ComStock Measure Documentation:

Photovoltaics With 40% Rooftop Coverage

Chris CaraDonna

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

This report is available at no cost from
NREL at www.nrel.gov/publications.

Technical Report
NREL/TP-5500-95004
September 2025

ComStock Measure Documentation:

Photovoltaics With 40% Rooftop Coverage

Chris CaraDonna

National Renewable Energy Laboratory

Suggested Citation
CaraDonna, Chris. 2025. *ComStock Measure Documentation: Photovoltaics With 40% Rooftop Coverage*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-95004. https://www.nrel.gov/docs/fy25osti/95004.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

This report is available at no cost from
NREL at www.nrel.gov/publications.

Technical Report
NREL/TP-5500-95004
September 2025

15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by NREL for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover photos (clockwise from left): Josh Bauer, NREL 61725; Visualization from the NREL Insight Center; Getty-181828180; Agata Bogucka, NREL 91683; Dennis Schroeder, NREL 51331; Werner Slocum, NREL 67842.

List of Acronyms

AC	alternating current
CBECS	Commercial Buildings Energy Consumption Survey
CO_2e	carbon emissions equivalent
DC	direct current
eGRID	Emissions and Generation Resource Integrated Database
EIA	U.S. Energy Information Administration
HVAC	heating, ventilating, and air conditioning
kBtu	thousand British thermal units
kg	kilogram
kW	kilowatt
lb	pound
LRMER	Long-Run Marginal Emissions Rate
MMBtu	million British thermal units
MMT	million metric tons
MWh	megawatt-hour
NREL	National Renewable Energy Laboratory
PADD	Petroleum Administration for Defense District
TBtu	trillion British thermal units
URDB	Utility Rate Database
USD	U.S. dollars

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), 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 data sets that provide insights into building stock characteristics, operational behaviors, utility bill impacts, carbon emissions equivalent (CO_2e), and annual and sub-hourly 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 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 to the U.S. commercial building stock. This amounts to ~385 GW of installed rated PV capacity. • Net metering impacts on calculated utility bill or CO_2e 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 with no resale back to the utility. However, the ComStock public dataset includes excess PV generation, enabling users to estimate these impacts as needed.
Performance Assumptions	• 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 1: 2025/comstock_amy2018_release_1/

National annual results for site energy, energy bills, and CO_2e are summarized in Table ES-2 through Table ES-4.

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	1524	0%	1524	0%
Electricity (Purchased)	1039	3173	33%	3173	33%
Other Fuel	0	54	0%	54	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	17	0%	17	0%
Electricity	32	108	30%	108	30%
Fuel Oil	0	1	0%	1	0%
Propane	0	1	0%	1	0%
Total	32	127	25%	127	25%

Table ES-4. Summary of Key Results for Annual CO_2e Savings

Electricity emissions avoided in this table are calculated using the Cambium Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy Cost 15-Year grid scenario. Other grid scenarios are presented in this report and in the public dataset. "Applicable" buildings are those that receive the upgrade based on the criteria defined for this study. MMT = million metric tons; CO_2e = carbon dioxide equivalent.

Fuel Type	Absolute Savings [MMT CO_2e]	Baseline Total (All Buildings) [MMT CO_2e]	Percent Savings (All Buildings)	Baseline Total (Applicable Buildings Only) [MMT CO_2e]	Percent Savings (Applicable Buildings Only)
Natural gas	0	102	0%	102	0%
Electricity	63	240	26%	240	26%
Fuel Oil	0	2	0%	2	0%
Propane	0	3	0%	3	0%
Total	63	346	18%	346	18%

Acknowledgments

The authors would like to acknowledge the valuable guidance and input provided by Andy Walker, Eric Bonnema, and Eric Ringold (National Renewable Energy Laboratory).

Table of Contents

List of Figures

List of Tables

1 Introduction

Photovoltaics (PV) are a renewable energy technology that has enjoyed a sharp uptick in adoption in recent years. Much of the increased penetration rate is attributed to the reduced costs and increased efficiency of modern PV modules [1]. State-of-the-art modules are now approaching nearly 25% efficiency, compared to less than 10% efficiency in the 1980s [2].

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 [3]. 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 [3]. 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 need to be maintained. Thus, although there is notable commercial building rooftop area available, some of these areas would not be applicable for PV panels.

This ComStock measure scenario analyzes the impact of mass rooftop PV adoption—40% rooftop coverage on all commercial buildings—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 [3]. 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 that 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 leverages the PVWatts® EnergyPlus objects. PVWatts is a National Renewable Energy Laboratory (NREL) tool that estimates the energy production of PV systems [4]. The workflow takes the baseline ComStock energy models, representing the building stock of today, and applies PVWatts objects with total power levels corresponding to 40% of each model's roof area. The panels are fixed with no tracking. This workflow is repeated for all ComStock models. The individual performance assumptions for the PV modules are summarized in Table 1 and described in the following sections.

Table 1. 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

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 [4]. 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 to metric, 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 (STC) 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 [6] to optimize the two parameters for maximizing solar collection based on latitude (summarized in Table 2). This represents one method for determining orientation, although others could be considered depending on what you are optimizing for (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 2. Title 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°

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 [7]. 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 [8]. The PVWatts assumption of 1.1 is on 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 [4]. 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 [4]. This is used to account for losses in real systems that are not explicitly modeled in PVWatts calculations, such as panel or inverter failure.

3.3 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 3. Note that ComStock does not currently estimate utility bills for district heating and cooling.

Table 3. 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 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 Carbon Emissions Equivalent

We present three electricity grid scenarios to compare the emissions of the ComStock baseline to the PV scenario. More are available in the ComStock public dataset. The choice of grid scenario will impact the grid emissions factors used in the simulation, which will determine the corresponding emissions produced per kilowatt-hour. Two scenarios—Long-Run Marginal Emissions Rate (LRMER) High Renewable Energy Cost 15-Year and LRMER Low Renewable Energy Cost 15-Year—use the Cambium dataset, and the last uses the Emissions and Generation Resource Integrated Database (eGRID) dataset [9], [10]. All three scenarios vary the emissions factors geospatially to reflect the variation in grid resources used to produce electricity across the United States. The Cambium datasets also vary emissions factors seasonally and by time of day. This study does not imply a preference for any particular grid emissions scenario, but other analysis suggests that the choice of grid emissions scenario can impact results [11]. Emissions from on-site combustion of fossil fuels use the emissions factors shown in Table 4, which are from Table 7.1.2(1) of the draft American National Standards Institute/Residential Energy Services Network/International Code Council 301 standard [14]. To compare total emissions from both on-site fossil fuel consumption and grid electricity generation, the emissions from a single electricity grid scenario should be combined with all three on-site fossil fuel emissions.

Table 4. On-Site Fossil Fuel Emissions Factors

Natural gas	147.3 lb/MMBtu (228.0 kg/MWh)[a]
Propane	177.8 lb/MMBtu (182.3 kg/MWh)
Fuel oil	195.9 lb/MMBtu (303.2 kg/MWh)

[a] lb = pound; MMBtu = million British thermal units; kg = kilogram; MWh = megawatt-hour

3.5 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) [5]. 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 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 [8].
- Net metering impacts on utility bills or carbon emissions equivalent (CO_2e) 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. 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.

4 Output Variables

Table 5 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 5. 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

5 Results

In this section, we present results both at the stock level and for individual buildings through savings distributions. Stock-level results include 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, cost savings, or CO_2e avoided. 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.

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, whereas the model with the upgrade scenario applied includes PV on 40% of the roof area. The roof area of the model is 8,750 ft^2.

Below is the reporting summary generated by the script that implements the measure scenario 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:** "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%."

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.

Table 6 shows the annual comparison between the baseline and the PV 40% measure scenario.

Total PV Electricity Consumption (kWh) represents the total annual electricity produced by the PV panels after losses, which is -95,648 kWh. The value is reported as a negative value because it is processed as a consumption value in the dataset (negative consumption equals generation).

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.

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 this case, about 63% of the PV generated was used directly by the building. This value can vary considerably based on building characteristics, operational behavior, and weather. In this instance, the building is in a heating-dominated climate with a gas heated system, so there is less opportunity to directly use the electricity generated on-site.

Table 6. Summary of Site Energy Consumption Between Baseline Model and Model With PV

End Use	Baseline	PV 40%	% Difference
Total PV Electricity Consumption (kWh)	0	-95,648	N/A
PV Electricity Consumption Used (kWh)	0	-64,310	N/A
PV Electricity Consumption Exported (kWh)	0	-31,338	N/A
PV Annual Capacity Factor	NA	16%	N/A
Site Purchased Electricity Consumption (kWh)	154,248	89,938	42%
Total Site Electricity Consumption (kWh)	154,248	154,248	0%
Net Site Electricity Consumption (kWh)	154,248	58,600	62%
Total Site Gas Consumption (kWh)	250,818	250,818	0%

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 [18], is 16% for this example (Table 6). This is 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 [19]. 16% is on the higher end of this range, which is understandable given Alamosa's high solar potential [18].

Site Purchased Electricity Consumption (kWh) represents the annual electricity purchased from the utility. The PV 40% scenario shows a 42% reduction in purchased electricity from using electricity from the added panels compared to the baseline model with no PV. This value does not consider excess PV electricity that would be 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). 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 scenario shows a 62% reduction compared to the baseline with no PV. 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, which could cause slight changes in heating and cooling loads and therefore gas consumption.

Figure 1 illustrates the impact of applying the PV 40% measure scenario for an example week in July. The top panel of the figure shows the electricity produced by the PV system for the PV 40% scenario. The maximum generation for this period is 53 kW, which is less than the rated system capacity of 68 kW after considering losses and less-than-rated solar conditions. The bottom panel compares purchased electricity between the two cases. There are many cases during this interval where purchased electricity drops to 0 for the PV 40% scenario, indicating that the PV output was sufficient to cover the total electrical load of the building during those times. The two scenarios show identical purchased electricity when PV output is 0, as expected.

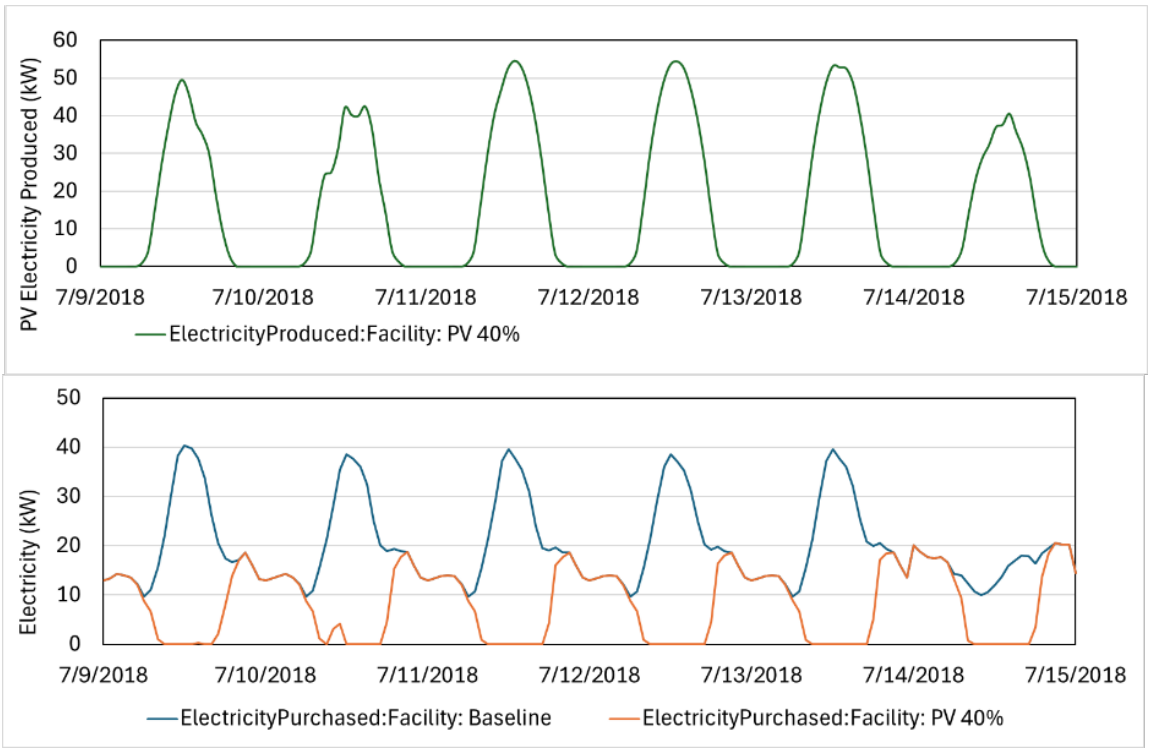

Figure 1. Comparison of generated electricity from PV (top) and purchased electricity for an example model between the baseline **and the PV 40% measure scenario (bottom)**

5.2 Stock Energy Impacts

The PV 40% measure results in 1,039 TBtu of PV electricity used on-site annually across the modeled U.S. commercial building stock in ComStock, with an additional 845 TBtu of excess generation exported to the grid (Figure 2). Therefore, the total amount of PV produced is 1,884 TBtu. PV electricity used on-site accounts for ~33% of the stock annual electricity usage modeled in ComStock. All other 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. This is consistent with the formatting of the data in the ComStock public dataset. Note that in the ComStock public dataset, PV generation is represented as negative electricity consumption.

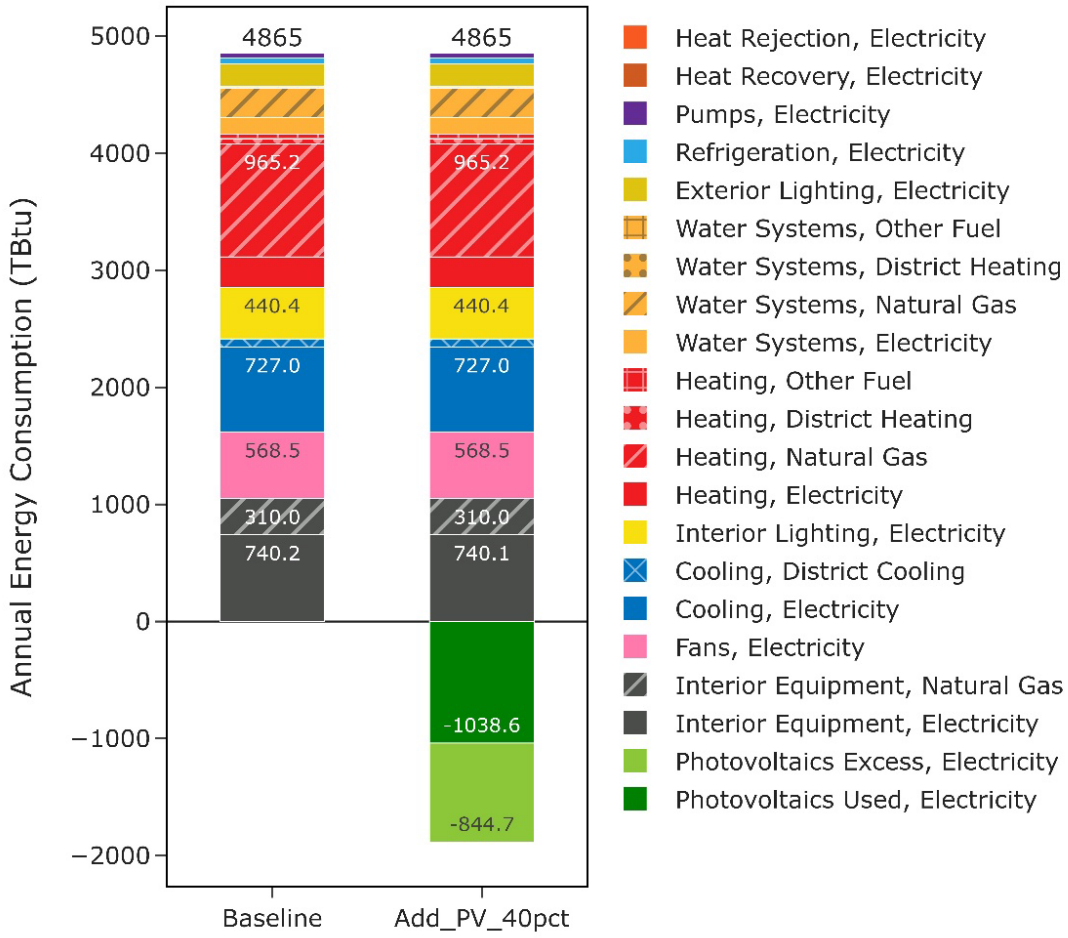

Figure 2. Comparison of annual site energy consumption between the ComStock baseline and the PV 40% measure scenario

Figure 2 shows 845 TBtu of excess PV generation—energy produced beyond the building's electricity demand during any time interval. This accounts for ~44% of the total PV electricity generated. In practice, excess PV electricity is generally sent to the electric grid. Alternatively, PV could be coupled with battery storage to use some of this electricity on site. Battery storage is not included in this study but may be investigated in future work. In some cases, higher amounts

of excess electricity can indicate an oversized PV system. This study uses a simple sizing methodology (40% of roof area), but future work may investigate a more sophisticated PV sizing approach.

5.3 Stock Utility Bill Impacts

The PV 40% measure scenario demonstrates ~25% ($28–$37 billion USD, 2022) utility bill savings for the U.S. commercial building stock modeled in ComStock, depending on the electricity rate structure (Figure 3). 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.

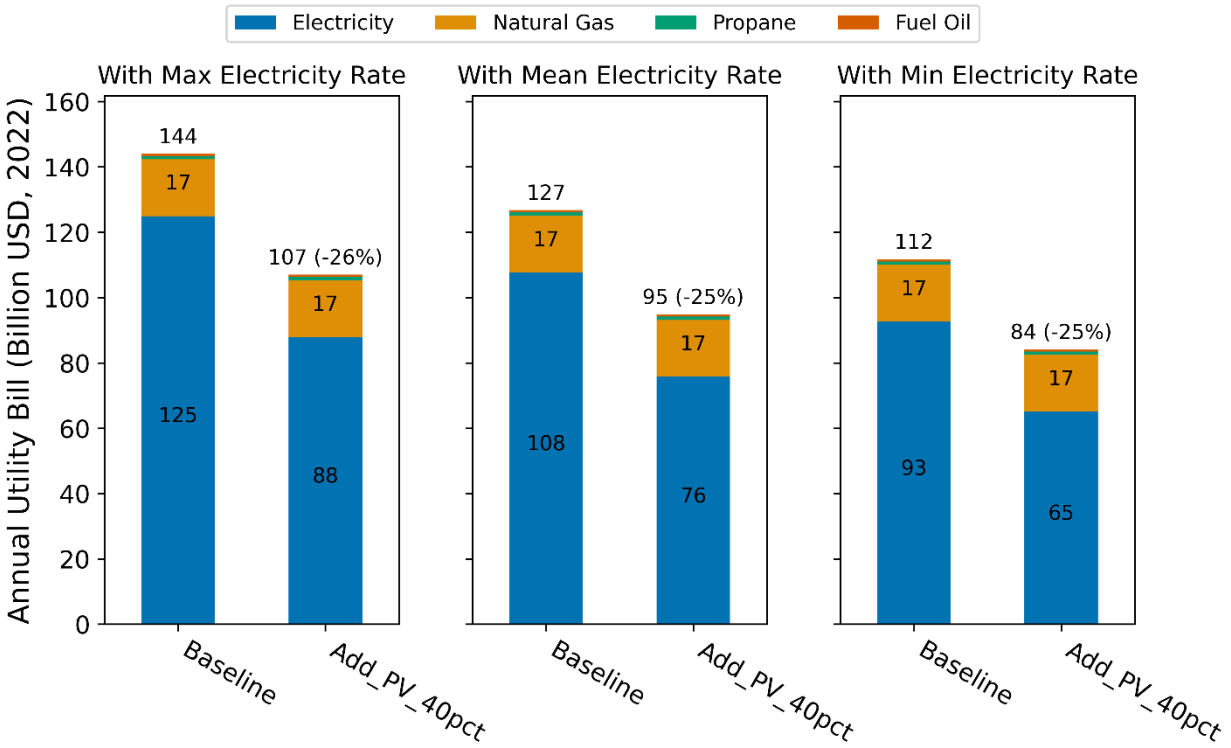

Figure 3. Annual utility bill impacts using the maximum, mean, and minimum bills across available rate structures for buildings for the PV 40% measure scenario

Figure 4 shows the distribution of utility bill savings for all ComStock models across fuel types. The median building shows over 20% 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. 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.

Figure 4 shows a small number of outliers in the distribution with changes to combustion fuel bills. This is caused by a bug in the ComStock model generation workflow where window blinds are sometimes not applied consistently between the baseline model and corresponding measure scenario model. The overall impact on the results is negligible, 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.

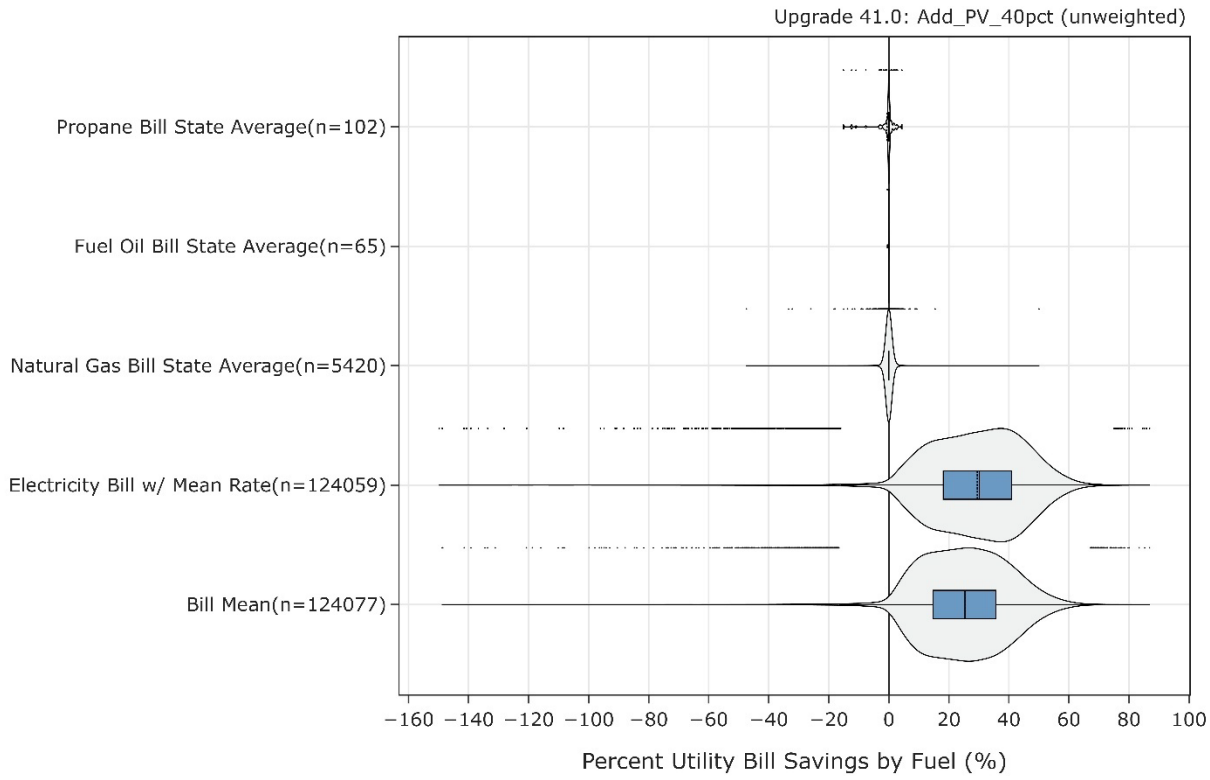

Figure 4. Percent annual utility bill savings distribution for ComStock models with PV 40% measure scenario by fuel type

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.

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.

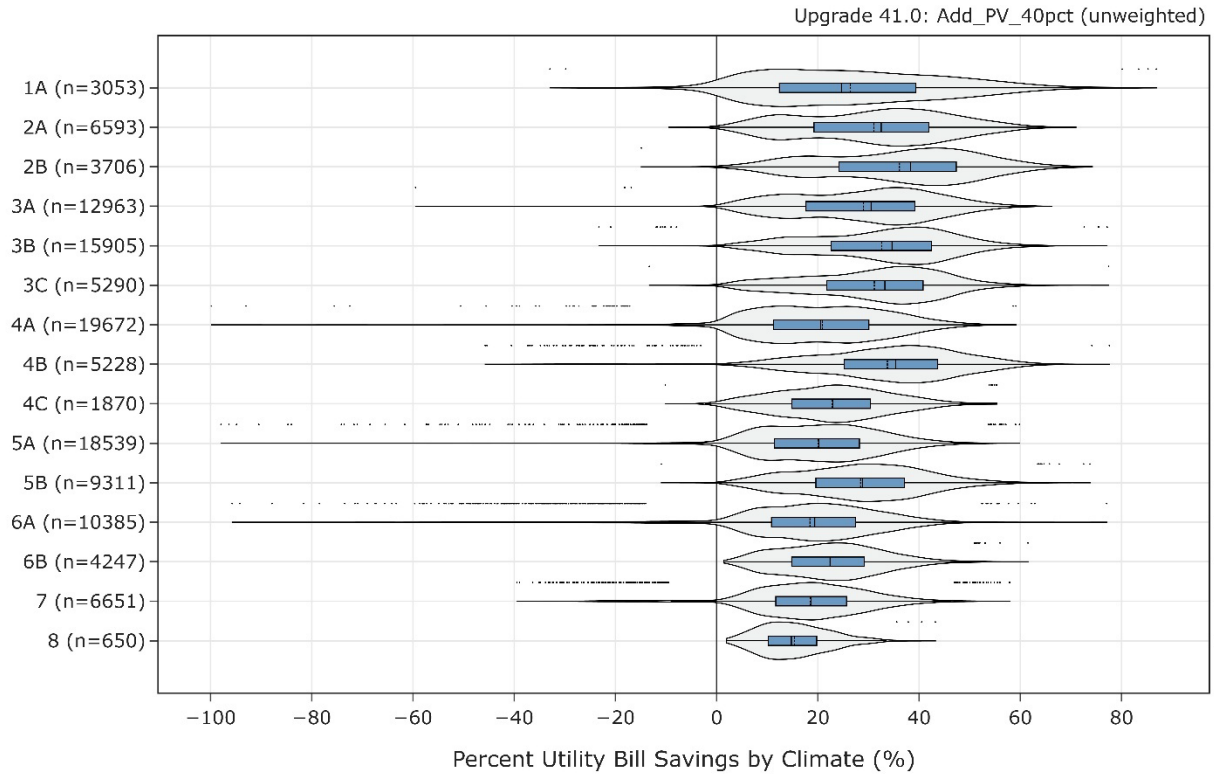

Figure 5. Percent annual utility bill savings distribution for ComStock models with PV 40% measure scenario by climate zone

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 Stock CO_2e Impact

The PV 40% measure scenario demonstrates between 11% and 25% (26–114 MMT CO_2e) CO_2e avoided for the U.S. commercial building stock modeled in ComStock, depending on the electricity grid scenario (Figure 6). This report reviews results for three scenarios, but others are included in the ComStock public dataset. Emissions avoided across all grid scenarios are solely from PV generation replacing some amount of purchased electricity from the grid. These values do not account for excess PV generation exported to the grid. However, the ComStock public dataset includes this information, allowing users to apply their own assumptions and incorporate it into their analyses as needed. Emissions induced due to on-site combustion fuels (e.g. natural gas) are identical across all scenarios, as these are not impacted by on-site PV generation. The baseline emissions induced vary considerably across grid scenarios due to differences in assumed generation sources. Lower emissions induced for a grid scenario suggest lower carbon intensity generation sources.

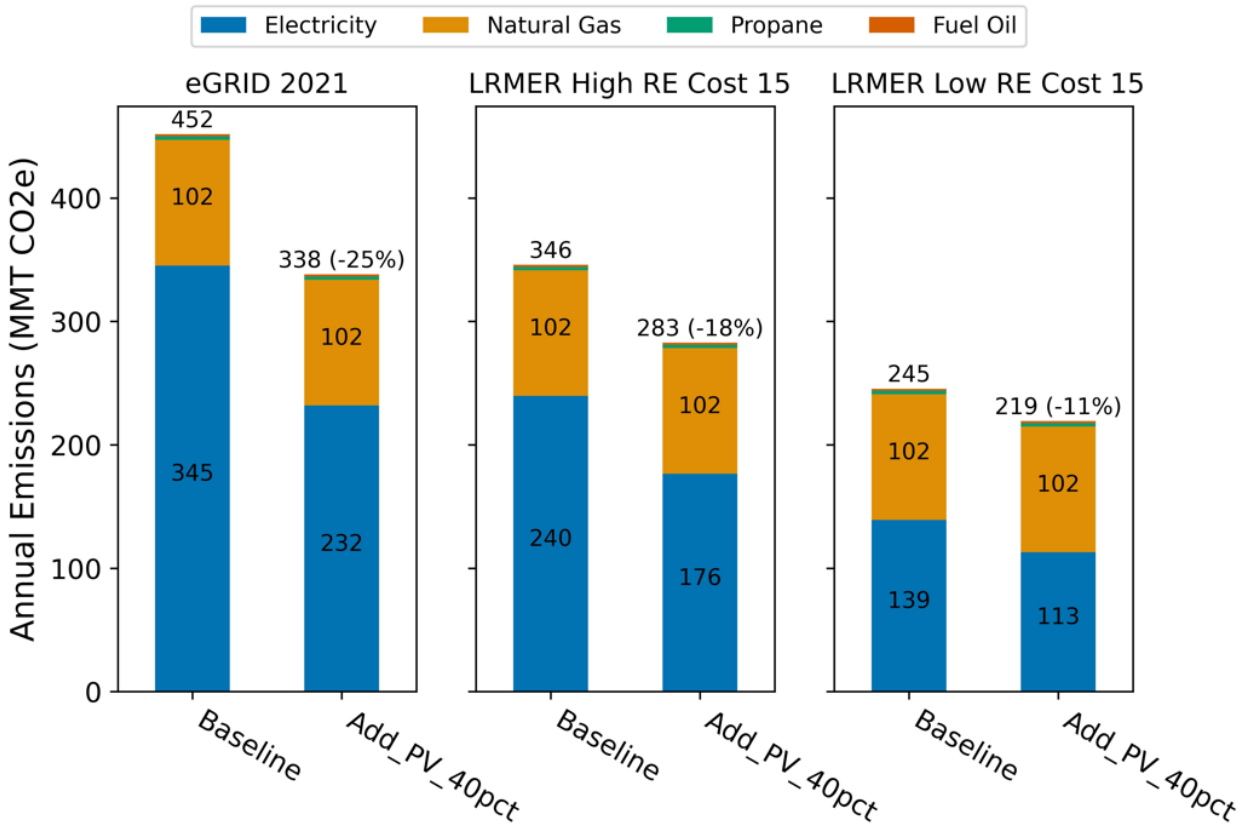

Figure 6. CO_2e comparison of the ComStock baseline and the PV 40% scenario

Three electricity grid scenarios are presented: Cambium LRMER High Renewable Energy Cost 15-Year, Cambium LRMER Low Renewable Energy Cost 15-Year, and eGRID. MMT stands for million metric tons.

5.5 Other Findings

Figure 7 shows the total installed PV capacity by state for the 40% PV measure scenario. The highest for this study is California, with over 50,000 MW of installed rated capacity. 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 ~385 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 8 shows the average capacity factor for all ComStock models in each state for the 40% PV scenario. Again, this is the ratio of actual energy output divided by the maximum possible output over the simulation period of one year. A higher value indicates 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 [19].

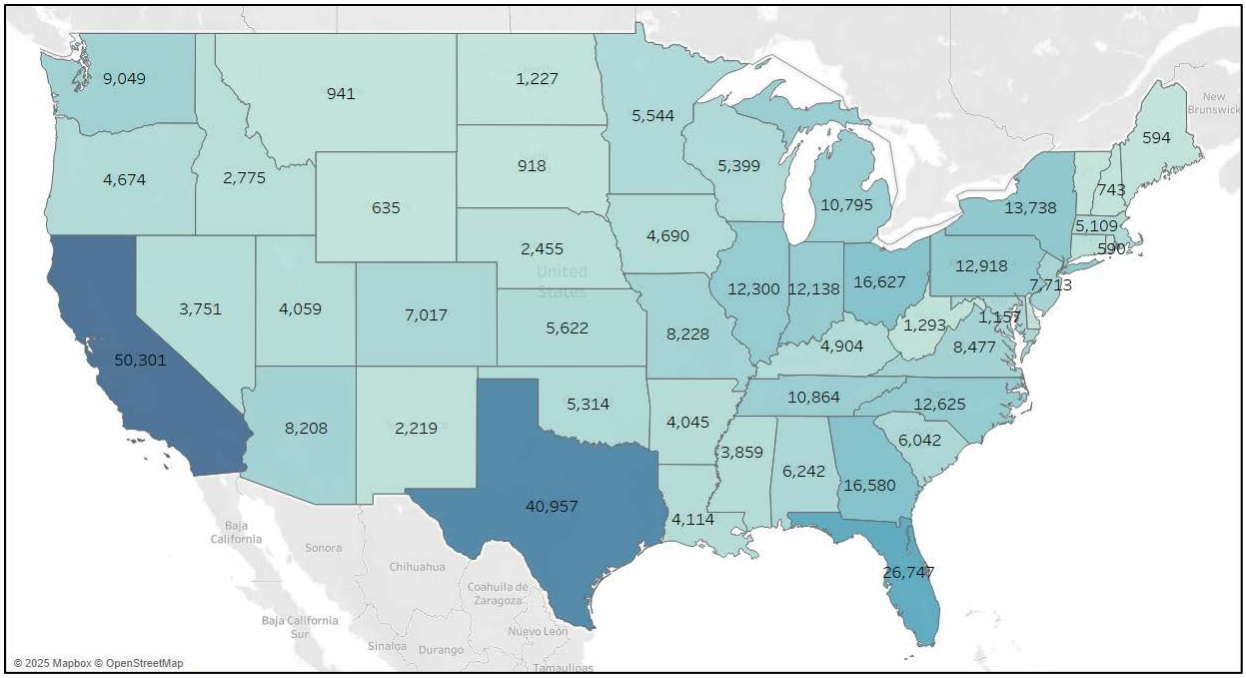

Figure 7. Total installed PV capacity (MW) for the 40% PV measure scenario for buildings modeled in ComStock

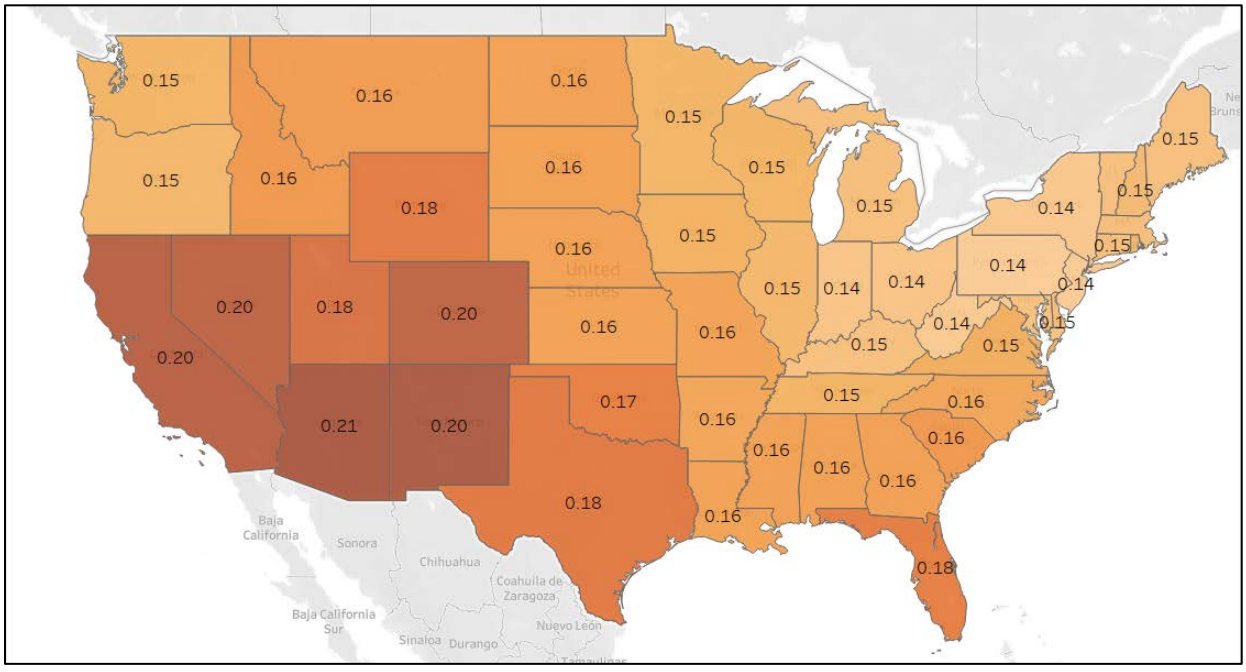

Figure 8. Average realized capacity factor by state for the 40% PV measure scenario

References

[1] "Average U.S. construction costs drop for solar, rise for wind and natural gas generators - U.S. Energy Information Administration (EIA)." Accessed: Apr. 28, 2024. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=54519

[2] "Photovoltaics and electricity - U.S. Energy Information Administration (EIA)." Accessed: Apr. 28, 2024. [Online]. Available: https://www.eia.gov/energyexplained/solar/photovoltaics-and-electricity.php

[3] "Energy Information Administration (EIA)- Commercial Buildings Energy Consumption Survey (CBECS)." Accessed: Apr. 28, 2024. [Online]. Available: https://www.eia.gov/consumption/commercial/

[4] "PVWatts Calculator." Accessed: Apr. 28, 2024. [Online]. Available: https://pvwatts.nrel.gov/

[5] P. Gagnon, R. Margolis, J. Melius, C. Phillips, and R. Elmore, "Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment," 2016. [Online]. Available: www.nrel.gov/publications.

[6] M. Z. Jacobson and V. Jadhav, "World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels," *Solar Energy*, vol. 169, pp. 55–66, Jul. 2018, doi: 10.1016/J.SOLENER.2018.04.030.

[7] "EnergyPlus™ Version 22.1.0 Documentation Input Output Reference," 2022.

[8] P. Grana, "What DC to AC inverter load ratio is ideal for your application?" Accessed: Jun. 09, 2025. [Online]. Available: https://www.solarpowerworldonline.com/2016/07/solar-inverters-clipping-dcac-inverter-load-ratio-ideal/

[9] "Cambium | Energy Analysis | NREL." Accessed: Sep. 02, 2022. [Online]. Available: https://www.nrel.gov/analysis/cambium.html

[10] "Emissions & Generation Resource Integrated Database (eGRID) | US EPA." Accessed: Sep. 02, 2022. [Online]. Available: https://www.epa.gov/egrid

[11] E. Present, Pieter Gagnon, Eric J.H. Wilson, Noel Merket, Philip R. White, and Scott Horowitz, "Choosing the Best Carbon Factor for the Job: Exploring Available Carbon Emissions Factors and the Impact of Factor Selection," 2022.

[12] G. Vijayakumar *et al.*, "ANSI/RESNET/ICC 301-2022 - Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index," Oceanside, CA, 2022.

[13] A. Parker *et al.*, "ComStock Reference Documentation: Version 1," Golden, CO, 2023. Accessed: Apr. 02, 2023. [Online]. Available: https://www.nrel.gov/docs/fy23osti/83819.pdf

[14] U.S. Energy Information Administration, "Use of natural gas - U.S. Energy Information Administration (EIA)." Accessed: May 22, 2024. [Online]. Available: https://www.eia.gov/energyexplained/natural-gas/use-of-natural-gas.php

[15] U.S. Energy Information Administration, "No. 2 Distillate Prices - Residential." Accessed: May 22, 2024. [Online]. Available: https://www.eia.gov/dnav/pet/pet_pri_dist_a_epd2_prt_dpgal_a.htm

[16] S. Ong and R. McKeel, "National Utility Rate Database: Preprint," Aug. 2012, doi: 10.2172/1050105.

[17] U.S. Energy Information Administration, “U.S. Energy Information Administration - EIA - Independent Statistics and Analysis.” Accessed: May 22, 2024. [Online]. Available: https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T07.06#/?f=A
[18] A. Walker, “SOLAR ENERGY: Technologies and Project Delivery for Buildings,” 2013.
[19] National Renewable Energy Laboratory, “NREL Annual Technology Baseline (ATB).” Accessed: Jun. 08, 2025. [Online]. Available: https://atb-archive.nrel.gov/electricity/2020/index.php?t=sd