispatch (Optimal Battery Dispatch scenario; Figure 14).

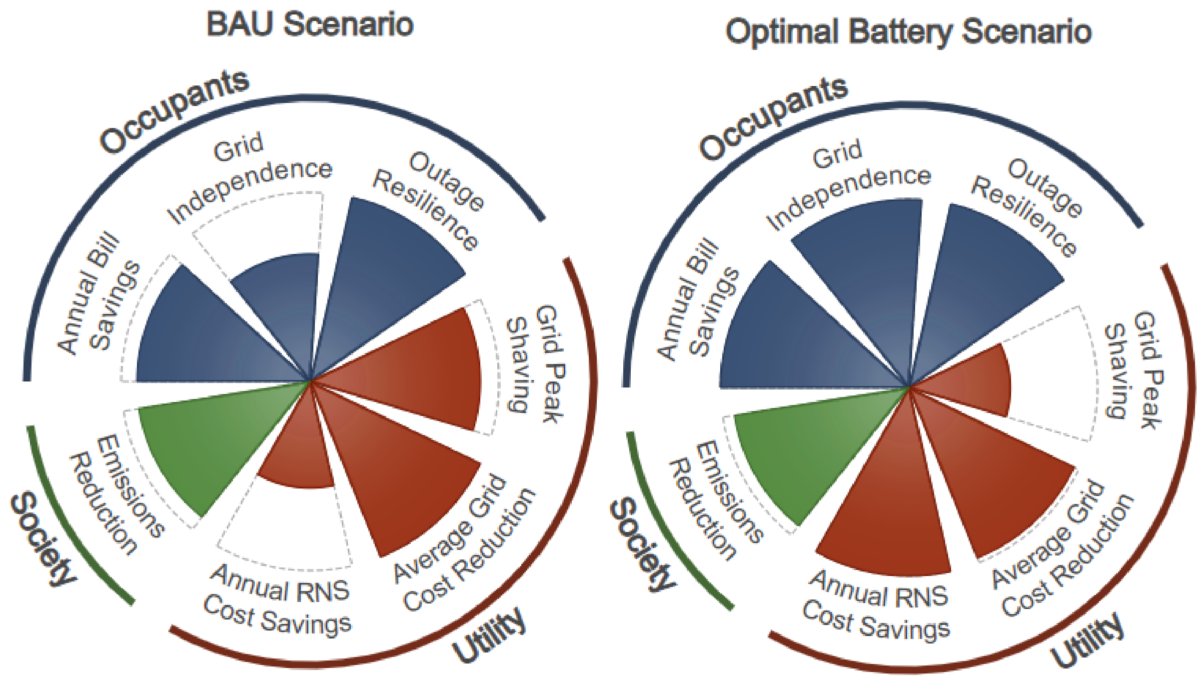

Figure 14. Scorecard for actual battery operations (BAU scenario) and for optimal battery dispatch (Optimal Battery Dispatch scenario)

With optimized battery dispatch (for customer and utility benefits), the McKnight Lane homes would see a $171 increase in annual bill savings and a 17% increase in grid independence compared to actual operations (BAU scenario). This is the maximum potential occupant benefit compared to all other scenarios. These increases are primarily driven by a decrease in the grid purchases to charge the battery.

With the battery dispatching only during the grid peak hours, battery utilization reduces significantly from an average of 4.76% in the BAU scenario to an average of 0.04% for the Optimal Battery Dispatch scenario, as shown in Figure 15. Battery capacity utilization is calculated as:

$$Battery\ Capacity\ Utilization\ (\%) = \frac{Total\ charging\ kWh + Total\ discharge\ kWh}{Battery\ Capacity\ kWh * 8760} * 100\%$$

Because the battery is not dispatched at a high frequency in the Optimal Battery Dispatch scenario, the grid purchases decrease, thereby decreasing the customer burden to bear the cost of these purchases. This decrease in grid purchases is also reflected in the Grid Independence metric, which doubles when the battery dispatch is optimized.

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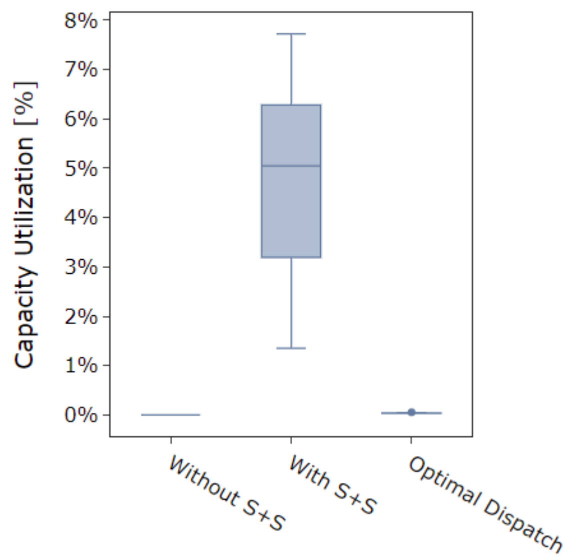

Figure 15. Capacity utilization of batteries across eight datasets for Baseload (homes without S+S), BAU (homes with S+S), and Optimal Battery scenarios

Benefits to the utility stakeholder from REopt-optimized battery dispatch is more mixed. It maximizes the annual RNS savings at $90.43 attributable to an average McKnight Lane home compared to $28.82 with the BAU scenario. This additional savings can largely be attributed to REopt's perfect foresight about when peak hours will occur. Additionally, the REopt model does not export battery energy to the grid and does not consider other grid costs or utility goals within the objective function. This hinders the model's ability to shave the grid peaks by dispatching batteries remotely during the highest LMP hours, which may not occur coincidentally with the RNS peaks. Therefore, we see a higher grid peak contribution (the inverse of grid peak shaving) for the Optimal Battery Dispatch scenario, at 39%, compared to that of the BAU scenario, which is 23%. Therefore, if the utility were to adopt the REopt optimal dispatch strategy for batteries, the contribution of batteries toward grid peak shaving reduces significantly, and although we observe maximum possible RNS savings, taking REopt's perfect foresight into consideration, these benefits may not be reflected in reality.

Our analysis highlights competing priorities when designing battery dispatch strategies. Significant increase in battery discharge (especially as seen in the 2018 and 2019 datasets) decreases the occupant benefits compared to the maximum potential benefit. Conversely, dispatching batteries only for RNS peaks (as seen in the 2017 datasets) decreases the utility benefit compared to the maximum potential benefit. These factors should be weighed accordingly by the stakeholders to arrive at an appropriate dispatch strategy.

4.2.3 Benefits from Dispatching Battery to Minimize Climate Costs

If carbon emissions are valued at a $/metric ton rate, climate costs become an additional driving factor for optimal battery dispatch. In the Climate Costs scenario, we include climate costs of grid emissions (at $51/tCO_2$) in the REopt objective function, along with customer and utility RNS costs. We do not include embodied carbon associated with installing the system. Unsurprisingly, the Climate Costs scenario thus achieves the highest emissions reduction across all scenarios (as illustrated by the extent of the petal in Figure 16).

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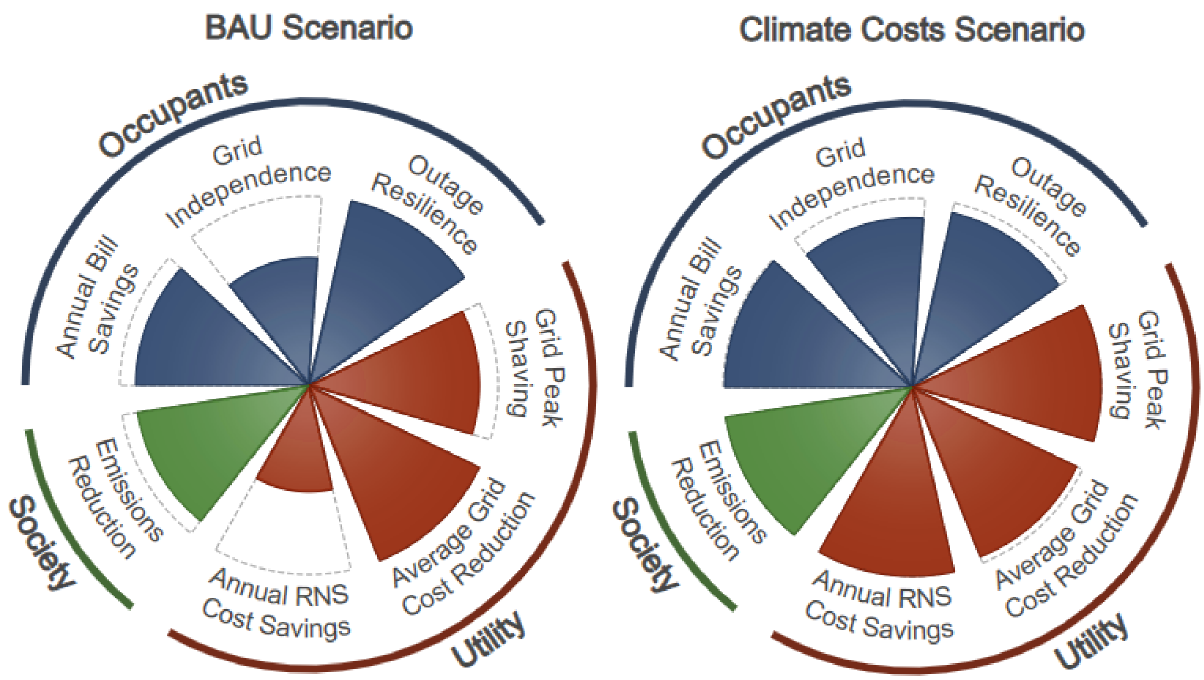

Figure 16. Scorecard for actual battery operations (BAU scenario) and for least climate costs battery dispatch (Climate Costs scenario)

The figure illustrates that maximum emissions reductions can be achieved without significant compromises to utility or occupant benefits. On average, each stakeholder group reaches more than 90% of the maximum achievable potential (in comparison, in the BAU scenario, the metrics average 77% of the maximum extent).

Benefits such as increased grid independence and annual RNS savings were also observed in the Optimal Battery Dispatch scenario (Section 4.2.2). In fact, that scenario saw the maximum possible occupant benefit—unsurprising given that REopt optimizes for least life cycle costs, and thereby maximizes occupant benefits. In comparison, the occupant benefits in the Climate Costs scenario are lower.

Nevertheless, the Climate Costs scenario provides high benefits across all stakeholder groups. Comparing the BAU and the Optimal Battery Dispatch scenarios, we find that the most crucial driving factor is the battery utilization. Achieving maximum emissions reduction via battery dispatch requires more frequent battery dispatch—discharging the battery during hours with higher marginal grid emission factors and charging during hours with lower marginal grid emission factors (Figure 10). This increased frequency compared to the Optimal Battery Dispatch scenario is reflected in the average battery capacity utilization, which is 3.58% for the batteries in the Climate Costs scenario compared to 0.04% in the Optimal Battery Dispatch scenario (Figure 17). The low-capacity utilization in the Optimal Battery Dispatch scenario can be explained by the battery being dispatched for RNS savings only. In contrast, the capacity utilization for the BAU scenario (with GMP's current battery dispatch strategy), is 4.76% on average across all eight datasets.

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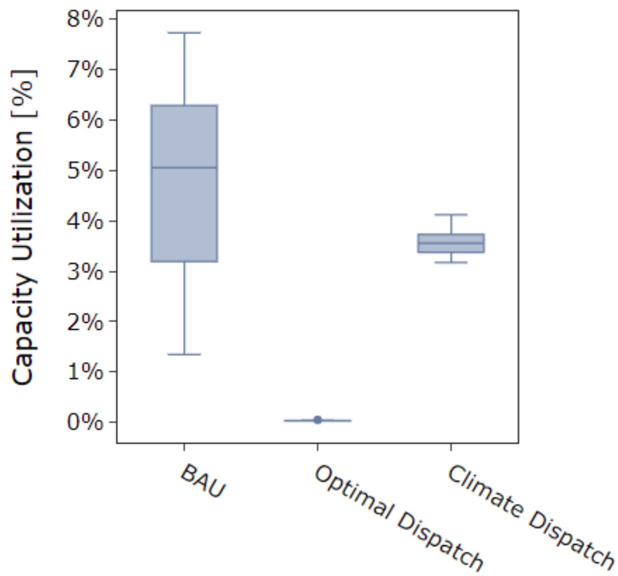

Figure 17. Capacity utilization of batteries across eight datasets for BAU (actual S+S), Optimal Battery Dispatch, and Climate Costs scenarios

The differences in capacity utilization—4.76%, 0.04%, and 3.58%, respectively, for BAU, Optimal Battery Dispatch, and Climate Costs scenarios—and the corresponding average utility benefit in the scorecards—71%, 75%, and 98%, respectively—present us with the following inference: There is certainly an optimal dispatch strategy that GMP can adopt to gain a holistic economic and system benefit. Neither the current strategy of very high savings nor dispatching only for RNS savings provides a high benefit across all utility metrics. However, a moderate frequency of dispatching the battery, and further aligning the dispatch to the marginal grid emissions factors, provide the highest benefits overall.

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5 Conclusions

In this study, we analyzed field data from the McKnight Lane community to quantify the value of the existing S+S systems and used REopt-modeled results to identify the additional value that could be derived from these systems. We developed a novel scorecard for visualizing and communicated these metrics across stakeholder groups using a novel scorecard. The following are key findings from this analysis.

Benefits from the Existing S+S Systems

The findings from this report highlight and validate the significant value provided by solar PV and storage installed in each of the 14 McKnight Lane homes. In analyzing a subset of these homes, we find that the McKnight Lane homes, when compared against equivalent homes without S+S, observe the following benefits:

- An average home sees an 85% ($75 per month) reduction in annual energy bills and 148 hours of resilience from outages (calculated assuming 100% of the load is critical).
- Across all 14 homes, the utility will save approximately $4,035 in RNS savings over the 10-year lifetime of the batteries and an estimated $2,199 per year from reduced grid costs. Additionally, the grid peak contribution from the McKnight Lane community decreases by 52%, thereby reducing its capacity burden on the grid.
- The existing S+S system reduces 32 metric tons of CO_2 per year across all 14 homes. This is a social cost savings of $1,642 per year, at a carbon cost of $51/t CO_2.[8]

Isolating the Benefits from the Storage

Comparing the benefits from installing only solar PV to the benefits from installing both solar and storage (i.e., Sized S+S versus BAU scenarios) in McKnight Lane homes, we find that the batteries provide significant system benefits.

- S+S systems provide the occupants with 148 hours of resilience compared to solar only, which provides no resilience benefits as these homes are not designed for islanded operation off of solar alone. Additionally, the utility sees 76% higher RNS savings and 79% higher grid peak shaving benefits with S+S compared to only installing solar.

However, solar-only homes would see higher occupant bill savings (19% more savings) and grid independence (17% higher) compared to the existing S+S homes. This is because there is no battery, and consequently, no need for some of the solar generation to be used to charge the battery.

Benefits from Optimal Battery Dispatch

Optimizing battery dispatch for customer and grid benefit through REopt (Optimal Battery Dispatch scenario) discharges the battery only during the RNS hours, which is a significantly lower frequency than GMP's existing dispatch strategy. With REopt's perfect foresight and customer-focused objective function in mind, this optimized dispatch strategy increases the occupant benefits substantially. The McKnight Lane homes would see a $171 increase in annual bill savings and a 17% increase in grid independence as compared to existing battery dispatch.

Benefits to the utility stakeholder from REopt-optimized battery dispatch is more mixed, with annual RNS savings tripling but the grid peak shaving benefits reducing to one-third of that observed from existing battery dispatch strategy.

Benefits from Dispatching Battery to Minimize Climate Costs

The Climate Costs scenario provides high benefits across all stakeholder groups, with the utility seeing the highest relative benefit. Compared to the existing battery dispatch strategy, dispatching battery in further alignment with the grid emissions factors would increase occupant benefits by 6%, utility benefits by 77%, and emissions reductions by 17%.

Impacts of Energy Arbitrage

From the timeseries data, it is notable that the battery dispatch strategy was ostensibly changed from dispatching for RNS and FCM savings to being dispatched for energy arbitrage. This was also observed in the high battery capacity utilization in the existing S+S systems. This study investigated how capacity utilization affects the benefits provided by the batteries. High battery utilization, while providing substantial benefits for the utility, decreases the occupant and societal benefits. Low battery utilization (such as in the case of the Optimal Battery Dispatch scenario) has the potential to maximize occupant benefits but has more mixed impact on the grid and societal benefits. We identified that a moderate frequency of battery dispatch and alignment of battery dispatch to the grid emissions factors maximizes the utility savings while not reducing the benefits for other stakeholders.

Conclusions from Scorecards

To facilitate the understanding of various value streams, benefits, and the impact of economic and system drivers for S+S systems, we developed a novel scorecard concept that presents results in a graphical format. Figure 18 summarizes the scorecards for various scenarios. By comparing the scorecards of the modeled scenarios to the BAU scenario, we arrive at the following conclusions:

- The variations in the metrics between the BAU and Sized S+S scenarios illustrate competing benefits between the occupant stakeholder group and the utility stakeholder group. Having only solar favors the occupants, while having S+S favors the utility and the grid. The metrics identified in this study would allow stakeholders in future projects to weigh these effects accordingly when determining appropriate S+S sizing.

- Comparing the scorecards for the BAU, Optimal Battery Dispatch, and Climate Costs scenarios highlights competing priorities when designing battery dispatch strategies (as discussed above in impacts of battery arbitrage). A high battery utilization decreases the occupant benefits compared to the maximum potential benefit (BAU). Dispatching batteries only for RNS peaks decreases the utility benefit compared to the maximum potential benefit (Optimal Battery Dispatch). In contrast, modeling battery dispatch strategy to align with minimizing climate emissions provides high benefits across all stakeholders. These factors should be weighed accordingly by the stakeholders to arrive at an appropriate dispatch strategy.

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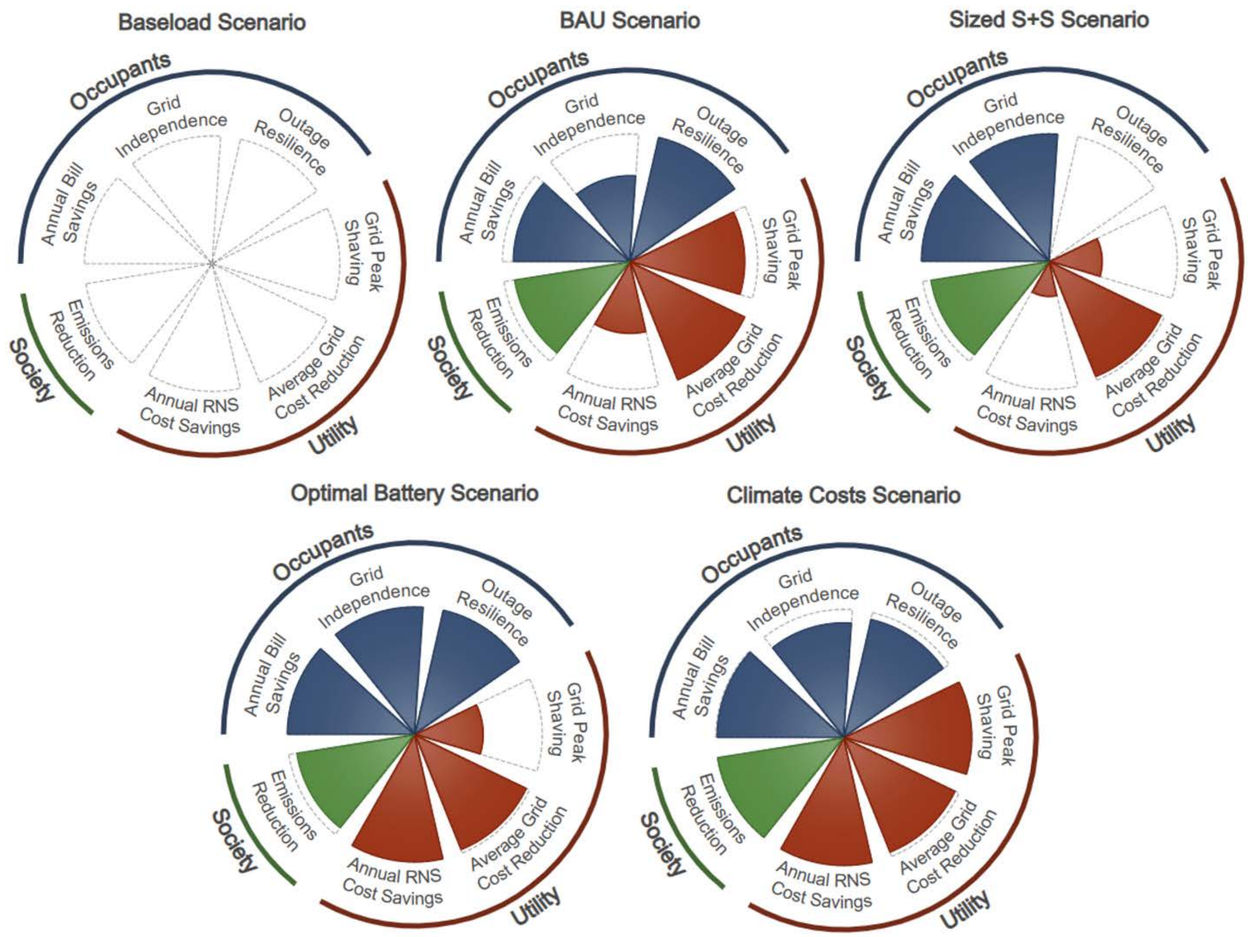

Figure 18. Scorecards for all scenarios visualizing various drivers and impacts of strategies adopted in various scenarios

In addition to identifying and communicating the drivers and impacts of various operation strategies for the McKnight Lane community, these scorecards also provide valuable insights for future projects. By comparing the scorecards of the modeled scenarios to the BAU scenario, we are able to identify additional nuances regarding competing priorities and scenario-specific areas that require equitable distribution of benefits. To the extent that the analysis framework can be applied and reproduced in other project sites, it is essential to weigh these drivers and resulting effects accordingly when determining an appropriate and equitable battery dispatch strategy and S+S sizing.

In conclusion, for the McKnight Lane community, the current benefits experienced by the occupants, utility and grid, and society at large are considerable. Although when compared to the modeled scenarios some room for improvements and equitable distribution of benefits could be identified, the existing benefits from the current S+S operations are exemplary.

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Appendix A. REopt Analysis and Results

This appendix provides additional details and assumptions used to develop the REopt models for the eight datasets identified in Table 1. Table A-1 presents the building and equipment characteristics of the modeled datasets, and Table A-2 presents the REopt model inputs and assumptions.

Table A-1. Characteristics of modeled homes

Home #	1	2	3	4	5	6
Data years modeled	2017, 2018	2019	2017	2019	2018, 2019	2018
Home square footage [ft^2]	930	930	930	930	930	930
Solar PV size [kW]	6	6	6	6	6	6
Storage size [kW/kWh]	4/6	4/6	4/6	4/6	4/6	4/6
PV azimuth (degrees)	135	135	90	135	315	270
Maximum PV capacity (based on rooftop area available) [kW]	7.5	7.5	7.5	7.5	7.5	7.5
HVAC size [tons]	1.2	1.2	1.2	1.2	1.2	1.2
Water heather size [gal]	65	65	65	65	65	65

REopt Analysis Assumptions

Each of the eight datasets (Table A-1)was modeled in REopt under varying scenarios, described in Section 3.1.2. Table A-2 summarizes the REopt assumptions used in modeling these homes.

Table A-2. REopt analysis assumptions

Electric utility parameters	Value	Reference
Utility rate	General Service Rate 6	
Net metering limit	500 kW	
Net metering compensation for export up to annual home load	\$0.17945/kWh (Rate 6 energy charge)	
Net metering compensation for export above annual site load	\$0.17650/kWh (Rate 1 energy charge)	
Regional Network Service charges and event hours	See Table 2	

PV parameters	Value	Reference
Array type	Rooftop, fixed	(Dobos, 2014)
Array azimuth	Various (based on individual homes) See Table 8	
DC-to-AC size ratio	1.2	(Dobos, 2014)
System losses	14%	(Dobos, 2014)
Capital cost	\$1600/kW-DC	(National Renewable Energy Laboratory, 2020)
O&M cost	\$16/kW/year	(National Renewable Energy Laboratory, 2020)
Incentives	5 years MACRS (100% bonus depreciation); 26% ITC	(Anderson K. , et al., 2021)
Performance-based incentive	\$0.053/kWh	

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Battery parameters	Value	Reference
Rectifier efficiency	96%	(Patsios, et al., 2016)
Round-trip efficiency	97.5%	(Patsios, et al., 2016)
Inverter efficiency	96%	(Patsios, et al., 2016)
Minimum state of charge	10%	(Patsios, et al., 2016)
Battery life	10 years	(DiOrio, Dobos, & Janzou, 2015)
Energy capacity cost	$354/kWh	(Boomberg New Energy Finance, 2020)
Energy replacement cost	$170/kWh	(Boomberg New Energy Finance, 2020)
Power capacity cost	$1690/kW	(Boomberg New Energy Finance, 2020)
Power replacement cost	$840/kW	(Boomberg New Energy Finance, 2020)
Incentives	5 years MACRS (100% bonus depreciation); 23.4% ITC	(Anderson K. , et al., 2021)

General economic parameters	Value	Reference
Analysis period	25 years	(National Renewable Energy Laboratory, 2020)
Ownership model	Third-party ownership	-
Host discount rate (nominal)	5.5%	(National Renewable Energy Laboratory, 2020)
Host effective tax rate	26%	(Anderson K. , et al., 2021)
Electricity cost escalation rate (nominal)	2.3%	(Energy Information Administration, 2020)
O&M cost escalation rate	2.5%	(National Renewable Energy Laboratory, 2020)

Health and climate parameters	Value	Reference
Social cost of CO_2 in first year	$51/ton	(Interagency Working Group on Social Cost of Greenhouse Gases, 2021)
Annual escalation of social cost of CO_2	1.78%	(Interagency Working Group on Social Cost of Greenhouse Gases, 2021)
Carbon dioxide emissions	AVERT 2019 hourly dataset (marginal) for Northeast Region	(EPA, 2020)

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Appendix B. Detailed Metrics Results

Table B-1 presents the actual metric values for each of the scenaios evaluated for each dataset in Table 1. Some of these metrics are the absolute metrics from which the relative metrics in Table 6 are calculated. To arrive at the scorecard metrics in Table 7, subtract the Baseload scenario metric values from each scenario's metric values below. Note that since indoor temperature was not measured, comfort penalties could not be quantified in this study.

Table B-1. Metric values for each home and each scenario

DATASET 1 (HOME 1; 2017)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$853.65	0.0000	0	$89.36	44.82%	$0.0442	1.574	
BAU	-$167.20	0.2674	458.12	$67.21	19.32%	$0.0017	-0.727	
Optimal Battery Dispatch	-$213.03	0.3267	367.58	$0.00	36.41%	$0.0032	-0.810	
Climate Costs	-$197.29	0.2529	341.76	$0.00	13.30%	$0.0033	-1.096	
Sized S+S	-$212.18	0.3237	1.99	$81.19	37.66%	$0.0035	-0.808	

DATASET 2 (HOME 2; 2018)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$1,270.82	0.0000	0	$80.85	53.37%	$0.0493	2.656	
BAU	$111.25	0.3093	105.81	$45.12	22.24%	$0.0096	-0.177	
Optimal Battery Dispatch	-$60.34	0.4626	117.55	$0.00	42.14%	$0.0118	-0.282	
Climate Costs	-$39.99	0.3919	105.12	$0.00	18.11%	$0.0125	-0.671	
Sized S+S	-$59.85	0.4612	1.69	$69.57	45.58%	$0.0118	-0.280	

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DATASET 3 (HOME 2; 2019)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$1,001.70	0.0000	0	$75.78	41.66%	$0.0384	1.943	
BAU	$150.47	0.0696	244.18	$61.63	29.88%	$0.0091	-0.271	
Optimal Battery Dispatch	-$32.13	0.2622	268.79	$0.00	37.80%	$0.0105	-0.364	
Climate Costs	-$14.65	0.1991	250.19	$0.00	18.50%	$0.0109	-0.668	
Sized S+S	-$30.96	0.2607	1.86	$71.02	39.65%	$0.0105	-0.361	

DATASET 4 (HOME 3; 2017)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$900.94	0.0000	0	$76.07	51.71%	$0.0433	1.685	
BAU	-$91.84	0.1790	129.61	$68.80	19.76%	$0.0035	-0.593	
Optimal Battery Dispatch	-$158.37	0.2701	131.62	$0.00	41.41%	$0.0053	-0.681	
Climate Costs	-$142.02	0.2111	109.07	$0.00	14.62%	$0.0057	-0.983	
Sized S+S	-$157.73	0.2676	1.95	$69.83	43.96%	$0.0056	-0.679	

DATASET 5 (HOME 4; 2019)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$1,113.71	0.0000	0	$92.40	35.94%	$0.0364	2.234	
BAU	$286.03	0.0696	63.73	$58.58	21.37%	$0.0093	-0.072	
Optimal Battery Dispatch	$20.70	0.3078	80.03	$0.00	32.33%	$0.0106	-0.208	
Climate Costs	$38.75	0.2498	69.58	$0.00	17.51%	$0.0110	-0.546	
Sized S+S	$21.40	0.3059	1.7	$86.98	33.84%	$0.0107	-0.205	

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DATASET 6 (HOME 5; 2018)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$1,109.39	0.0000	0	$117.21	56.47%	$0.0571	2.257	
BAU	$284.44	0.0981	72.59	$70.86	27.29%	$0.0203	0.084	
Optimal Battery Dispatch	$87.11	0.2895	82.71	$0.00	41.42%	$0.0226	-0.007	
Climate Costs	$103.28	0.2413	73.42	$0.00	20.54%	$0.0235	-0.327	
Sized S+S	$87.69	0.2877	1.72	$112.08	51.33%	$0.0226	-0.005	

DATASET 7 (HOME 5; 2019)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$1,080.13	0.0000	0	$104.97	47.25%	$0.0360	2.124	
BAU	$342.27	0.0161	59.41	$68.46	20.57%	$0.0098	0.024	
Optimal Battery Dispatch	$86.82	0.2592	77	$0.00	37.45%	$0.0116	-0.096	
Climate Costs	$104.85	0.2048	61.92	$0.00	17.28%	$0.0121	-0.425	
Sized S+S	$88.14	0.2576	1.66	$99.92	45.26%	$0.0117	-0.093	

DATASET 8 (HOME 6; 2018)

Scenario	Annual Bill [$]	Cover Factor Demand	Average Resilience [Hours]	Annual RNS Cost [$]	Grid Peak Contribution [%]	Average Grid Cost [$/kWh]	Annual Emissions [tCO2]	Annual Comfort Penalty [$]
Baseload	$1,123.93	0.0000	0	$86.83	53.91%	$0.0538	2.282	
BAU	$350.81	0.1292	53.27	$52.23	25.57%	$0.0192	0.254	
Optimal Battery Dispatch	$164.20	0.3081	60.83	$0.00	45.24%	$0.0214	0.159	
Climate Costs	$183.64	0.2492	52.5	$0.00	19.66%	$0.0221	-0.193	
Sized S+S	$164.84	0.3062	1.52	$77.66	45.24%	$0.0214	0.161	

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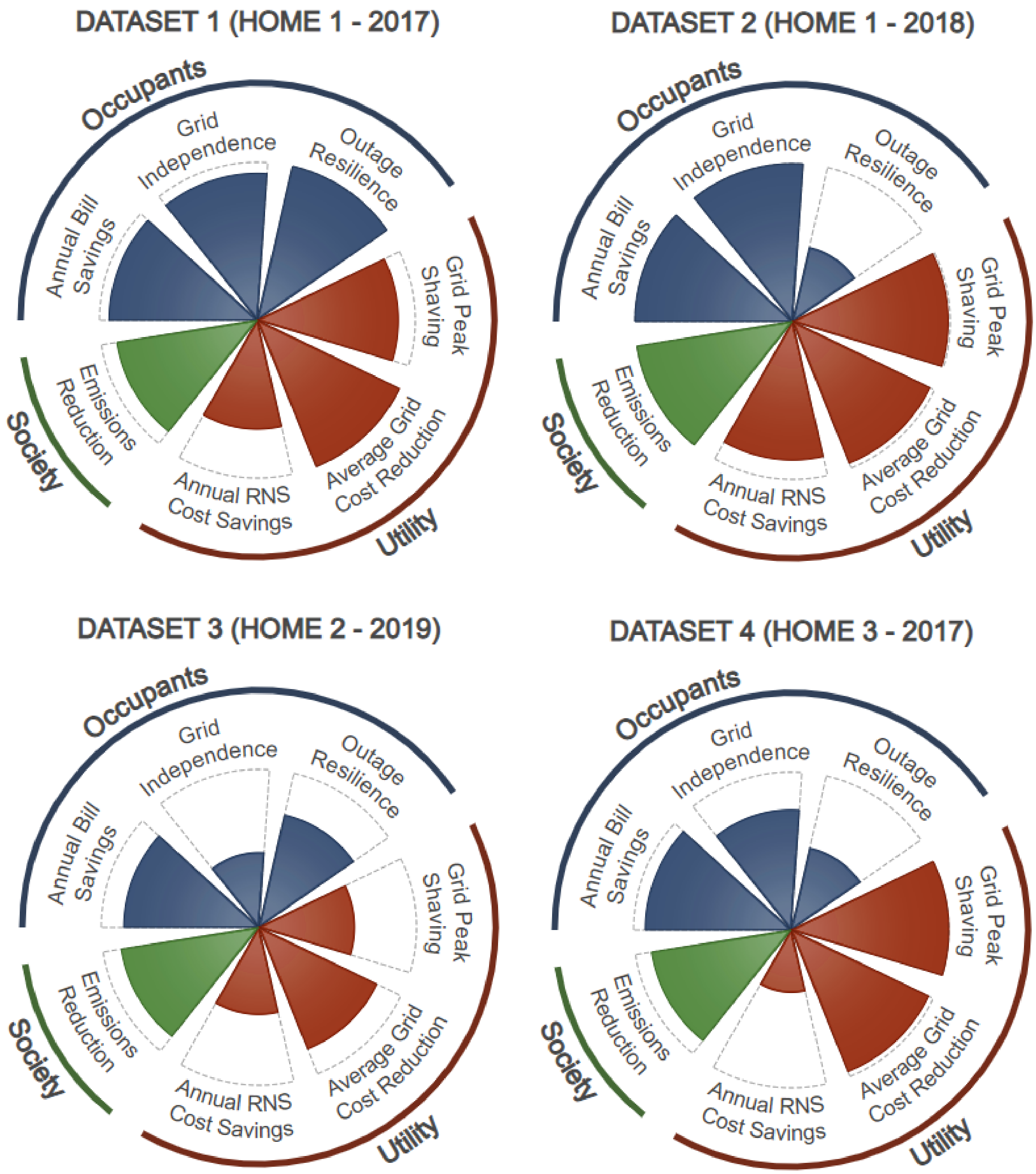
Scorecards for Individual Homes for Existing S+S

To compare the existing benefits from S+S (i.e., BAU scenario) for individual datasets in Table 1 against the Baseload scenario—which has zero benefits—we produced scorecards of the seven metrics identified in Table 6. Comapring these scorecards against each other, we can percieve the differences in benefits between homes and years by stakeholder group.



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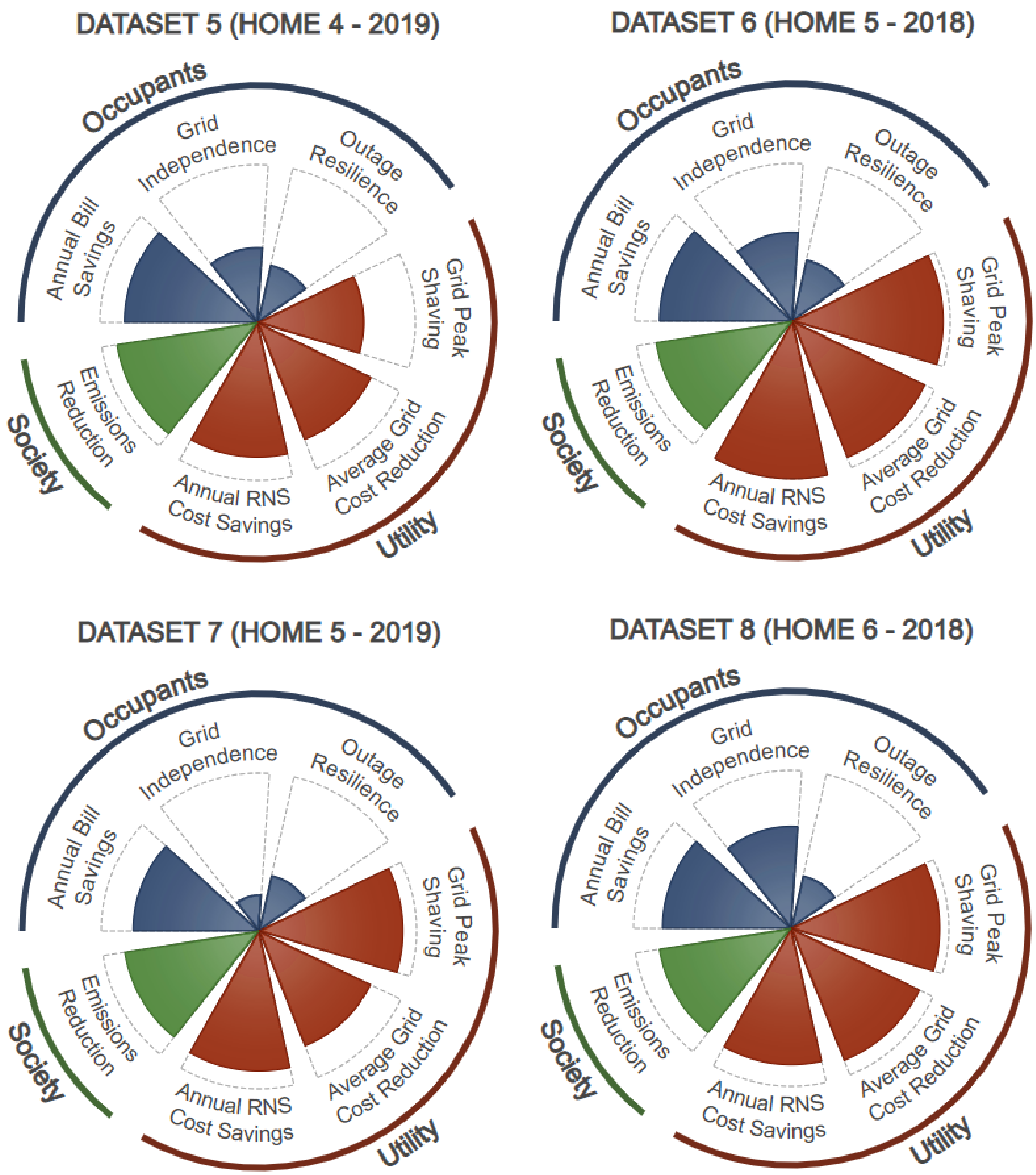

Figure B-1. Scorecards for individual datasets for the BAU scenario compared to the Baseload scenario

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