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Evaluating the Capabilities of Behind-the-Meter Solar-plus-Storage for Providing Backup Power during Long-Duration Power Interruptions

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Report Organization

- Introduction
- Data and Methods
- Synthetic Event Analysis
- Historical Event Analysis
- Key Take-Aways and Future Work
- Appendix: Supplementary Results

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Context and Motivation

- Early adoption of behind-the-meter (BTM) solar photovoltaic+energy storage systems (PVESS) has been driven to a significant degree by reliability or resilience concerns
- Grid reliability concerns may become more pronounced or more costly to mitigate over time, with rising climate and wildfire impacts and greater amounts of variable generation
- Understanding the backup power capabilities of BTM PVESS is critical to informing customer investments and early adoption as the industry scales up and other value-streams develop
- Understanding these capabilities can also inform grid planning and policy-making (e.g., forecasting PVESS growth, prioritizing grid investments, developing customer programs, etc.)
- Existing literature includes case studies on PVESS in backup power applications, but little information exists on how systems would perform across a broad range of conditions and contexts

Project Overview

Objective: Evaluate the capabilities of BTM PVESS for providing back-up power to individual customers over *long-duration* power interruptions

- Goal is to establish a baseline set of performance estimates and identify key performance drivers

Approach: Simulation-based analysis, using modeled hourly solar and end-use level load profiles, simulating battery storage dispatch during interruptions

Scope:

- Includes both residential and commercial building types
- Considers both critical-load and whole-building backup
- Characterizes backup-power performance across climate, building stock, and outage conditions

Planned Follow-On Work:

- Evaluate backup performance during short-duration interruptions
- Explore interactions with other DERs and other competing uses for storage

Data and Methods

Overview of Analysis Structure

Power Interruptions*

- Synthetic events for every U.S. county and month
- Historical long-duration events (10 events, 4 counties each)

End-Use Load Profiles*

- Simulated hourly profiles from NREL's ResStock and ComStock models
- 3 residential and 3 commercial building types

Solar Profiles*

- Simulated using NREL's System Advisor Model (SAM)

Assumptions / Scenarios

- PV & storage sizing
- Critical loads
- Event start-day, time, & duration
- Initial state of charge (SoC)

Storage Dispatch Model: Dispatch storage to meet specified critical load during power interruption

Output Metric: Percent of critical load or total load served during interruption

**All time-series input data temporally and geospatially aligned*

Power Interruptions

Synthetic Events

- **Goal:** Provide standardized and geographically expansive analysis
- Simulate for every U.S. county and month
- Base-case assumes 3-day interruption
  - Run sensitivities with 1-10 day interruptions
- Load and solar generation profiles based on TMY3 weather data
- Base-case analysis assumes interruptions begin on the median “net load” day each month, starting at 12am, with batteries fully charged
  - Run sensitivities where interruptions begin on the lowest and highest net load day each month, and with other start times and initial SoC

Historical Events

- **Goal:** Provide relatable examples of the resilience capabilities of PVESS in actual events that may represent more extreme weather than in the synthetic analysis*
- A sample of 10 historical events:
  - **Hurricanes** Harvey (2017), Irma (2017), Florence (2018), Michael (2018), and Isaias (2020)
  - **Wildfires** in California (2019)
  - **Winter storms** in Washington state (2019) and Oklahoma (2020)
  - **Thunderstorms** in Iowa (2020) and Texas (2020)
- Use data from PowerOutage.US to identify start and end times for each event
- Focus on 4 affected counties per event: urban, rural, vulnerable, longest interruption

**Events selected from the years 2017-2020, as those are the years for which the required interruption and weather data were available.*

End-Use Load Profiles

Analysis relies on end-use load profile data from NREL's ResStock and ComStock models, consisting of one year of simulated hourly interval load data disaggregated by end-use category

- Building types selected (from those available in ResStock/ComStock):
  - Residential: single-family detached, mobile home, multi-family (10-unit)
  - Commercial: stand-alone retail (box store), secondary school, hospital
- Synthetic events analysis
  - Relies on NREL's public EULP dataset: statistically representative sample of ~800,000 building models across all building types; based on TMY3 weather
  - *Cross-county comparisons* use the median[1] building model in each county (or PUMA[2] region)
  - *Intra-county comparisons* based on all building models within a select set of counties
- Historical events analysis
  - Custom set of ResStock/ComStock simulations for the weather years and counties for each event
  - 500 building models per building type per county (residential and schools); 100 building models (hospital/retail)

[1]In selecting the median building model (by kWh usage) for each county, we also ensure that the end-uses are representative of that county (e.g., space heating tech., air conditioning, etc.).
[2]We aggregate individual counties to PUMA (Public Use Microdata Area) regions if fewer than 10 building models are available for any given building type within a county. PUMAs are non-overlapping census derived categorization for similarly populated geographies.

Critical Load Definition

- Critical load selection based on end-use categories available in ResStock and ComStock
- Residential: Three different backup configurations considered
  - *Limited Critical Loads*: refrigeration, lighting during evening hours, well pump, and basic plug loads (e.g., computer, internet, cell charging manually set at 70 Watts)
  - *Critical Loads*: All of the above plus heating and cooling-related end-uses (analysis focuses mostly on this scenario)
  - *Whole-Building*: All loads
- Commercial: Only whole-building backup considered, given more limited breakdown in end-use categories

ResStock End-Use Categories

Bath fan	Ceiling fan	Clothes dryer
Clothes washer	Cooking range	Cooling energy
Dishwasher	Exterior holiday light	Exterior lighting
Extra refrigerator	Fans cooling	Fans heating
Freezer	Garage lighting	Heating energy
Heating suppl. energy	Hot tub heater	Hot tub pump
House fan	Interior lighting	Plug loads
Pool heater	Pool pump	Pumps cooling
Pumps heating	Range fan	Recirculating pump
Refrigerator		Water systems
Well pump		

Limited Critical Loads (yellow): Interior lighting, Refrigerator, Well pump. Heating/Cooling end-uses (red): Cooling energy, Fans cooling, Fans heating, Heating energy, Heating suppl. energy, Pumps cooling, Pumps heating.

ComStock End-Use Categories (school)

Cooling energy	Exterior lighting	Fans
Heat recovery	Heat rejection	Heating
Interior equipment	Interior lighting	Pumps
Refrigeration	Water systems	

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PVESS System Sizing

PV Sizing

Residential

- Base-case for single-family and mobile homes assumes PV systems sized to generate 100% of annual energy consumption[1]
- Multi-family sizing subject to roof-area constraints
- Sensitivities with PV systems based on 50% of annual energy consumption

Commercial

- Base-case: the lesser of 100% of annual energy consumption or available roof area
- Also consider scenario with no roof constraints (i.e., allow ground-mounting)

[1]*See appendix for info on PV size relative to roof area*

Storage Sizing[2]

Residential

- Consider both 10 kWh and 30 kWh, reflective of range typically observed in the market today
- Also includes sensitivity up to 100 kWh, representative of a large EV battery capable of providing home backup

Commercial

- Include a case based on storage sized at 30% of average daily PV generation, equal to median commercial sizing in the market today
- Also include cases with storage sized to meet 1-day and 3-days of average residual load that would otherwise be served by grid power

[2]*All storage modeled as 2-hour duration, AC-coupled*

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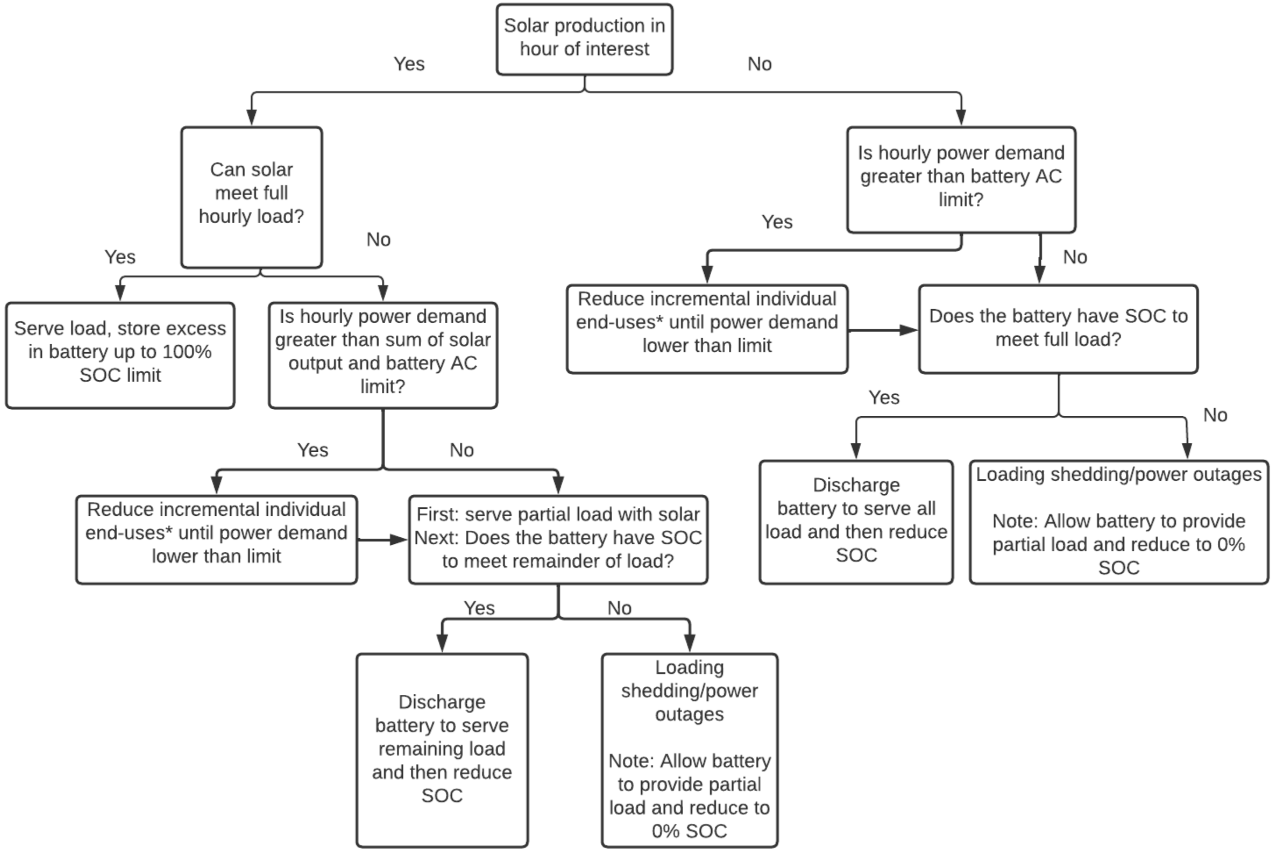
Storage Dispatch Model

- Model dispatches storage to meet specified loads in each hour sequentially, given PV production[1], battery state-of-charge, and power constraints on the battery
- If the PVESS cannot meet all specified loads in an hour, individual loads are dropped in their entirety, starting with the lowest priority load, until remaining loads can be fully served
- No optimization performed over the full outage time period to reserve SoC for future hours
- Analysis does not account for sub-hourly load spikes, often most significant for air conditioning and electric heating loads, though a sensitivity analysis with 15-minute interval data was performed without significant change in results
- PVESS assumed to remain undamaged



[1]*Solar production simulation assumes a fixed-tilt, 1.2 inverter loading ratio, south facing PV system with 14% losses (NREL SAM defaults).*

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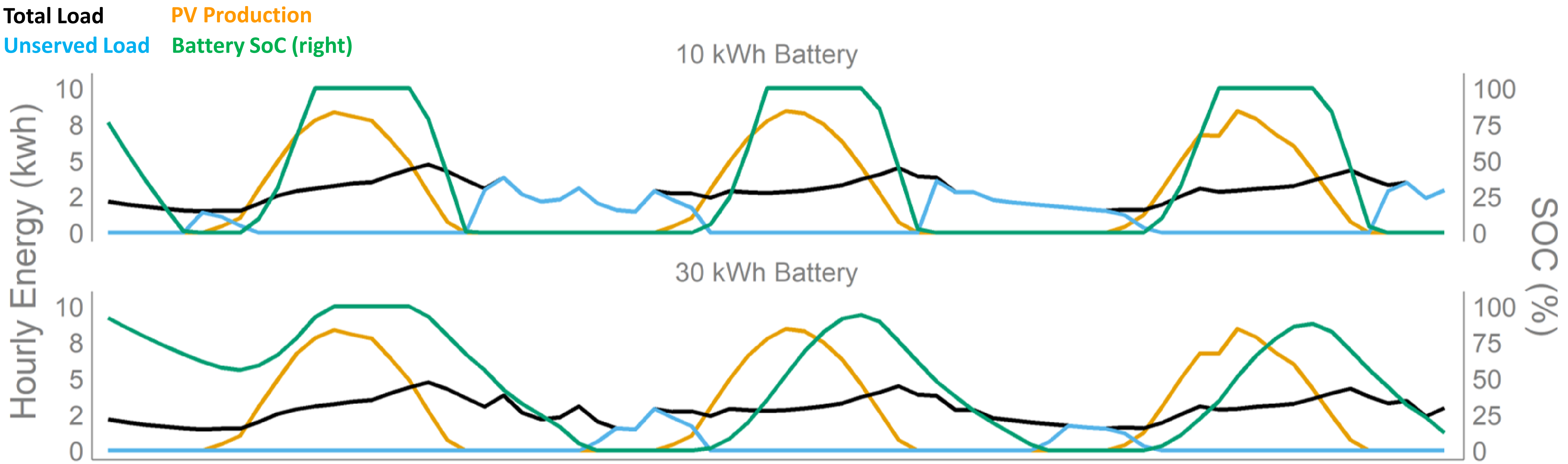
Illustrative Examples of Storage Dispatch during Interruption

Examples are for the same customer and event, but different storage sizes

- Unserved load occurs in both cases, after battery SoC drops to 0% in the evening hours; is greater for the 10-kWh battery case
- Curtailed PV is not shown explicitly, but occurs whenever PV production exceeds total load and the battery SoC is at 100%; also greater in the 10-kWh battery case



Synthetic Event Analysis

Synthetic Event Analysis: Organization of Results

1

Single-Family Detached Homes: Scenario Analysis

- Based on county-median homes
- Explores backup performance with PVESS size, critical load definition, outage conditions

2

Single-Family Detached Homes: Variation across Building Stock

- Based on full distribution of modeled homes in six geographically diverse counties
- Explores how backup performance varies with key building stock characteristics

3

Mobile Homes and Multi-Family Homes

- Based on county-median homes for each building type
- Considers range of PV & storage sizes, with base-case critical load & outage assumptions

4

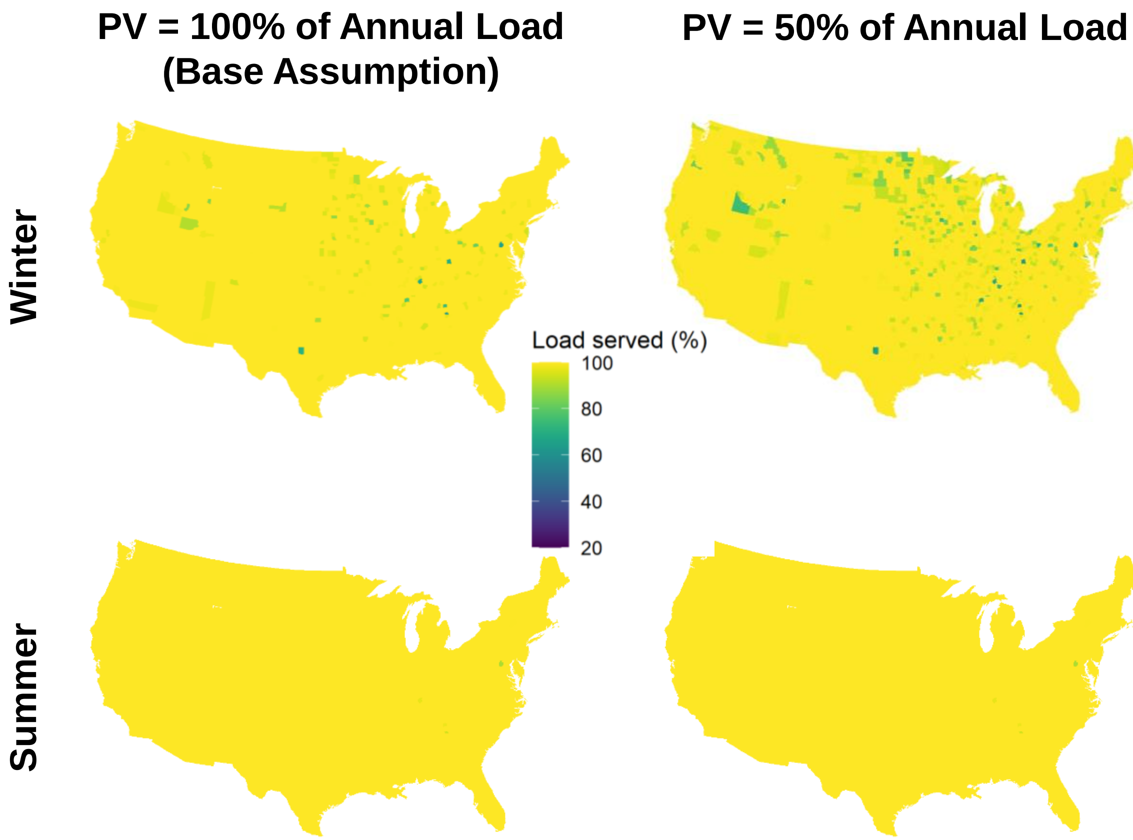
Commercial Buildings: Scenario Analysis

- Similar approach as scenario analysis for single-family detached homes (section 1), though with a more limited set of scenarios

Backup Performance for a PVESS with 10 kWh of Storage

Backup of limited critical loads (no heating/cooling)

Average percent of load served over summer and winter months, for each county-median home

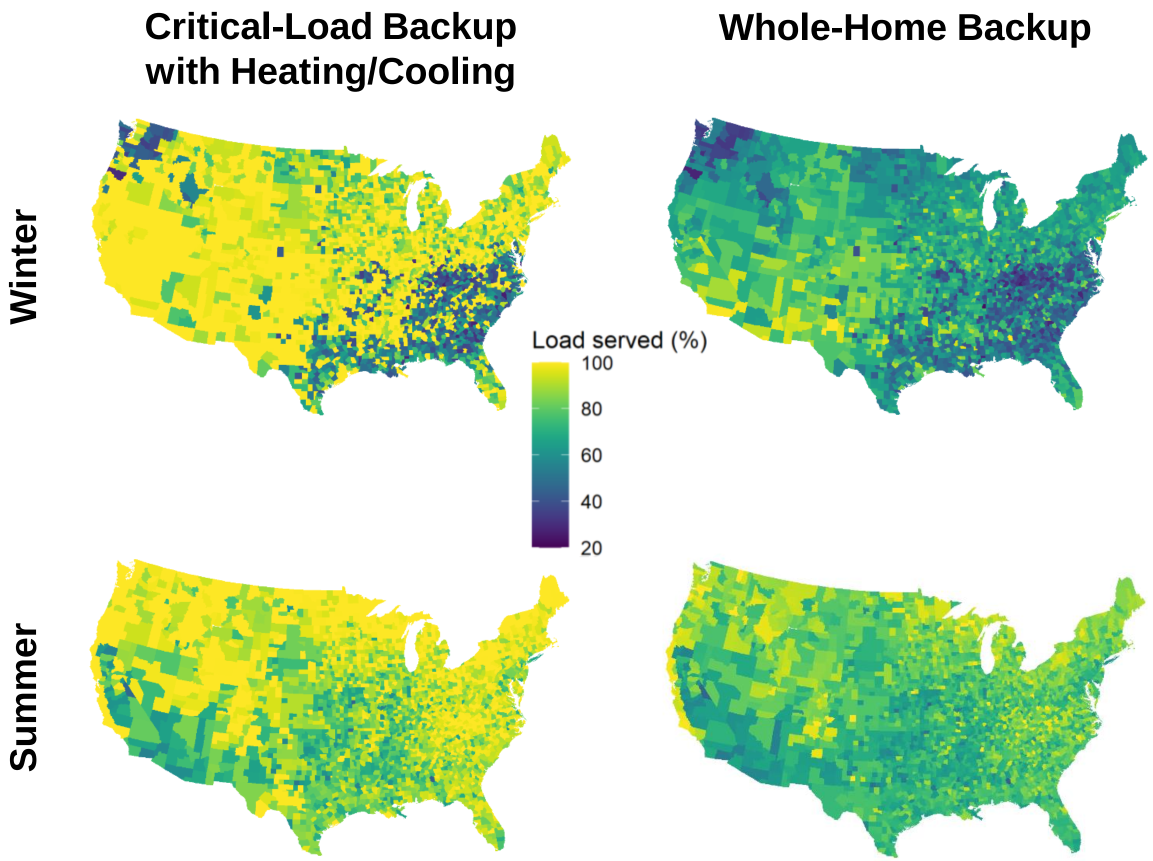


- First we consider backup power performance during a 3-day outage for a PVESS with a relatively small amount of storage (10 kWh), common among current installations but not necessarily sized for backup power purposes
- In almost all counties, this system can more or less fully supply backup power to limited critical loads that exclude heating and cooling
- This is true in most counties even with relatively small PV systems sized to generate 50% of annual customer load
- Performance in winter months can be lower in northern counties, which have greater seasonal variability in solar insolation

Backup Performance for a PVESS with 10 kWh of Storage

Backup of critical loads with heating/cooling and whole-home backup

Average percent of load served over summer and winter months, for each county-median home



- Backup performance is significantly lower if critical loads include heating and cooling
  - Across all counties and months, 85% of critical load served on average (86% population weighted average)
  - These numbers would naturally be higher if customers accept lower heating and cooling service levels (e.g., temperature set-backs)
- Performance is lowest in winter months in regions where electric heating is common (southeast and northwest) and in summer months in regions with large cooling loads (southwest and southeast)
- Not surprisingly, backup performance is significantly lower for whole-home backup
  - 73% of total load served on average (population weighted)

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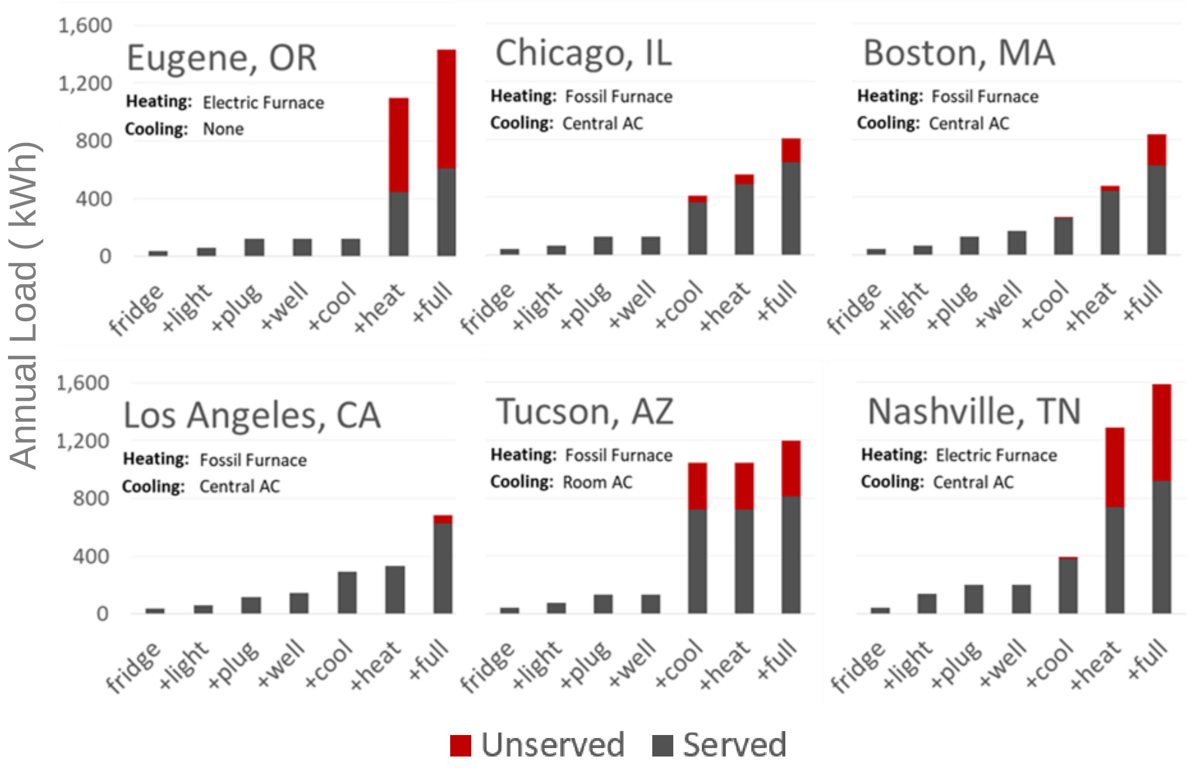
Backup Performance for a PVESS with 10 kWh of Storage

Breakdown by end-use for a representative set of locations

Served and unserved load as additional end-uses are incrementally added to backup service



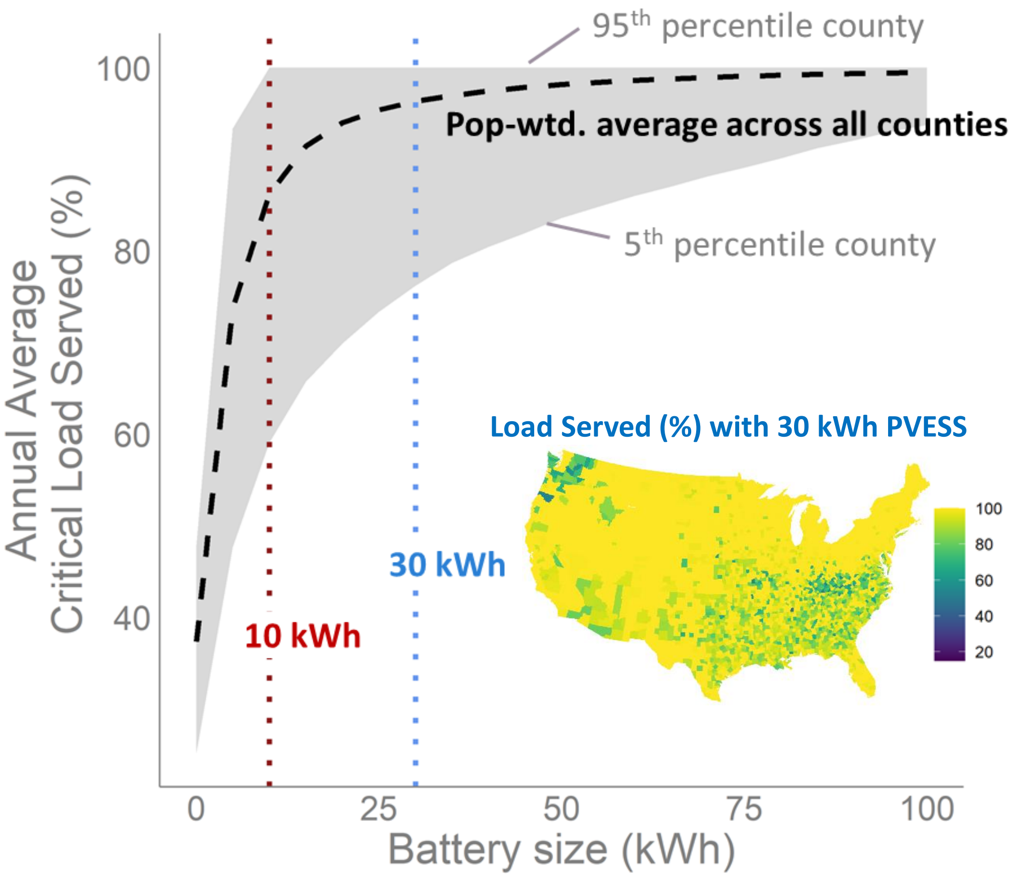
Notes. Results are based on the county-median single family home for each location, and the values plotted represent the sum of served and unserved load over all 12 monthly interruption events, for each critical load configuration.

- End-uses included in the Limited Critical Load scenario (the first four listed along the x-axis) are quite small and thus easy to backup
- Cooling loads vary along a continuum
  - In some regions, a 10 kWh PVESS can serve most, if not all, cooling demand
  - In the worst case shown (Tucson), the system still meets about 2/3 of cooling demand*
- Heating loads—if electric resistance—are quite large and more difficult to serve
  - In Eugene and Nashville, the 10 kWh PVESS meets roughly 1/3 to ½ of the heating energy*
  - Fossil-based heating can also go partially unserved in cold-weather climates, due to energy required by furnace fans

**These statistics likely overstate heating load served with a 10 kWh battery, given the battery's power constraints and the power draw of electric heating and cooling equipment. Future slides compare results for electric furnace to heat pump technologies.*

Increasing Backup Performance with Battery Size

Backup performance across battery size, for critical load with heating and cooling



- Now consider a system with 30 kWh of storage
  - At the upper end of sizes currently observed in the market, and more indicative of how a customer might size their system for backup
  - 96% of critical load served on average across counties, with range of 76-100% between the 5th and 95th percentile values
  - Spread reflects the same geographical patterns as observed before (map insert): counties at the lower end have electric heating and/or high cooling loads
- Larger batteries increase performance further, but with diminishing returns, given fixed PV sizing
  - Matters most for counties at the lower percentile end

Remaining analysis of single-family homes assumes 30 kWh storage and critical load with heating/cooling

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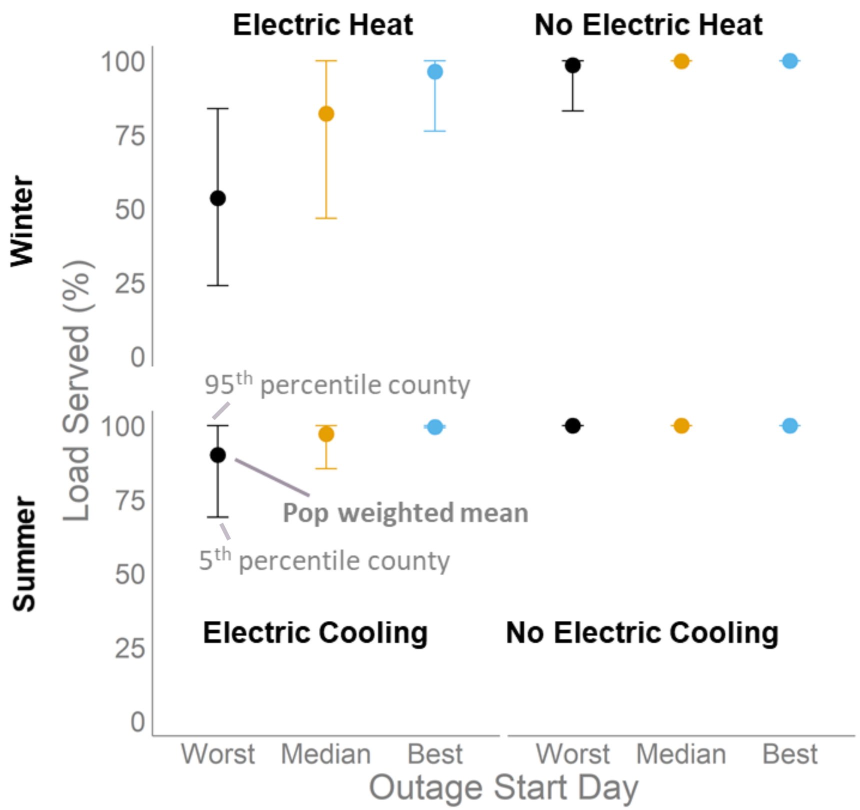
Sensitivity to Outage Start-Day *within* Each Month

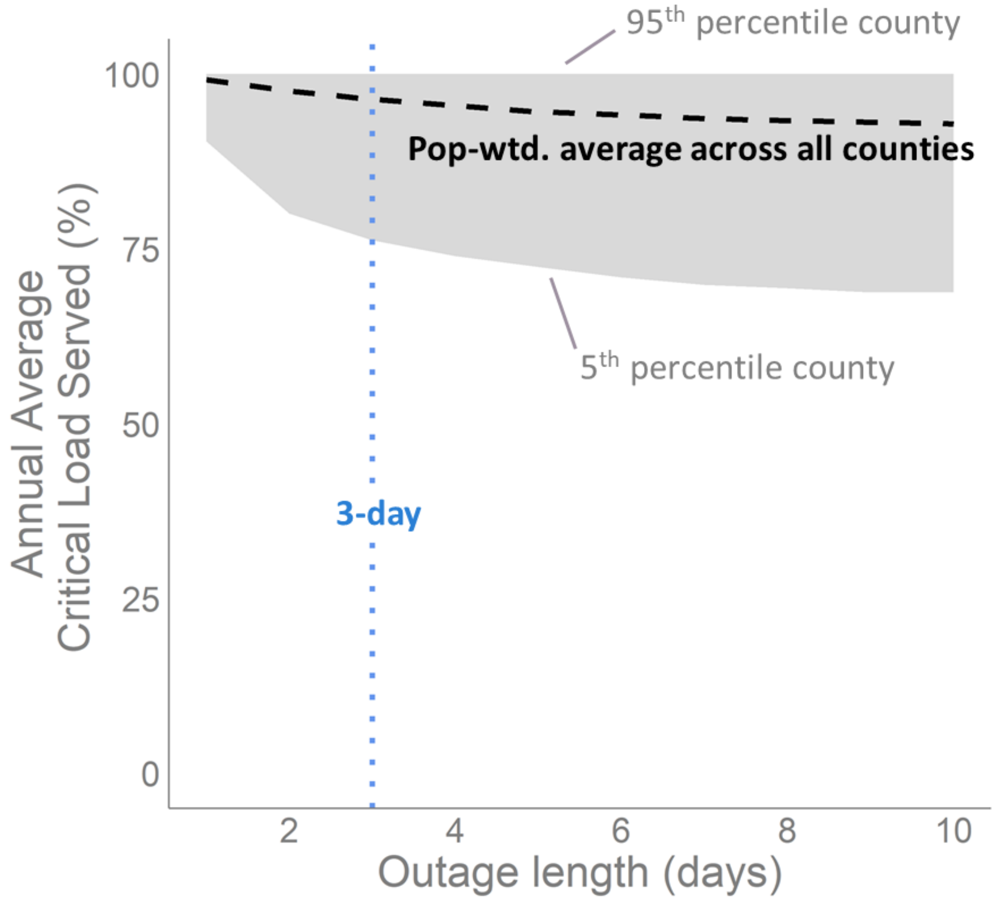
Backup performance for the worst vs. best outage start-day each month, segmented by season and end-use technology



- Preceding analysis assumes that interruptions begin on the median net-load day each month, but loads and solar can vary significantly within any month
- Sensitivity shown here considers scenarios where interruptions instead begin on the "worst" or "best" days each month (the highest or lowest net-load day)
- Effects depend on season and end-use characteristics
  - Across county-median homes with electric heat, avg. performance in winter months drops to 53% of load on the worst days, compared to 96% for the best days
  - Summer-month effects are less pronounced though still notable for homes with A/C in hot climates (the lower percentile band in the panel on the lower left)
- To be sure, effects shown here reflect intra-month variations *within a typical meteorological year*; greater variations could occur with extreme weather

Sensitivity to Outage Duration

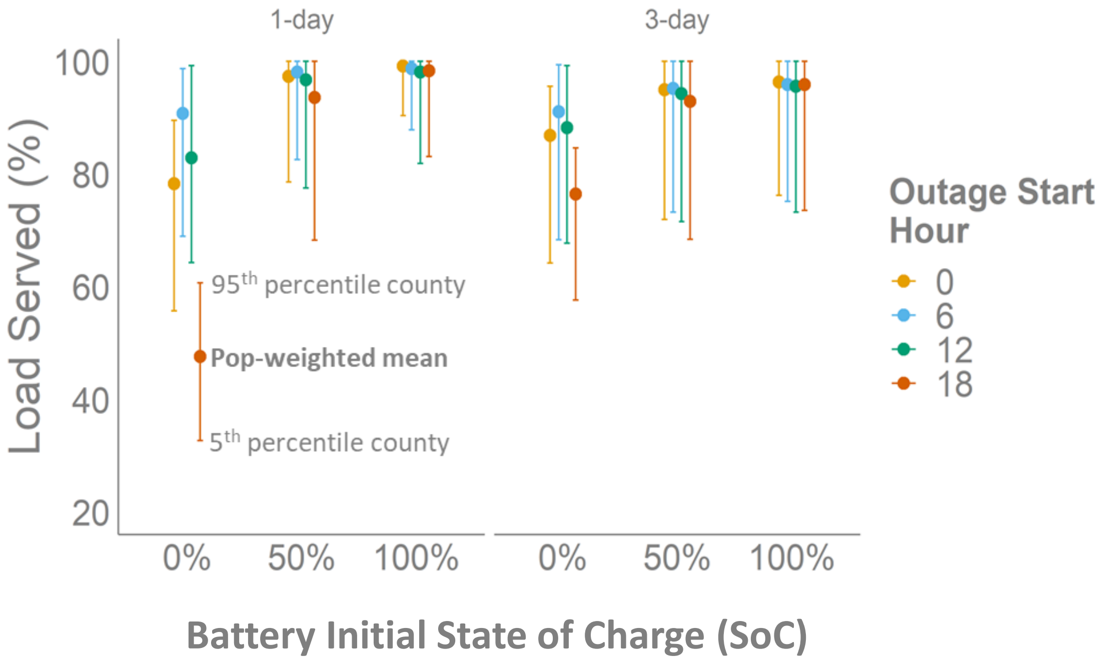
Backup performance based on outage duration



- The base scenario assumes a 3-day outage (and that batteries start with 100% SoC)
- Backup performance declines with outage duration, for two reasons
  - The initial stored energy in the battery is depleted, at which point the ability to meet critical load becomes limited by daily PV generation
  - The longer the duration of the outage, the greater the chance of an especially “low solar” or “high load” day
- That said, the effects are generally modest
  - E.g., average load served declines from 96% to 92% as outage length increases from 3 to 10 days
  - The biggest effects occur for counties at the low end of the percentile range, as outage length extends beyond 1-day

Sensitivity to Outage Start-Time and Initial State-of-Charge

Backup performance based on outage start-time and initial SoC, for 1-day and 3-day outages



- Base-case assumes that interruptions begin at 12 am (hour=0) and that initial SoC is 100%
- These two factors are inter-dependent, in terms of how they impact backup performance, and matter mostly over the first 24 hours of an event
- In the extreme, a 1-day event that starts immediately after the sun sets (hour=18) will be much harder to meet without any initial SoC (48% of load served vs. 98% if the battery starts fully charged or 94% if it starts with a 50% SoC)
- These initial conditions become progressively less important over longer duration events, in terms of average performance over the entire event

Synthetic Event Analysis: Organization of Results

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Commercial Buildings: Scenario Analysis

- Similar approach as scenario analysis for single-family detached homes (section 1), though with a more limited set of scenarios

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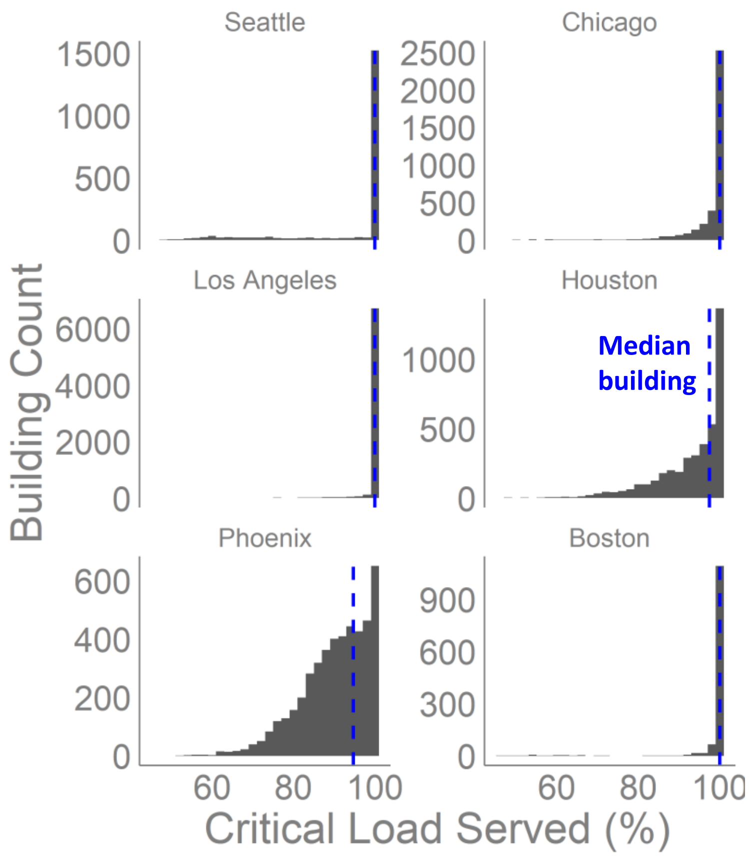
Overall Variation in Backup Performance across Homes

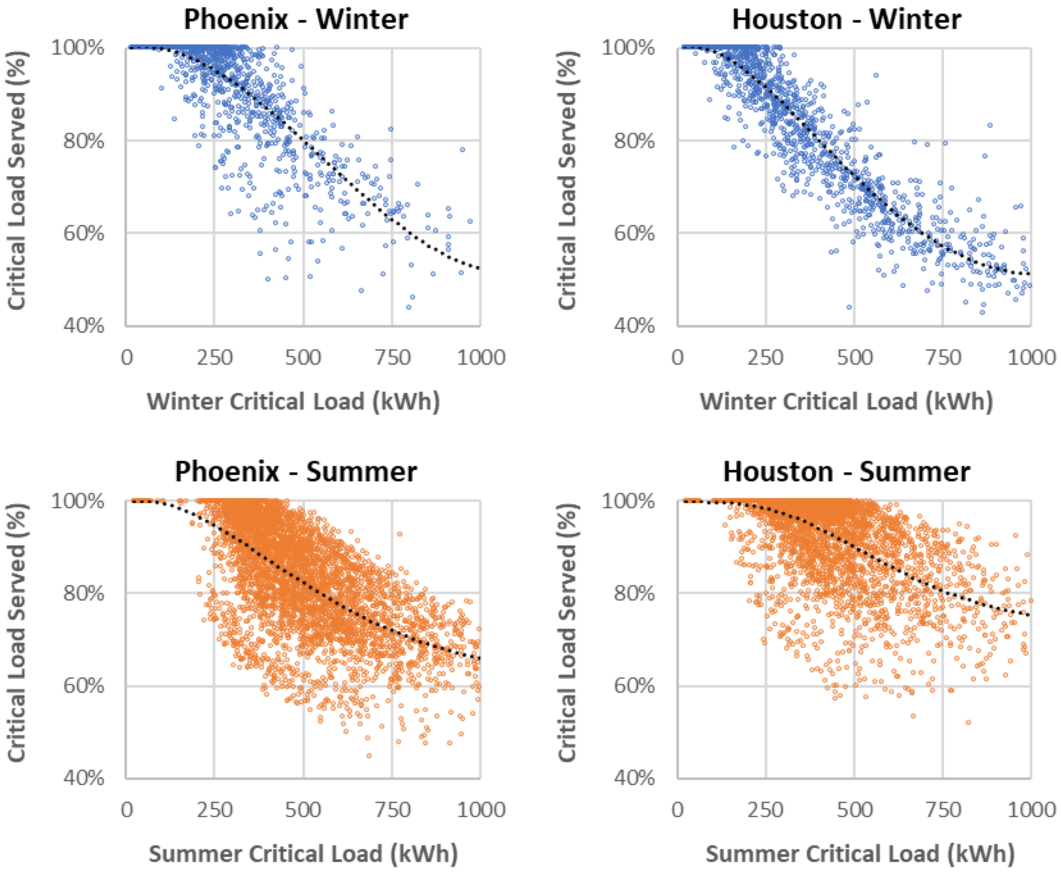
Distribution in backup performance across all modeled homes in six counties



- Preceding analysis focused on the median single-family detached home in each county, highlighting broad geographical trends
- But results can also vary across homes *within* a county, reflecting variation in the underlying building stock
- The figures here show how backup performance varies across all individual single-family detached homes modeled for a select set of high-population counties (assuming 30 kWh storage and backup of critical loads)
- Performance varies most significantly across homes in Houston (Harris County) and Phoenix (Maricopa County); less so in the others, partly due to less cooling load and/or lower penetration of electric space heating
- The following slides explore some of the drivers for this variation, focusing mostly on Houston and Phoenix

General Relationship to Amount of Critical Load

Variation in backup performance with the amount of critical load to serve in winter/summer months



- In general, backup performance declines with a greater amount of critical load to serve
  - PV scales with load but battery size is fixed at 30 kWh in this scenario; higher usage customers see more PV curtailed
  - Scatter around those trends reflects differences in customer load shapes and daily variation in critical load amounts, among other factors
- Differences in critical load levels across homes reflect a number of fundamental drivers:
  - Square footage
  - Heating and cooling equipment type (especially electric vs. gas/oil heating)
  - Efficiency (of building envelope and end-uses)
  - Occupant/behavioral factors (e.g., set points)

Notes: Critical load amounts are the totals over the 9 outage days per season (3-day outages in each of the three months). Each dot represents an individual building model from ResStock.

Impact of Space Heating Type

Backup performance in winter months as a function of heating equipment type

- Space heating type can be a major determinant of backup performance during winter months
- Effects are especially pronounced in cold-weather climates, though the vast majority of homes in those regions currently have fossil heat
  - In Chicago and Boston, 100% of winter critical load is served for homes with fossil heat (in the median case) vs. 41% and 43%, respectively, for homes with electric resistance heat
- Backup performance improves with heat pumps vs. electric resistance heating (though limited sample of heat pump homes in Chicago/Boston)
  - 89% (heat pump) vs. 69% (resistance) of critical load served in Seattle; 96% vs. 77% for Houston
  - One example of how more-efficient end-uses can improve backup performance

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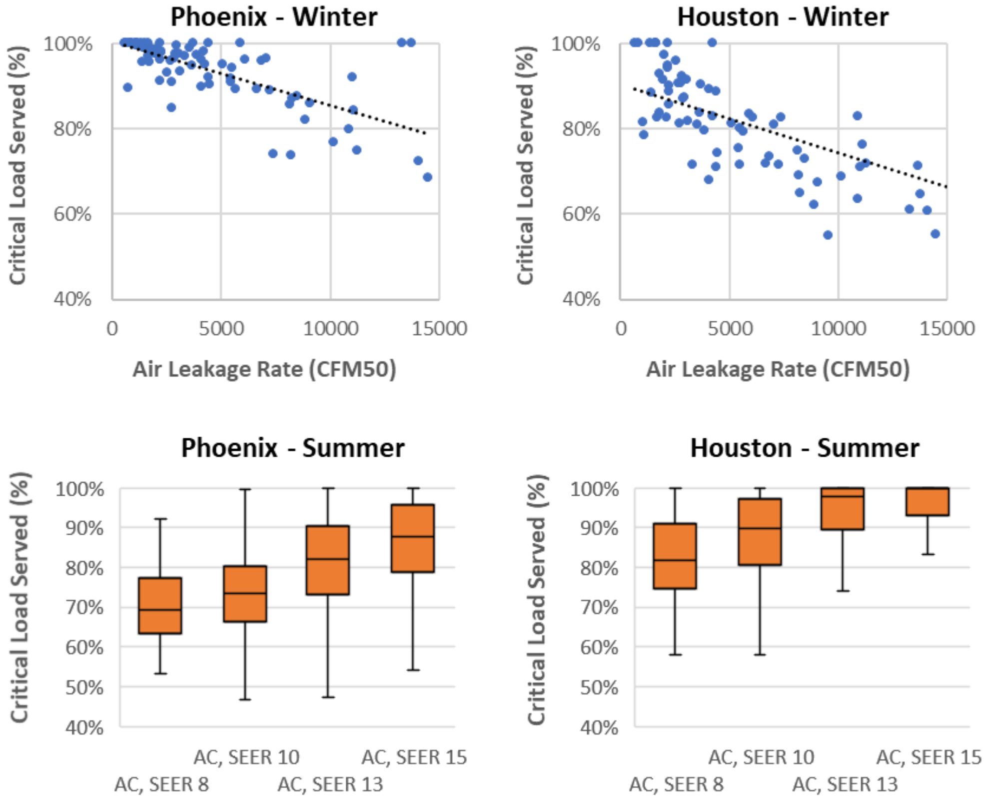
Impact of Energy Efficiency: Infiltration and A/C Efficiency

Two of the more impactful efficiency features modeled in ResStock

Backup performance as a function of infiltration rates and A/C efficiency



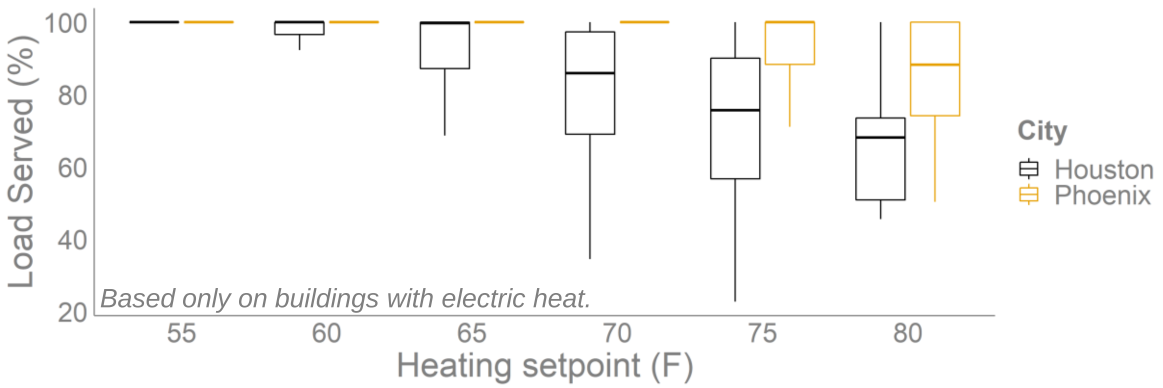
Notes: CFM50 = cubic feet per minute at 50 pascals of pressure. Each data point in the top chart is an average over multiple buildings with the same CFM50.

- The top figure compares backup performance in winter months based on infiltration (air leakage) for electric heated homes in Phoenix/Houston
- Performance is about 20% lower for the leakiest homes; effects would likely be more pronounced for electric heated homes in cold climates
- The bottom figure compares backup performance in summer months based on the efficiency of the central air-conditioner (A/C)
- As shown, backup performance is higher by 10-20% for homes with high efficiency A/C, relative to homes with lower efficiency A/C units
- Both trends illustrate the potential value of improving building and equipment efficiency in conjunction with installing PVESS for backup

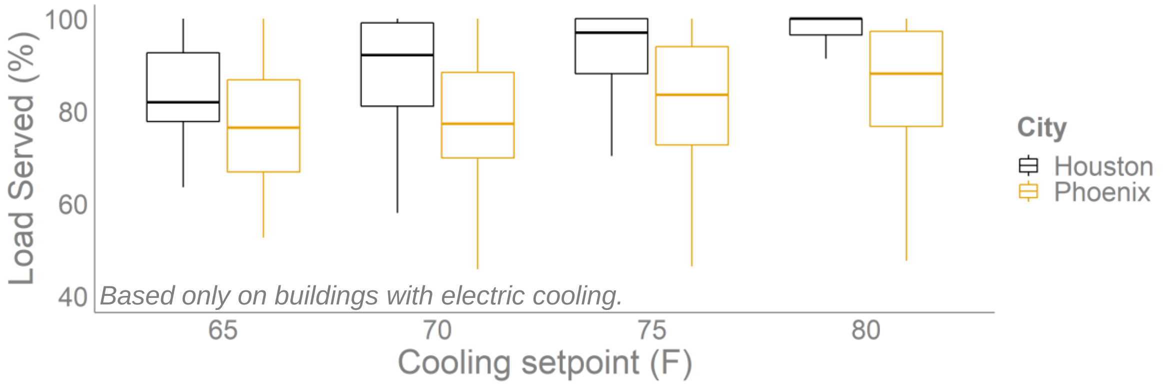
Impact of Heating and Cooling Set-Points

Backup performance in winter and summer months as a function of heating/cooling set-points

Winter



Summer



- Illustrates performance impacts if customers accept less heating or cooling service
- Heating set points most relevant to electric heated homes, common in Houston/Phoenix
  - Average heating set-point is 70°
  - Phoenix: Vast majority of homes fully served at that level
  - Houston: Vast majority fully served at 60°
  - Outcomes would be very different for electric heated homes in cold-weather climates
- Cooling set points important in hot climates
  - Across the range of set points shown (65-80°), median summer critical load served rises by 18% in Houston and 12% in Phoenix
  - Most homes in Houston fully served at 80°

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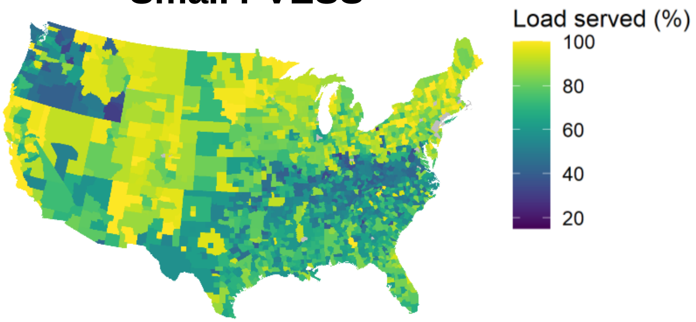
Backup Performance for Mobile Homes

Base-case outage conditions and critical load sensitivities

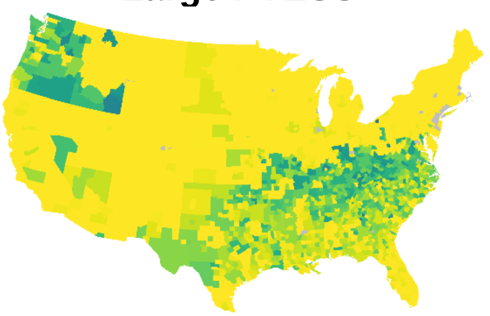
Average percent of critical load served for each county-median mobile home, by PVESS size

Small PVESS

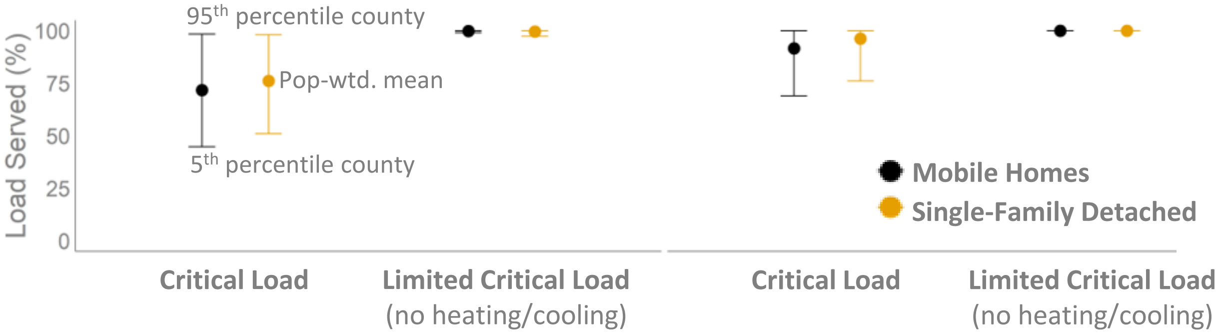


PV sized to generate **50%** of annual load* with **10 kWh** storage

Large PVESS



PV sized to generate **100%** of annual load* with **30 kWh** storage



- Two bookend PVESS system sizes considered here, with a focus on meeting critical load with and without heating and cooling
  - The small PVESS meets 72% of critical load, on average, across counties, while the large PVESS meets 92%
  - Similar geographical patterns as with single-family detached homes
  - The small PVESS fully serves limited critical loads, in almost all counties
- Performance is generally similar to single-family detached homes, reflecting similar electricity consumption levels and roof areas
  - Though performance for mobile homes is slightly lower due to greater prevalence of electric heat
  - Smaller PVESS may be more applicable to some mobile homes if roof can bear limited weight

*PV sizing is subject to roof-area constraints (see appendix), but does not account for the load bearing capabilities of the roofs.

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Multi-Family: Additional Details on the Modeling

The specific application considered here is of PVESS providing backup to the dwelling units in a relatively small (10-unit) building; these choices are driven by the data limitations below

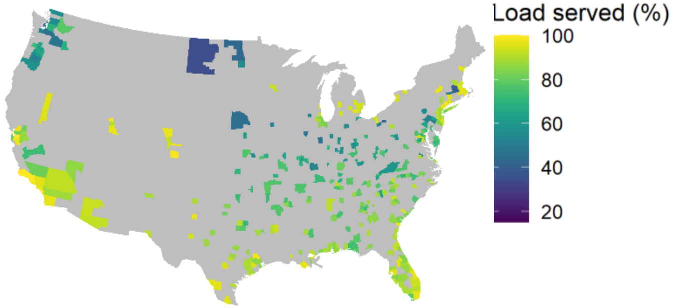
- ResStock models multi-family buildings in terms of individual dwelling units, not the whole building, which has several implications:
  - No common area loads; analysis therefore considers backup only for the dwelling units
  - Requires that we aggregate profiles for multiple individual dwelling units to create a diversified load profile
- To produce building level profiles we aggregate individual building models for dwelling units with the same fuel end-use (i.e. electric vs. gas) in each region
  - The higher the number of units, the more limited the geographical coverage; 10-units is the sweet spot
  - Even then, the coverage is much more sparse than for the other residential building types (limited mostly to high-population counties/PUMAs)
- We assume a 2-story building, which becomes significant when accounting for roof-area constraints on the PV sizing

Backup Performance for 10-Unit Multi-Family Homes

Base-case outage conditions and critical load sensitivities

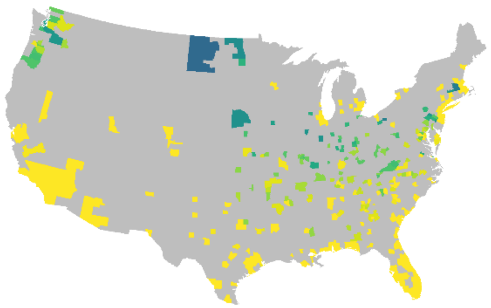
Average percent of critical load served for each county-median multi-fam. home, by PVESS size

Small PVESS

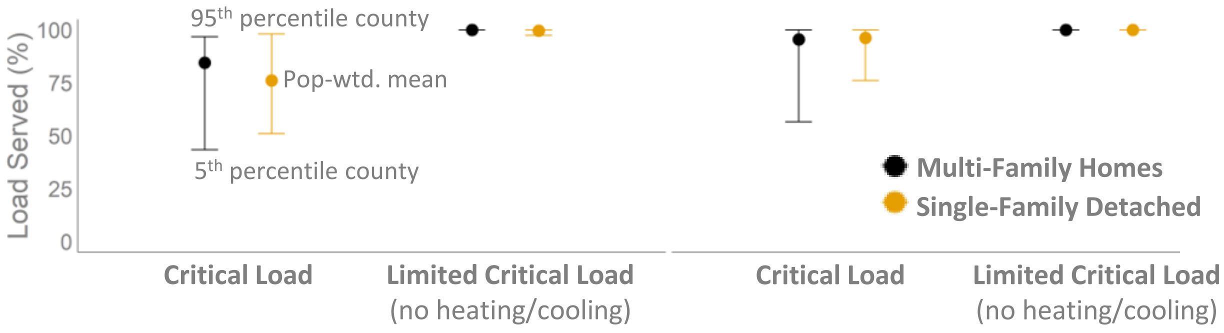


PV sized to generate **50%** of annual load* with **10 kWh** storage per unit

Large PVESS



PV sized to generate **100%** of annual load* with **30 kWh** storage per unit



- The small PVESS meets 76% of critical load, on average, across counties/PUMAs, while the large PVESS meets 95%
- Two key differences between multi- and single-family homes:
  - Roof area constraints are more likely to be binding on PV sizing for multi-family
  - Multi-family dwelling units are generally smaller and have less electricity consumption
- Backup performance is generally lower in northern latitudes, given the roof constraints and poor solar insolation in winter months
- Backup performance in the Southeast is higher for multi-family than for single-family, as multi-family homes consume roughly half the energy

*PV sizing subject to roof-area constraints (see appendix).

Synthetic Event Analysis: Organization of Results

1

Single-Family Detached Homes: Scenario Analysis

- Based on county-median homes
- Explores backup performance with PVESS size, critical load definition, outage conditions

2

Single-Family Detached Homes: Variation across Building Stock

- Based on full distribution of modeled homes in six geographically diverse counties
- Explores how backup performance varies with key building stock characteristics

3

Mobile Homes and Multi-Family Homes

- Based on county-median homes for each building type
- Considers range of PV & storage sizes, with base-case critical load & outage assumptions

4

Commercial Buildings: Scenario Analysis

- Similar approach as scenario analysis for single-family detached homes (section 1), though with a more limited set of scenarios

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Commercial Sector: Summary of Key Modeling Details

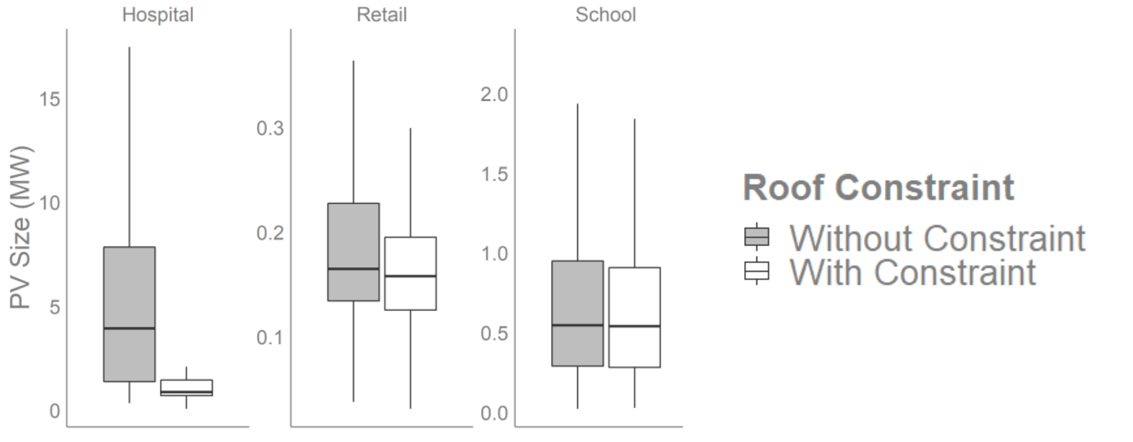
- **Sampling approach:** For standalone retail, we use a similar approach as with residential, where we identify the median building model for each county; for schools and hospitals, we instead use all available ComStock models (i.e., no sampling)
- **Whole-building backup only:** Consider only whole-building backup, given limited granularity in end-use categorization

A key point to stress is that we are modeling backup performance for buildings under ***normal operating conditions, not as an emergency shelter***

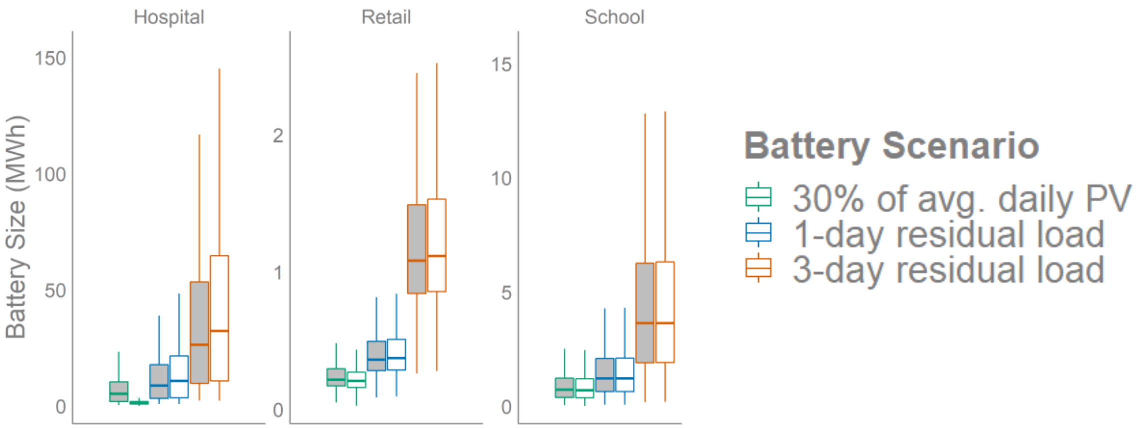
- **PV sizing:** Assume PV is sized to generate 100% of annual consumption subject to roof-area constraint; also consider a case without roof-area constraint (i.e., allow ground-mounting)
- **Storage sizing:** Consider one case representative of typical current commercial installations (not necessarily sized for backup purposes) as well as two other configurations that are more indicative of how a customer might size their system for backup needs

PV and Battery Sizing under Each Scenario

PV system sizes



Battery system sizes

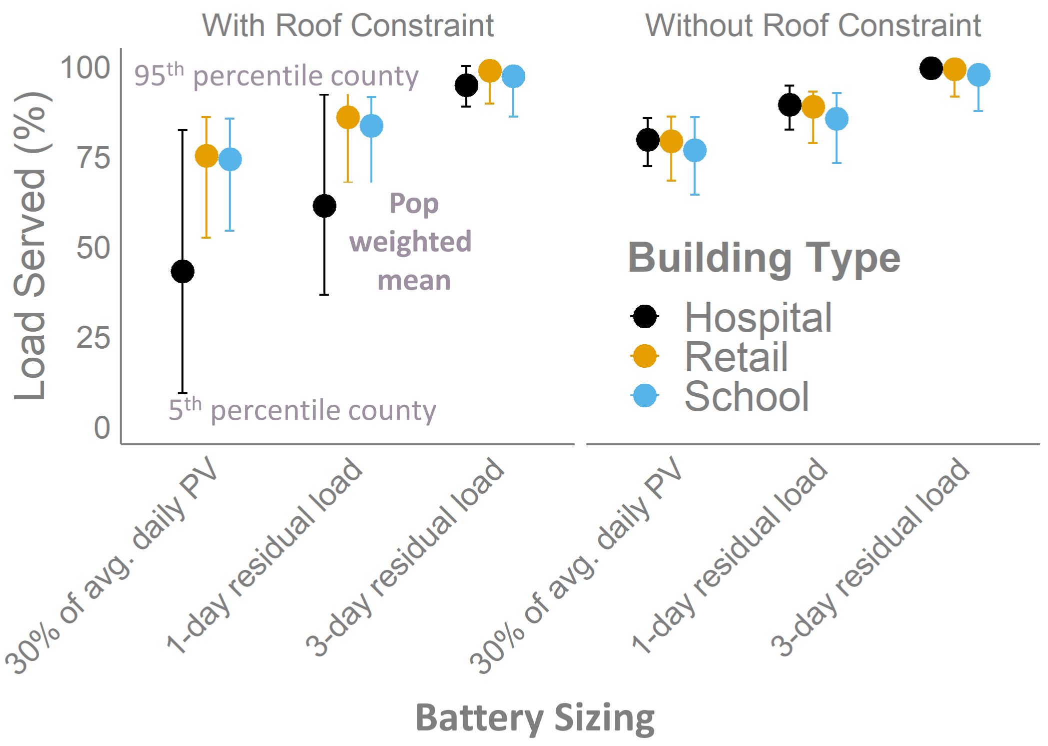


- The PV roof-area constraint is heavily binding for most hospitals; rarely so for retail and schools, as ComStock models those as 1-story buildings
- Under the “base” configuration, the battery is sized at 30% of average daily PV generation, based on observed sizing among actual installs
- The alternative cases size the battery in order to replace the electricity that would ordinarily be supplied by the grid (the “residual load” cases) over either an average 1-day or 3-day period
- Battery sizes in the 1-day case are generally similar to the base configuration, and are at least 3x larger in the 3-day case
- The 3-day scenario leads to extraordinarily large batteries for some of the hospitals in the sample

Note: Battery sizing outliers (not shown) can go as high as 200, 10, and 100 MWh for the hospital, retail, and school building models, respectively, in the 3-day residual load scenario

Backup Performance across PVESS Sizing Cases

Average load served across all monthly outage events

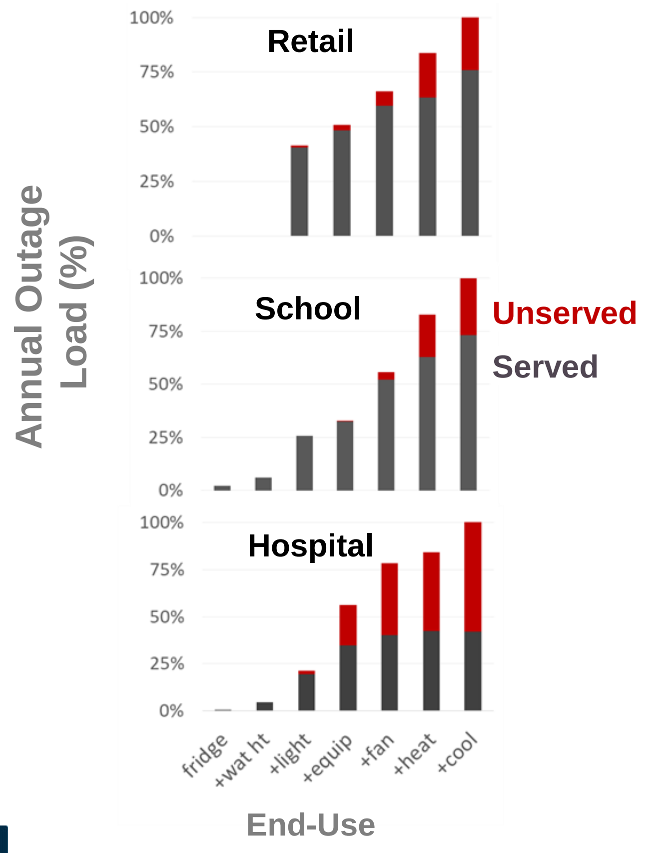


Notes. For retail, the central estimates refer to the population weighted mean across county-median buildings and the error bands are the 5th and 95th percentile counties. For hospitals and schools, the values instead represent the simple mean and percentiles across all individual building models, which are naturally distributed according to population.

- For retail and schools, roof-constrained PV with a typically sized battery (i.e. 30% of avg. daily PV generation) meets ~75% of building load, on average, across the outage events
- For hospitals, backup performance is much lower when PV is limited to available roof area
  - 43% of load served, on average, for a system with storage sized at 30% of daily PV generation
  - Hospital results may be most useful for showing how PVESS can displace fuel consumption by fossil backup generators, as opposed to fully substituting for all backup needs
- If roof-area is not a constraint, performance is generally similar across building types, rising from roughly 77% to 99% of load served across the three storage sizing scenarios

Backup Performance with Incremental End-Use Additions

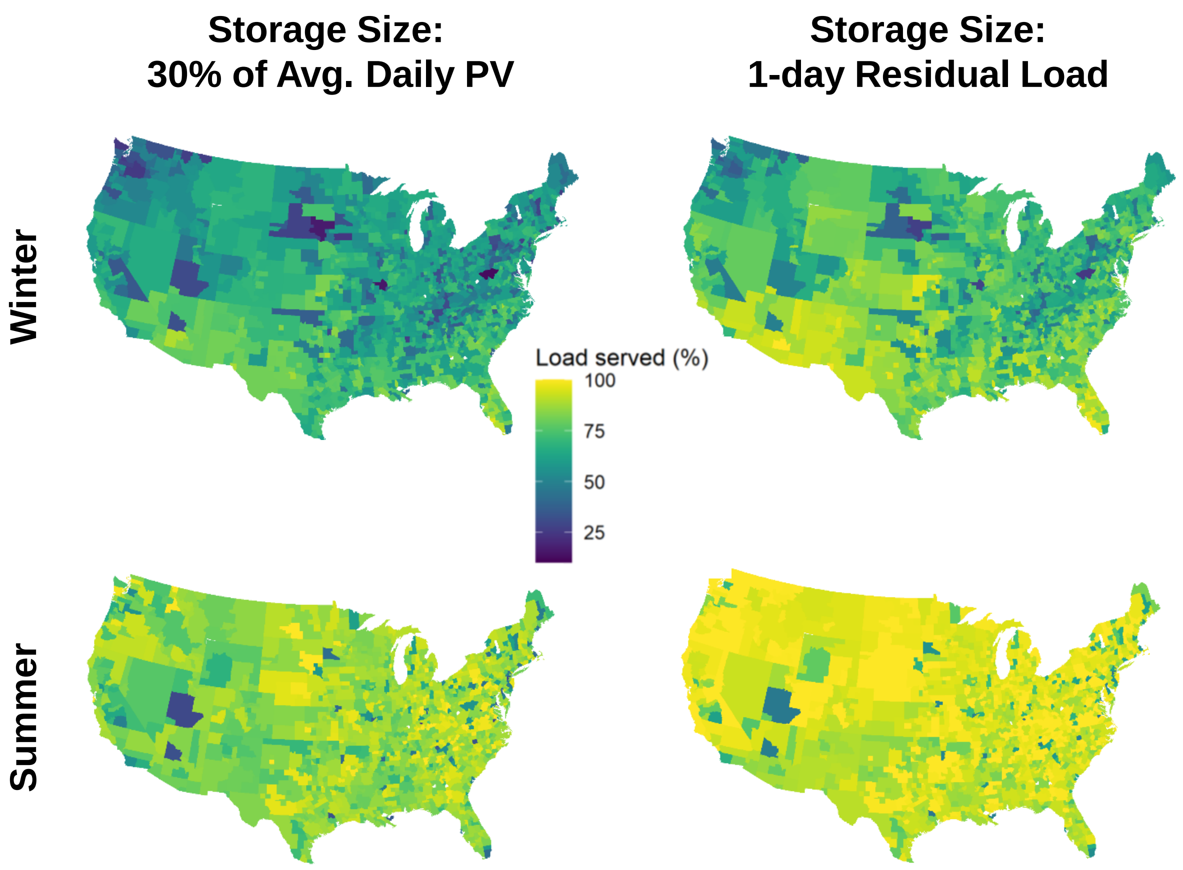
Served and unserved load as additional end-uses are incrementally added to backup service



- ComStock end-use loads can be grouped into: refrigeration, water heating, lighting (interior and exterior), general equipment, fans, space heating, and space cooling
- The figures here are based on the median building for each building type, among those with electric heat, and show load served for the base PVESS configuration
- The PVESS is able to almost fully backup refrigeration, water heating, and lighting, which represent 20-40% of total energy consumption, depending on building type
- Hospitals have particularly high equipment loads, a significant portion of which go unserved
- Electric heating in commercial buildings (when present) is not as dominant as for residential buildings
- Heating, cooling, and fan loads are large, in aggregate, and could be a source of load flexibility to explore in future work

Geographic Trends: *Standalone Retail*

Average percent of load served over summer and winter months, for each county-median building



Notes. Figures are based on the case with PV constrained to available roof area.

- Focus here is on standalone retail, as that was the commercial building type with the most uniform geographical coverage
- Performance during winter months is slightly higher in southern latitudes, due to greater solar insolation
- Conversely, during summer months performance is slightly lower in southern latitudes, due to greater cooling demand
- But in general, geographical trends are quite modest and much weaker than in the residential sector (some random variability due to counties where roof-area constraints bind)
- Maps also foreshadow finding on the next slide, showing that backup performance is generally stronger during the summer

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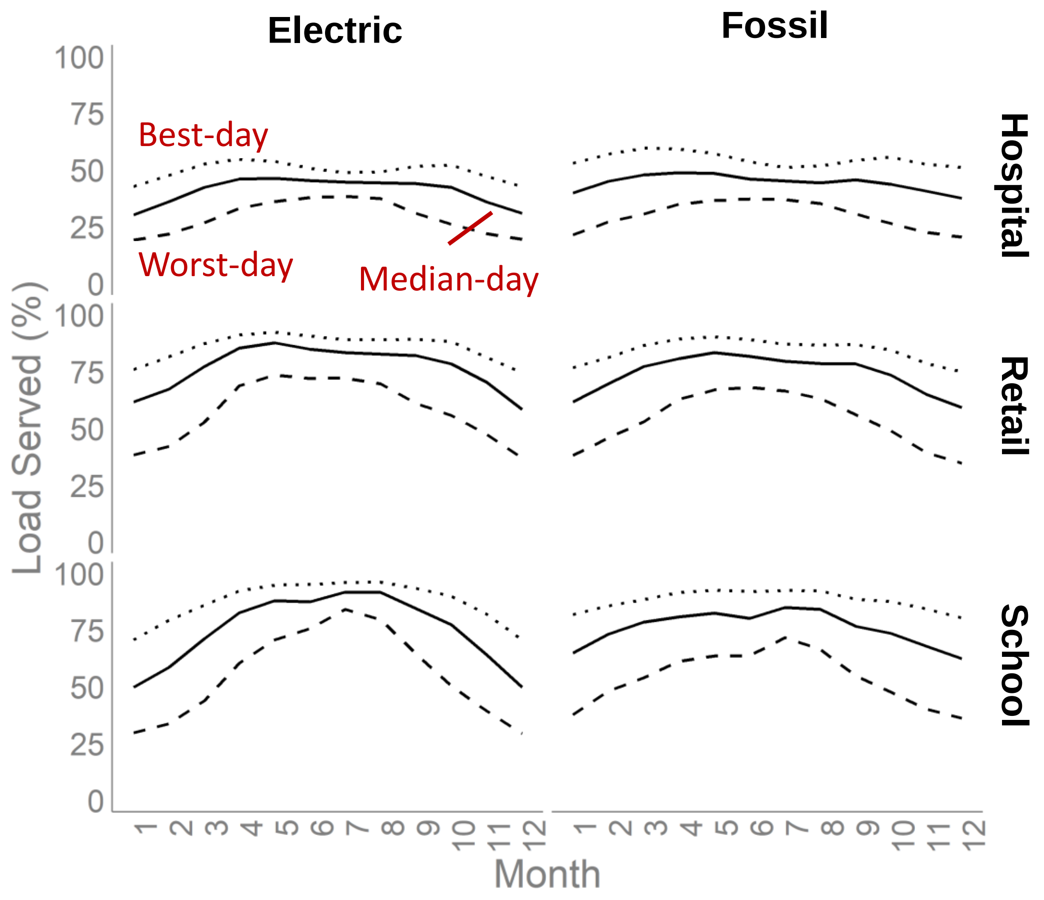
Seasonal Trends and Ranges across Outage Start-Days

Average percent of load served by month, across all building models, segmented by heating type

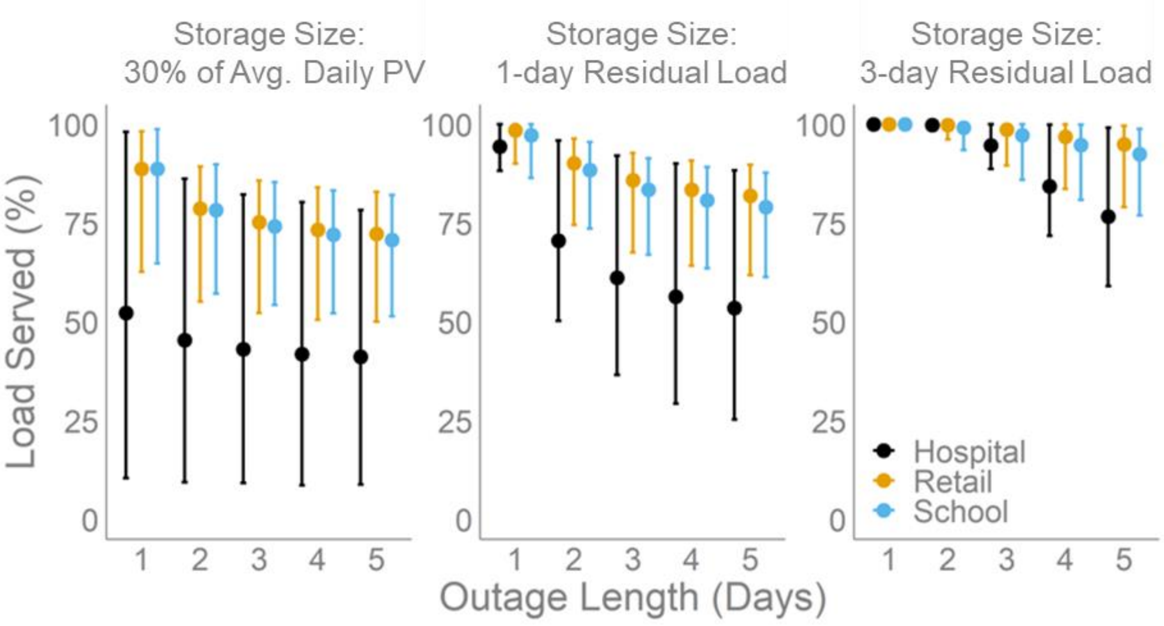


- As a general matter, backup performance is stronger in summer months, due to greater solar insolation levels
  - Less pronounced for hospitals, which have flatter load profiles, and more pronounced for schools, which have lower occupancy during summer
  - Slightly more pronounced for buildings with electric heat, though differences are modest, given that even fossil-heated buildings have significant fan-load for heating in winter months
- The specific day on which the outage begins matters much more in winter months, given greater variability in solar insolation levels
  - For standalone retail with fossil heat, 38-77% of load is served between the worst and best days in January, compared to 68-89% in June

Notes. Figures are based on the case with PV constrained to available roof area, and battery storage sized at 30% of avg. daily PV production.

Backup Performance for Varying Outage Lengths

Average load served across all monthly outage events, for varying outage durations



Notes. The figures are based on the case with roof-constrained PV. For retail, the central estimates refer to the population weighted mean across county-median buildings and the error bands are the 5th and 95th percentile counties. For hospitals and schools, the values instead represent the simple mean and percentiles across all individual building models.

- As in the residential analysis, performance degrades with longer outages, reflecting the drawdown of the initial SoC on the battery, and greater probability of low solar/high load days
- Over a 1-day outage, our base PVESS size would be able to almost entirely serve load for retail and schools, declining to roughly 72% of load, on average, for a 5-day outage
- Sizing the battery for average residual load over some period (e.g., 1-day or 3-days) can dramatically improve performance
  - Some unserved load during that period is likely to occur, given daily variations in residual load
  - And as shown previously, this kind of battery sizing strategy can require very large batteries

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Historical Event Analysis

Historical Event Analysis: Overview

Answers the question: *How would PVESS have performed in providing backup power during specific historical long-duration interruption events?*

- Allows us to (1) better capture correlation between weather (which impacts PV production and load) and the occurrence of long-duration outages and (2) showcase concrete examples of the resilience capabilities of PVESS in actual events
- A sample of 10 historical events selected (see next slide)
  - Drawn from the years 2017-2020, given the available hourly outage and weather data
- Hourly outage data from PowerOutage.US used to identify start/end-times for each event, based on when ≤10% customers in each county were without power
- For each event, focus on four affected counties: urban, rural, vulnerable*, and longest interruption
- NREL generated end-use load profiles with ResStock and ComStock for each event, using weather data for the corresponding period and the selected counties
  - Statistically representative sample of building models generated for each residential and commercial building type, per county, per event
- Similar PVESS assumptions** as in the synthetic analysis (e.g., standard sizes, 100% initial SoC)
- As in synthetic analysis, residential results focus on backup of critical load with heating/cooling, while commercial results focus on whole-building backup under normal business operations

**Vulnerable county selected using United States Federal Emergency Management Agency's social vulnerability index.*
***We assume that PVESS are not damaged by extreme weather during these historical events*

Historical Interruption Event Sample

Event	Month/ Year	States[1]	Selected Counties	Duration (Days)	Max % Out[2]
Hurricane Harvey	8-9/2017	TX	Aransas, Goliad, Nueces, Refugio	6.8-16.8	74-99%
H. Irma	9/2017	FL	Bradford, Collier, Highlands, Miami-dade	6.3-9.9	82-97%
H. Florence	9/2018	NC	Carteret, New Hanover, Pamlico, Robeson	6.2-10.0	84-99%
H. Michael[3]	10/2018	FL, GA, NC, VA	Bay, Clay, Danville, Guilford, Lancaster, Leon, Liberty, Pittsylvania	2.7-15.5	45-100%
H. Isaias	8/2020	CT, NJ, NY	Hunterdon, Litchfield, Passaic, Suffolk	3.0-6.2	26-66%
Public Safety Power Shutoff (CA)	10/2019	CA	Alameda, Trinity, Lake, Mendocino	1.9-4.6	52-85%
Thunderstorm (TX)	4/2020	AL, TX	Blount, Gregg, Marion, Upshur	1.8-2.8	44-100%
Derecho (IA)	8/2020	IA	Benton, Linn, Polk, Poweshiek	3.1-10.8	49-99%
Winter Storm (WA)[4]	1/2019	WA	King, Pierce, Thurston	0.7-1.4	31-54%
Winter Storm (OK)	10-11/2020	OK	Caddo, Cleveland, Kiowa, Oklahoma	5.7-12.3	40-70%

Notes. (1) The states listed are those corresponding to the selected counties, though other states may have been affected by any given event. (2) Max % Out refers to the maximum percentage of customers experiencing an outage during the event (3) For Hurricane Michael, we selected eight counties in order to reflect the broad geographical footprint of the event. (4) For the winter storm in Washington state, only the three counties shown experienced widespread outages, and the duration of those outages was significantly shorter than the other events analyzed; however, the event was retained in the sample for the purpose of geographic diversity.

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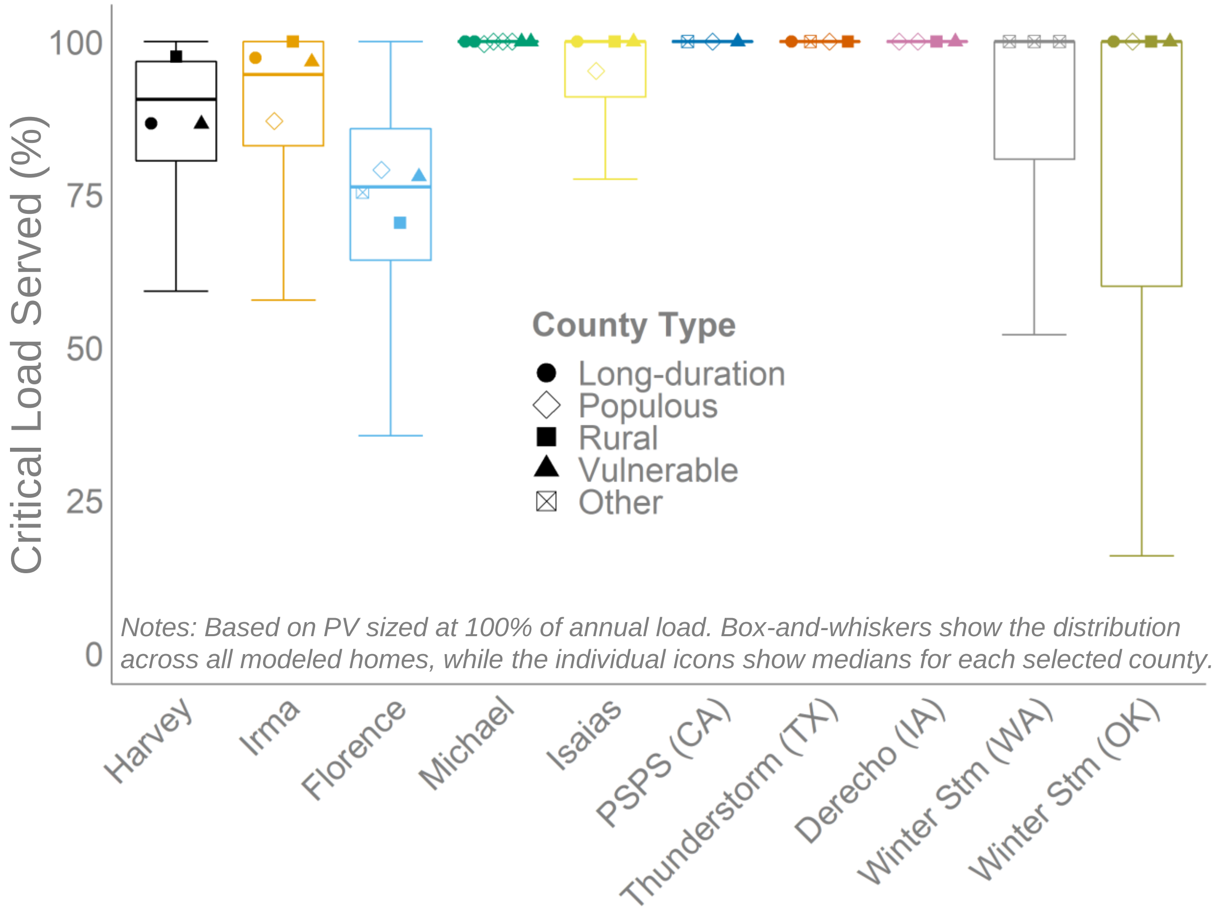
Performance Comparison across Historical Events:

Single-family detached homes with 30 kWh storage

Backup performance by event: single-family homes



- System meets critical load for all modeled homes for Thunderstorm (TX), PSPS (CA), Derecho (IA), and Hurricane Michael
- Performance varies widely across the hurricane events, partly as a result of differences in solar insolation levels (e.g., Florence had 3 days with almost no solar)
- For the two winter storms analyzed, all critical load was served in the median case, but a sizeable fraction of customers—those with electric heating—see much lower levels of backup
- No consistent differences across county types (e.g., rural vs. urban vs. vulnerable)
- As shown on later slides, performance can vary considerably over the course of the event

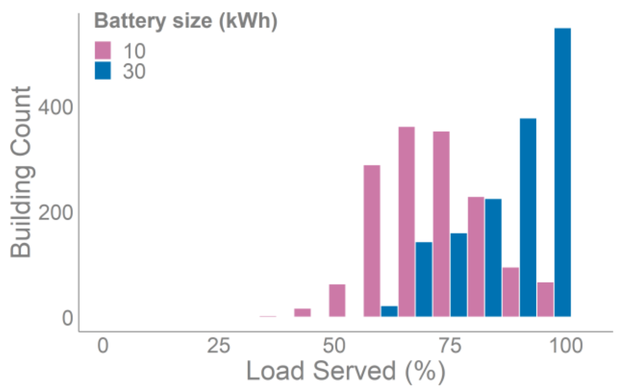
Individual Event Summaries

- Four events featured here; others included in the Appendix:
  - Hurricane Harvey: A particularly long interruption event
  - Hurricane Florence: Prolonged period of low solar insolation
  - California PSPS: Impacts a region (San Francisco Bay Area) with relatively high PVESS uptake
  - Oklahoma Winter Storm: A winter event

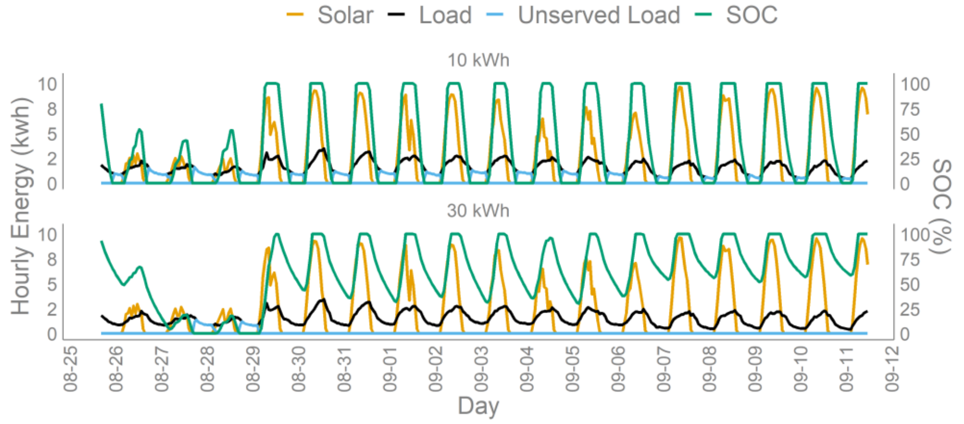
- Each event summary provides an overview of:
  - Distribution in outcomes across individual single-family detached homes
  - Time series view to show how backup performance varies over the event
  - Comparisons across all building types and selected counties

Hurricane Harvey: Performance Summary

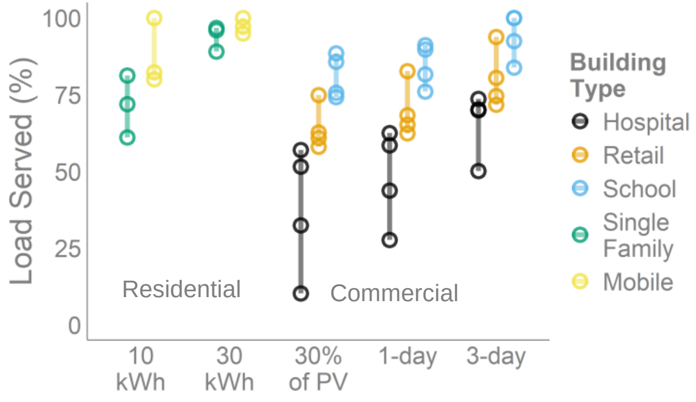
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size

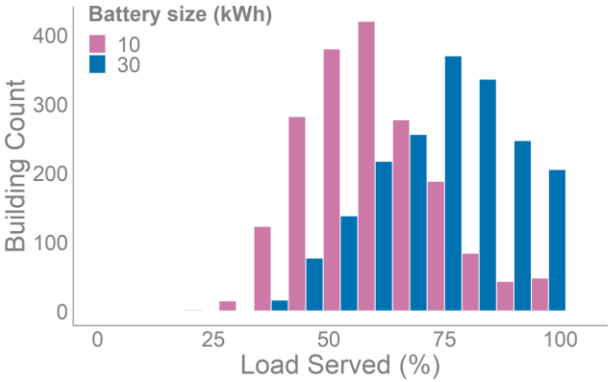


- Median load served moves from 71% with a 10 kWh battery to 91% with 30 kWh battery
- Low solar production occurred during first 3 days of event, depleting the battery, but recovers with solar in later days
- Results did not consider load flexibility opportunities such as increasing temperature set-points
- In the 10 kWh case, on days with good solar insolation the battery fills up early in day, resulting in solar curtailment and regular nightly load shedding
- Mobile homes perform best across all building models, though we do not consider roof constraints

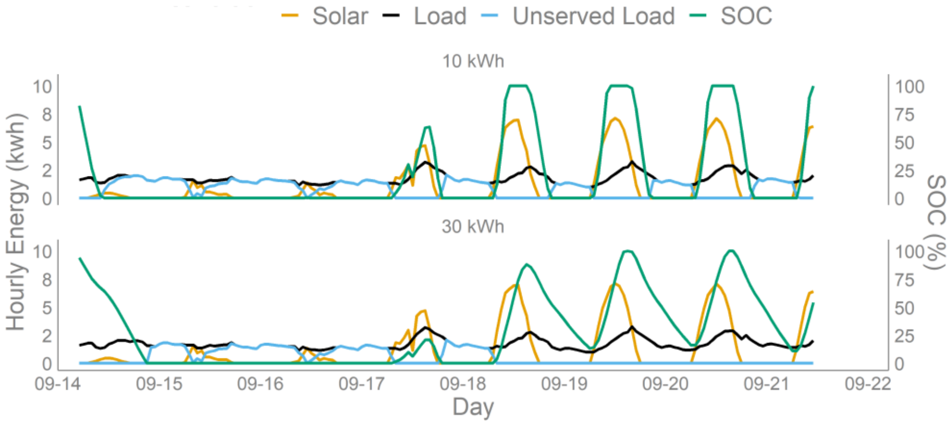
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Hurricane Florence: Performance Summary

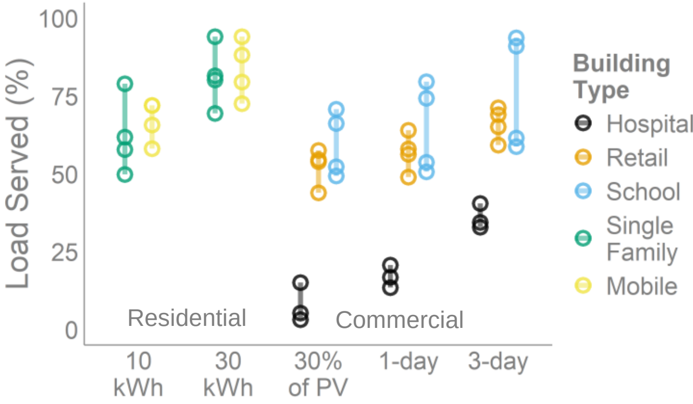
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size



- Median load served moves from 68% with a 10 kWh battery to 76% with 30 kWh battery
- Low solar insolation for many days at beginning of outage event results in poor performance, but recovers with solar in later days
- On days with good solar insolation, 10 kWh battery fills up early in day, resulting in significant solar curtailment and regular nightly load shedding
- Hospitals perform particularly poorly in this event

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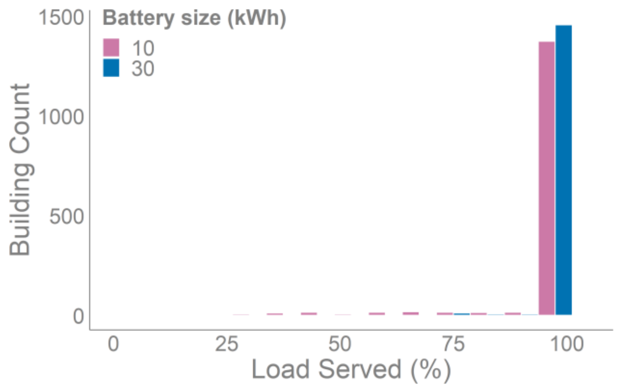
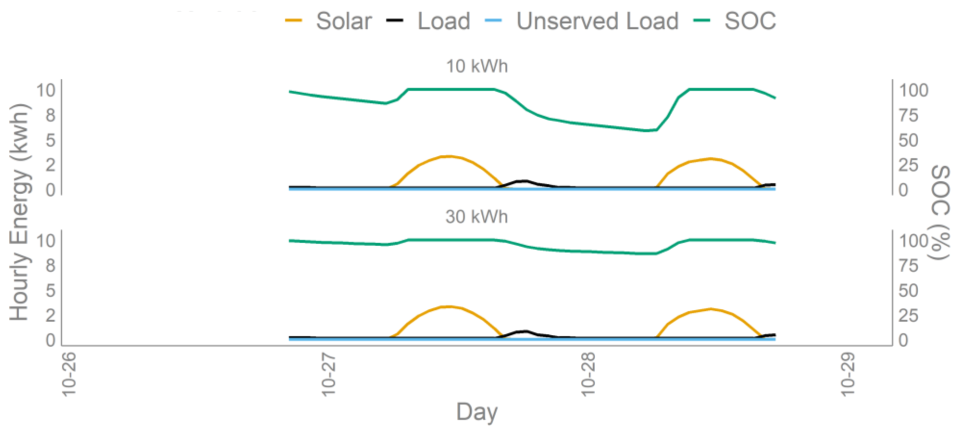
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

CA PSPS: Performance Summary

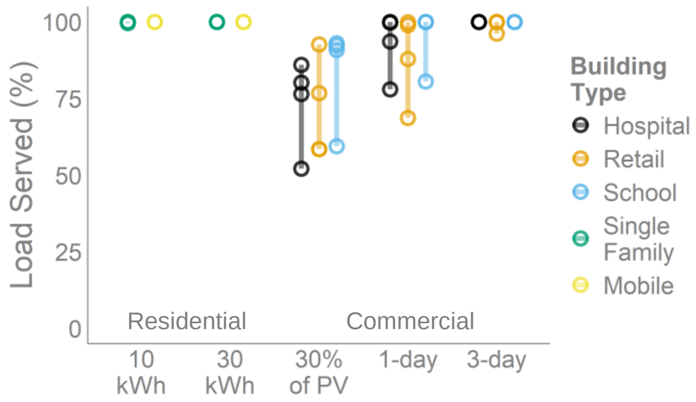
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size

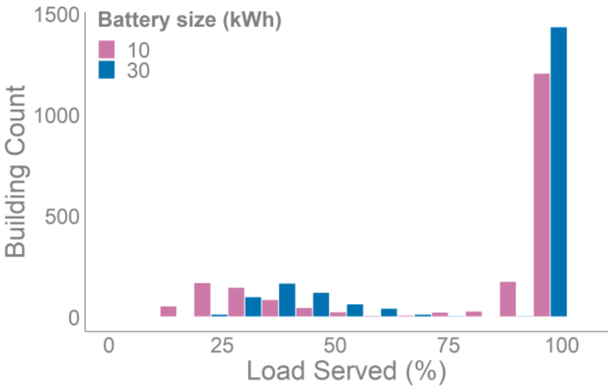


- Median load served is 100% with either a 10 kWh or 30 kWh battery
- Strong solar insolation combined with limited load results in easier to supply power, at least in the residential building model cases
- Almost all residential building models considered can serve critical load during this event
- Small load in time-series chart due to lack of cooling/heating loads in median single-family home

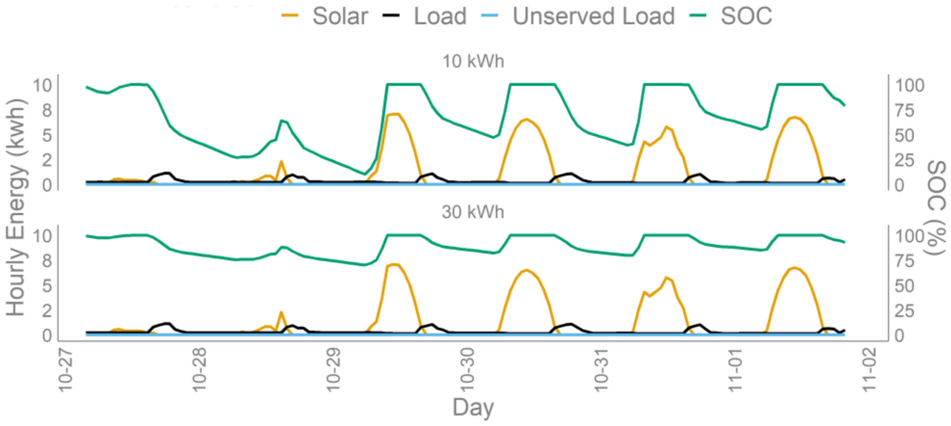
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Winter Storm (OK): Performance Summary

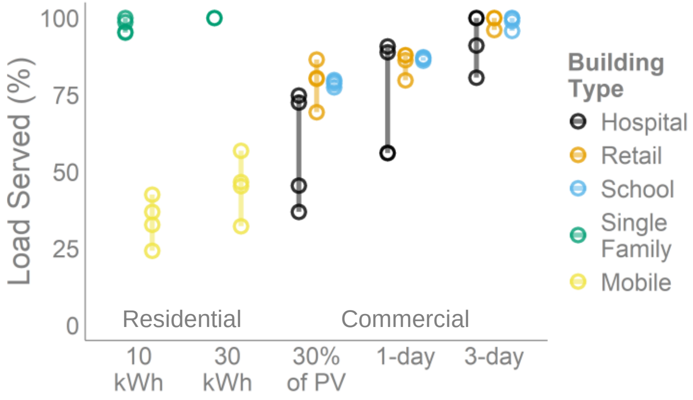
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size



- Median load served moves from 98% with a 10 kWh battery to 100% with 30 kWh battery
- A decent subset of single-family homes perform worse as a result of electric heating
- Electric heating dominates in the mobile home category, significantly dropping performance

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Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Key Take-Aways and Future Work

Key Take-Aways: Residential Buildings

- Providing backup power to limited critical loads without heating/cooling can generally be achieved with a relatively small PVESS
- Providing backup to heating and cooling loads can be challenging with small battery systems, depending on climate and building stock characteristics
- The single biggest determinant to backup performance is the presence of electric space heating—mostly electric-resistance at present, and most prevalent in the southeast and pacific northwest
- Backup performance can vary considerably across individual homes based on the efficiency of heating and cooling equipment, infiltration levels, and temperature set-points, among other factors
- Backup performance for mobile and multi-family homes is generally similar to single-family detached homes, for comparably sized systems, though some regional differences exist due to higher rates of electric heating for mobile homes, and due to roof-area constraints and lower usage levels for multi-family homes
- Backup performance is not especially sensitive to the length of the event (beyond 1-day), but can be quite sensitive to day-to-day variability in solar insolation levels and temperatures

Key Take-Aways: Commercial Buildings

- Roof area constraints on PV system sizing are a major determinant to PVESS backup performance and can vary considerably based on building type (based partly on the number of stories)
- Providing full-building backup for a multi-day outage would require significantly larger systems than what is typically observed in the market today, for systems installed primarily for other purposes
- Geographical variation in backup performance is related mostly to solar insolation levels (i.e., in northern vs. southern latitudes; geographical variation in building stock and in heating/cooling loads are considerably less impactful than in the residential sector)
- Seasonal trends in backup performance are also driven by variation in solar insolation level (higher in the summer, and lower in the winter)

Planned and Potential Areas for Future Work

Planned

- Explicitly capturing temperature set-point adjustments during interruptions
- Modeling efficiency and electrification measures across a broader set of geographies (e.g., heat pumps in cold-weather climates)
- Stochastic analysis of short-duration power interruptions
- Modeling impacts of other battery uses (e.g., bill management) on initial SoC at onset of power interruption

Potential

- Accounting for power limits on battery given minute-by-minute variation in loads
- Analyzing opportunity for pre-cooling/heating with solar that would be otherwise curtailed
- Developing a standardized approach to simulating extreme weather events
- Exploring a broader set of commercial building types and emergency shelter use-cases
- Refining commercial building end-uses to designate critical loads
- Accounting for the impacts of snow cover on PV performance
- Validate results with actual load data from smart meters for historical events

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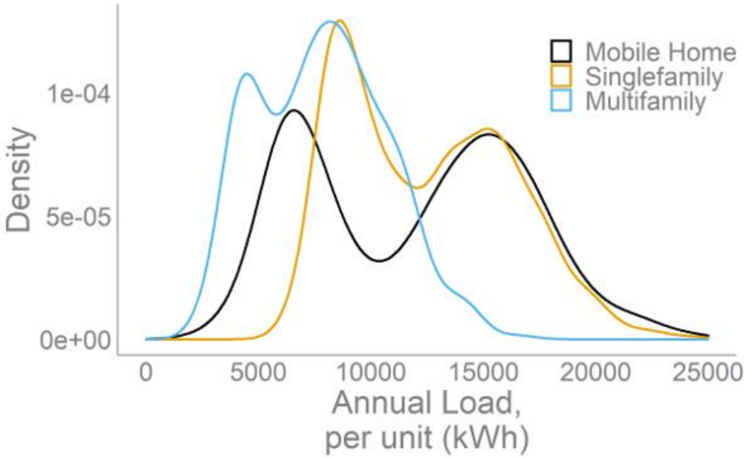
Appendix

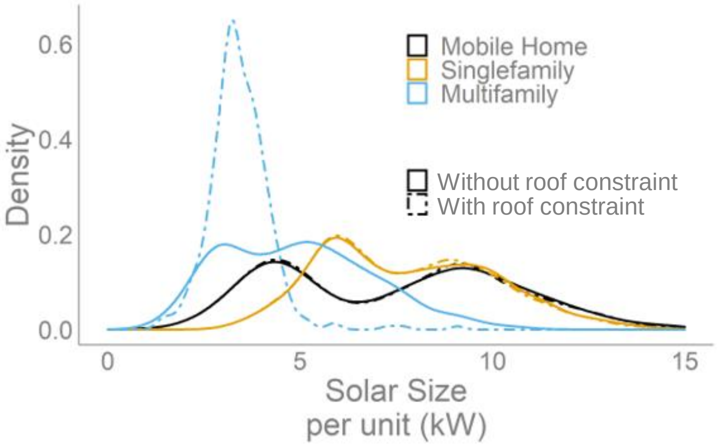
County-Median Residential Buildings:

Comparison of Annual Consumption and PV Sizing

Annual Consumption



PV System Size (100% of annual load case)



- These figures compare the distributions of county-median buildings across the three residential building types, as used within the synthetic event analysis
- As shown in the figure on the top, annual electricity consumption levels are similar for single family and mobile homes, but considerably lower for multifamily
- The figure on the bottom compares the distribution in PV system sizes, showing the effects of roof area constraints for each building type
- As shown, PV system sizes for single family and mobile homes are similar, and the roof area constraints generally are not binding
- In contrast, PV system sizes for multi family homes are much smaller, particularly when constrained by available roof area

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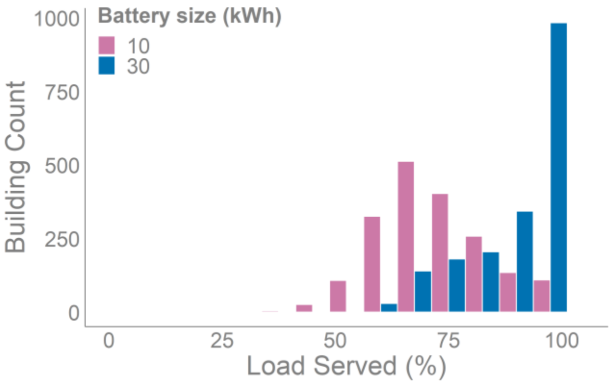
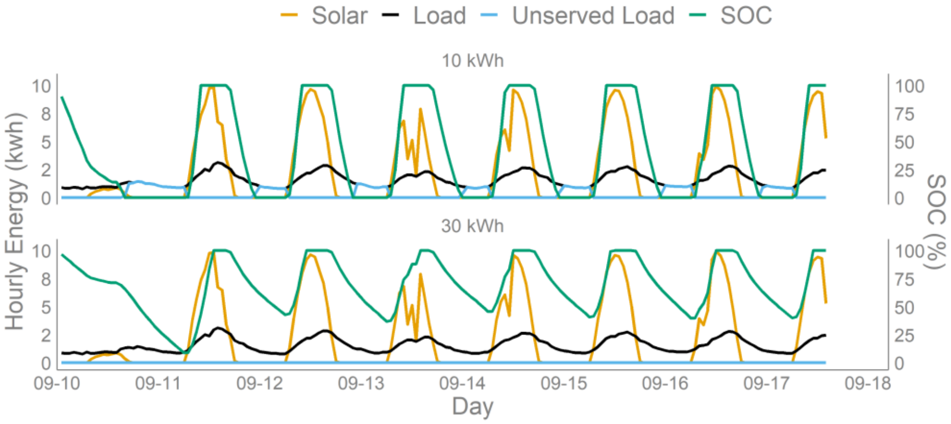
Hurricane Irma: Performance Summary

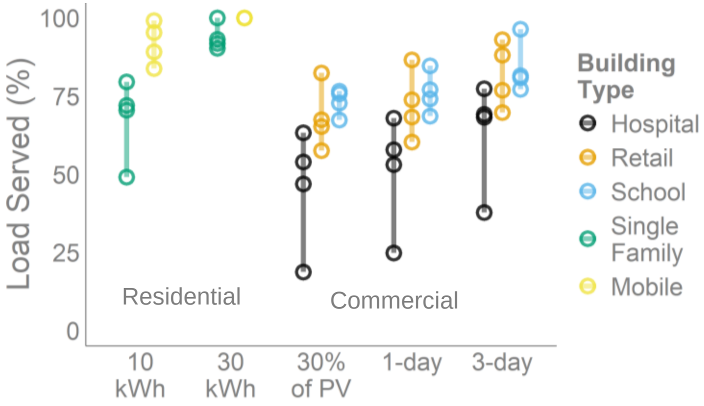
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size

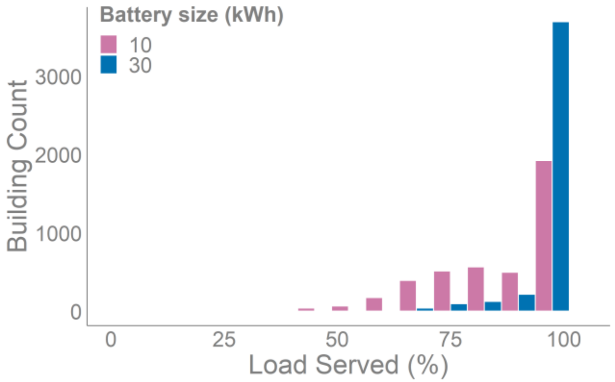


- Median load served moves from 71% with a 10 kWh battery to 95% with 30 kWh battery
- Low solar production occurred during in first day of event, depleting the battery, but recovers with solar in later days
- On days with good solar insolation, 10 kWh battery fills up early in day, resulting in significant solar curtailment and regular nightly load shedding
- Mobile homes perform best across all building models

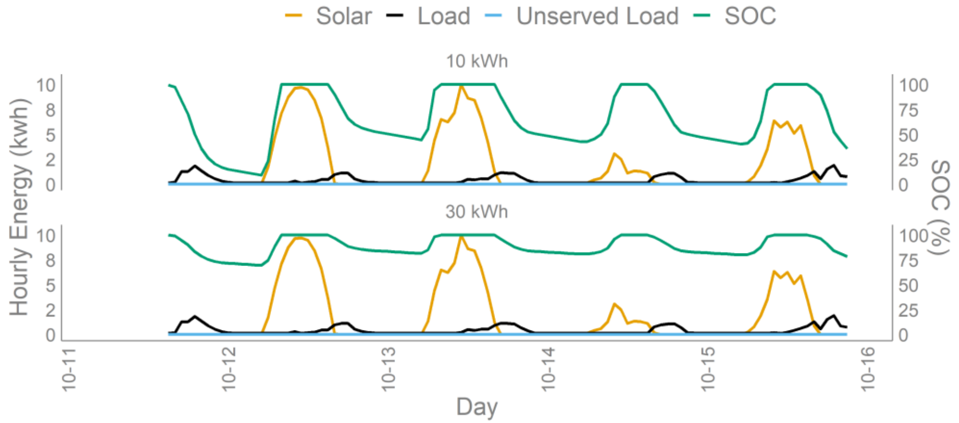
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Hurricane Michael: Performance Summary

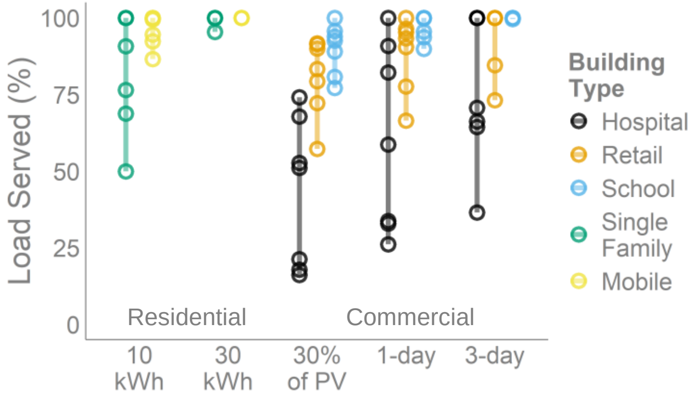
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size

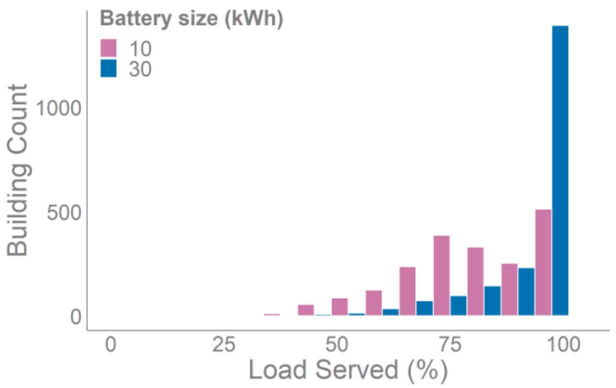


- Median load served moves from 91% with a 10 kWh battery to 100% with 30 kWh battery
- Low solar insolation on third day of outage is mitigated by battery energy capacity
- On days with good solar insolation, 10 and 30 kWh battery fills up early in day, resulting in significant solar curtailment but lower load amount results in limited load shedding
- Wider-range across building types partially do to more individual counties modeled for Michael

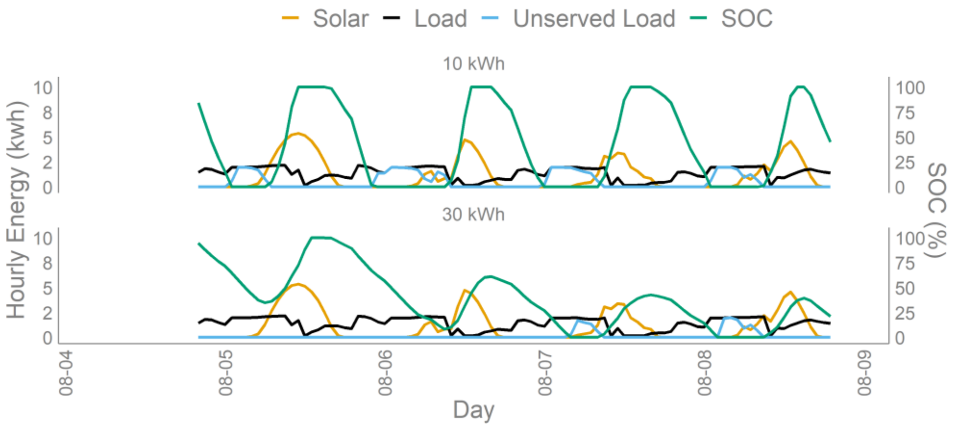
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Hurricane Isaias: Performance Summary

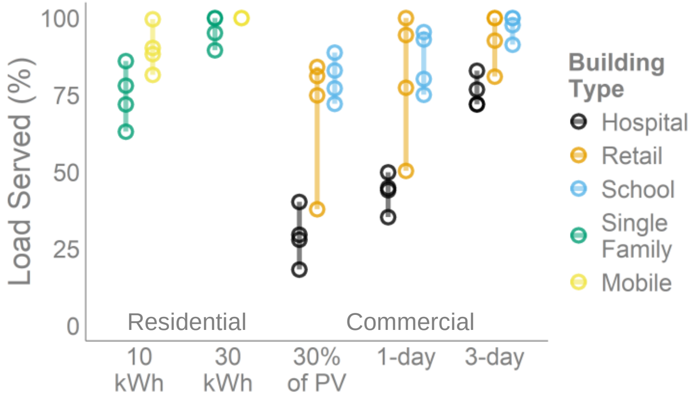
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size



- Median load served moves from 81% with a 10 kWh battery to 100% with 30 kWh battery
- Lower solar insolation on second half of event leads to load shedding even in the 30 kWh battery case
- Hospitals perform particularly poorly in this event

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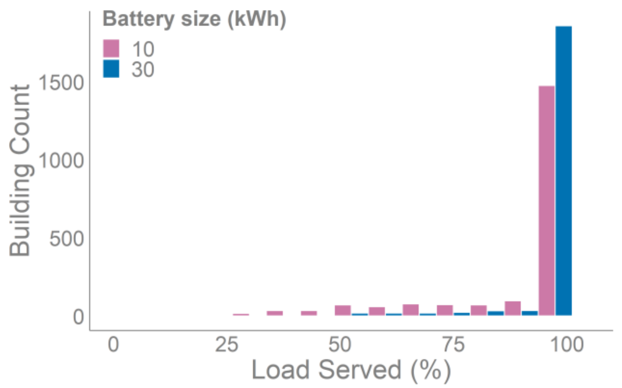
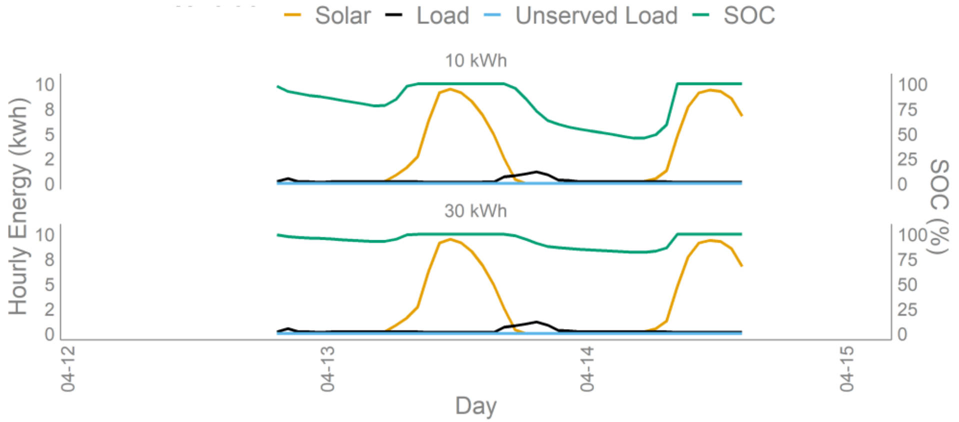
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Thunderstorm (TX): Performance Summary

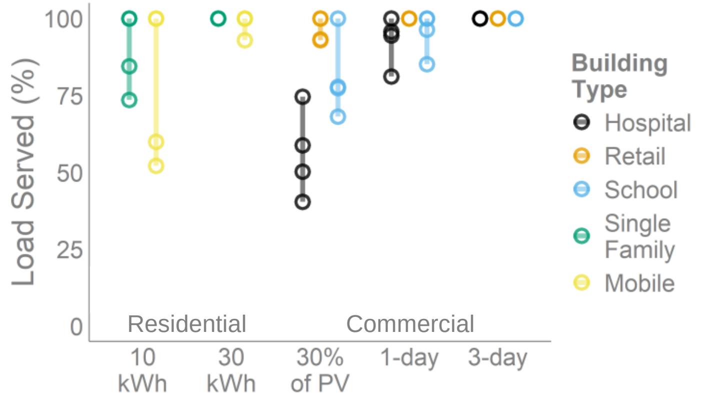
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size

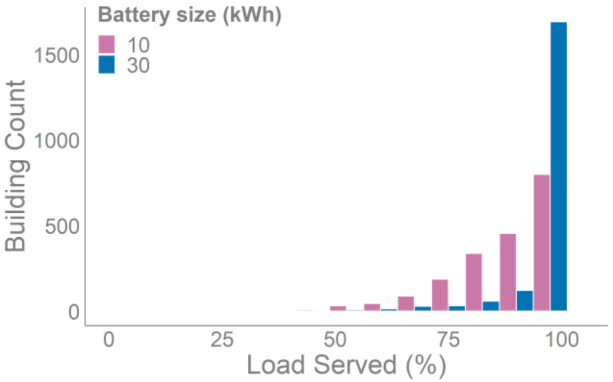


- Median load served is 100% with either a 10 kWh or 30 kWh battery
- Strong solar insolation combined with limited load results in easier to supply power. Significant solar curtailment also occurs during this event
- Retail building type performs the best during this event

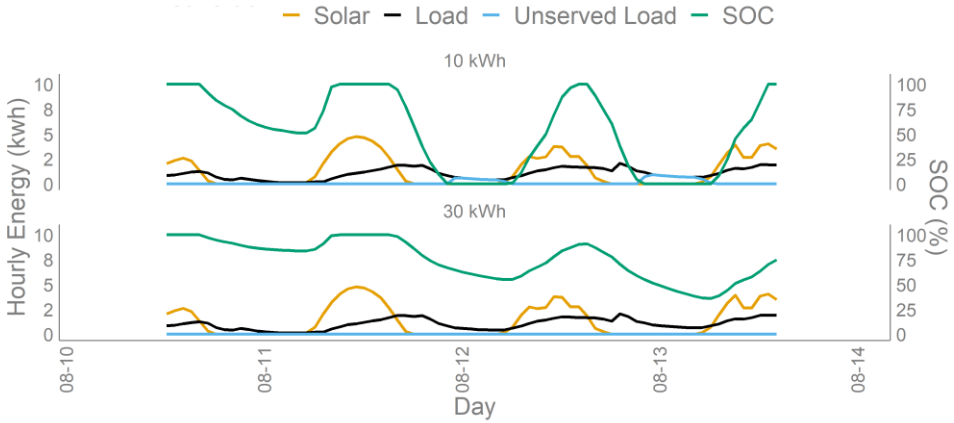
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Derecho (IA): Performance Summary

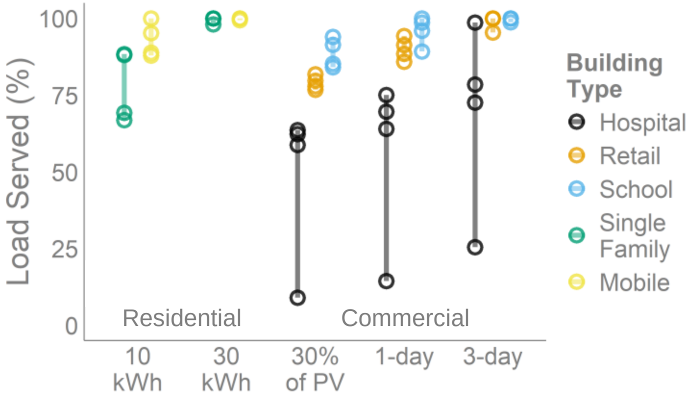
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size



- Median load served moves from 91% with a 10 kWh battery to 100% with 30 kWh battery
- Strong solar insolation combined with limited load results in easier to supply power. Significant solar curtailment also occurs during this event
- School building type performs the best during this event

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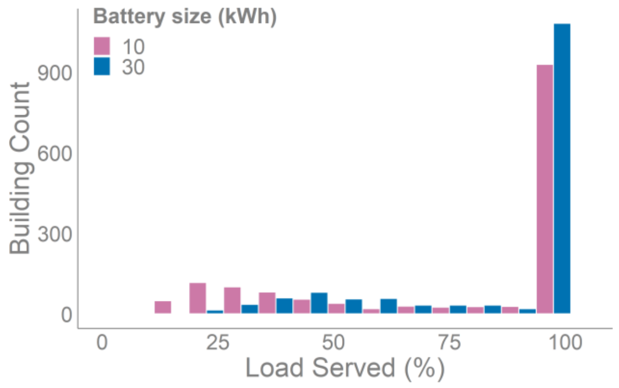
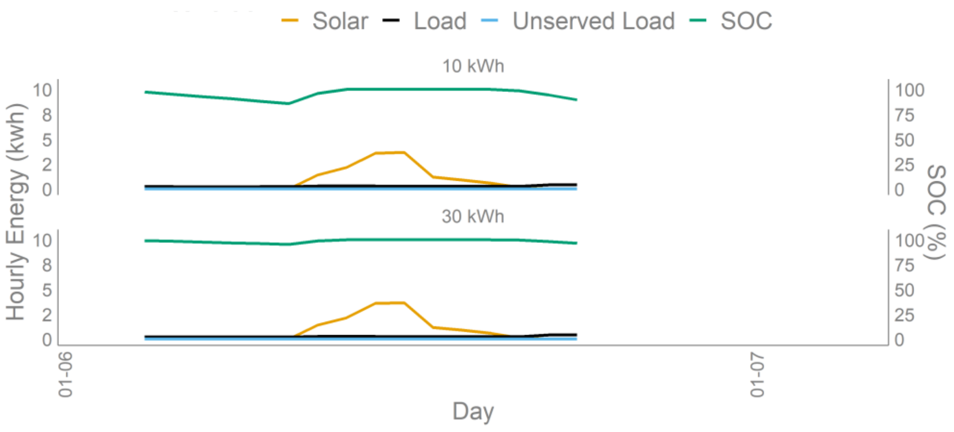
Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.

Winter Storm (WA): Performance Summary

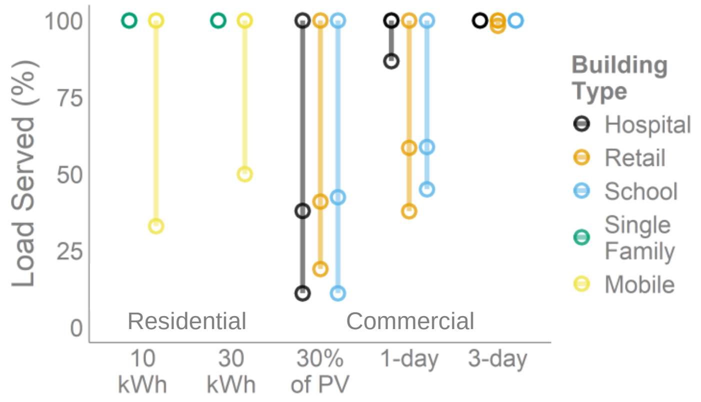
Distribution in percent of critical load served across all single-family home models



Time-series for median single-family home



Backup performance for each county-median building by building type and storage size



- Median load served is 100% with either a 10 kWh or 30 kWh battery
- A decent subset of single-family homes perform worse as a result of electric heating
- Very short duration event
- Electric heating in one county's median mobile home significantly drops performance

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Notes: Residential results assume PV sized at 100% of annual load; commercial results apply roof-area constraints. The time series chart is based on the median home for the most-populous of the selected counties. See synthetic event analysis for further explanation of commercial storage sizing scenarios.