Solar + Storage Synergies for Managing Commercial-Customer Demand Charges

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Table of contents

Overview

This work is part of a series of studies exploring demand charge savings from solar

- Prior studies focused on demand charge reductions from solar PV *on a standalone basis* (without storage), for both residential and commercial customers
- Those studies highlighted several constraints on the ability of solar PV to reduce demand charges, which storage could help to alleviate

This analysis estimates demand charge reductions from solar + storage

- Across 15 commercial building types in 15 U.S. locations, with varying solar and storage system sizes and a range of demand charge designs
- Over a 17-year period that captures weather-related variability in PV generation and customer loads

This study quantifies "synergies" between solar and storage—that is, the potential for demand charge savings greater than the sum of what each would achieve alone

Motivation for this analysis

- **Demand charge rates (based on some measure of customer peak demand) are ubiquitous and often mandatory for commercial customers**
  - Account for approximately 25% of utility revenue from C&I electricity sales
- **As prior studies in this series have shown, demand charge reductions from solar on a standalone basis are often limited by:**
  - **Poor coincidence between PV generation and load profiles for many customers**—particularly true for “non-coincident” demand charges and becomes more pronounced for larger systems, which tend to push the customer’s net peak load into evening hours
  - **Intermittent cloud cover**—passing clouds can cause solar generation to temporarily drop, setting that month’s peak; more endemic to some locations than others
- **Storage has the potential to mitigate both of the above issues**
  - By discharging during peak load times outside of daylight hours and by buffering drops in solar production due to passing clouds

Overview of demand charge designs

The most common demand charge is a single $/kW rate, assessed monthly based on the customer's peak demand that month. There are variations on that basic formulation, which are described below.

Seasonal differentiation

- Some months have a higher demand charge level (in $/kW) than others
- Summer / non-summer is a common seasonal distinction

Frequency of billing demand measurement and ratchets

- Billing demand is determined on a monthly or annual basis
- Demand ratchets set a minimum billing demand, determined as a percentage of the maximum demand in the previous year

Averaging interval

- Billing demand is measured as an average load over a predefined time interval
- Commonly 15, 30, or 60 minutes

Coincident measurement

- Non-coincident: Based on customer's maximum demand
- Alternative: Maximum customer demand during predefined peak period window
- Alternative: Customer load at the actual time of system peak

Peak period (time-of-use) billing demand window

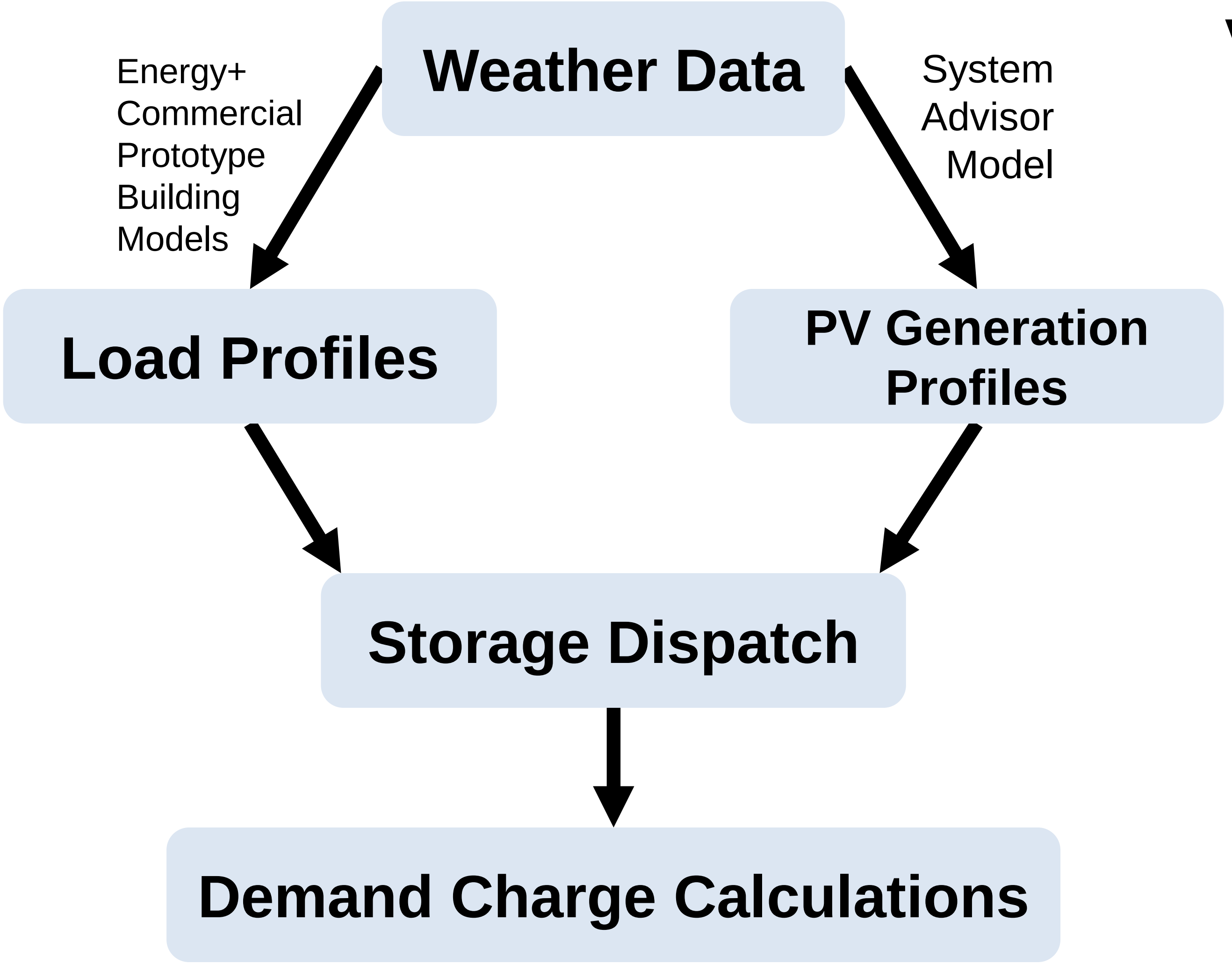
- Billing demand is determined during a predefined peak period window (e.g., 4pm – 9pm on weekdays)

Tiering

- Demand charge changes with increasing billing demand.
  - For example, first 5 kW billed at $10/kW, any demand above that billed at $5/kW

Table of contents

Methodology



All data was for the years 1998-2014 at hourly resolution, unless otherwise noted

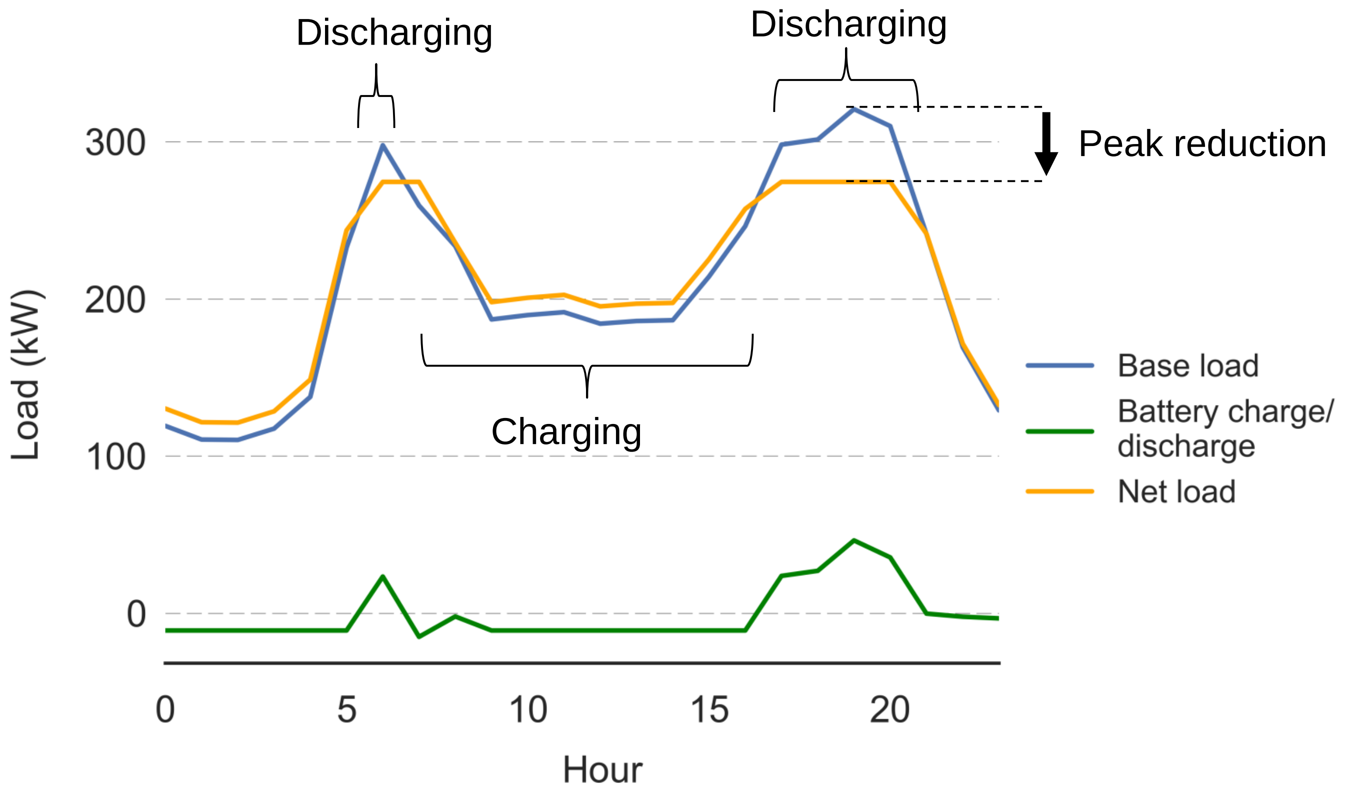
Variables considered for generating load/PV profiles

Customer Characteristics	**15 cities**	Albuquerque, NM; Atlanta, GA; Baltimore, MD; Boulder, CO; Duluth, MN; Helena, MT; Houston, TX; Las Vegas, NV; Los Angeles, CA; Miami, FL; Minneapolis, MN; Chicago, IL; Phoenix, AZ; San Francisco, CA; Seattle, WA
	15 customer types	Based on DOE Commercial Reference Buildings: Super Market, Quick Service Restaurant, Full Service Restaurant, Primary School, Secondary School, Strip Mall, standalone Retail, Small Office, Medium Office, Large Office, Hospital, Midrise Apartment, Small Hotel, Large Hotel, Warehouse
System attributes	**10 PV system sizes**	Sized such that PV generates 10%-100% of annual customer load (in 10% increments)
	10 storage system sizes	Sized such that battery's inverter capacity (in kW) is 10% - 100% of the customer's lifetime peak load (in 10 % increments)

→ **2,250** combinations of solar alone
→ **2,250** combinations of storage alone
→ **22,500** combinations of solar + storage systems

Storage dispatch

Illustrative example showing the battery dispatching to shave the customer's demand peak



Key storage dispatch assumptions:

- Optimized solely for demand charge reduction
  - Does not consider other functions, such as peak/off-peak arbitrage or participation in ancillary services markets
- Dispatches with perfect foresight
- 83% round-trip efficiency*
- Battery capacity (kWh) = 3x battery power (kW)*

** While both the round-trip efficiency and the capacity-to-power ratio are important design considerations that impact the financial performance of the system, they do not meaningfully influence the trends discussed in this research, which are focused on demand reduction and the synergies between solar and storage*

Demand charge designs modeled

Demand Charge Design	Description
Basic non-coincident demand charge	Based on maximum customer demand, averaged over a 60-minute interval, at any time during the month
Peak period demand charge	Billing demand is defined as the maximum demand during specified peak period windows. Several different peak period windows are considered: - Afternoon peak: 12 – 5 PM - Transition peak: 12 – 10 PM - Evening peak: 5 – 10 PM
Averaging intervals	Both the basic non-coincident demand charge and peak period demand charge structures are considered with varying averaging intervals: 30 minutes, 1 hour, 2 hours, and 4 hours

Demand charge savings metric

$$\textbf{Billing demand reduction } (\%) = \frac{\textbf{reduction in billing demand } (\textbf{kW}) \textbf{ from solar} + \textbf{storage}}{\textbf{billing demand } (\textbf{kW}) \textbf{ without solar} + \textbf{storage}}$$

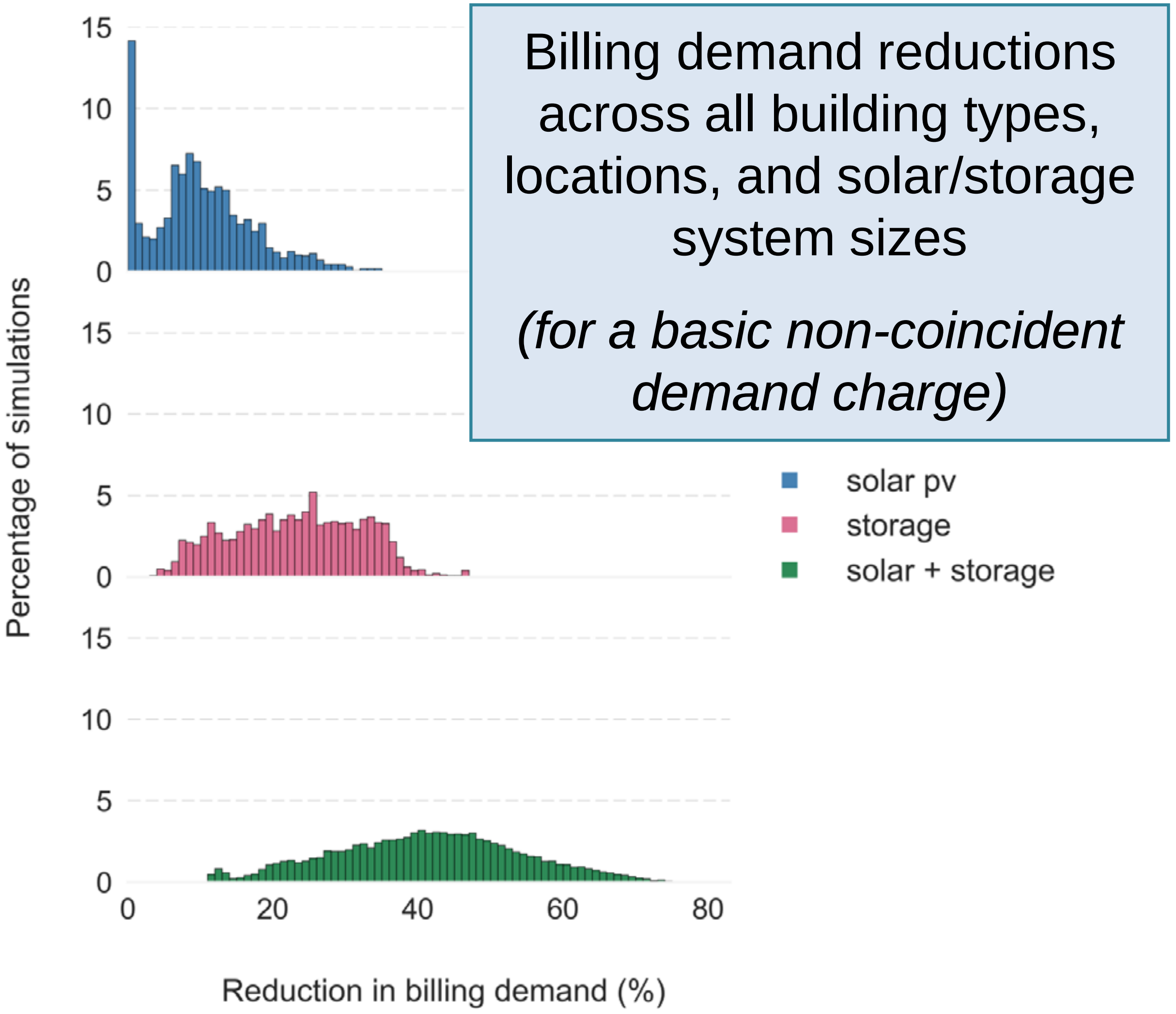
- We report results in terms of the percent reduction in billing demand, relative to what it would be without solar + storage
- “Billing demand” is the demand (in kW) used to calculate a customer’s monthly demand charge
  - Under demand charge designs with a flat $/kW rate, a given percent reduction in billing demand (kW) yields the same percent reduction in that month’s demand charges ($)
  - Under more complex demand charge designs, such as those with tiered charges, the percent reduction in billing demand may be greater or less than reduction in demand charges

Analysis boundaries and limitations

- This analysis focuses on the customer-economics of solar + storage; it does not attempt to characterize the value of those systems to the bulk power system
- The assumption of perfect foresight for storage dispatch is an idealization; the results are therefore an upper bound to the performance of storage systems in minimizing demand charges
  - The impact of this idealization is partially mitigated by the fact that billing demand is typically based on average demand over an interval of time: for example, if a PV system’s generation suddenly decreased from a cloud, a co-located storage system would not need to have to anticipated this; it would only need to dispatch a corresponding amount of energy within the averaging window
- The simulated load profiles used in this analysis reflect weather-related variability and differences associated with commercial building type and location, but they do not reflect <u>all</u> sources of load variability
  - E.g., they do not reflect variations in occupancy patterns or end-use equipment for a given building type and location
  - Does not necessarily indicate a systematic under- or over-estimation of average demand charge savings across the entire set of customers modeled, but it may understate the variability in demand charge savings across customers
- The smallest demand charge averaging interval considered in our analysis is 30 minutes, whereas some demand charges use 15-minute averaging intervals
  - Our results indicate that demand charge savings for solar+storage decrease with the length of the averaging interval, hence 15-minute average intervals would likely yield higher demand charge savings than the estimates presented here

Table of contents

Solar + storage yields greater demand charge savings than either technology alone, but also a wider performance range

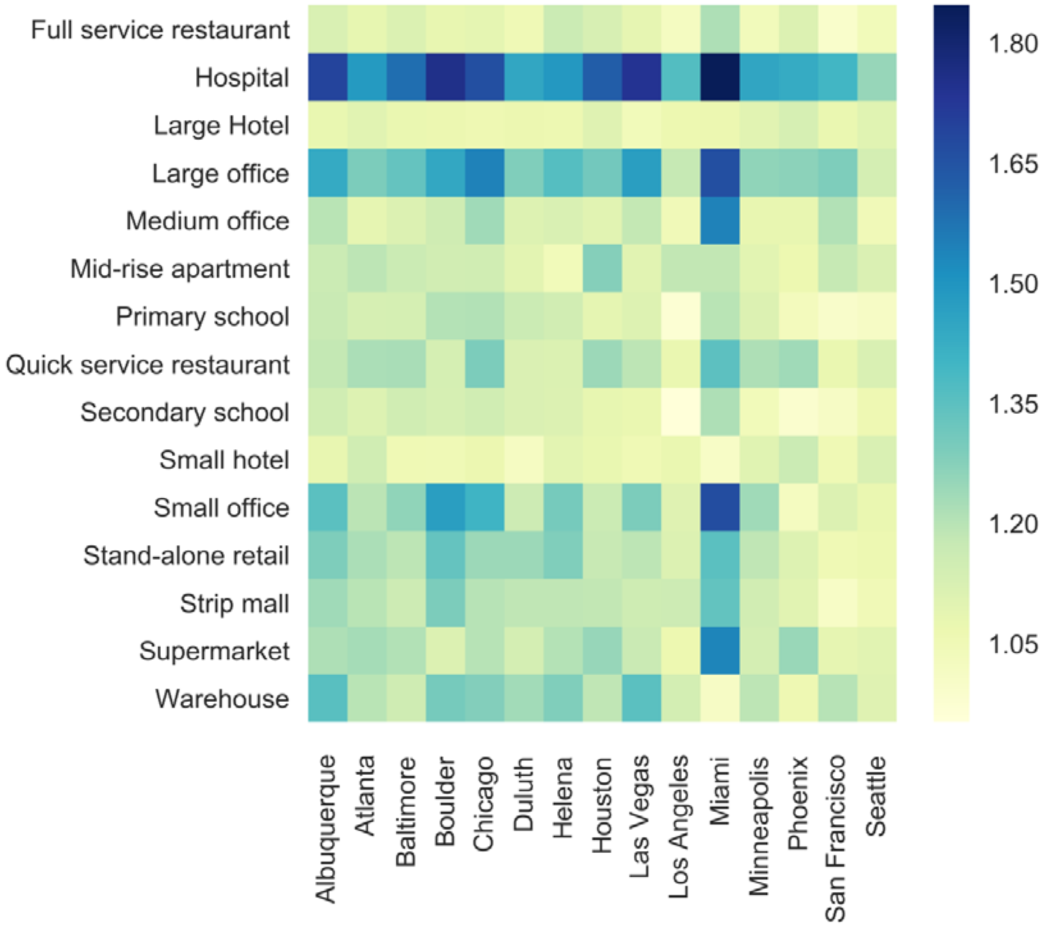


The figure shows the distribution of average monthly billing demand reductions across all building types, locations, solar sizes, and storage sizes. Each data point is the average percentage reduction, for a single load/solar/storage combination, across all months of the 17-year historical weather period.

- Co-deploying solar + storage allows for substantially greater billing demand reduction than either technology alone
  - Median reduction = **42%** for solar + storage, compared to **8%** for solar and **23%** for storage only
  - Billing demand reductions from solar + storage often greater than the sum of the reductions from each alone → suggestive of synergies
- Billing demand reductions from solar + storage also span a wide range across all simulations, reflecting underlying variations in:
  - System size, which yield diminishing returns to scale in terms of incremental demand reductions
  - Customer load and PV generation profiles, which vary by building type and location
- These themes are explored in the following slides

A metric for solar + storage synergy: cooperation ratio

$$\text{Cooperation ratio} = \frac{\text{billing demand reduction (solar + storage)}}{\text{billing demand reduction (solar alone)} + \text{billing demand reduction (storage alone)}}$$



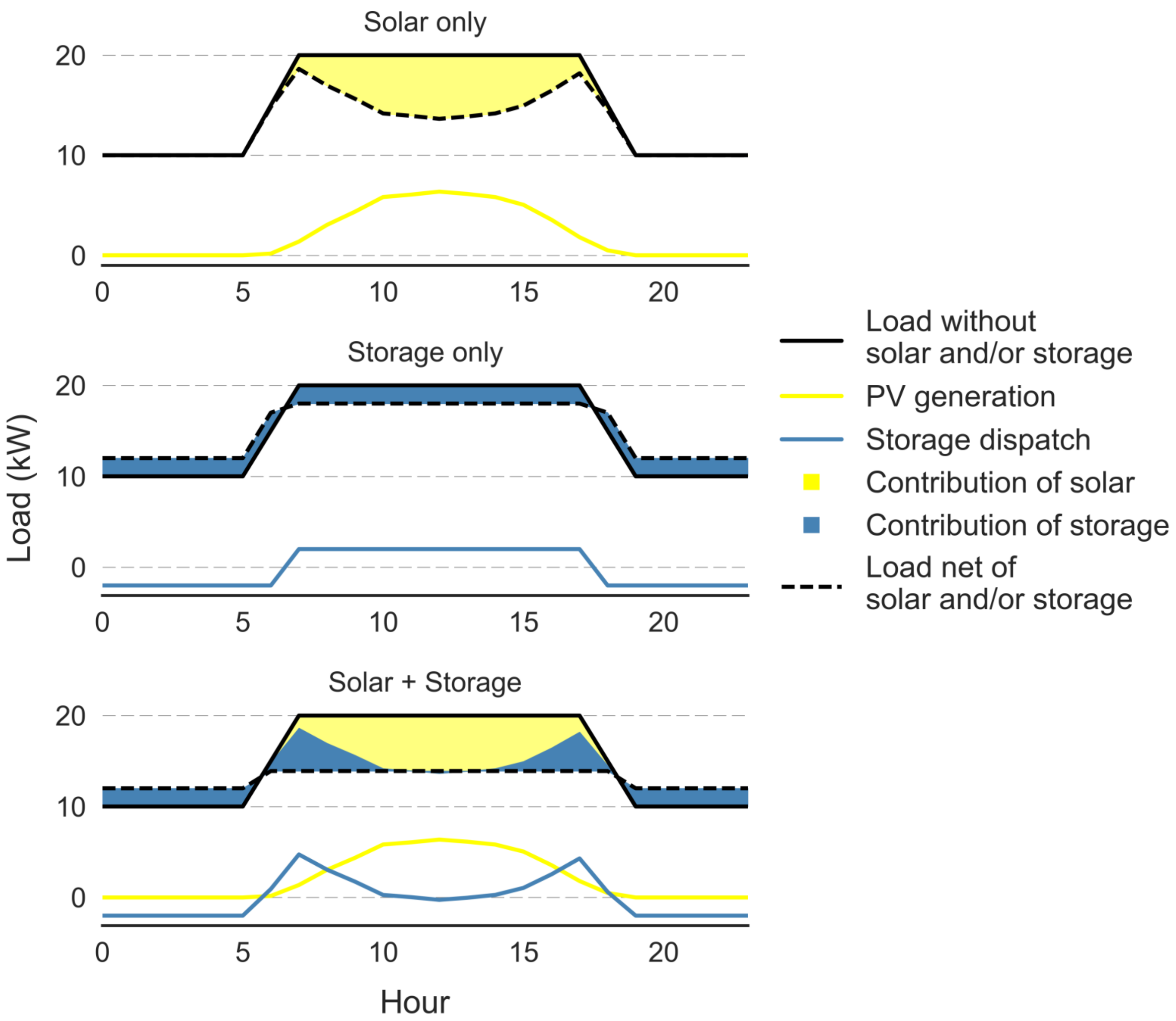
This figure shows the average cooperation ratios for all buildings and all locations PV is sized to meet 20% of the customer's annual load (in kWh) and battery power is sized to be 20% of the customer's peak demand (in kW)

Cooperation ratio > 1 means that solar + storage system decreases billing demand by more than the sum of each technology alone

Two separate conditions can lead to high cooperation ratios, shown in the next 2 slides:

- Buildings with relatively wide peak load periods that extend beyond daylight hours (hospitals and large offices, in our analysis)
- Locations with intermittent clouds but an otherwise strong solar resource (such as Miami)

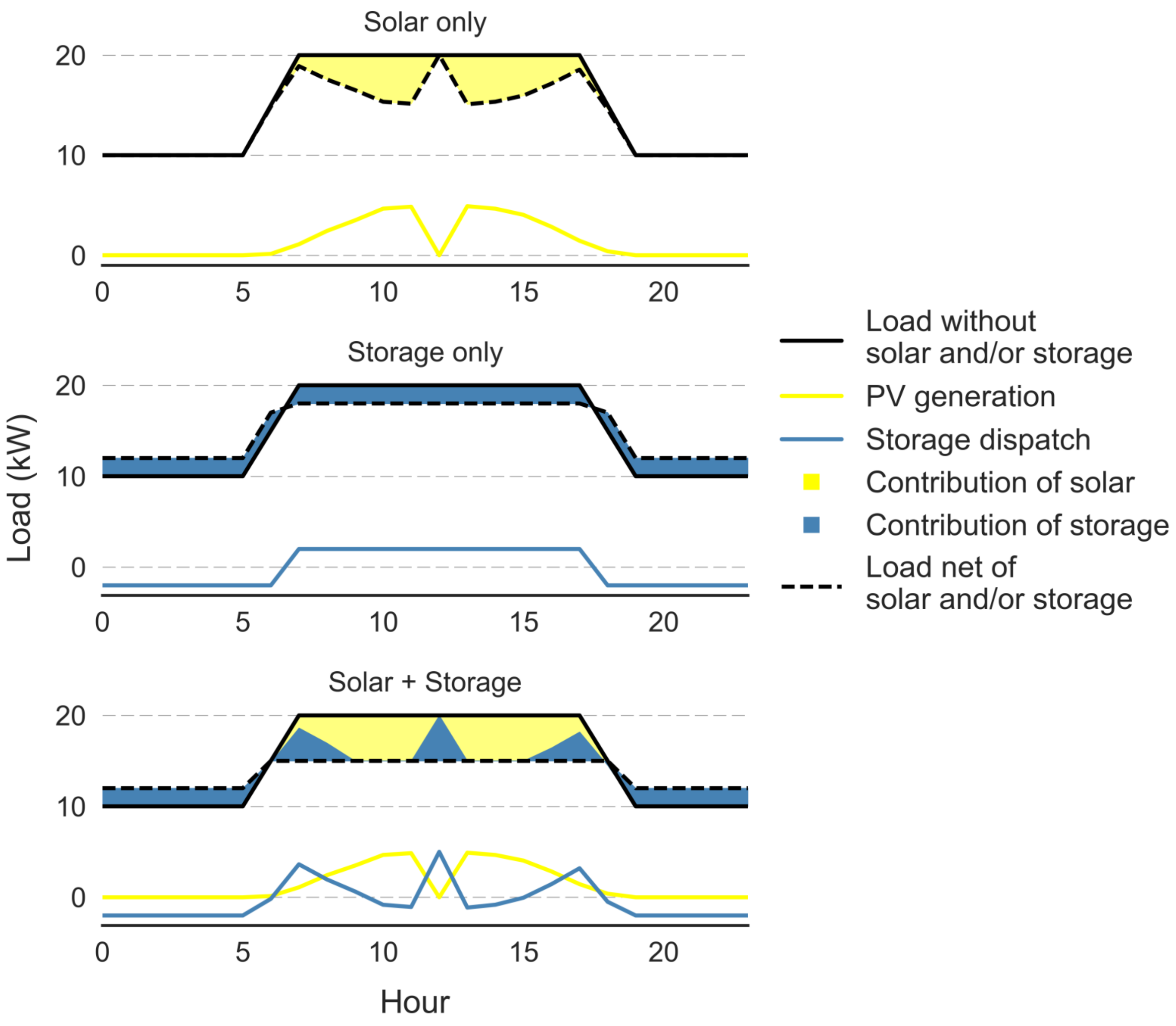
Synergy #1: Solar can create narrow peak loads that storage is able to easily clip



A clear example is a building with a broad peak load that extends into early morning and/or evening hours

- Solar-alone (top figure) has little or no impact on load in those hours, leaving residual narrow peaks
- Storage-alone (middle figure) would be optimally discharged slowly over the broad peak, yielding small billing demand reduction (relative to storage capacity)
- When the two technologies are combined (bottom figure), storage is dispatched to clip the early morning and evening peaks, producing a greater billing demand reduction for a given quantity of energy discharged

Synergy #2: Storage can buffer transient dips in solar production



Transient dips in solar production can occur for various reasons, most commonly due to passing clouds

- With solar alone (top figure), a drop in solar production on a single day can substantially reduce or eliminate a month's demand charge savings
- Storage can act as a buffer for these transient dips in solar production (bottom figure), preserving demand charge savings
- Demand reductions achieved by acting as a buffer are greater than what storage would achieve on a standalone basis (middle figure)

Discussion of the cooperation ratio metric

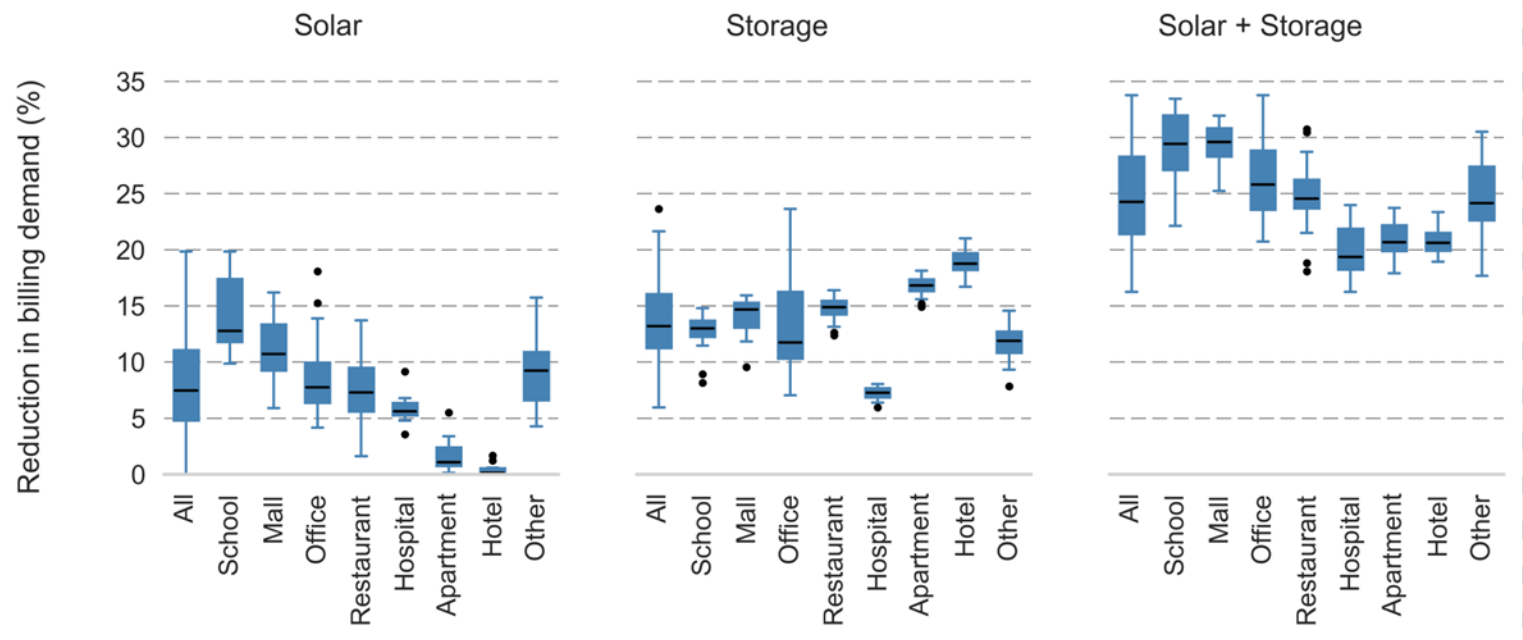
- Cooperation ratio is a measure of synergy, not absolute performance
  - In the hypothetical example shown here, Building Y has *greater* synergy for co-deployment than Building X (cooperation ratio of 1.5 vs. 1.0), but *lower* absolute demand reduction (30 kW vs. 40 kW)
  - Buildings with wide peaks that extend outside of daylight hours (such as hospitals, in our work) are an example of this: relatively high cooperation ratios but lower demand charge reductions than other buildings with more favorable load profiles

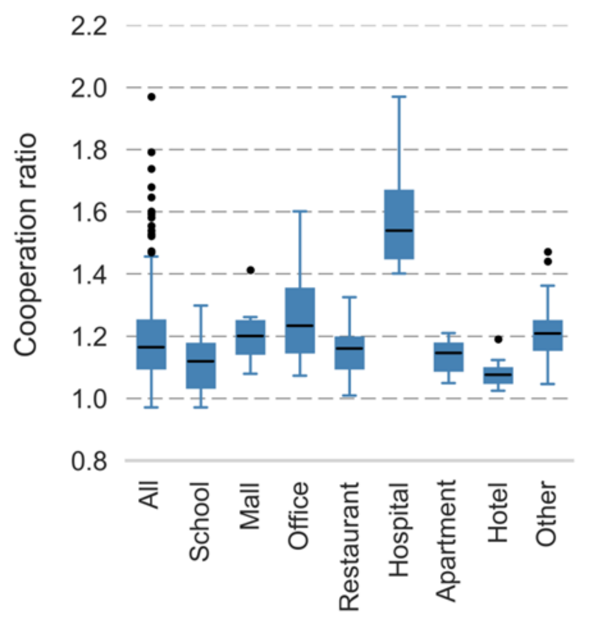
Hypothetical billing demand reductions from solar and storage on two different buildings
(each with the same size solar and storage systems)

	Solar-alone reduction	Storage-alone reduction	Solar+storage reduction	Cooperation ratio
Bldg. X	20 kW	20 kW	40 kW	1.0
Bldg. Y	10 kW	10 kW	30 kW	1.5

- Cooperation ratio—like demand charge savings more generally—relates to customer-economics, not value to the utility system
  - Thus a high cooperation ratio does not necessarily mean that there are synergies in terms of avoided costs for the utility
  - Whether or not this is the case depends on the alignment between demand charges and utility cost causation (a topic outside the scope of the current analysis)

Variations in billing demand reduction and cooperation ratio across building types





Legend:

Line – median

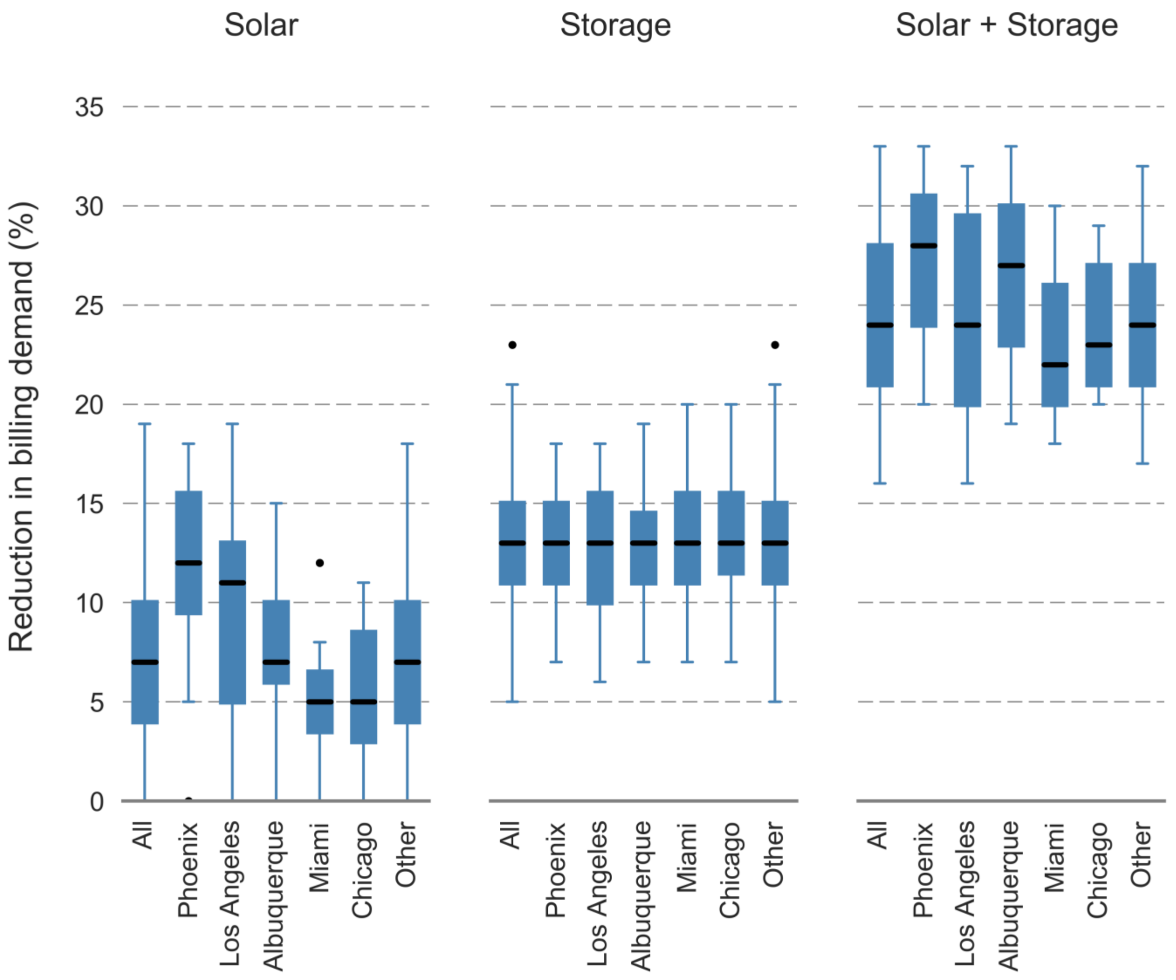
Box – first and third quartile

Whiskers – 1.5x inner quartile range

Figures show the distribution in average billing demand reduction and cooperation ratio for each building type across all locations. PV systems sized to meet 20% of annual load (in kWh) and battery sized to be 20% of customer's peak demand (in kW)

- Solar-only systems have significant variation in demand charge reductions across building types
  - Afternoon peaking (schools) have the highest demand reductions, while evening-peaking buildings (apartments, hotels) have the lowest
- Storage-only systems have less variation across usage types
  - Buildings with narrow peaks (hotels) have the highest billing demand reductions, while those with wide peaks (hospitals) have the lowest
- Building types that performed well with standalone solar also performed the best with solar + storage systems
- Building types with the highest cooperation ratios (such as hospitals) do not necessarily have the most significant reductions in billing demand, as it indicates a *relative* increase in demand reduction

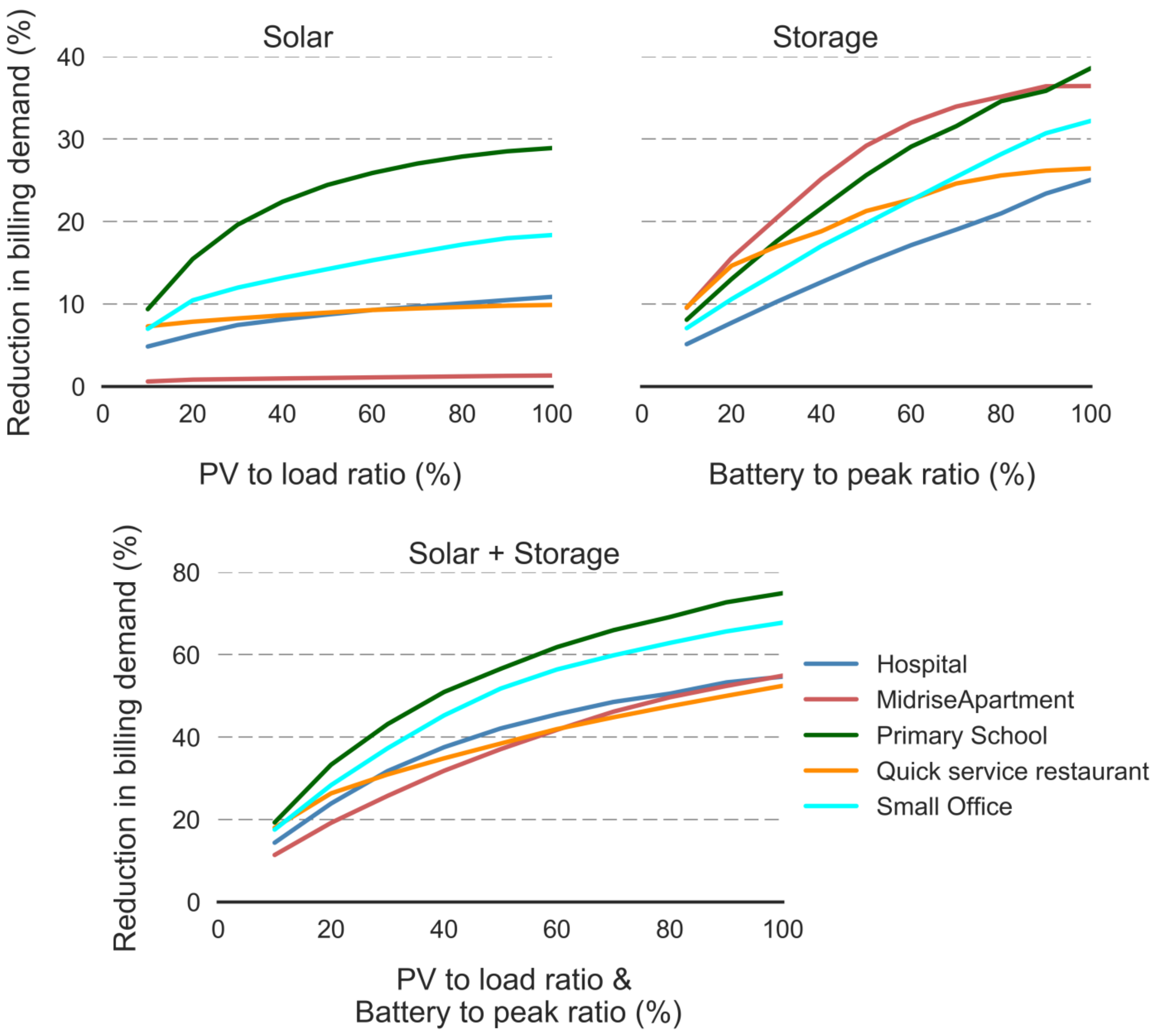
Variations in billing demand reduction across locations



Figures show the distribution in average billing demand reduction across all building types in each location. PV systems sized to meet 20% of annual load (in kWh) and battery sized to be 20% of customer's peak demand (in kW).

- **Solar-only:** Demand reductions greatest in regions with stronger solar resource (e.g. Phoenix, Los Angeles)
- **Storage-only:** Demand reductions less sensitive to location
  - This is because simulated commercial building load profiles are similar across locations
  - Note that temperature-driven changes in storage performance were not considered here
- **Solar + storage:** Locational differences in demand reductions are in between the other two cases (less than solar-only, more than storage-only)

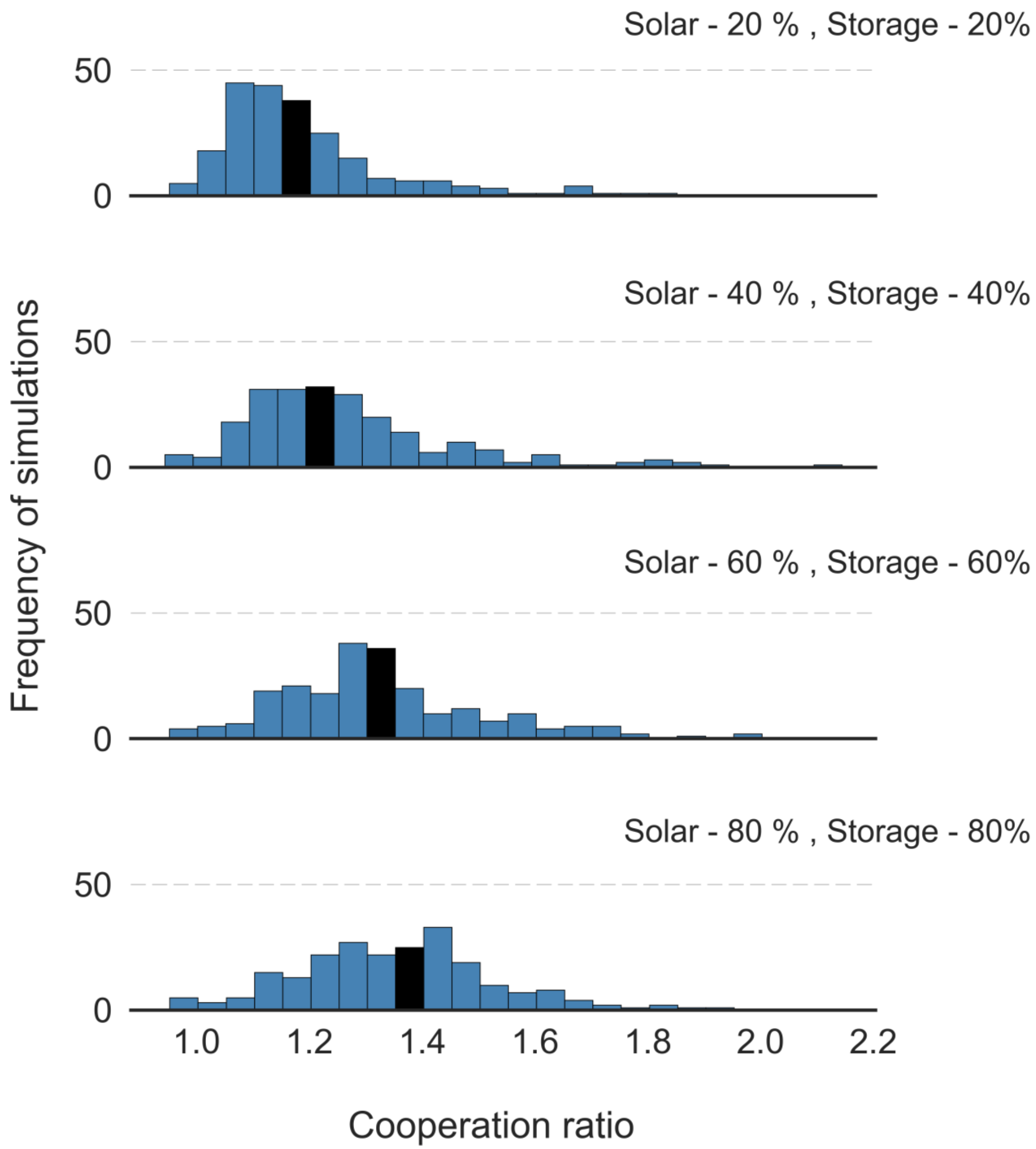
Diminishing returns with increasing size



These figures show the average billing demand reduction across a range of system sizes for several building types in Albuquerque

- The efficacy of standalone solar in reducing billing demand decreases as the system gets larger (upper left-hand figure)
  - Increasing solar progressively shifts peak load further outside of daylight hours
  - See earlier studies in this series for more-complete discussion of these dynamics
- Standalone storage also has diminishing returns with increasing size for some buildings, though less strongly than solar-alone
  - Peaks become wider as they are clipped, requiring greater kWh storage capacity for each incremental kW of billing demand reduction
- Solar + storage together exhibit diminishing returns that fall approximately between the two technologies alone
  - Partly because cooperation ratio increases with system size (see next slide)

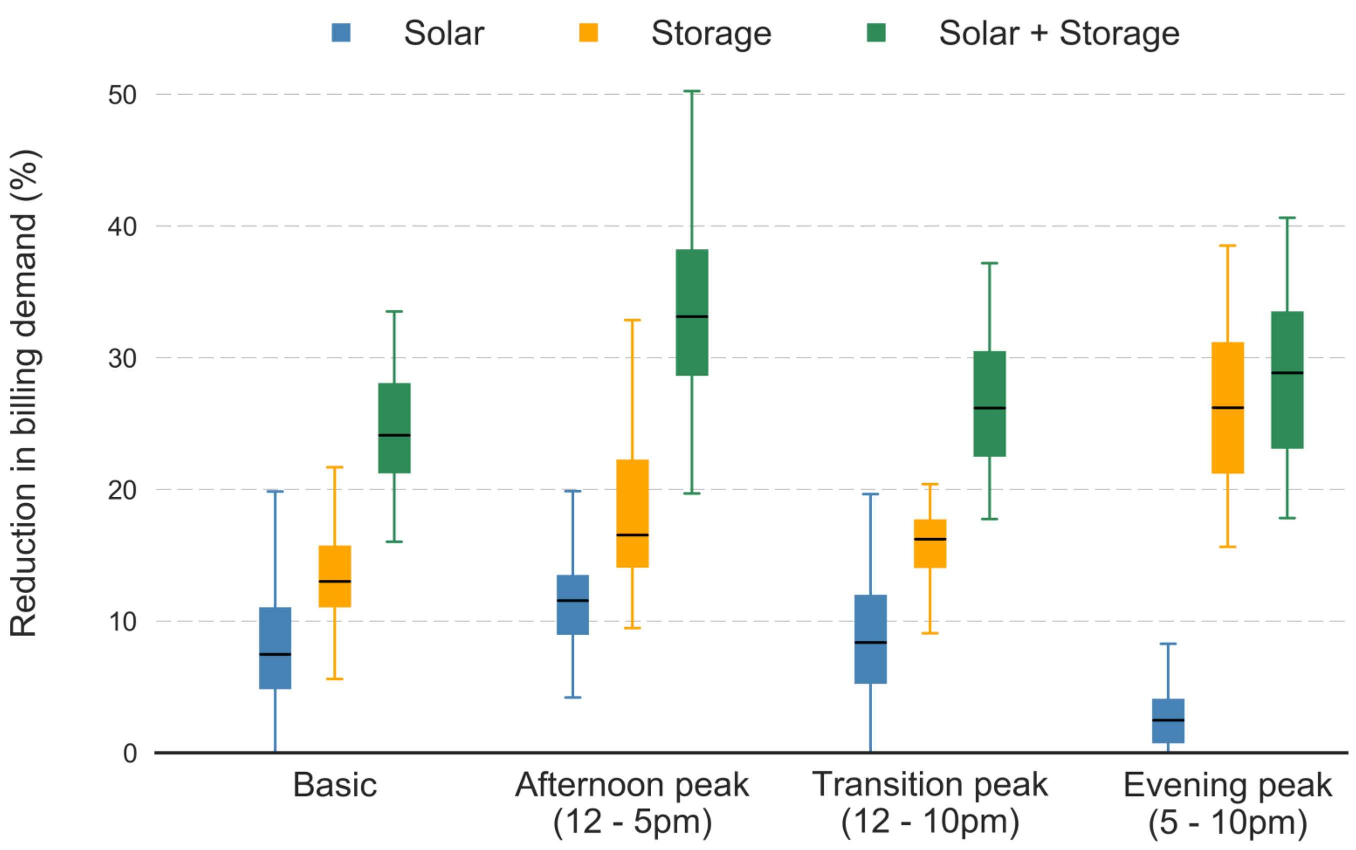
Cooperation ratios increase with system size



This figure shows the distribution of average cooperation ratios for all buildings and all locations as a function of the size of the solar+storage systems. The black bars are median values. PV is sized to meet the stated percentage of the customer's annual load (in kWh) and battery power is sized to be the stated percentage of the customer's annual non-coincident peak demand (in kW)

- Larger solar PV systems create progressively narrower and taller peaks, which are progressively easier for storage systems to clip
- I.e., Synergy #1 becomes more pronounced as the system sizes get larger

Demand charge savings from solar + storage are greater under “peak period” demand charge designs

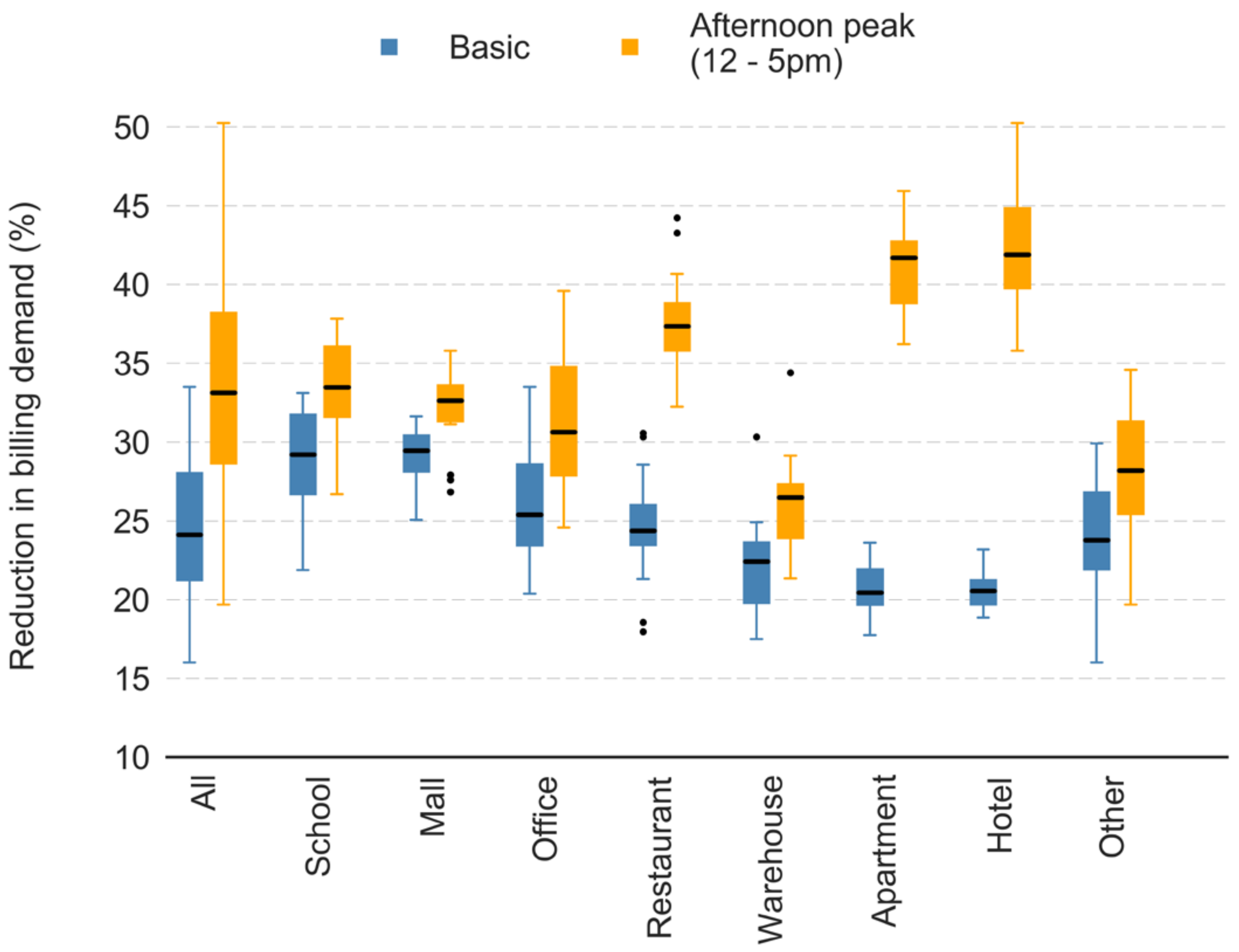


This figure shows the distribution of average billing demand reduction under different peak-period demand charge windows. PV is sized to meet 20% of customer’s annual load (in kWh) and battery power is sized to be 20% of customer’s peak demand (in kW)

Some demand charges are based on maximum demand during a defined “peak period”

- Demand charge reductions from storage—whether standalone or co-deployed with solar—are generally greater under these designs
  - Storage discharged during designated peak period, rather than spread over wider range of hours
- **For standalone storage:** demand charge reductions are greater when the peak period is based on evening hours
- **For solar + storage:** Demand reductions are greater when based on an afternoon peak period
  - In part, this is because of greater coincidence between solar profile and afternoon peak period
  - But also reflects greater synergies between solar and storage

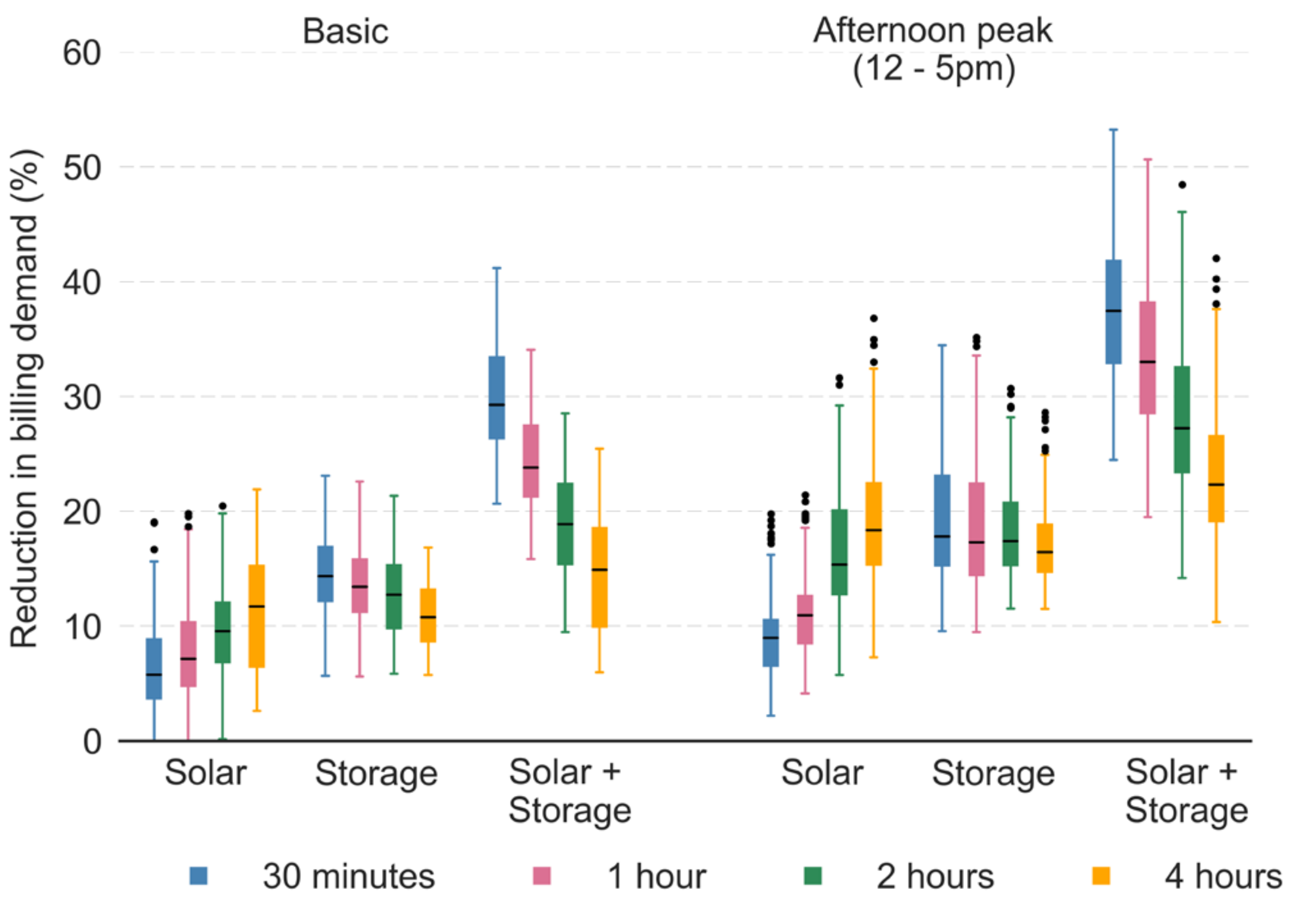
The advantages of an "afternoon peak" demand charge are most pronounced for certain building types



This figure shows the distribution of average reduction in billing demand for solar + storage systems. PV is sized to meet 20% of customer's annual load (in kWh) and battery power is sized to be 20% of customer's peak demand (in kW)

- Buildings that peak late in the day (e.g. hotels and apartments) have the greatest billing demand reduction under an afternoon peak period
  - The storage system's size is the same in both basic and afternoon peak scenarios
  - Because their afternoon peak demand is lower than their evening demand, a battery of a given size has a greater percentage impact
  - For example, a building may have a 100 kW evening peak but only a 50 kW afternoon peak. If a 20 kW battery can clip 20 kW from the billing demand in both cases, it equates to a 20% and 40% reduction respectively
  - Whether this translates to a corresponding decrease in demand charges depends on the difference between the actual $/kW rates in the two tariffs, which is not resolved here
- All other buildings see more modest improvements, primarily driven by the storage having a shorter window that it needs to clip

Billing demand reductions for solar + storage are generally greater for demand charges with shorter averaging intervals



Distribution of average reduction in billing demand across locations for several building types and averaging intervals. PV is sized to meet 20% of customer's annual load (in kWh) and battery power is sized at 20% of customer's non-coincident peak demand

Billing demand is typically measured as an average over some interval (most commonly 15-minutes)*

- Longer averaging intervals effectively serve as a proxy for storage, by smoothing out short-duration peaks that storage would otherwise be able to clip
- Demand reductions from solar + storage thus tend to be greater for demand charges with *shorter* averaging intervals
  - Many demand charge rates are based on 15-minute interval averages, resulting in even greater demand reductions than shown here for 30-minute interval averages
- This is the opposite trend for solar-only, where demand reductions are greater for *longer* averaging intervals.
  - For solar + storage systems with much larger solar and/or much smaller storage system sizes than assumed in this figure, the trends can invert and more closely resemble those for solar-only.

* *The averaging interval should not be confused with the duration of the peak period; these are different design elements. The shortest averaging interval examined in our analysis is 30 minutes, as this is the resolution of the underlying weather data used to simulate building loads and solar generation.*

Table of contents

Conclusions

- **Solar and storage are mutually beneficial.** Though one might anticipate that solar + storage could "cannibalize" demand reduction opportunities for the other, this analysis shows the opposite: namely, that each technology incrementally reduces demand charges by a greater amount when deployed with the other than on its own. Some of the most economic opportunities (from the customer perspective) for storage may therefore be in facilities that already have solar, and vice-versa.
- **Demand charge savings from solar + storage are highly customer-specific.** Demand reductions from solar + storage systems vary substantially from customer to customer, depending on commercial building type, location, and system sizes (albeit to a somewhat lesser degree than for standalone solar). Identifying market opportunities for solar + storage may therefore require fairly specialized targeting.
- **Demand charge design matters for the economics of solar + storage.** This analysis examines two aspects of demand charge design: non-coincident demand charges vs. peak-period demand charges and the averaging interval over which demand is measured. The results show clearly that these details can significantly impact the level of demand reduction from solar + storage systems, though not always in the same manner as for each technology individually. Understanding those interactions will be important as utilities continue to refine demand charge designs.

Table of contents

Methodology – further details

Solar insolation and weather data

- Solar insolation data and other weather data were downloaded from the National Solar Research Database, managed by the National Renewable Energy Lab (https://maps.nrel.gov/nsrdb-viewer/) for each location on a one half hour timescale for years 1998 through 2014

Energy Plus building load simulations

- Commercial Reference Building Models (https://energy.gov/eere/buildings/commercial-reference-buildings), developed by the National Renewable Energy Laboratory for the US Department of Energy, were selected for the 15 cities considered in the analysis.
- Only new construction category models were used.
- The weather data files from the NSRDB were converted to Energy Plus weather files and used as an input into the Energy Plus simulation platform, developed by Lawrence Berkeley National Laboratory and managed by the National Renewable Energy Laboratory
- The outputted files were annual load profiles for each customer type and location by 30 minute increments

PV generation profiles

- The same weather data files were converted into a file format to be read by the System Advisor Model, developed by the National Renewable Energy Laboratory
- PV generation profiles were generated for each location considered in this analysis

Demand charge savings calculations

- Calculations were performed using the Python programming language