ComStock Measure Documentation: Photovoltaics With 40% Rooftop Coverage and Battery Storage

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List of Acronyms

AC	alternating current
CBECS	Commercial Buildings Energy Consumption Survey
DC	direct current
EIA	U.S. Energy Information Administration
GW	gigawatt
GWh	gigawatt-hour
HVAC	heating, ventilating, and air conditioning
kBtu	thousand British thermal units
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
lb	pound
MMBtu	million British thermal units
MMT	million metric tons
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
PADD	Petroleum Administration for Defense District
PV	photovoltaics
TBtu	trillion British thermal units
URDB	Utility Rate Database
USD	U.S. dollars
Wh	watt-hour

Executive Summary

Building on the 3-year effort to calibrate and validate the U.S. Department of Energy's ResStock™ and ComStock™ models, this work produces national datasets that empower analysts working for federal, state, utility, city, and manufacturer stakeholders to answer a broad range of questions regarding the U.S. commercial building stock, such as the mass adoption of rooftop solar photovoltaics (PV) with battery storage, the focus of this report.

ComStock is a highly granular, bottom-up model that uses various data sources, statistical sampling methods, and advanced building energy simulations to estimate the annual subhourly energy consumption of the commercial building stock across the United States. The "baseline" model intends to represent the U.S. commercial building stock as it existed in 2018. The methodology of the baseline model is discussed in the ComStock Reference Documentation.

The goal of this work is to develop energy efficiency and demand flexibility measures that cover market-ready technologies and study their mass adoption impact on the baseline building stock. "Measures" refers to various "what-if" scenarios that can be applied to buildings. The results for the baseline and measure scenario simulations are published in public datasets that provide insights into building stock characteristics, operational behaviors, utility bill impacts, greenhouse gas emissions, and annual and subhourly energy usage by fuel type and end use.

This report describes the modeling methodology for a single end-use savings shape measure—PV With 40% Rooftop Coverage and Battery Storage—and briefly introduces key results. The full ComStock public dataset can be accessed via the ComStock data lake or the data viewer at comstock.nrel.gov. The public dataset enables users to create custom aggregations of results for their use cases (e.g., filtering to a specific county).

Key modeling assumptions and technology details are summarized in Table ES-1.

Table ES-1. Summary of Key Modeling Specifications

Measure Scenario Description	• This study investigates the impact of adding 40% rooftop PV coverage with battery storage to the U.S. commercial building stock. This amounts to ~394 gigawatts (GW) of installed rated PV capacity, 553 gigawatt-hours (GWh) of battery energy storage, and 123 GW of battery power. • Net metering impacts on calculated utility bills are not included in this study. For these metrics, the PV panels simply reduce the electricity demand on the building meter at the time of generation, or charge the battery system, with no resale back to the utility. However, the ComStock public dataset includes excess PV generation, enabling users to estimate these impacts as needed. • This report extends the previously released ComStock measure scenario study—Photovoltaics With 40% Rooftop Coverage [1]. The only difference in the current study is the addition of battery storage to the PV system.
Performance Assumptions	• Battery storage is sized per building model based on installed rated PV direct current (DC) capacity and building type following the guidance of California Energy Commission Title 24 [2]. • Batteries are controlled to charge when PV generation exceeds building electrical

	demand and discharge when building electrical demand is greater than PV generation. • PV panels are modeled as higher performance with 21% rated efficiency, 96% inverter efficiency, 1.10 direct current/alternating current (DC/AC) ratio,14% system losses, and azimuth/tilt angles that vary by location. • Total panel area is modeled at 40% of the roof area for each model. Total rated PV power for a building is based on the calculated total panel area and the assumed efficiency of 21%.
Applicability	This measure is applied to all ComStock models.
Release	2025 Release 2: 2025/comstock_amy2018_release_2/

National annual results for site energy and energy bills are summarized in Table ES-2 and Table ES-3.

Table ES-2. Summary of Key Results for Annual Site Energy Savings

"Applicable" buildings are those that receive the upgrade based on the criteria defined for this study. TBtu = trillion British thermal units.

Fuel Type	Absolute Savings [TBtu]	Baseline Total (All Buildings) [TBtu]	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only) [TBtu]	Percent Savings (Applicable Buildings Only)
Natural Gas	0.0	1562.7	0.0	1562.7	0.0
Electricity (Purchased)	1360.7	3249.5	41.9	3248.3	41.9
Other Fuel	0.0	54.5	0.0	54.5	0.0

Table ES-3. Summary of Key Results for Annual Utility Bill Savings

Electricity bill savings in this table are calculated using the mean available electricity rate available for each building. Other electricity rate structures are available in this report and in the public dataset. "Applicable" buildings are those that receive the upgrade based on the criteria defined for this study. USD = U.S. dollars.

End Use/Fuel Type	Absolute Savings [Billion USD, 2022]	Baseline Total (All Buildings) [Billion USD, 2022]	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only) [Billion USD, 2022]	Percent Savings (Applicable Buildings Only)
Natural Gas	0.0	17.8	0.0	17.8	0.0
Electricity (Purchased)	41.5	109.8	37.8%	109.8	37.8%
Fuel Oil	0.0	0.7	0.0	0.7	0.0
Propane	0.0	1.0	0.0	1.0	0.0
Total	41.5	129.3	32.1%	129.3	32.1%

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1 Introduction

This report extends the previously released ComStock measure scenario study—*Photovoltaics With 40% Rooftop Coverage* [1]. The only difference in the current study is the addition of battery storage to the PV system.

Photovoltaics (PV) are an energy generation technology that has seen a sharp increase in adoption in recent years. Much of the increased penetration rate is attributed to the reduced costs and improved efficiency of modern PV modules [3]. State-of-the-art modules are now approaching nearly 25% efficiency, compared to less than 10% efficiency in the 1980s [4].

Despite increased overall PV adoption rates, commercial buildings still use PV at relatively low rates. According to the 2018 Commercial Buildings Energy Consumption Survey (CBECS), fewer than 2% of commercial buildings have on-site PV [5]. This statistic might have increased since the survey was conducted. However, it still underscores the potential to reduce electricity consumption—and subsequently energy costs—through widespread adoption of rooftop PV in commercial buildings.

Commercial buildings generally have flat roofs, with fewer than 10% of the building stock having a pitched roof [5]. Ballasted PV panels can be placed on flat roofs at the preferred pitch and azimuth angle for the location to maximize energy and/or cost reduction. Pitched roofs generally require a system that mounts into the roof. Some commercial buildings use a portion of the roof for heating, ventilating, and air conditioning (HVAC) and other equipment, so PV panels would have to work around these constraints. Rooftops can also be used for occupant space, such as rooftop patios, so these areas would need to be avoided as well. Additionally, with any configuration, proper access pathways must be maintained. Thus, although there is notable commercial building rooftop area available, some of these areas would not be applicable for PV panels.

Battery storage enables buildings to utilize more of the PV generated on-site, as it allows electricity to be stored during times where there is excess generation beyond the current needs of the building. This energy can then be used during periods when the building demand is more than PV generation, effectively reducing the electricity sent back to the grid and subsequently the electricity purchased from the utility. This can be financially beneficial when the cost to purchase electricity is more than what the utility pays for excess electricity sent back to the grid, often called net metering, or if the PV system is not grid connected [6]. One study found that PV with storage can be more financially effective for projects where there are demand charges or time of use pricing and/or where electricity is generally more expensive (e.g., over $0.30/kWh) [7]. Note that the referenced study assumes battery discharging algorithms intended to optimize operation for when electricity is most expensive or timed to shave peak demand.

There are numerous schemes for sizing and designing PV + battery storage systems. Two key factors in battery design are storage capacity and power capacity. Storage capacity, often measured in kilowatt-hours (kWh), indicates how much energy the battery can hold. Power capacity, often measured in kilowatts (kW), refers to how quickly the battery can deliver that energy. Sizing battery storage systems is not trivial, especially since building owners may have different goals. Commonly, the goal is to maximize the life cycle cost savings of the system [6], but there are other potential sizing goals. One might prioritize resilience, while another may focus on maximizing life cycle cost savings. These two goals could lead to different battery system designs, even for the same building.

The California Energy Commission 2022 Building Energy Efficiency Standards include requirements for sizing battery systems, summarized in Table 1, Wh = watt-hour.

Equation *1*, and Equation 2 [2]. These requirements are intended to size battery systems relative to the photovoltaic (PV) system capacity and building primary use. Note there are numerous other schemes for this, including full life cycle cost assessments for specific projects.

Battery energy capacity (measured in kilowatt-hours) represents the total amount of energy a battery can store and is calculated using the rated DC capacity of the PV system, a building-type-specific energy capacity factor (Factor B), and the battery's round-trip efficiency (Wh = watt-hour.

Equation *1*). This ensures the system can store a meaningful amount of energy relative to the scale of solar generation and typical building loads.

Battery power capacity (measured in kilowatts, or kW) reflects the maximum rate at which the battery can discharge energy. It is calculated by multiplying the PV system size by a power capacity factor (Factor C), which also varies by building type (Equation 2). This ensures the battery can deliver energy at a rate suitable for the building's operational needs during discharge events.

Table 1. Energy and Power Capacity Requirements for PV Battery Storage Required by the CEC by Building Type [2]

Building Type	Factor B: Energy Capacity Factor (Wh/W)	Factor C: Power Capacity Factor (W/W)
Grocery	1.03	0.26
High-Rise Multifamily	1.03	0.26
Office, Financial Institutions, Unleased Tenant Space	1.68	0.42
Retail	1.03	0.26
School	1.87	0.46
Warehouse	0.93	0.23
Auditorium, Convention Center, Hotel/Motel, Library, Medical Office Building/Clinic, Restaurant, Theater	0.93	0.23

Wh = watt-hour.

Equation 1. Batter energy capacity calculation from [2]

$$kWh\_batt = kW\_PVdc \times B / \sqrt{D}$$

Where:

- *kWh_batt* = Rated usable energy capacity of the battery storage system (in kWh)
- *kW_PVdc* = Required PV system capacity (in kWdc)
- *B* = Battery energy capacity factor (from Table 1, varies by building type)
- *D* = Rated single charge-discharge cycle AC to AC (round-trip) efficiency of the battery storage system.

Equation 2. Battery power capacity calculation from [2]

$$kW\_batt = kW\_PVdc \times C$$

Where:

- *kW_batt* = Rated power capacity of the battery storage system (in kWdc)
- *kW_PVdc* = Required PV system capacity (in kWdc)
- *C* = Battery power capacity factor (from Table 1, varies by building type)

There are various control schemes for charging and discarding battery storage systems. Ultimately, the choice of control strategy balances the goal of minimizing life cycle costs of the PV-plus-battery system with the practical challenges of implementing more complex controls [6], [7]. Utility rate structure, especially those with the prevalence of time of use pricing, heavily influences the control scheme financial outcomes[7]. One simple method is to charge the battery when the PV system is generating more electricity than the building is using—storing the excess energy that otherwise would have been curtailed or sent back to the grid—and then discharging the battery when the building electricity demand is higher than the PV generation. This can be more financially beneficial than net metering alone, depending on the electricity rate structure and net metering rates for PV. Another option is to control the discharging based on electricity rate structure where the discharging intents to align with when electricity is most expensive, or to control peak demand charges. Additionally, the battery could also be charged using grid electricity during cheaper times when time of use rates are in effect.

This ComStock measure scenario analyzes the impact of mass rooftop PV adoption—40% rooftop coverage on all commercial buildings— plus battery storage, for the U.S. commercial building stock.

2 ComStock Baseline Approach

The ComStock baseline model does not currently include PV. However, according to the 2018 CBECS, fewer than 2% of commercial buildings have on-site PV [5]. Thus, although this study does not account for buildings that already have PV, the impact of this prevalence is likely minimal.

ComStock assumes all roofs to be flat. Flat roofs are not required for commercial PV, but the roof style can impact the panel mounting type and possibly the panel angle. This work does not consider these potential constraints and assumes any panel angle can be used on every roof. Additionally, ComStock does not currently include shading from neighboring buildings and trees. Although many commercial buildings do not have notable shading limitations, this analysis may overestimate the potential of PV for those that do. This may be particularly impactful for buildings with lower heights than their neighbors or surrounding wooded areas.

3 Modeling Approach

3.1 Applicability

The rooftop PV measure scenario is applicable to all models in the ComStock baseline. No building models are excluded. In practice, some commercial buildings may be less suitable for rooftop PV (e.g., the roof does not have 40% of the area available for PV), which these applicability criteria do not consider. In addition, as mentioned, the ComStock baseline does not currently include the estimated <2% of commercial buildings that already have PV. Therefore, this study likely slightly overestimates the potential for mass commercial rooftop PV adoption in the stock.

3.2 Measure Scenario Modeling Methodology

This study uses PVWatts® EnergyPlus objects and follows the same methodology as a comparable ComStock study (rooftop PV measure) [1], with the key difference being the inclusion of battery storage in the current analysis. PVWatts is a National Renewable Energy Laboratory (NREL) developed tool that estimates the energy production of PV systems [8]. The workflow takes the baseline ComStock energy models, representing the building stock of 2018, and applies PVWatts objects with total power levels corresponding to 40% of each model's roof area. The panels are fixed with no tracking. Battery storage is then added according to Equations 1 and 2. This workflow is repeated for all ComStock models. The individual performance assumptions for the PV modules are summarized in **Error! Reference source not found.** and described in the following sections.

Table 2. Summary of Assumptions for PV Modeling

Parameter	Value
Inverter Efficiency	96%
DC/AC Ratio	1.10
System Losses	14%
Panel Rated Efficiency	21%
Panel Area	40% of roof area
Title and Azimuth	Varies by latitude
Battery Capacity	Varies by rated PV capacity and building type
Battery Power	Varies by rated PV capacity and building type

3.2.1 Rated PV Module Rated Power

The rated PV system power in the models is based mainly on panel efficiency, which is assumed here to be 21% to reflect the high-performance options commonly available today. This matches the "premium" panel efficiency in the PVWatts tool [8]. The power rating also depends on the total panel area, which is set to 40% of the model's total roof area (noting that this work models the PV system as a single array rather than individual panels). Panel efficiency is 21%, which corresponds to 210 W/m² under standard test conditions (1,000 W/m² irradiance). Total PV capacity is then calculated based on this module area and panel efficiency. This routine is applied individually to each ComStock model.

For example, a building with 1,000 ft² of roof area would receive 400 ft² (40%) of PV module area. Converting, this is approximately 37.2 m². Note that, in reality, additional roof area would be required to account for panel spacing, access, and so on. At 210 W/m² (21% panel efficiency under standard test conditions of 1,000 W/m² irradiance), the resulting system would be rated at about 7.8 kilowatts (kW) DC.

The 40% roof area assumption used in this analysis is intended to be a simple starting point. More sophisticated approaches may be explored in future work. This assumption directly impacts the rated system power applied to the models. A 2016 NREL report suggests smaller values in some cases (e.g., buildings under 5000 ft^2 average only 26% area), but this type of nuance is not currently included [7].

3.2.2 Tilt and Azimuth

Tilt angle is measured as the angle of the panel relative to horizontal. A completely horizontal panel has a tilt angle of 0 degrees, while a vertical panel has a tilt angle of 90 degrees. Azimuth angle is measured as the angle clockwise to true north. A completely north-facing array has an azimuth angle of 0 degrees, while a south-facing array has an azimuth angle of 180 degrees.

The PV arrays modeled in this work are assumed to be fixed, so tilt and azimuth are set at a fixed value for each model and remain constant throughout the simulation. They are calculated using the methodology from [10] to optimize the two parameters for maximizing solar collection based on latitude (summarized in Table 3). This represents one method for determining orientation, although others could be considered, depending on what parameters are most important (e.g., time of use pricing). Note that the tilt angle is always at least 10 degrees to allow rainwater to effectively clean the panels. The panels are not spaced and are essentially modeled as one large, tilted panel with an area equaling 40% of the roof area.

Table 3. Tilt Formula by Orientation

Orientation	Azimuth (°)	Tilt Formula
Northern Hemisphere	180	Tilt = 1.3793 + (Latitude) × [1.2011 + (Lat) × (−0.014404 + (Latitude) × 0.000080509)]
Southern Hemisphere	0	Tilt = |−0.41657 + (Latitude) × [1.4216 + (Latitude) × (0.024051 + (Latitude) × 0.00021828)]|
All	—	If |Tilt| < 10°, then Tilt = 10 degrees

3.2.3 Other Parameters

The DC-to-AC size ratio compares an inverter's AC rating to the array's DC rating. This study uses the PVWatts default of value of 1.10 for all systems. This means that a PV array with a nameplate capacity of 10 kW DC would have an inverter nameplate of 9.1 kW AC. This is modeled in PVWatts by limiting the power output based on the rated AC size [11]. Note that this parameter can be optimized to life cycle cost when designing PV systems, although this type of detailed analysis is not included in this work. This value can vary substantially, with estimates ranging from 1.1–1.3 [12]. The PVWatts assumption of 1.1 is at the conservative end, with higher values potentially providing more favorable economics in some cases.

In this work, the inverter efficiency is modeled at 96% for all models, which is the default in PVWatts [8]. This value reflects the nominal rated AC-to-DC conversion efficiency and is the ratio between the inverter's rated AC power to DC power. For example, this represents a system with 9.6 kW AC and 10 kW DC.

In this work, the system losses are modeled at 14% for all models, which is the default in PVWatts [8]. This is used to account for losses in real systems that are not explicitly modeled in PVWatts calculations, such as panel or inverter failure.

3.2.4 Battery Storage Sizing and Control

This measure scenario follows the battery storage sizing methodology outlined in the California Energy Commission's 2022 Building Energy Efficiency Standards [2]. Battery energy capacity is calculated using the rated DC capacity of the PV system, a building-type-specific energy capacity factor (Factor B from Table 4), and the battery's round-trip efficiency (Wh = watt-hour.

Equation *1*). Battery power capacity is calculated by multiplying the PV system size by a power capacity factor (Factor C), which also varies by building type (Equation 2).

Table 4. Energy and Power Capacity Requirements for PV Battery Storage Following the Guidelines of the CEC [2] by ComStock Building Type

ComStock Building Type	Factor B: Energy Capacity Factor (Wh/W)	Factor C: Power Capacity Factor (W/W)
Grocery	1.03	0.26
Small Office, Medium Office, Large Office	1.68	0.42
Retail Strip Mall, Retail Standalone	1.03	0.26
Primary School, Secondary School	1.87	0.46
Warehouse	0.93	0.23
Small Hotel, Large Hotel, Outpatient, Hospital, Quick-Service Restaurant, Full-Service Restaurant	0.93	0.23

This measure scenario uses a simple charging and discharging scheme. The battery charges when the PV system generation exceeds the power demand of the building up to the system's maximum defined battery energy capacity. The battery never charges using grid-provided electricity. The battery discharges when the PV system generation is less than the power demand of the building until the battery is depleted. The maximum rate of charge and discharge is defined by the battery power capacity (Equation 2). More sophisticated charging/discharging algorithms may be studied in future work.

3.3 Utility Bills

ComStock provides utility bill estimates for several fuel types in buildings: electricity, natural gas, propane, and fuel oil. The current implementation represents utility bills circa 2022, which is the most current year of utility data available from the U.S. Energy Information Administration (EIA). This section provides a high-level overview of the methodology behind utility bills in ComStock; more detailed information is available in the ComStock reference documentation [13]. Summary statistics from this implementation are shown in Table 5. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 5. Summary Statistics of Utility Bill Implementation in ComStock by Fuel Type

Fuel Type	Minimum Price ($)	Average Price ($)	Maximum Price ($)
Natural gas	$0.007/kBtu ($0.70/therm)	$0.012/kBtu ($1.20/therm)	$0.048/kBtu ($4.80/therm)
Propane	$0.022/kBtu ($2.20/therm)	$0.032/kBtu ($3.20/therm)	$0.052/kBtu ($5.20/therm)
Fuel oil	$0.027/kBtu ($2.70/therm)	$0.033/kBtu ($3.30/therm)	$0.036/kBtu ($3.60/therm)
Electricity	$0.003/kBtu ($0.01/kWh)	$0.035/kBtu ($0.12/kWh)	$3.530/kBtu ($12.04/kWh)

To estimate natural gas bills, we use the 2022 EIA averages by state. To create an energy price in dollars per thousand British thermal units (kBtu), we use the 2022 EIA Natural Gas Prices—Commercial Price and the EIA Heat Content of Natural Gas Delivered to Consumers [14].

We estimate propane and fuel oil bills using 2022 EIA averages by state. To create an energy price in dollars per thousand British thermal units (kBtu), we use Residential No. 2 Distillate Prices by Sales Type and EIA Residential Weekly Heating Oil and Propane Prices (October–March), and EIA assumed heat content for these fuels [15]. Residential prices are used because commercial prices are only available at the national resolution. Additionally, most commercial buildings using these fuels are assumed to be smaller buildings, where a residential rate is likely realistic. For states where state-level pricing was available, we used these prices directly. For other states, we used Petroleum Administration for Defense District (PADD) average pricing. For states where PADD-level pricing was not available, we used national average pricing.

The primary resource for ComStock electric utility rates is the Utility Rate Database (URDB), which includes rate structures for about 85% of the buildings and 85% of the floor area in ComStock [16]. The URDB rates include detailed cost features such as time of use pricing, demand charges, and ratchets. ComStock only uses URDB rates that were entered starting in 2013, and a cost adjustment factor is applied such that the rates reflect 2022 U.S. dollars.

URDB rates are assigned to ComStock models at the census tract level. The URDB can include several rate structures for a census tract. Instead of attempting to presume any single rate, multiple rates from the model's census tract are simulated; the ComStock dataset includes the minimum, median, mean, and maximum simulated rates for each model.

Many precautions are implemented to prevent less reasonable rates from being applied. This includes removing noncommercial rates, rates with non-building-load keywords (e.g., security light, irrigation, snow, cotton gin), rates where the load profile does not follow any potential minimum/maximum demand or energy consumption qualifiers, and rates that cause unrealistically low (<$0.01/kWh) or high (>$0.45/kWh) blended averages. Additionally, any bill that is lower than 25% of the median or higher than 200% of the median is eliminated to avoid extreme bills.

For buildings with no URDB electric utility assigned, or for buildings where none of the stored rates are applicable, the annual bill is estimated using the 2022 EIA Form-861 average prices based on the state each model is in [17]. Although this method does not reflect the detailed rate structures and demand charges, it is a fallback for the 15% of buildings in ComStock with no utility assigned.

3.4 Limitations and Concerns

- This study assumes that all roofs have 40% unshaded area available for a PV array, which may not be the case for all buildings. For example, a 2016 NREL report suggests smaller values in some cases (e.g., buildings under 5000 ft^2 average only 26% area) [9]. This may overestimate the potential of PV in some cases. Alternatively, some buildings show negative net metered electricity usage with PV covering 40% of the roof area. This can suggest an oversized PV system in some cases, depending on the goals of the project.
- The ComStock baseline does not include any PV. CBECS 2018 estimates that ~2% of commercial buildings use PV, so this study may slightly overestimate the impact of mass adoption of PV.
- The PV assumptions in this work primarily follow the defaults used in the PVWatts tool. Although these are meant to be reasonable, real PV systems designs may vary, which can impact performance.
- The PV Watts module used in this analysis does not consider roof shading from the PV panels. Shading could affect the solar heat gain on the roof. The overall impact of this potential roof shading is likely minimal, especially in the context of larger multistory commercial buildings. However, it could have some impact on heating and cooling loads.
- This study uses a DC-to-AC size ratio of 1.1, which is the default assumption in PVWatts. This is a conservative estimate, with other sources suggesting higher values of 1.2–1.3. A higher value can increase the prevalence of clipping, where PV output beyond what the inverter can handle is lost. However, a higher ratio can be more economical for some projects [12].
- Net metering impacts on utility bills are not included in this study; the PV panels simply reduce the electricity demand on the building meter at the time of generation, with no resale back to the utility, and charge the battery if there is excess generation. This may underestimate the savings presented in this report and in the ComStock public dataset. However, PV energy that is generated but not used by the building is reported in the public dataset, enabling users to account for excess generation as needed.
- This analysis models the functionality of a battery energy storage system, but not a physical battery or its associated impacts. For example, the model does not account for battery space requirements, conditioning of that space, or any waste heat released into the building.
- This analysis uses one of many battery control schemes. The choice of control scheme can have large impacts on utility bill savings. The results of this study should not be used to draw conclusions about other more sophisticated control schemes that might be more financially beneficial. Other control schemes may be studied in future work.
- The battery sizing algorithm used in this study is one of many possible approaches. More sophisticated sizing algorithms, such as performing full life cycle cost assessments of each building, could provide more optimal financial outcomes. This may be investigated in future work.

4 Output Variables

Table 6 includes a list of output variables that are calculated in ComStock. These variables are important in terms of understanding the differences between buildings with and without the 40% PV measure applied. These output variables can also be used to understand the economics of the upgrade (e.g., return on investment) if cost information (i.e., material, labor, and maintenance costs for technology implementation) is available.

Table 6. Output Variables Calculated From the Measure Application

Variable Name	Description
com_stock_sensitivity_reports.com_report_pv_system_size_kw	Total photovoltaic design capacity in kW
simulation_output_report.electricity_pv_kwh	Annual PV electricity energy consumption in kWh, where negative values indicate generation
simulation_output_report.purchased_site_electricity_kwh	Annual purchased electricity following any on-site generation
simulation_output_report.net_site_electricity_kwh	Annual net electricity energy consumption in kWh, with negative values indicating excess on-site electricity generation sent back to the grid
simulation_output_report.total_site_electricity_kwh	Building annual total site electricity energy consumption; does not include impacts of PV
out.params.battery_capacity_kwh..kWh	Installed battery energy capacity
out.params.battery_max_charge_kw..kW	Installed battery power capacity used for charging
out.params.battery_max_discharge_kw..kW	Installed battery power capacity used for discharging

5 Results

In this section, we present results both at the stock level and for individual buildings through savings distributions. Stock-level results reflect the combined impact of all the analyzed buildings in ComStock, including buildings that are not applicable to this measure. Therefore, they do not necessarily represent the energy savings of a particular or average building. Stock-level results should not be interpreted as the savings that a building might realize by implementing the measure.

We also present total site energy savings in this section. Total site energy savings can be a useful metric, especially for quality assurance/quality control, but this metric on its own can have limitations for drawing conclusions. Further context should be considered, as site energy savings alone do not necessarily translate proportionally to savings for a particular fuel type (e.g., gas or electricity), source energy savings or cost savings. This is especially important when a measure impacts multiple fuel types or causes decreased consumption of one fuel type and increased consumption of another. Many factors should be considered when analyzing the impact of an energy efficiency strategy, depending on the use case.

As a helpful comparison, we discuss 3 scenarios in the results:

(1) The ComStock baseline, representing the building stock circa 2018.

(2) The PV 40% roof area measure scenario [1], which is an existing ComStock measure scenario that adds PV to 40% of the building roof area.

(3) The PV 40% roof area with battery storage measure scenario, which is the focus of this study.

(4) The only difference between (3) and (2) is the addition of the battery storage system in (3).

5.1 Single-Building Measure Tests

In this section, we describe the operation of a small office building in Alamosa County, Colorado (climate zone 6B) to demonstrate the measure scenario application on a single building. This model uses packaged rooftop units with direct expansion cooling and gas furnace heating. The "baseline" model includes no PV. The PV 40% roof area measure scenario applies PV on 40% of the roof area, and the PV 40% roof area with battery storage measure scenario does the same thing, but with a battery storage system sized as per the methods described in this report. The roof area of the model is 8,750 ft^2.

Below is the reporting summary generated by the script that implements the measure scenarios for ComStock models. Note that many of these reported metrics are consistent for all buildings in this study.

- **Measure reporting initial condition**: "The building started with 8,750 ft^2 of roof area. The user specified 40% of the roof area to be covered with PV panels, which totals 3,500 ft^2 of PV to be added."

- **Measure reporting final condition (PV 40%):** "The building finished with 68 kW of PV covering 3,500 ft^2 of roof area. The module type is Premium, the array type is FixedRoofMounted, the system losses are 0.14, the tilt angle is 33°, and the azimuth angle is 180°. The inverter has a DC-to-AC size ratio of 1.1 and an inverter efficiency of 96%."

- **Measure reporting final condition (PV 40% with battery):** "The building finished with 68 kW of PV covering 3500 ft^2 of roof area. The module type is Premium, the array type is FixedRoofMounted, the system losses are 0.14, the tilt angle is 33°, and the azimuth angle is 180°. The inverter has a DC to AC size ratio of 1.1 and an inverter efficiency of 96%. For storage, the model has a total battery capacity of 128.3 kWh, a maximum discharging power of 29 kW, and a maximum charging power of 29 kW.

As a reminder, the assumed rated panel efficiency for this analysis is 21%. For 3,500 ft^2 (325 m^2) of panel area, this would yield a rated capacity of 68 kW (PV capacity (kW) = area (m^2) × solar irradiance (1 kW/m^2) × efficiency). Again, achieving 3,500 ft^2 of actual panel surface area would require more than 3,500 ft^2 of roof area to account for panel spacing and access, which will vary by project.

Following Wh = watt-hour.

Equation *1* to validate battery energy capacity, kWh_batt = kW_PVdc × B / √D = (68 kW * 1.68) / √(0.95*0.95) = 128 kWh. Following Equation 2 to validate battery power capacity, *kW_batt = kW_PVdc × C* = 68 kW * 0.42 = 29 kW. Both calculated battery sizing values align with expectations following the methodology defined in this study.

Table 10 shows the annual comparison between the baseline, and the PV 40% and PV 40% with battery storage measure scenarios.

Total PV Electricity Consumption (kWh) represents the total annual electricity produced by the PV panels after losses. The value is reported as a negative value because it is processed as a consumption value in the dataset (negative consumption equals generation). Results show 95,648 kWh and 90,742 kWh for the PV-only and PV with battery storage scenarios, respectively. The value is slightly lower for the battery storage scenario due to battery charging losses.

PV Electricity Consumption Used (kWh) refers to the annual amount of PV electricity consumed directly by the building. Because this study does not include battery storage, PV electricity is either used immediately to meet building demand or exported to the grid when generation exceeds demand within a given time interval. This metric captures only the portion of PV generation that is consumed on-site and excludes any excess sent to the grid. Results show 64,310 kWh and 84,868 kWh for the PV-only and PV with battery storage scenarios, respectively. The battery storage enables more of the PV energy to be used on site.

PV Electricity Consumption Exported (kWh) represents the portion of PV generation that exceeds the building's electricity load during any time interval and is therefore sent to the grid. In the PV-only scenario, 63% of the electricity generated by the photovoltaic system was consumed directly on site, whereas in the PV + battery storage scenario, on-site utilization increased to 94%. The battery storage enables more PV energy generated to be used on site, and therefore less is exported to the grid. This value can vary considerably based on building characteristics, operational behavior, and weather.

Table 7. Summary of Site Energy Consumption Between Baseline Model and Model With PV

End Use	Baseline	PV 40%	PV 40% w/ Battery
Rated PV Power (kW)	0	68	68
Battery Energy Capacity (kWh)	0	0	128
Total PV Electricity Produced (kWh)	0	-95,648	-90,742
PV Electricity Consumption Used (kWh)	0	-64,310	-84,868
PV Electricity Consumption Exported (kWh)	0	-31,338	-5875
PV Annual Capacity Factor	NA	16%	15%
Site Purchased Electricity Consumption (kWh)	154,248	89,938	69,384
Total Site Electricity Consumption (kWh)	154,248	154,248	154,248
Net Site Electricity Consumption (kWh)	154,248	58,600	63,509
Total Site Gas Consumption (kWh)	250,818	250,818	250,818

PV Annual Capacity Factor, which is the ratio of actual energy output divided by the maximum possible output (full nameplate DC power) over a time period [6], is 16% and 15% for the PV and PV with battery storage scenarios, respectively (Table 10). The battery storage scenario is slightly lower due to losses with charging the battery. These values are in line with other available resources, such as NREL's Annual Technology Baseline for commercial fixed-axis PV, which provides a range of 12%–19%, depending on location [18]. 15-16% is on the higher end of this range, which is understandable given Alamosa's high solar potential [6].

Site Purchased Electricity Consumption (kWh) represents the annual electricity purchased from the utility. The PV only scenario shows a 42% reduction in purchased electricity from using electricity from the added panels compared to the baseline model with no PV, while the PV with battery storage scenario shows a 55% reduction. This value does not include excess PV electricity that would be sent to the grid, however, increasing PV used on site will decrease the PV sent to the grid. The lowest possible value for this output is 0, indicating that all the building's electricity needs were met by PV. Note that this is highly unlikely without the use of storage as the building's electricity loads would need to coincide with hours of adequate PV generation.

Total Site Electricity Consumption (kWh) represents the electricity used by the various end uses in the building. This value is consistent between scenarios, as adding PV does not necessarily change the power consumption of the equipment in the building (e.g., the power used by lights does not change when adding PV), nor does adding battery storage. Additionally, heating and cooling loads remain unchanged in this analysis because it does not account for potential shading effects from the PV panels. If included, such shading could cause slight changes in total site electricity consumption, though the impact would likely be minimal.

Net Site Electricity Consumption (kWh) is the Total Site Electricity Consumption minus the Total PV Electricity Production (negative consumption). Therefore, this includes the impact of PV electricity not used by the building (exported) and sent to the grid. The PV-only scenario shows a 62% reduction compared to the baseline with no PV, while the PV with battery storage scenario shows a 59% reduction. The savings for net electricity are higher than purchased electricity because the purchased electricity does not consider the impact of excess electricity sent back to the grid, while the net electricity values do. Although not the case in this example, the net site electricity value can be negative if the annual electricity generated by the PV system exceeds the annual total site electricity consumption.

Total Site Gas Consumption (kWh) is also consistent between scenarios, as gas consumption is not affected by adding PV. As with Total Site Electricity Consumption, shading from the PV modules is not included in this work, nor are there any thermal impacts of the battery system, which could cause slight changes in heating and cooling loads and therefore gas consumption.

Figure 1 illustrates the impact of applying the two PV measure scenarios for an example week in July. The top panel of the figure shows the electricity produced by the PV scenarios. Both show generation for this period less than the rated system capacity of 68 kW after considering losses and less-than-rated solar conditions. PV energy used to charge the battery is not accounted for here until it is dispatched, so the PV 40% scenario often shows higher electricity produced during the middle of the day than the battery storage scenario since the battery storage scenario is often charging during these times. Non-daytime hours often show more PV produced with the battery storage scenario. These are times where the battery storage is dispatching stored PV electricity.

The lower panel (Figure 1) shows electricity purchased between the three cases. Both PV scenarios reduce daytime purchased electricity compared to the baseline. They typically reach zero purchased electricity during part of midday. The PV + battery scenario further reduces purchases by using stored solar when generation falls short of demand. Purchased electricity aligns between the 3 scenarios during periods where solar generation is 0 and the battery storage in the battery storage scenario is depleted.

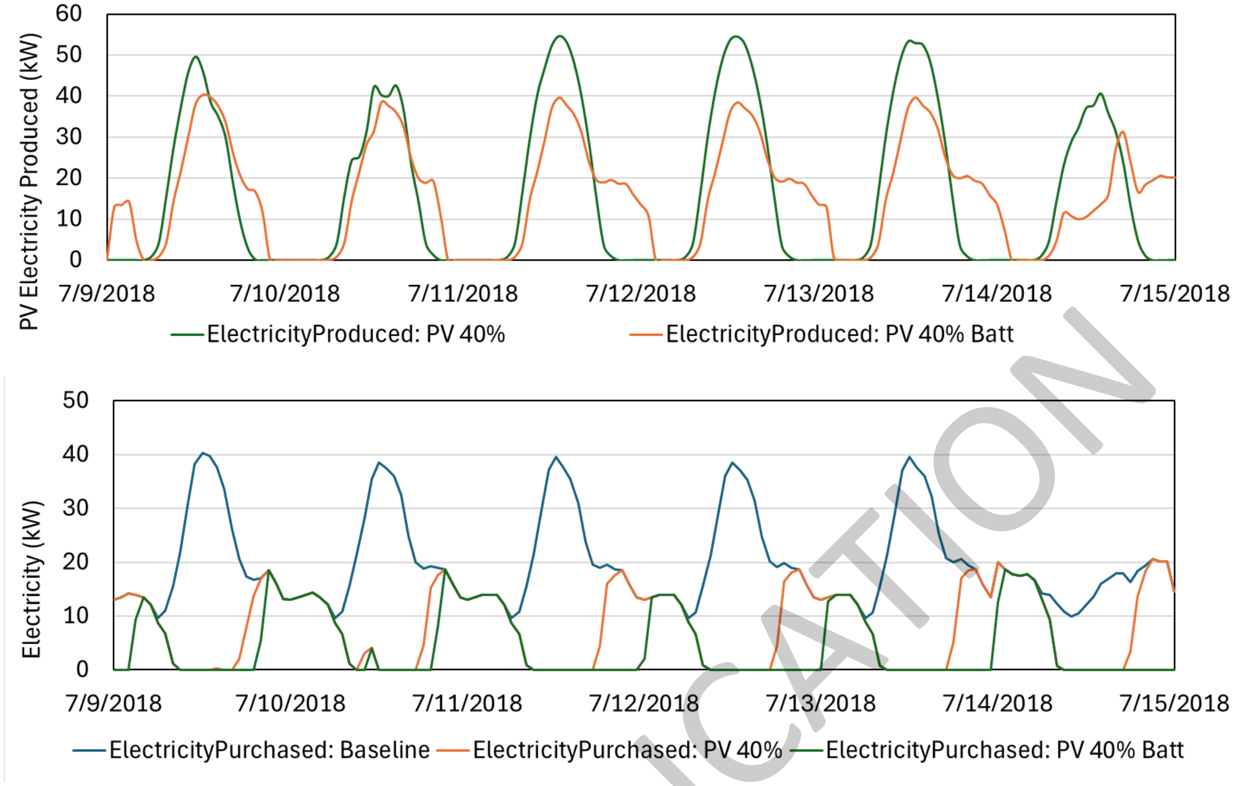

Figure 1. Comparison of generated electricity from PV (top) and purchased electricity for an example model between the baseline and the PV 40% measure scenario (bottom)

5.2 Stock Energy Impacts

The PV on 40% roof area with battery storage measure results in 1,361 TBtu of PV electricity used on-site annually across the modeled U.S. commercial building stock in ComStock, with an additional 476 TBtu of excess generation exported to the grid (Figure 2). Therefore, the total amount of PV produced, after losses, is 1,837 TBtu for this measure scenario. PV electricity used on-site accounts for ~42% of the stock annual electricity usage modeled in ComStock. Note that PV generation is represented as negative electricity consumption in the ComStock public dataset, while battery charging is positive electricity consumption.

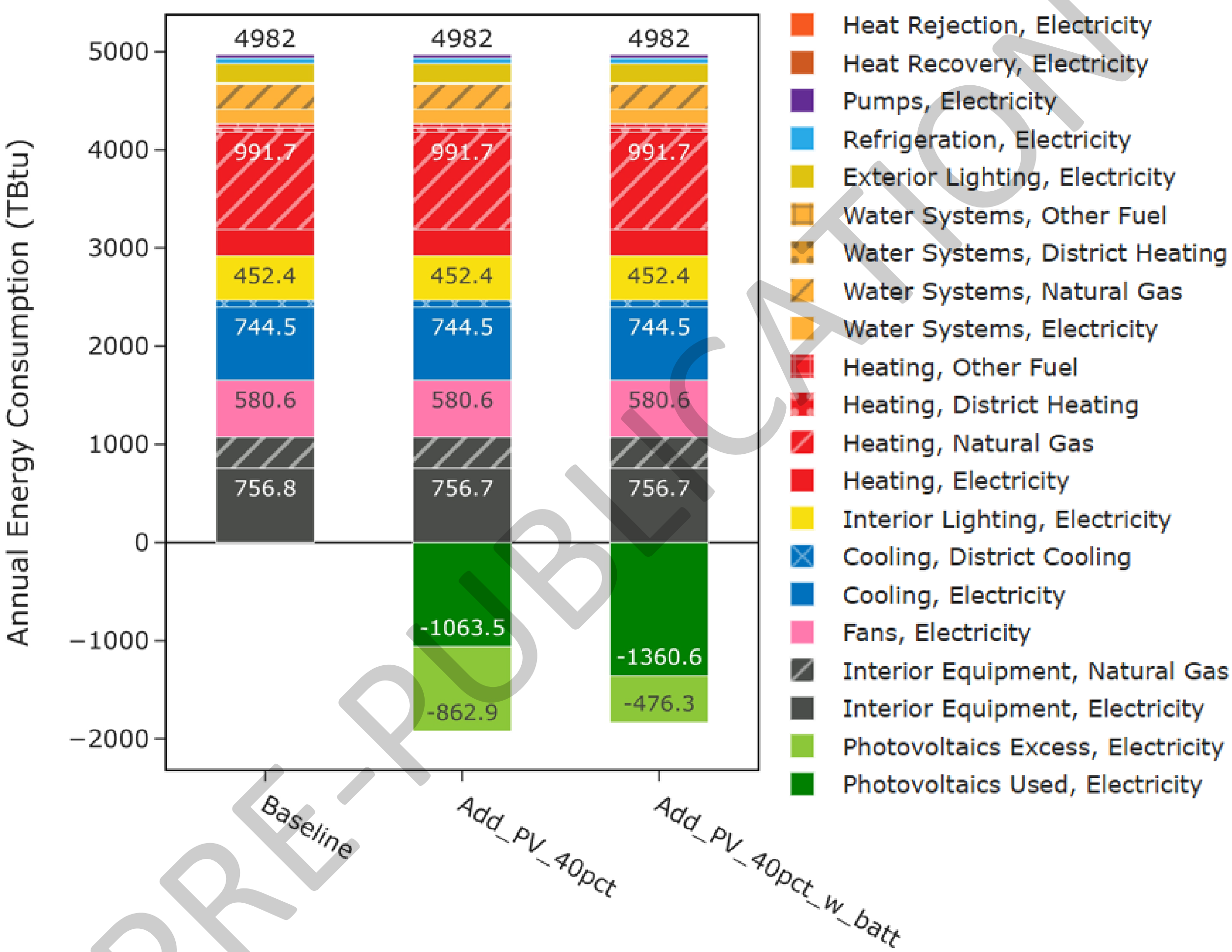

Figure 2. Comparison of annual site energy consumption between the ComStock baseline and two alternative scenarios: PV on 40% roof area ('Add_PV_40pct'), and PV on 40% roof area with battery storage ('Add_PV_40pct_w_batt').

Compared to the PV measure scenario without battery storage ('Add_PV_40pct'), adding battery storage increases the total PV electricity used on-site by 28%, from 1,064 TBtu to 1,361 TBtu (Figure 2). At the same time, excess PV generation sent back to the grid decreases by 45%, from 863 TBtu to 476 TBtu. This outcome is expected, as battery storage allows surplus PV generation to be stored on-site and used later when PV output alone cannot meet the building's electricity demand. The combined total of 'Excess' and 'Used' PV electricity is slightly lower with battery storage due to efficiency losses during battery charging and discharging.

All primary end uses remain unchanged between scenarios, as PV offsets electricity consumption from the grid but does not reduce the actual electricity demand of equipment in the building. The exception to this is Electricity for Interior equipment, which shows a 0.1 TBtu decrease (<0.001% change) between the baseline and the PV scenarios (Figure 2). This is due to a bug in the ComStock model generation workflow related to elevator schedules.

5.3 Stock Utility Bill Impacts

The PV 40% measure with battery storage scenario demonstrates 31-33% ($35–$49 billion USD, 2022) utility bill savings for the U.S. commercial building stock modeled in ComStock, depending on the electricity rate structure (Figure 3**Error! Reference source not found.**). This report reviews utility bill results for the maximum, mean, and minimum electricity rate structures available for each building. Bill savings are solely due to reducing purchased grid electricity by using generated on-site PV electricity. This bill analysis does not consider excess PV electricity sent back to the grid. However, excess PV generation is reported in the ComStock public dataset if users want to include it in their analysis. For example, users could assume and apply some $/kWh for electricity sold back to the grid. Doing so would increase bill savings further. Utility bills from on-site combustion of fossil fuels do not change across scenarios because they are unaffected by PV generation.

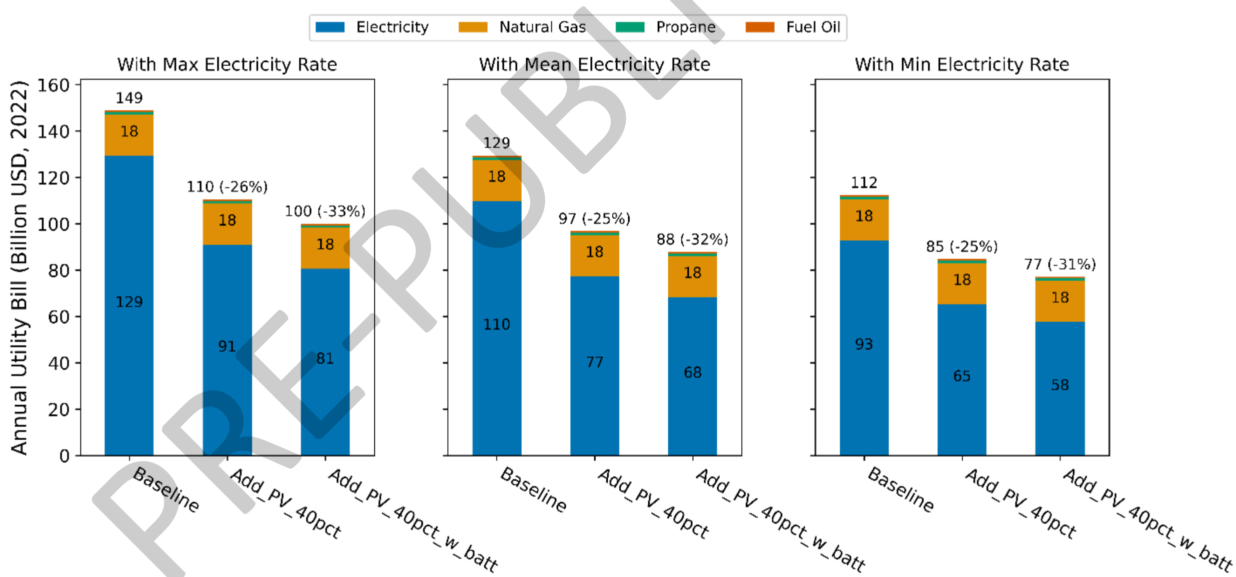

Figure 3. Annual utility bill impacts using the maximum, mean, and minimum bills across available rate structures for buildings for the PV 40% measure scenario

Compared to the PV measure scenario without battery storage ('Add_PV_40pct'), adding battery storage provides an additional 7% ($8 to $10 billion) in utility bill savings annually, depending on the electricity grid scenario (Figure 3). This is attributable to battery storage allowing buildings to use more electricity generated by the PV on-site, therefore reducing both purchased electricity and electricity sent back to the grid. Again, this analysis does not include any cost savings for electricity sent back to the grid – generally known as net metering – although users could add this to their own analysis using information available in the ComStock public dataset.

Figure 4 shows the distribution of utility bill savings for all ComStock models across fuel type. The median building shows over 30% total bill savings using the mean electricity bill. This is solely due to reductions in purchased electricity. One notable factor for percentage of total bill savings is the prevalence of on-site combustion fuels, which are not reduced by adding PV. Buildings with higher gas bills will generally experience smaller total percentage bill savings from PV.

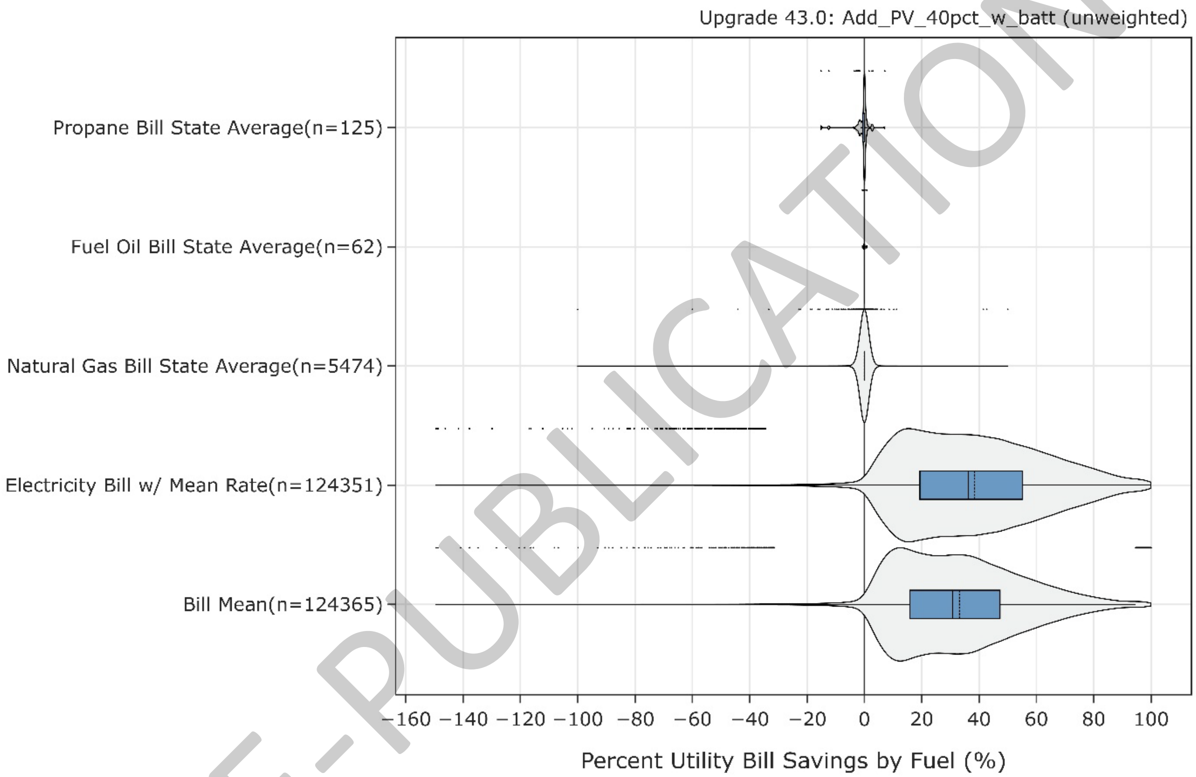

Figure 4. Percent annual utility bill savings distribution for ComStock models with PV 40% with battery storage measure scenario by fuel type

Results shown in this plot are the savings for the average available utility rate per building. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of unweighted ComStock models that were applicable for energy savings for the fuel type category.

Some buildings (mostly outliers in the distribution) show negative electricity bill savings (increased bills) when adding PV. This is primarily caused by ComStock's current electric utility rate selection scheme. ComStock selects applicable rates from the URDB, sometimes based on demand limits. Adding PV sometimes reduces these demand limits, which can change the included rates for a building. Therefore, these bill increases are generally caused by differences in the included electric utilities for a model, rather than a real increase in any single bill.

However, some of the models with increased electricity bills as well as the outliers showing change in the combustion fuel bills, are also affected by a few bugs (GitHub issues [350](), [355](), and [373]()) in the ComStock model generation workflow that can create some model discrepancies between the baseline and corresponding upgrade models. The overall impact on the results is small, but users should be aware that they may find some instances of this unexpected behavior when using the ComStock public dataset until this issue is resolved in future work.

Figure 5 shows the percentage of total utility bill savings by climate zone, based on the mean electric rate. Warmer climates generally exhibit greater savings due to higher solar resource availability and a larger share of electric end uses that PV can offset (e.g., more cooling and electric heating, less gas heating). Outliers with increased utility bills are caused by the same factors discussed in Figure 4.

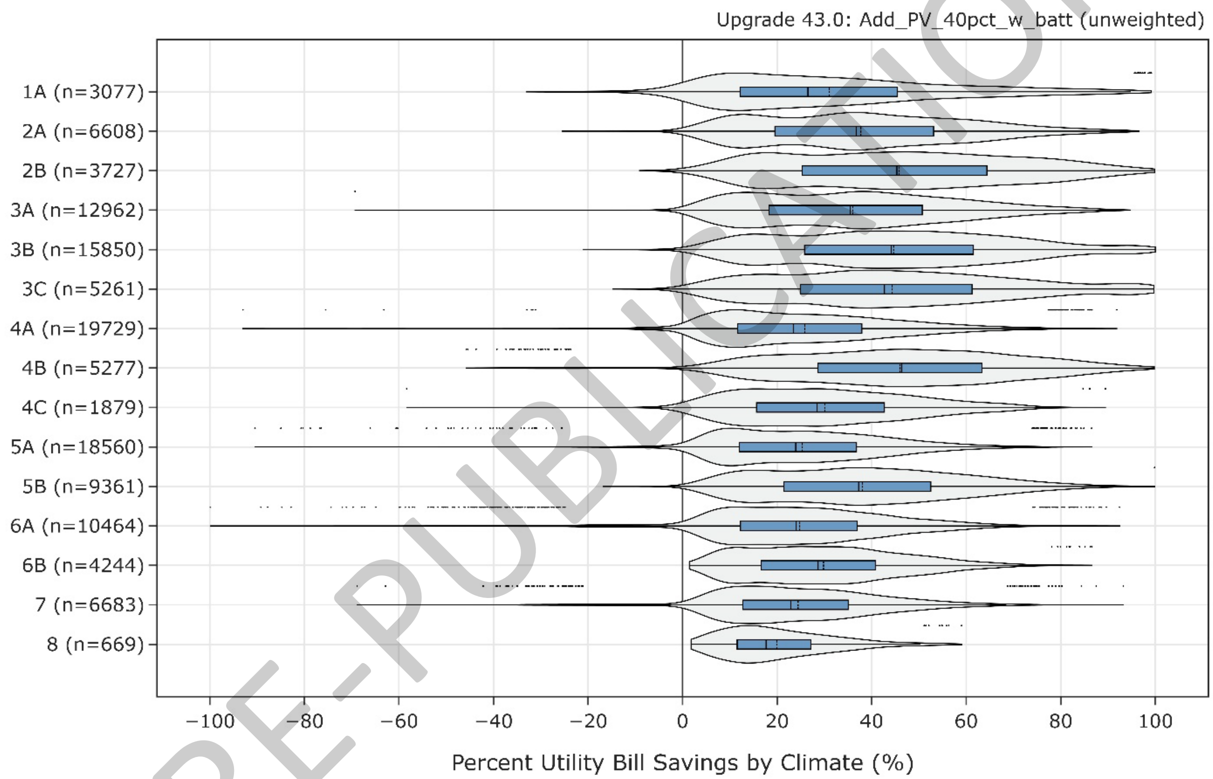

Figure 5. Percent annual utility bill savings distribution for ComStock models with PV 40% measure scenario by climate zone

Results shown in this plot are the savings for the average available utility rate per building. The data points that appear above some of the distributions indicate outliers in the distribution, meaning they fall outside 1.5 times the interquartile range. The value for n indicates the number of unweighted ComStock models that were applicable for energy savings for the fuel type category.

5.4 Other Findings

Figure 7 shows the total installed PV capacity by state for the 40% PV with battery storage measure scenario. California has the highest installed rated capacity with over 49. Because the sizing of the PV systems is simply 40% of the roof area, this means that installed capacity is primarily driven by floor area and number of stories. Nationally, this study includes ~394 GW of installed capacity. For reference, the Energy Information Administration (EIA) estimates about 12 GW of installed commercial-scale solar as of June 2023 [21].

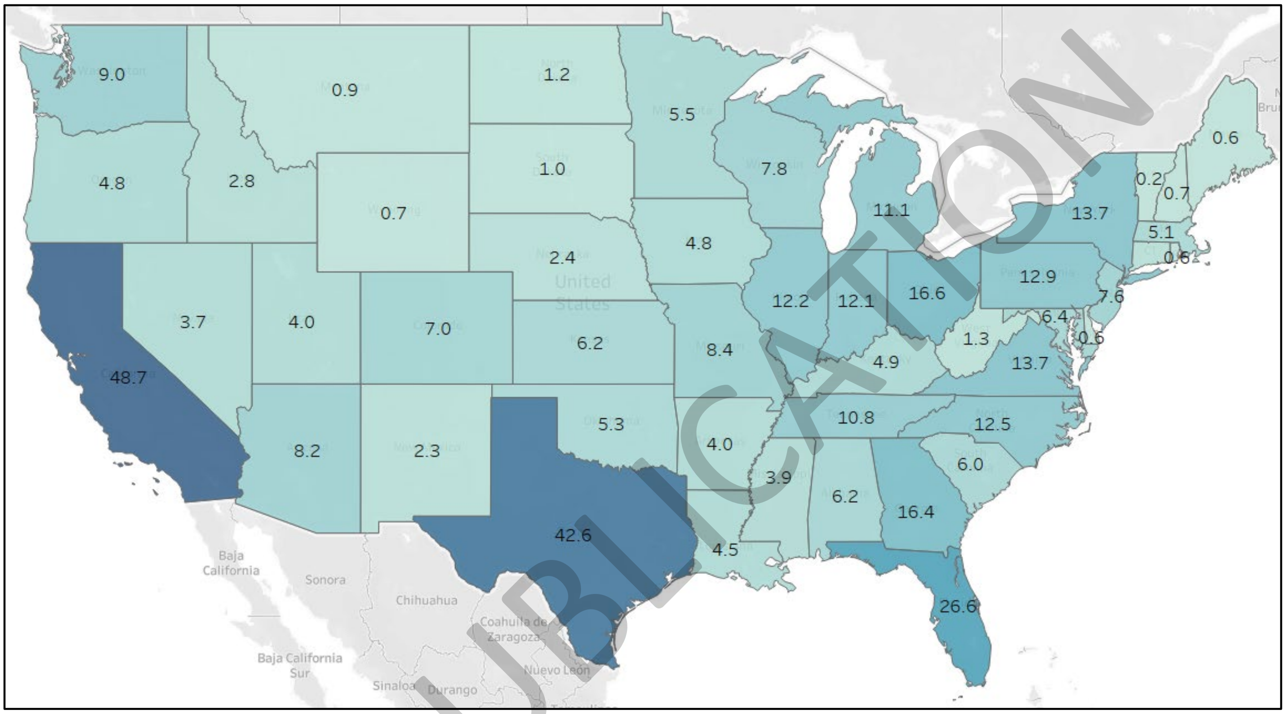

Figure 6. Total installed rated PV capacity (GW) for the 40% PV with battery storage measure scenario for buildings modeled in ComStock.

Higher values indicate more effective utilization of installed PV capacity, typically due to greater solar resource availability. The values range from 0.14 in the Midwest/Northeast to 0.21 in the Southwest. This aligns with other published resources, such as NREL's 2020 Annual Technology Baseline [18].

Figure 8 shows the total installed battery energy capacity for all ComStock models in each state for the 40% PV with battery storage measure scenario. Again, this is the total amount of energy the batteries can store. California has the highest storage capacity in this scenario with 68 GWh, largely driven by the number of buildings in California but also the battery storage sizing methodology discussed in this report. In total, the 40% PV with battery storage scenario yields 553 GWh on installed battery energy capacity across all states. For context, Wood Mackenzie estimates 137 GWh of installed battery storage in the U.S. as of 2025 across all sectors, including utility scale [19].

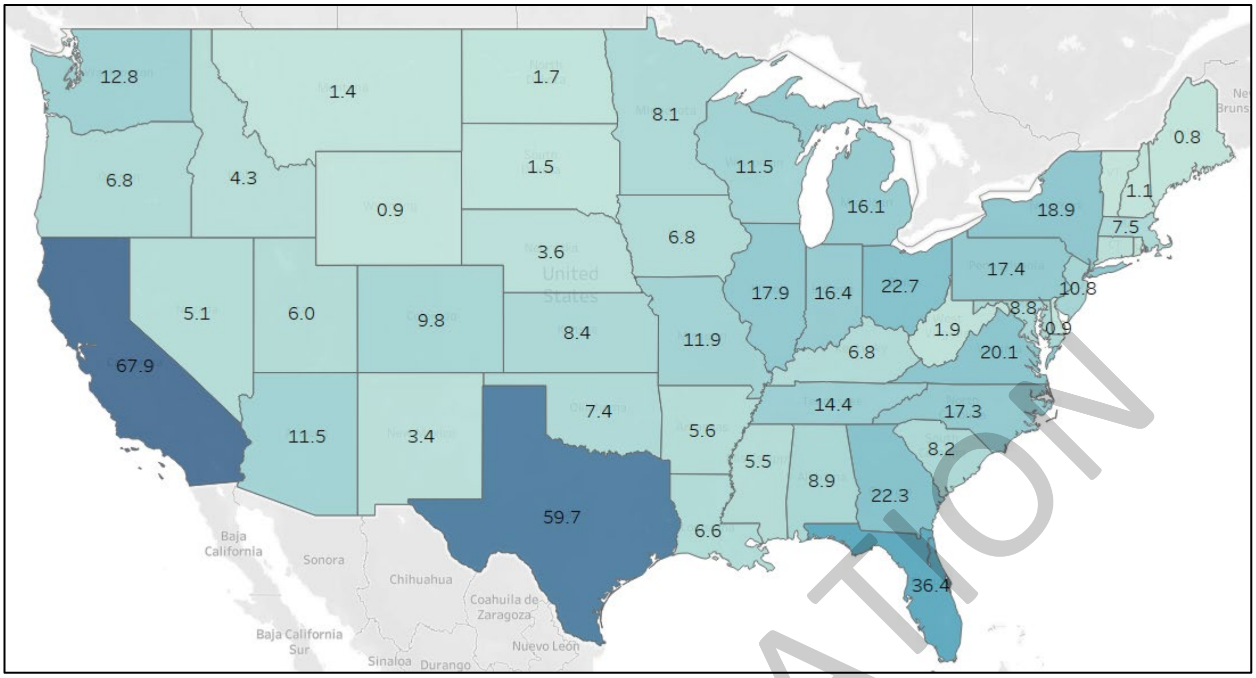

Figure 7. Total installed battery storage capacity (GWh) for the 40% PV with battery storage measure scenario for buildings modeled in ComStock

Figure 8 shows the total installed battery charge/discharge capacity for all ComStock models in each state for the 40% PV with battery storage measure scenario. Again, California shows the highest capacity for this measure scenario with 68 GW, driven by the number of buildings in the state coupled with the battery sizing methodology used in this study. Across all states, this measure scenario yields 135 GW of battery power. For context, Wood Mackenzie estimates that the U.S. currently has 45 GW of installed battery power in 2025 [19] across all sectors, while the EIA estimated 26 GW of utility-scale battery power in 2024, and projected ~45 GW by the end of 2025 [20].

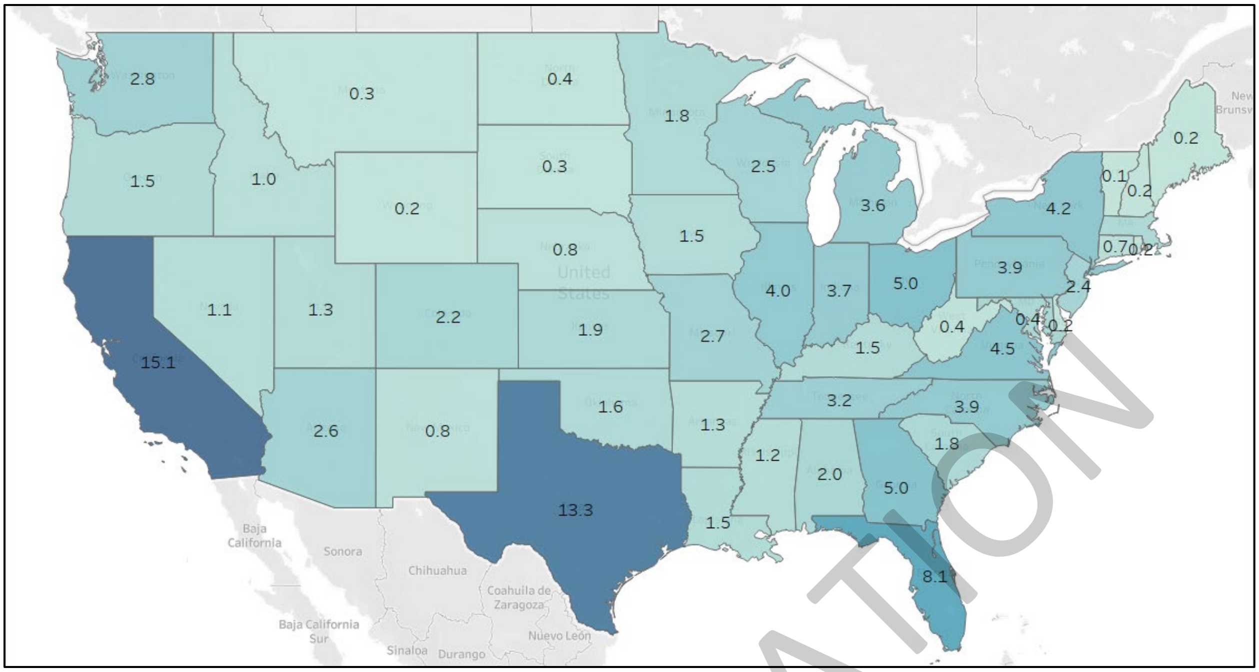

Figure 8. Total installed battery charge/discharge capacity (GW) for the 40% PV with battery storage measure scenario for buildings modeled in ComStock

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