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Solar+Storage for Household Back-up Power:

Implications of building efficiency, load flexibility, and electrification for backup during long-duration power interruptions

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Report Organization

- Introduction
- Data and Methods
- Results
- Conclusions
- Appendix

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 and resilience concerns
- These concerns may become more pronounced with more frequent and severe extreme weather events and wildfires, and also more costly to mitigate with conventional means
- Understanding backup power capabilities of BTM PVESS is critical to informing customer investments and product development as the industry scales up and other value streams develop; can also inform grid investments, policy-making, and customer program design
- Recent work by this team (Gorman et al., 2022 and 2023) explored backup performance of typical PVESS configurations during long-duration power interruptions across the *existing* building stock
- This study extends that work by exploring PVESS backup power applications as homes become more efficient, electrified, and flexible

Project Overview

Objective: Evaluate how the use of PVESS for backup power during long-duration interruptions is impacted by energy efficiency, load flexibility, and electrification

- Provide forward-looking insights into the potential role of PVESS in backup power applications
- Inform system, product, business model, and policy design that considers potential synergies and tradeoffs associated with pairing PVESS and other DERs

Approach: Simulation-based analysis using modeled solar and end-use level load profiles; estimate minimum battery storage size required to serve designated critical loads during power interruptions

- Purely technical analysis; later work will explore economic considerations

Key Elements of Study Scope:

- Long-duration power interruptions (≥24 hours)
- Single-family residential buildings across a diverse set of climates and geographies
- Bundles of efficiency, load flexibility, and electrification measures applied to baseline building stock
- Sensitivities around interruption conditions and backup load configurations

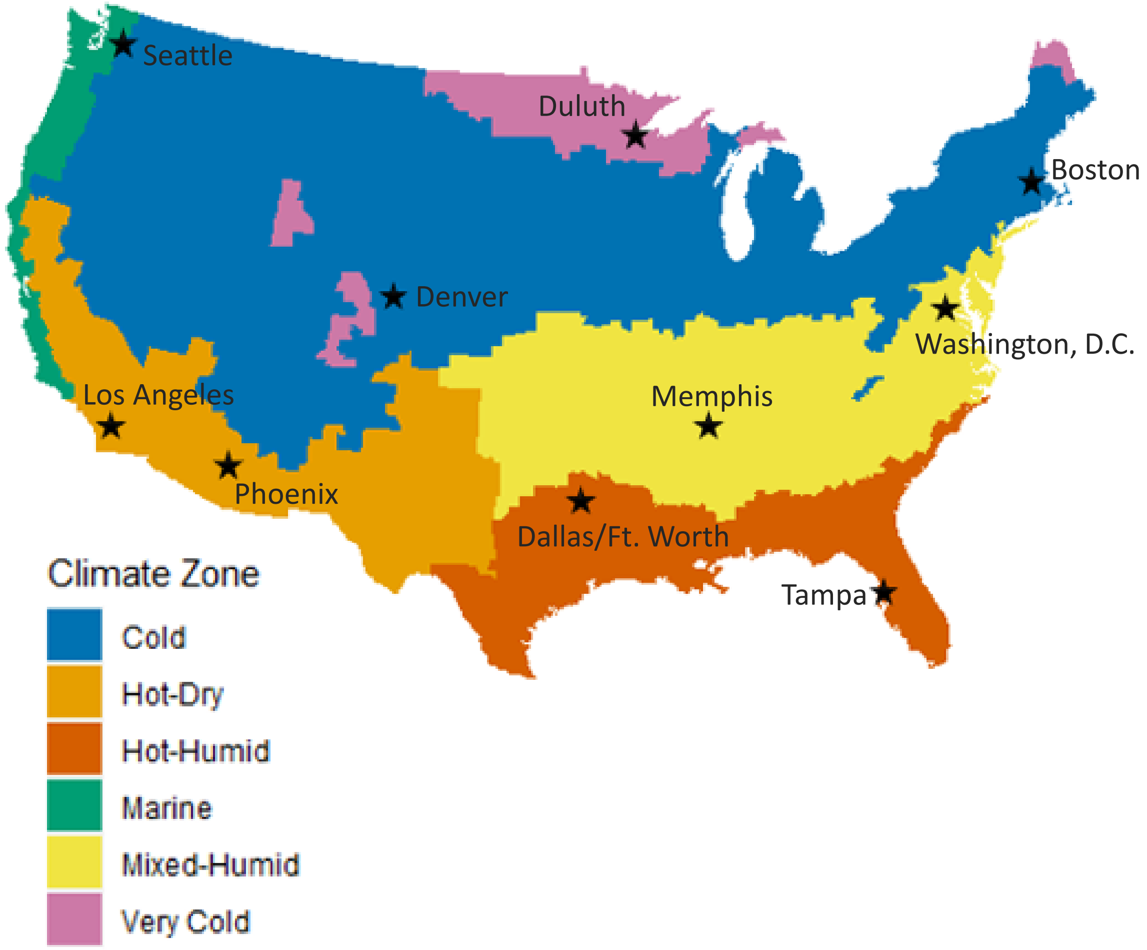
Data and Methods

Data and Methods Overview

Each element described further in the following slides

- 10 locations (counties) representing a diversity of climates and geographies
- Baseline load profiles for single-family homes from NREL ResStock: statistically representative distribution of ~1000 building models per location; 15-min interval
- Varying combinations of building efficiency, load flexibility, and electrification measures layered onto the baseline building stock
- Baseline assumptions (subject to sensitivity analysis)
  - Heating and cooling loads included in the critical load for backup power
  - 3-day power interruption
  - Power interruption occurs on the 90th percentile net-load day (slide 14 explains what this means)
- Solar systems sized at 100% of annual consumption, up to available roof area
- Analysis solves for the minimum storage size needed to provide backup for the given set of critical loads (without consideration of cost or space constraints)

Ten Locations Studied



- Selected ten counties, each encompassing a metropolitan area
- Locations span a diverse range of climates (hot, cold, and temperate) and solar insolation levels (sunny/cloudy and lower/higher latitude)
- Locations also capture important regional differences in current building stock conditions (e.g., high prevalence of electric-resistance based heating in the Southeast and Northwest)

Building Load Simulations

- Developed using NREL's ResStock building simulation platform, which produces load profiles disaggregated by end-use; 15-minute interval data for this study
- Create statistically representative sample of 1,000 baseline building models for each location, reflecting characteristics of the present-day building stock
- Modify baseline buildings with a series of energy efficiency, electrification, and load flexibility measures
  - Energy efficiency measures focus on building envelope (insulation and air sealing)
  - Electrification measures include heat pumps, water heaters, dryers, and cooking equipment
  - Multiple heat pump configurations
  - Load flexibility measure consists of HVAC set-point adjustment
- 17 different load scenarios considered, yielding a total of 170,000 unique building load profiles (17 x 10 locations x 1000 homes/location)

Additional Measure Details

- **Load flexibility:** Uniformly increase cooling set points by 5°F and decrease heating set points by 6°F for all buildings (based on typical setbacks in the baseline stock)
    - Side analysis explores the potential for using curtailed PV to pre-cool/pre-heat (slide 52)
- **Building envelope efficiency:** Insulation and air-sealing measures, corresponding to the “enhanced enclosure” measure bundle in NREL’s End-Use Savings Shapes Round 1
- **Heat pump retrofits:** Multiple measure variants involving different heat pump efficiency levels (minimum vs. high efficiency), sizing conventions (max-cooling* vs. max-load), and backup heating type (electric resistance vs. existing fossil heat); see slide 48 for details
- **Other building electrification:** heat-pump water heater, heat-pump dryer, induction range, and electric oven

Note: *We did not model electric vehicles as a backup load, though we discuss EVs as a potential source of storage capacity that could be used to provide backup for the home*

*The max-cooling heat pump scenario refers to the ACCA Manual S/J standard

Measure Bundles

Measure Bundle	Set-points	Bldg Envelope	Heating Tech*	Backup Heat*	HP sizing*	Other End-Uses
1 **Baseline**	Baseline	Baseline	Baseline	Baseline	Baseline	Baseline
2 with Set-point Adjustment	Adjusted	Baseline	Baseline	Baseline	Baseline	Baseline
3 **Enhanced Building Envelope**	Adjusted	Enhanced	Baseline	Baseline	Baseline	Baseline
4 **Min-Eff. HP**, Sized to Cooling Load	Adjusted	Baseline	Min-Eff. HP	Fossil	Max-cooling	Baseline
5 Sized to Max Load	Adjusted	Baseline	Min-Eff. HP	Fossil	Max-load	Baseline
6 **High-Eff. HP,** Sized to Cooling Load	Adjusted	Baseline	High-Eff. HP	Fossil	Max-cooling	Baseline
7 Sized to Max Load	Adjusted	Baseline	High-Eff. HP	Fossil	Max-load	Baseline
8 **Bldg. Env + Set-point + High Eff HP**	Adjusted	Enhanced	High-Eff. HP	Fossil	Max-cooling	Baseline
9 without Set-point Adjustment	Baseline	Enhanced	High-Eff. HP	Fossil	Max-cooling	Baseline
10 with HP Sized to Max Load	Adjusted	Enhanced	High-Eff. HP	Fossil	Max-load	Baseline
11 and no Set-point Adjustment	Baseline	Enhanced	High-Eff. HP	Fossil	Max-load	Baseline
12 with Electric Backup Heat	Adjusted	Enhanced	High-Eff. HP	Electric	Max-cooling	Baseline
13 and HP Sized to Max Load	Adjusted	Enhanced	High-Eff. HP	Electric	Max-load	Baseline
14 **Full Electrification**	Adjusted	Enhanced	High-Eff. HP	Fossil	Max-cooling	Electric
15 with HP Sized to Max Load	Adjusted	Enhanced	High-Eff. HP	Fossil	Max-load	Electric
16 and no Set-point Adjustment	Baseline	Enhanced	High-Eff. HP	Fossil	Max-load	Electric
17 with Electric Backup Heat	Adjusted	Enhanced	High-Eff. HP	Electric	Max-load	Electric

*Further details on heat pump (HP) measure bundles and modeling are provided in the appendix slide 48.

Three Backup Load Scenarios

Base-case analysis assumes backup of critical loads, as defined here; other backup cases are sensitivities

- Limited Critical Load: Includes fridge, freezers, nighttime lighting, well pumps, water heating, cooking, 70W of plug load
- Critical Load: Includes all limited critical loads, plus heating and cooling equipment
- Whole Home: All loads

* Modeled end-uses are based on those present in ResStock; does not include home medical equipment

End-Uses Disaggregated in ResStock*

🟨 Limited Critical Loads 🟧 Critical Loads (incremental)

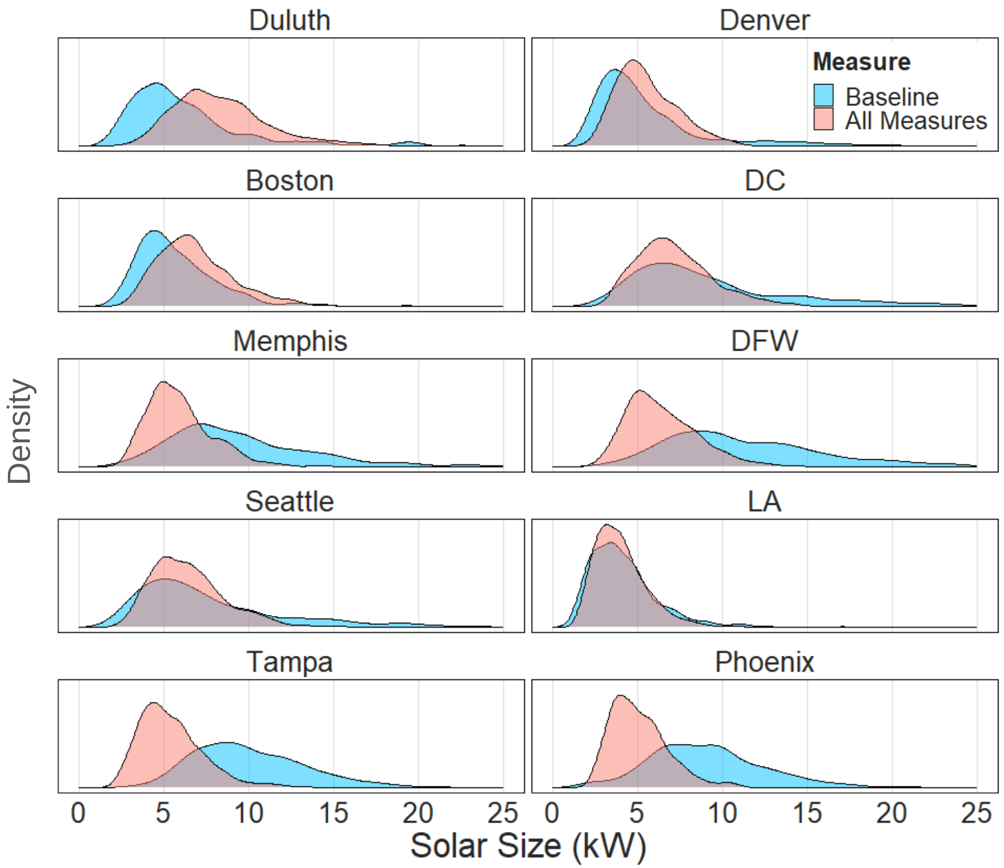
Ceiling fan	🟧 Heating supplement energy
Clothes dryer	Hot tub heater
Clothes washer	Hot tub pump
🟨 Cooking range	🟨 Interior lighting*
🟧 Cooling energy	🟨 Plug loads*
Dishwasher	Pool heater
Exterior lighting	Pool pump
Extra refrigerator	🟧 Pumps cooling
🟧 Fans cooling	🟧 Pumps heating
🟧 Fans heating	🟨 Range fan
🟨 Freezer	🟨 Refrigerator
Garage lighting	🟨 Water heating
🟧 Heating energy	🟨 Well pump

*A portion of interior lighting and plug loads are included in the limited critical loads

PV System Sizing and Generation

- PV system sizes stipulated based on customer's annual consumption, subject to available roof area
  - PV system sizes vary across load scenarios, based on changes in consumption
  - Hourly PV generation simulated with NREL's System Advisor Model (SAM)*
  - See slide 49 for PV size distribution as % of roof area
- Presumption is that PV systems are sized for reasons other than backup power (e.g., to minimize utility bills)
  - Sizing assumption consistent with current installation practices in most major markets (EnergySage 2023)
  - PV systems sized for resilience purposes could be larger (Simpkins et al. 2016)

PV Sizing Distributions



The two distributions shown here correspond to the PV sizes for the baseline building stock and for the scenario with all measures (load flexibility, building envelope efficiency, heat pump, and other electrification) applied to the Baseline building stock.

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* *Assumes SAM default values (e.g., for orientation, losses, DC-to-AC, etc.)*

Power Interruption Events

Analysis involves specifying long-duration power interruption events for each customer, with a given duration, start-day, and start-hour

- Duration: Base-case analysis assumes 3-day power interruption, with sensitivities ranging from 1-7 days
- Start-day: Base-case analysis assumes interruption commences on the 90th percentile net-load day* for each customer, in each load scenario
  - Net-load = Gross load – PV production (calculated for each day)
  - Corresponding season depends on the region and individual customer (see slide 50)
  - Sensitivities conducted to capture more or less extreme conditions
- Start-hour: All interruptions assumed to commence at midnight
  - Prior analysis found that interruption start-time has limited impact for multi-day events, provided that storage is fully charged at the beginning of the event (see p.22 in Gorman et al., 2022)

** The 90th percentile net-load day is the day with the 36th highest net load out of the 365 days in the year; it could be considered a "challenging but not extreme" day, in terms of the difficulty of serving backup load.*

Weather Data

- Weather data used as an input for load and PV simulations, and thus also to select the timing of interruption events
- Analysis relies primarily on typical meteorological weather year (TMY3) weather
  - Selects actual weather data from the “most typical” month of a given historical period
  - Considers both average and extreme weather to select “most typical” month
  - Historical weather comes from either 1976-2005 or 1991-2005, depending on geography
- For two locations (Boston and Phoenix), we also run a portion of the analysis over a full 11-year historical weather period (2011-2021), in order to benchmark the TMY-based results (see Appendix slides 57-58)
  - Allows us to compare to more recent weather than used to construct TMY
  - Also allows us to potentially observe more-extreme weather than captured in TMY

Storage Dispatch and Sizing

Optimization model solves for the minimum storage size (usable kWh) required to serve specified critical loads over a given power interruption

- Storage power capacity (kW) constrained by assuming a 1-hour duration battery (i.e., max kW charge/discharge is equal to kWh rating)
  - Intended to provide a relatively weak constraint, but results provided on appendix slide 51 show that a stronger kW constraint (e.g., assuming a 2-hour duration battery) would rarely bind
  - Constraints related to instantaneous start-up current are not considered in this analysis
  - Reliance on 15-minute interval data means that shorter duration power spikes are not captured
- Storage assumed to have 100% state of charge (SoC) at the start of the interruption
  - For long-duration interruptions, particularly those associated with extreme weather events, customers likely have some advance warning and can ensure their battery is charged up

Other assorted assumptions: 85% round-trip efficiency; no minimum or maximum SoC specified (model solves for “usable” capacity, so results can be grossed up to reflect min/max SoC limits)

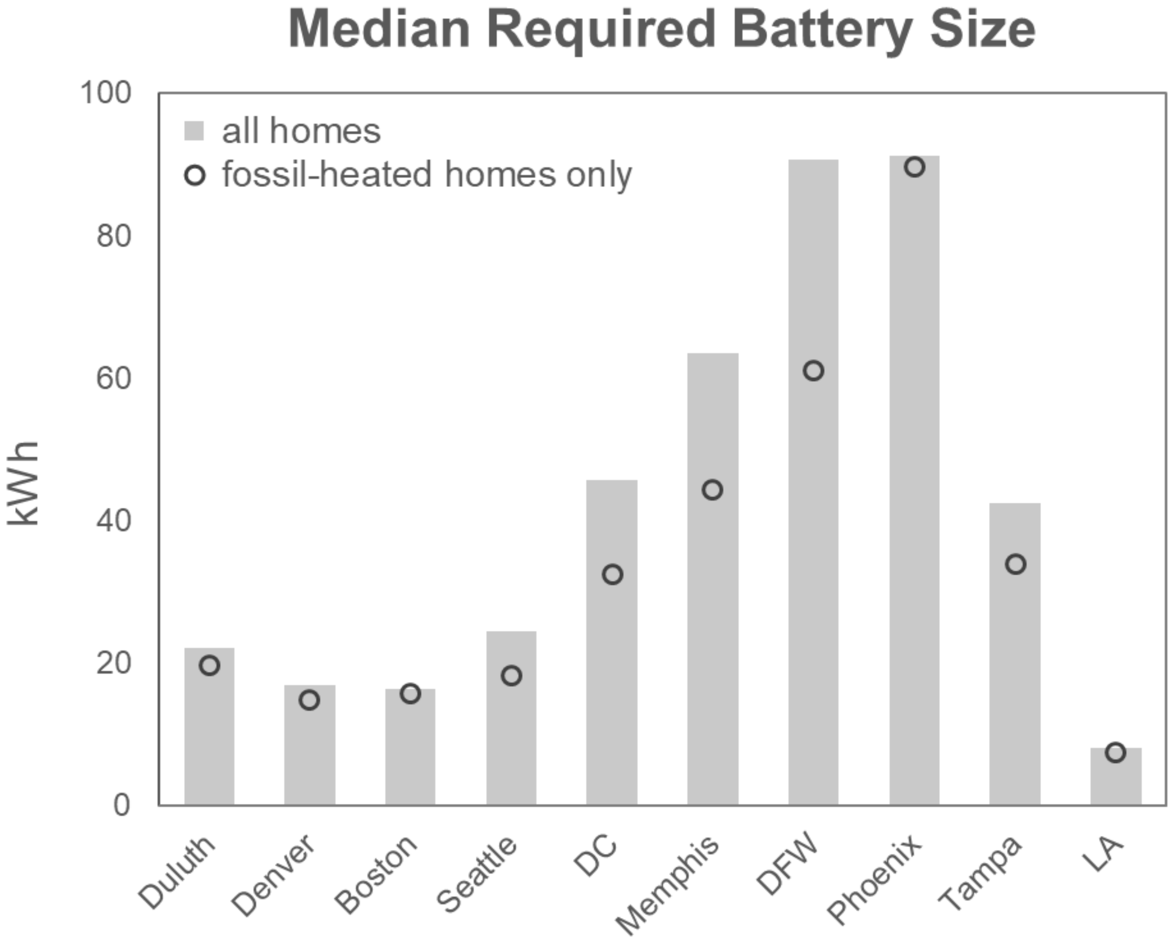
Results

Results Organization

- **Backup power battery sizing for the baseline (present-day) building stock**
  - Median required battery size
  - Impact of electric-resistance heating
  - Distribution in required battery sizing across homes
  - Linear trend between battery sizing and net load
- **Impacts on battery sizing as DER measures are sequentially added**
- **Sensitivity cases**

Median Required Battery Size for the Baseline Building Stock

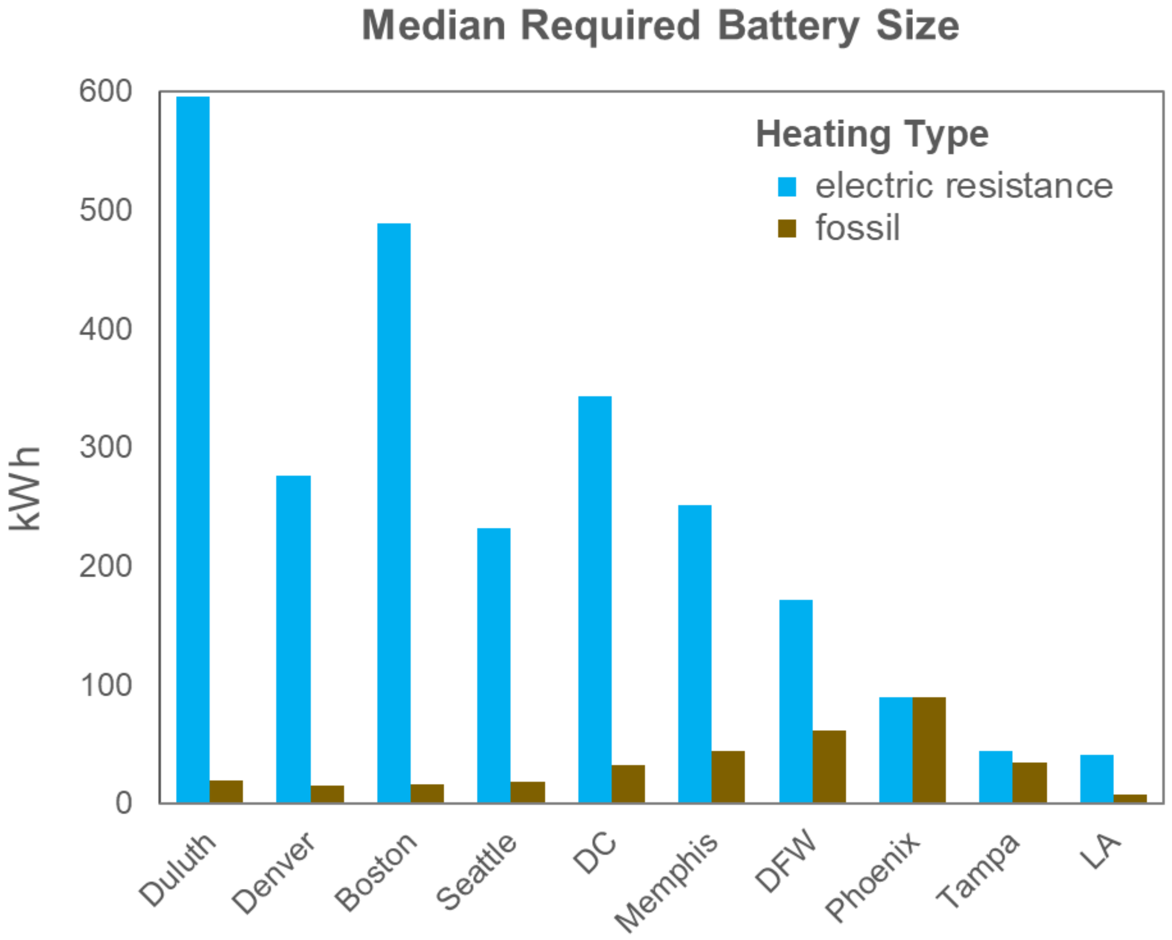
- The primary metric for our analysis is the:
  - **Median** required battery size across all modeled buildings in each location
  - For providing backup to critical loads that include **heating and cooling**
  - Over a **3-day** power interruption
  - Starting on the **90th percentile** net-load day
- For the baseline building stock, median required battery sizes across all homes in each location range from roughly 10 kWh in LA up to 90 kWh in DFW and Phoenix
- Electric resistance heating is common in some locations (see slide 47); required battery size among only fossil-heated homes is lower



Locations are grouped along the x-axis based loosely on climate and solar insolation levels, with the coldest locations on the left, the hottest regions in the middle toward the right, and LA on the far right representing the most temperate region.

Required Battery Sizing: Electric Resistance vs. Fossil Heating

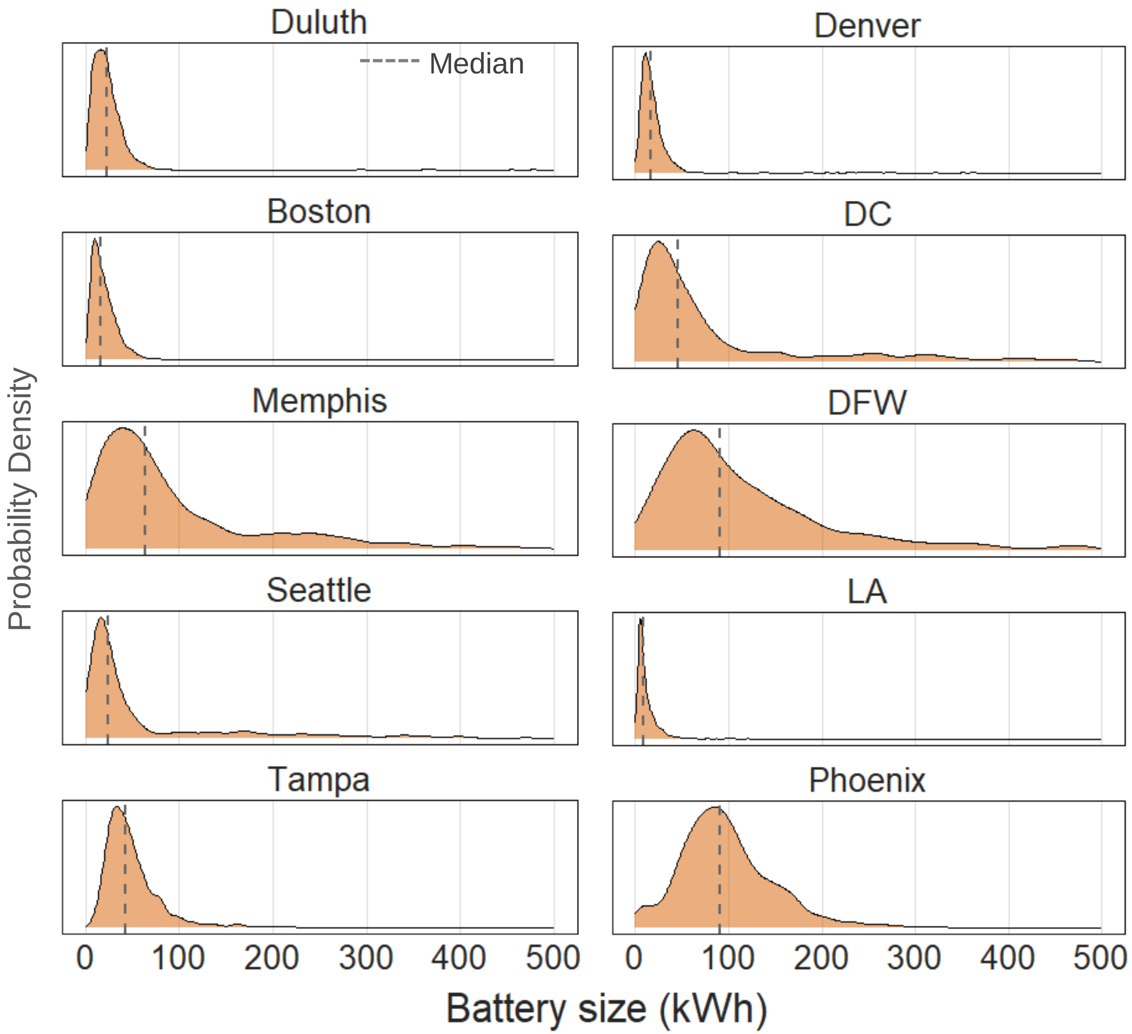
- Electric-resistance heating is highly energy intensive (distinct from electric heat pumps)
- Providing backup power to homes with electric-resistance heating over a 3-day interruption would require extremely large batteries in most locations (i.e., not a practical solution)
- Homes with fossil heat generally require significantly less storage
- Later results (see slide 28) show how replacing electric-resistance heating with efficient heat pumps can make PVESS backup power much more practical (though in cold climates may still require relatively large batteries)



For all locations other than Boston, at least 10% of homes in the baseline building stock have electric resistance heating. The figure excludes homes in the baseline stock with heat pumps; later analyses will focus in depth on homes with heat pumps.

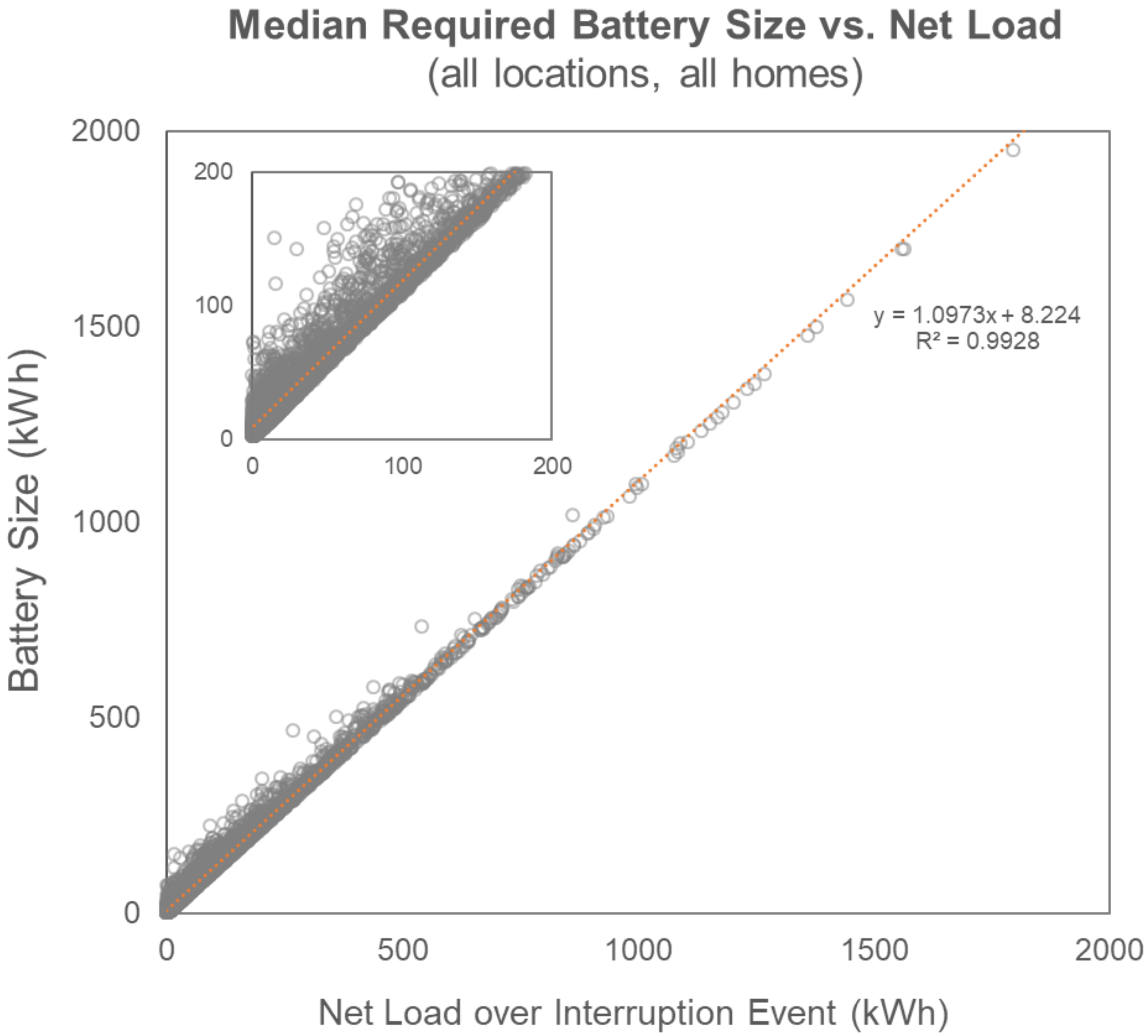
Distribution in Battery Sizing for Baseline Building Stock

- While we focus mostly on medians in our analysis, required battery sizing varies widely across individual homes in each location
- Some locations exhibit particularly wide variation as a result of greater underlying variation in consumption levels, related mostly to heating and cooling loads
- Locations with large amounts of electric-resistance heating (esp. Memphis and DFW) have long, fat tails
- Later analysis (slide 32) shows how efficiency, load flexibility, and (in many cases) heat pump measures can both *shift* and *compress* these distributions



Linear Trend between Battery Sizing and Net Load

- Each dot in the figure is an individual home, showing required battery size vs. net load over the 3-day interruption event
- In general, relationship is linear: roughly 1.1 kWh increase in battery size for each kWh increase in net load across all locations
- This basic relationship underlies many of the results presented in this report and can also serve as a useful heuristic for sizing battery systems
- Deviations above the trend line (see insert) include cases where the load shape/timing during the interruption impacts storage sizing, solar curtailment occurs, and/or the battery power constraint binds



Results Organization

- **Backup power battery sizing for the baseline (present-day) building stock**
- **Impacts on battery sizing as DER measures are sequentially* added**
  - Set-point adjustments
  - Building envelope efficiency upgrades
  - Heat pump retrofit
  - Other electrification measures (hot water, cooking, dryer)
  - Summary
- **Sensitivity cases**

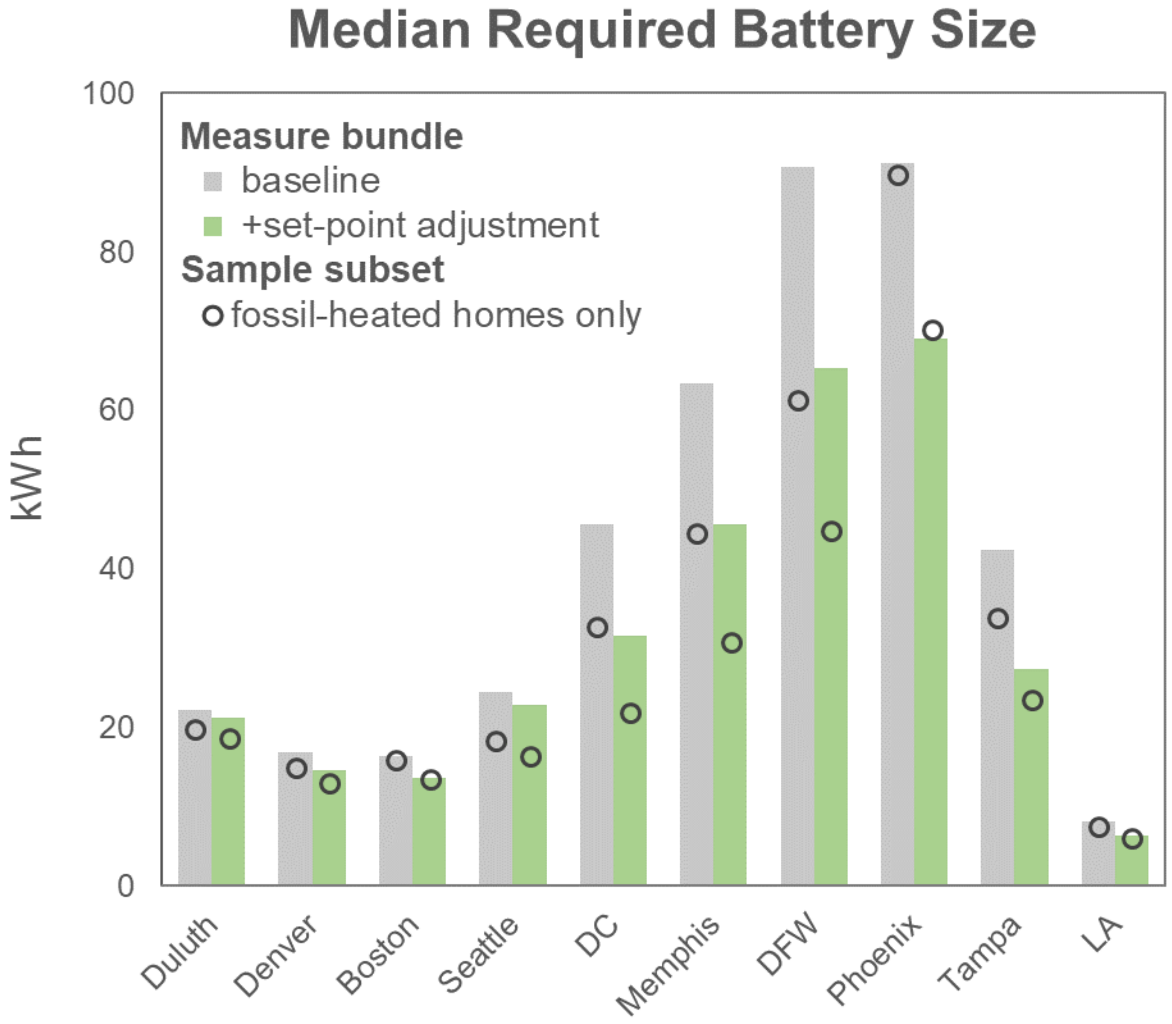
**Main results show incremental impacts of each measure based on the order listed here; sensitivity cases in the Appendix show how incremental impacts can differ with an alternate ordering*

Reminder…

- Results shown here are based on:
  - **Median** required battery size across all modeled buildings in each location
  - For providing backup to critical loads that include **heating and cooling**
  - Over a **3-day** power interruption
  - Occurring under **90th percentile** net-load conditions
- Sensitivity analyses will explore deviations from the assumptions above

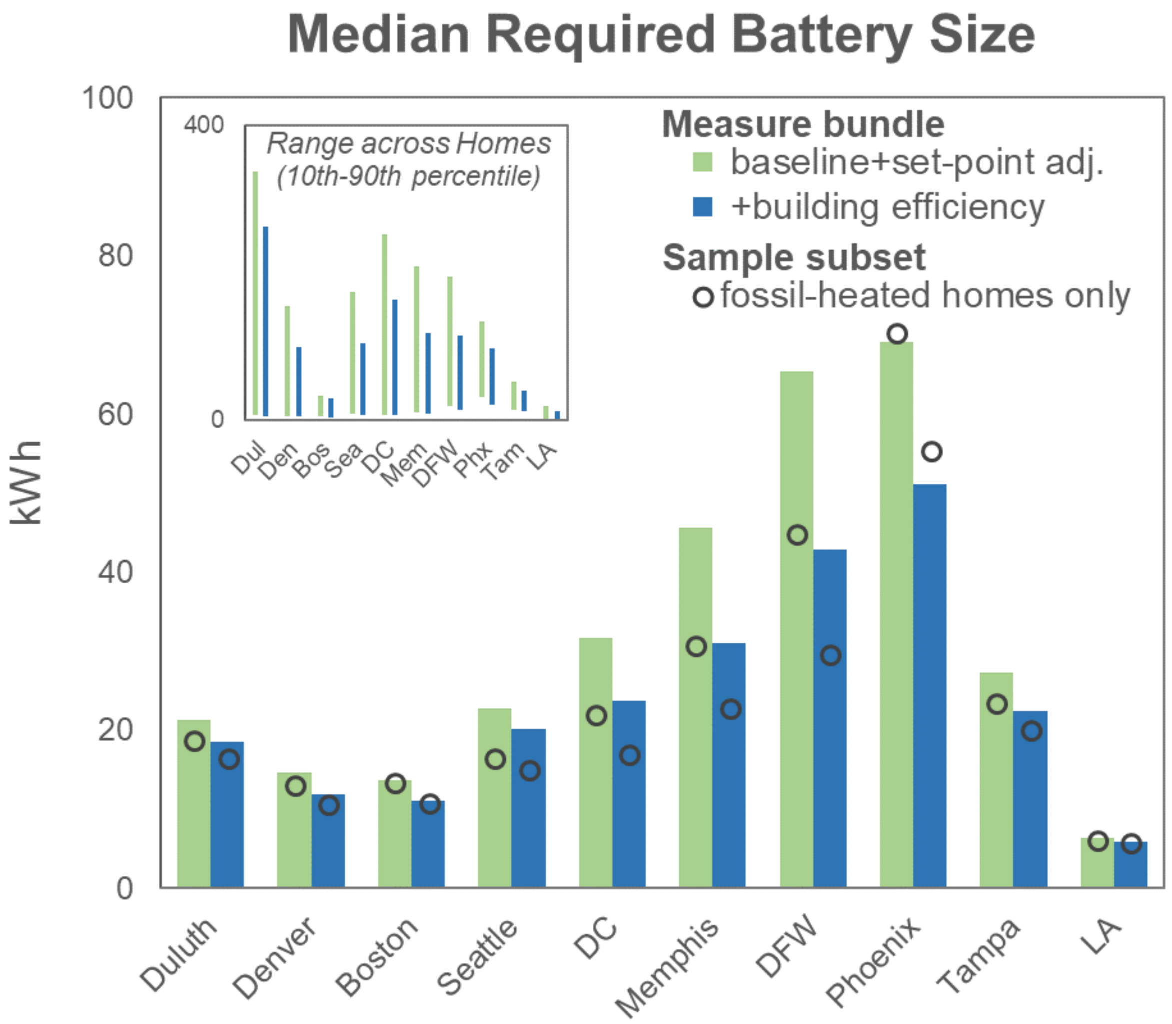
Impact of Temperature Set-point Adjustments

- Applying set-point adjustments reduces required battery size across all locations
- Largest reductions (14-25 kWh) are in the five locations with hot summers and/or concentration of electric-resistance heating (DC, Memphis, DFW, Tampa, Phoenix)
- Reductions are a bit smaller, but still sizeable, for just fossil-heated homes in those locations
- Effects in other locations are fairly negligible, due to mild summers and predominantly fossil-based heating; effects in these locations are larger once heat pumps are installed across the building stock (see slide 54)



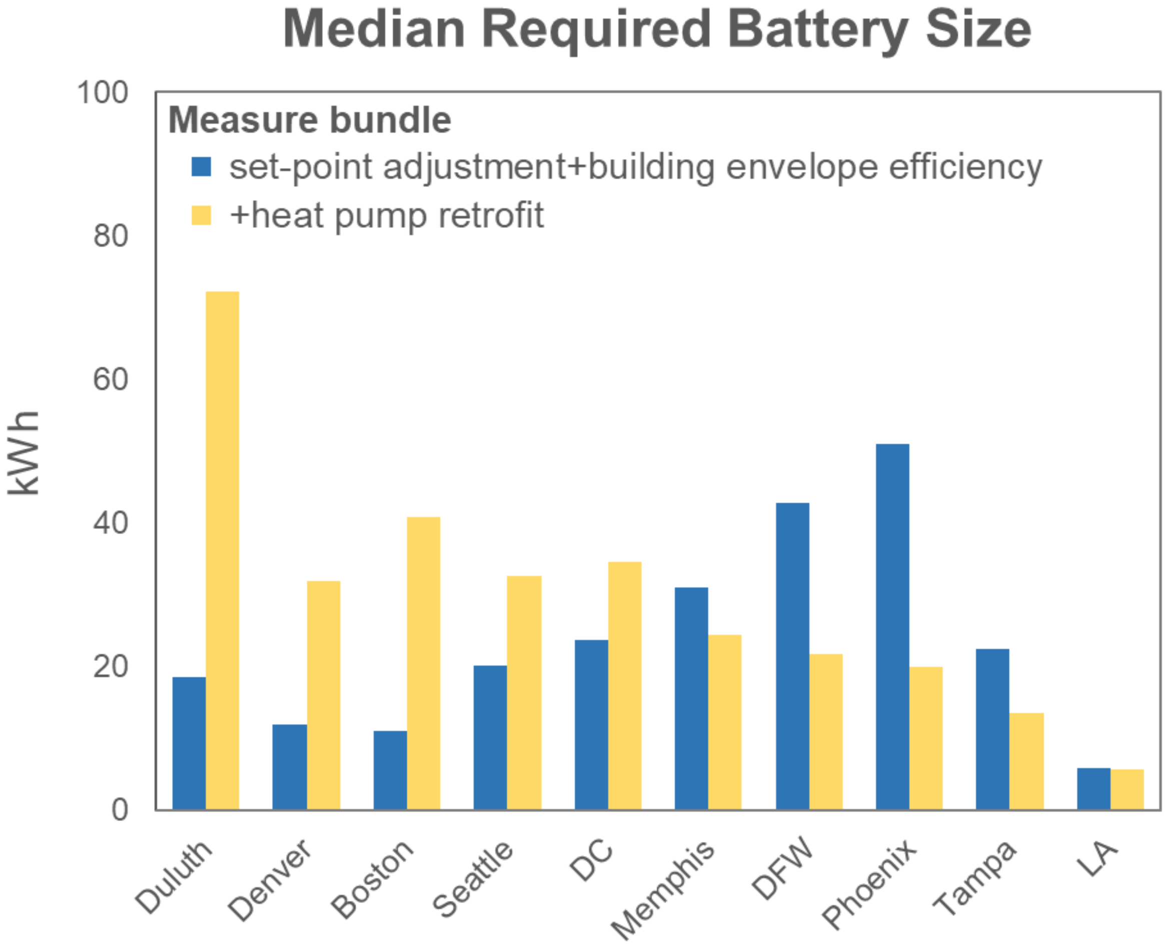
Incremental Impact of Building Envelope Efficiency Upgrades

- Building envelope efficiency measures further reduce battery sizing across all locations
- Largest reductions are in Memphis, DFW, and Phoenix (15-22 kWh), followed by DC and Tampa (5-8 kWh)
- Effects in other locations are negligible but are larger after heat pumps are installed across the building stock (see slide 55)
- Distributions across homes in each location also tighten (see insert) as effects are greatest for the most inefficient baseline homes
- Impacts on battery sizing would be larger with deeper efficiency savings; measures modeled here yield 3-12% reduction in median annual energy consumption across the 10 locations



Incremental Impact of Heat Pump Retrofits

- Directionality of impact depends on the location
- In hot locations (Memphis, DFW, Tampa, Phoenix), heat pump retrofits reduce median battery sizing by ~10-30 kWh, by replacing inefficient A/C, though effects may be muted as peak loads shift to winter/heating season
- In cold locations, heat pump retrofits generally necessitate larger batteries (10-30 kWh more in Denver, Boston, Seattle; 50 kWh more in Duluth), though the opposite is true for homes with electric resistance heat (see next slide)
- Impact of heat pump retrofits on battery sizing can also heavily depend on the timing of the interruption event (slide 38) and heat pump configuration (slides 59-60)



Heat pump measure shown here assumes all homes retrofitted with high-efficiency heat-pump, sized to maximum load, with fossil backup heat.

Incremental Impact of Heat Pump Retrofits

Focusing on homes with electric-resistance heat in the baseline

- It is uncommon, but not unheard of, for homes in cold-weather locations to have electric resistance heating
- Replacing electric-resistance heating with heat pumps can dramatically reduce backup battery sizing, especially in regions with cold winters
- Duluth is an extreme case, but in many other locations, median required battery sizes are reduced from 100-250 kWh to 30-50 kWh (still a significant amount of storage, but potentially achievable)

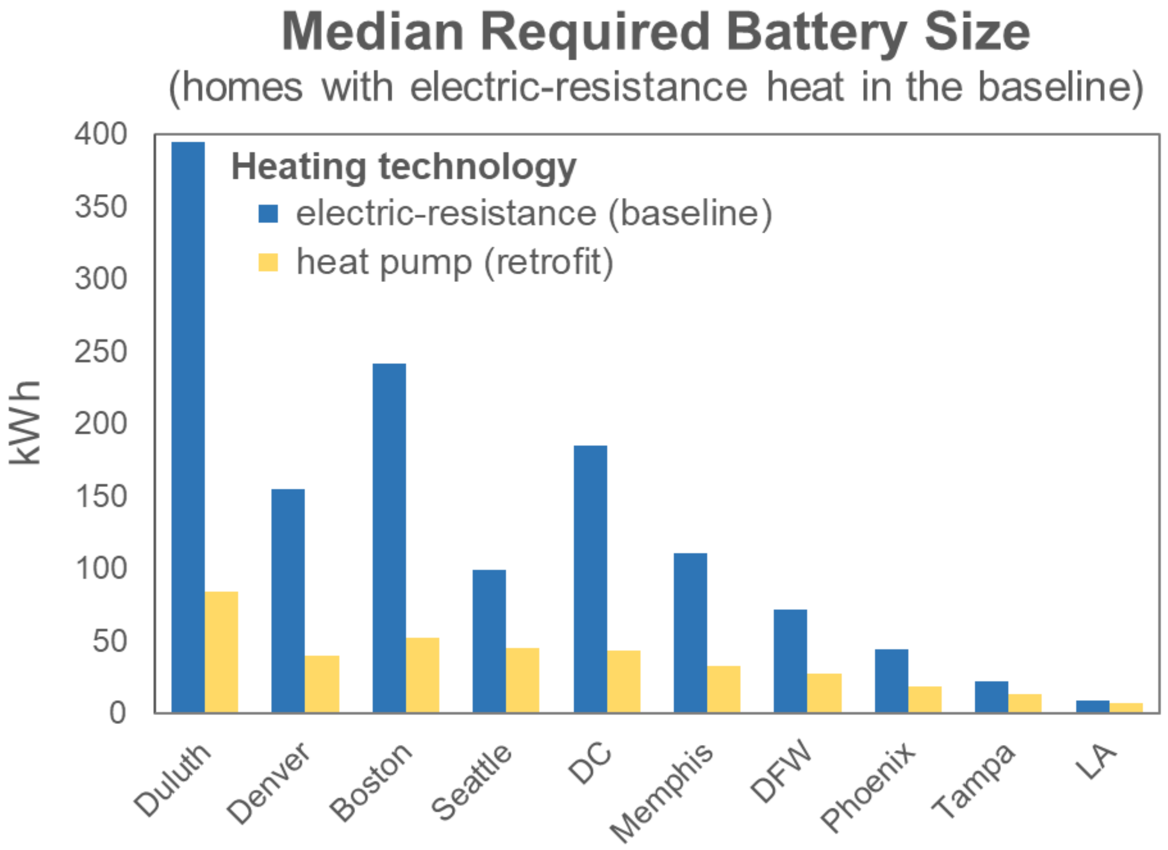
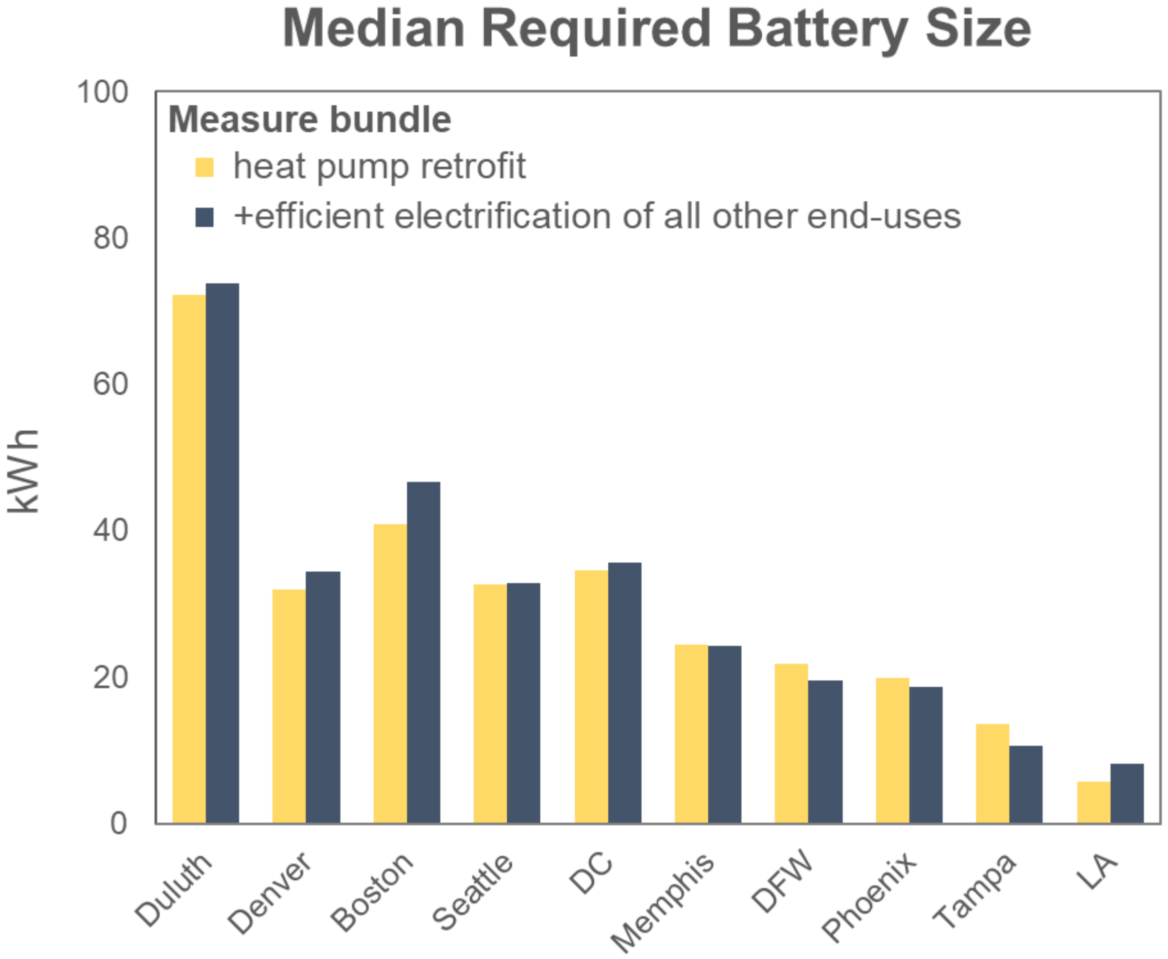


Figure is based on the subset of modeled homes in each location with electric-resistance heating in the baseline building stock. Both scenarios shown here include set-point adjustments and building envelope efficiency upgrades. Heat pump measure based on the same configuration as in earlier results.

Incremental Impact of Additional Electrification Measures

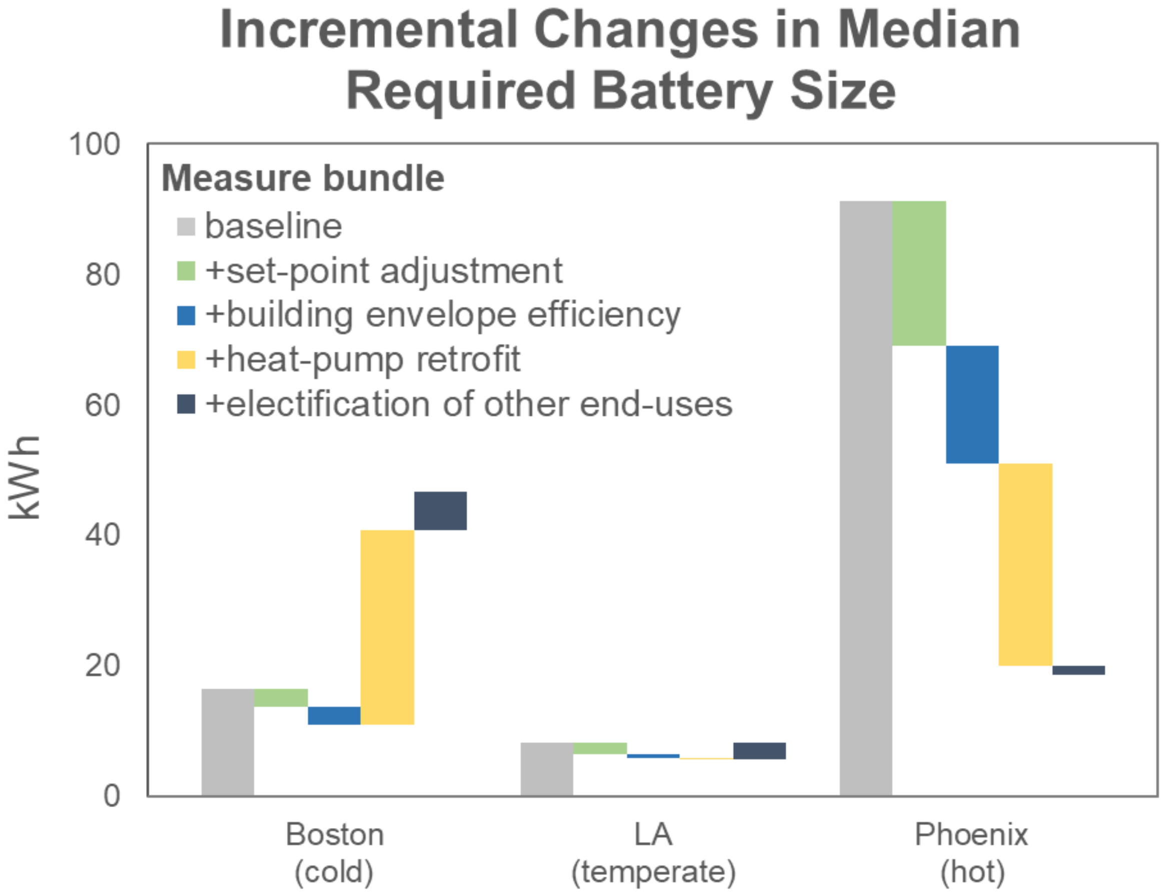
- Water heating and cooking are also included in the set of critical loads for backup
- Efficiently electrifying these end-uses (with heat pump water heaters and induction stoves) has negligible impact on battery sizing, given the small energy consumption by these loads relative to heating and cooling
- Median required battery size declines (slightly) in some locations from replacing inefficient electric end-uses (e.g., replacing electric resistance water heating with heat-pump water heating) and from the "side-effect" of heat-pump water heaters in reducing space cooling loads



Both measure bundles also include set-point adjustments and building envelope upgrades, and assume high-efficiency heat pumps sized to maximum load with fossil backup heat.

Putting it All Together (for a few representative locations)

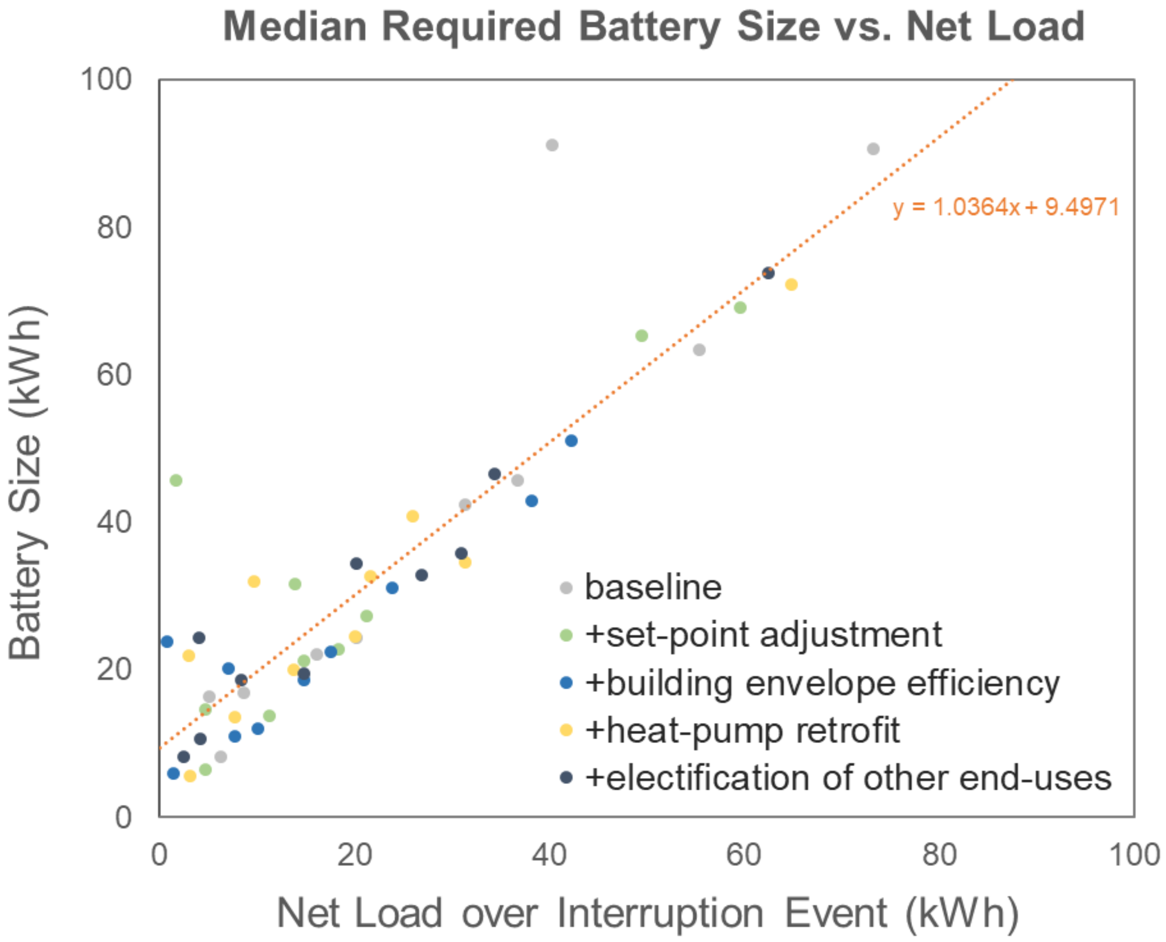
- HVAC set-point adjustments and building envelope efficiency upgrades reduce required battery sizing, especially in hot climates (e.g., from 90 to 50 kWh in Phoenix)
- In cold climates, heat pump retrofits increase required battery sizing when replacing fossil heat (e.g., from 10 to 40 kWh in Boston)
- Conversely, in hot climates, heat pump retrofits decrease battery sizing (e.g., from 50 to 20 kWh in Phoenix) by replacing less efficient A/C
- Electrifying water heating and cooking has negligible impact on required battery sizing
- None of this matters much in temperate climates, for the interruption conditions assumed



Each step in the chart shows the incremental effect of adding the respective measure bundle to all measures listed above. See earlier slides for definitions of measure bundles. See Appendix for waterfall chart with all 10 study locations.

Impacts on Battery Sizing as a Function of Net Load

- ☐ Earlier scatter plot showed how required battery sizing across buildings in the baseline stock varied linearly with net load
- ☐ The figure here shows the same linear relationship applies when comparing results across DER measures
- ☐ The implication is that the DER measures impact required battery sizing primarily as a result of their effect on the total quantity of electricity consumption during the interruption (and on PV sizing), more so their effect on the specific load shape
- ☐ The same relationship would also apply to PV sizing (e.g., larger PV systems reduce net load, linearly reducing required battery size)

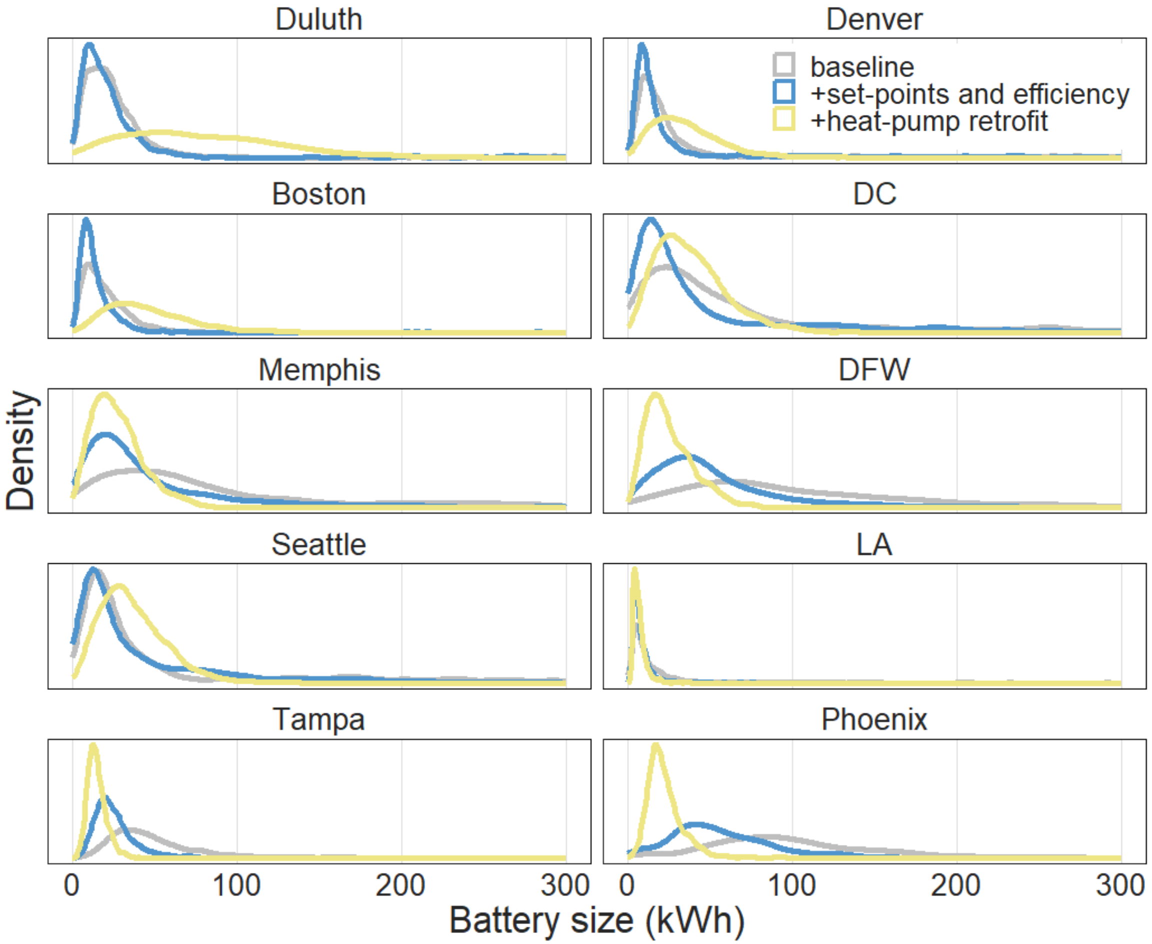


Each dot in the figure is the median required battery size, and corresponding median net load, for a given location and measure bundle. As with previous figures, each measure bundle is layered on to the measures listed above.

Impacts on the Distribution of Required Battery Sizing across Homes in Each Location

- As previously noted, required battery sizing varies widely across homes in each location
- Changes in median battery sizing correspond to *shifts* in the underlying distribution; but the DER measures analyzed also impact the *spread* in these distributions
- Efficiency and (to a lesser extent) load flexibility measures tend to compress these distributions
- Heat pump retrofits compress the distributions in hot climates and in regions with a high concentration of electric-resistance heating in the baseline stock (e.g., Memphis and DFW)
- But in predominantly fossil-heated cold climates, heat pumps significantly widen the distributions

Distribution in Median Required Battery Size across Homes in Each Location

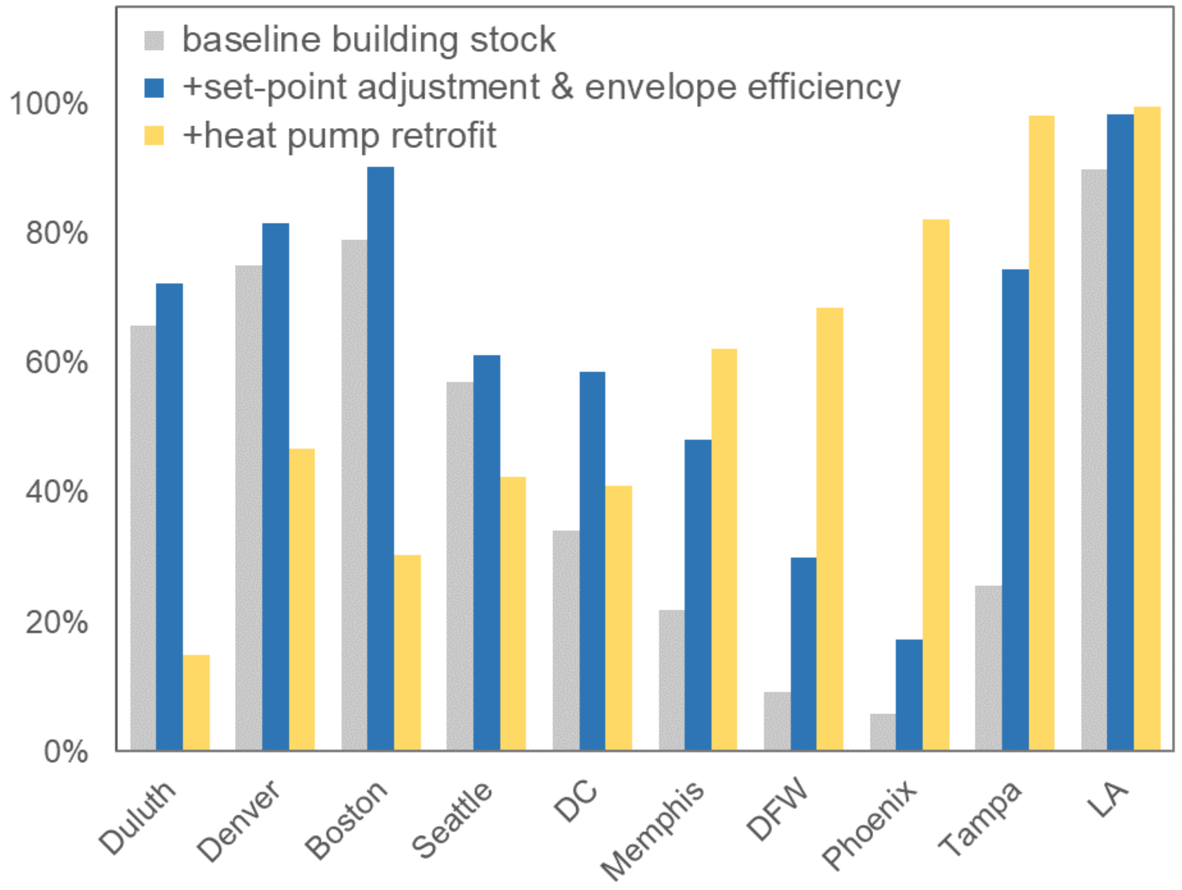


Addressable Market for PVESS Backup with ≤30 kWh Storage

- ☐ 30 kWh of battery storage is at the upper end of the size range typically observed in the residential market today (~2 PowerWalls)
- ☐ A system of that size could provide backup power to some portion of the existing building stock, ranging from 6% of homes in Phoenix to 90% of homes in LA (for the interruption conditions assumed so far in this analysis*)
- ☐ Through a combination of set-point adjustments, envelope efficiency upgrades, and (in mild winter climates) heat pump retrofits, this addressable market can be raised to at least ~60% of homes in all 10 regions

* *I.e., a 3-day interruption beginning on the 90th percentile net-load day in a typical year*

Percent of Homes where Backup Could be Provided by a PVESS with ≤30 kWh Storage



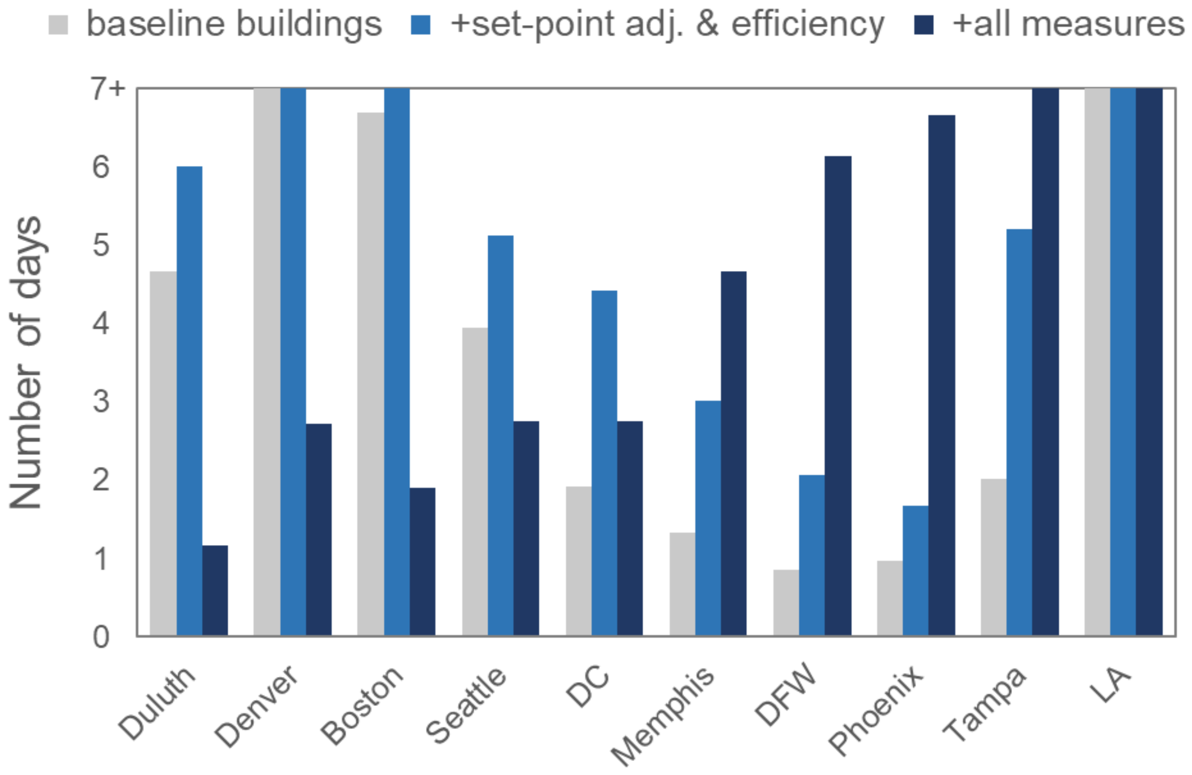
Results Organization

- Backup power battery sizing for the baseline (present-day) building stock
- Impacts on battery sizing as DER measures are sequentially added
- **Sensitivity analyses**
  - Interruption event duration
  - Interruption timing (more or less extreme weather conditions)
  - Heat pump configuration (sizing and source of backup heat)
  - Backup load configuration

Sensitivity to Interruption Event Duration

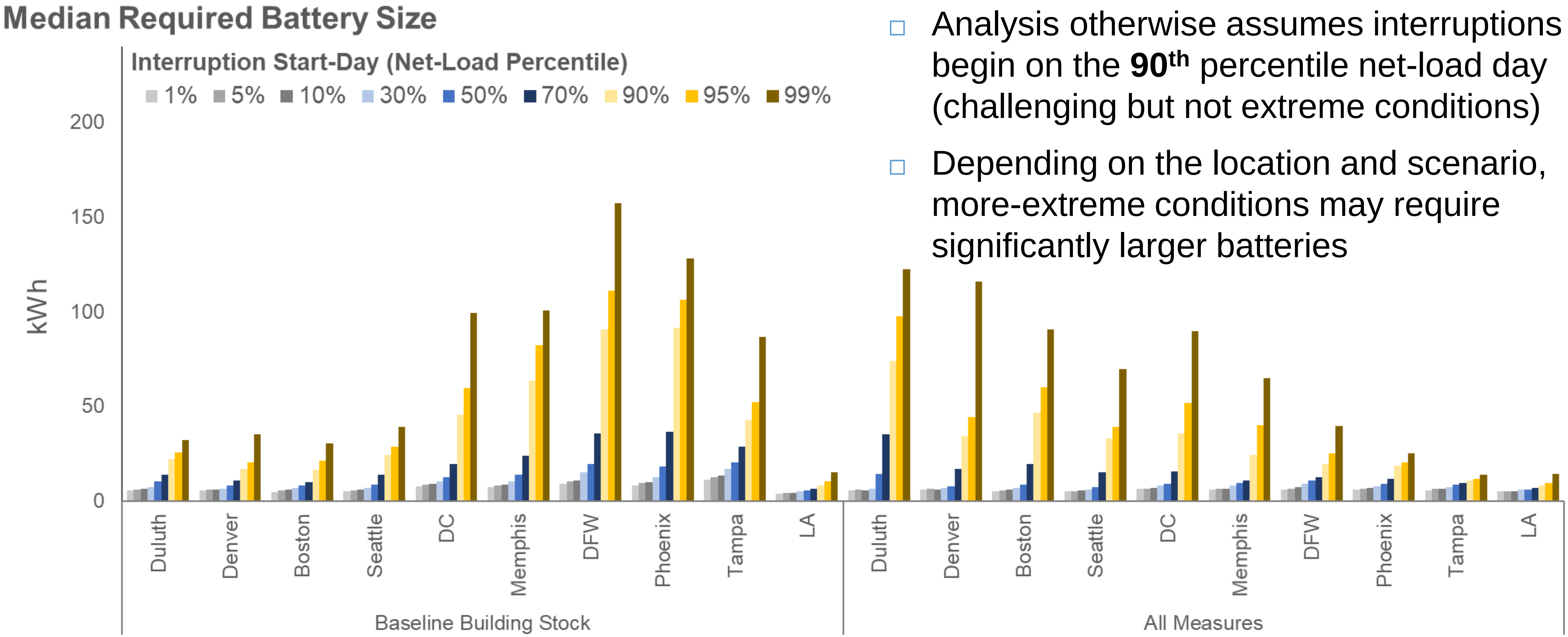
- Longer events require larger batteries, as daily PV generation typically is not enough to fully replenish the battery, and so the initial SoC gets drawn down over the course of the event
    - Required battery sizing scales more-or-less linearly with interruption duration (see slide 53)
- Efficiency, load flexibility, and (in mild winter climates) heat pumps extend the period over which a given PVESS can provide backup
    - In Phoenix, the measures extend the backup period for a 30 kWh PVESS from 1 to ~7 days
- In cold locations, electrifying space heating tends to have the opposite effect
    - Shortens the backup period for a 30 kWh PVESS in Denver and Boston from 7+ days to ~2 days

Median Number of Days over which a PVESS with a 30 kWh Battery Could Provide Backup Power



Based on providing backup power to critical loads that include heating and cooling. Analysis considered interruptions up to 7 days. The "+all measures" case includes set-point adjustments, building envelope efficiency upgrades, and all electrification measures, including heat pumps.

Battery Sizing across all Interruption Start-Day Scenarios



- Analysis otherwise assumes interruptions begin on the **90th** percentile net-load day (challenging but not extreme conditions)
- Depending on the location and scenario, more-extreme conditions may require significantly larger batteries

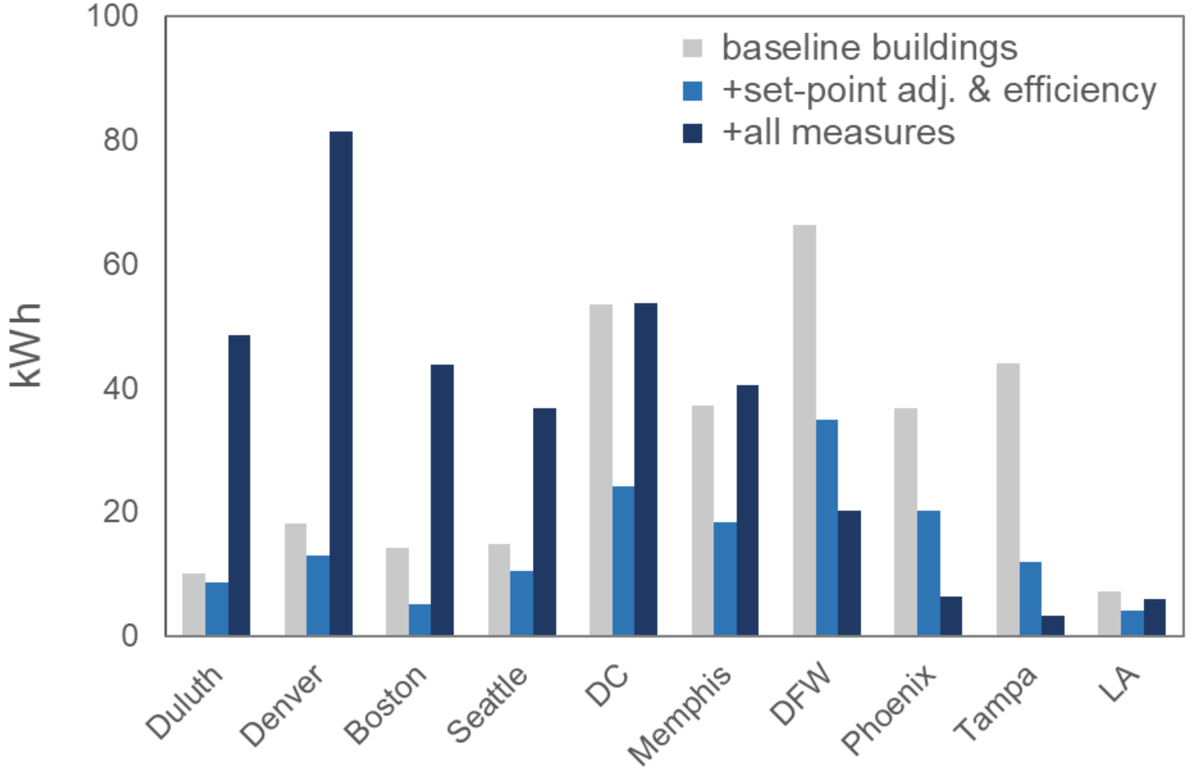
"All Measures" includes set-point adjustments, building envelope upgrades, and all electrification measures, including heat pumps.

Sensitivity to Interruption Timing:

90th vs. 99th percentile net-load conditions

- Interruption timing matters most for heating and cooling loads, thus most important for homes with large electric heating/cooling loads
- For that reason, interruption timing has largest impact on battery size for inefficient hot-weather homes in the baseline stock and for homes in cold-winter regions with electric heat
- Load flexibility and efficiency can significantly reduce sensitivity to interruption timing
- Heat pumps can reduce that sensitivity in mild-winter locations or for homes that would otherwise use electric-resistance heating
- But for homes in cold locations, heat pumps can require significantly larger batteries for backup on the coldest days

Additional Battery Capacity Needed if Interruption Starts on 99th Percentile Net-Load Day
(relative to 90th percentile)

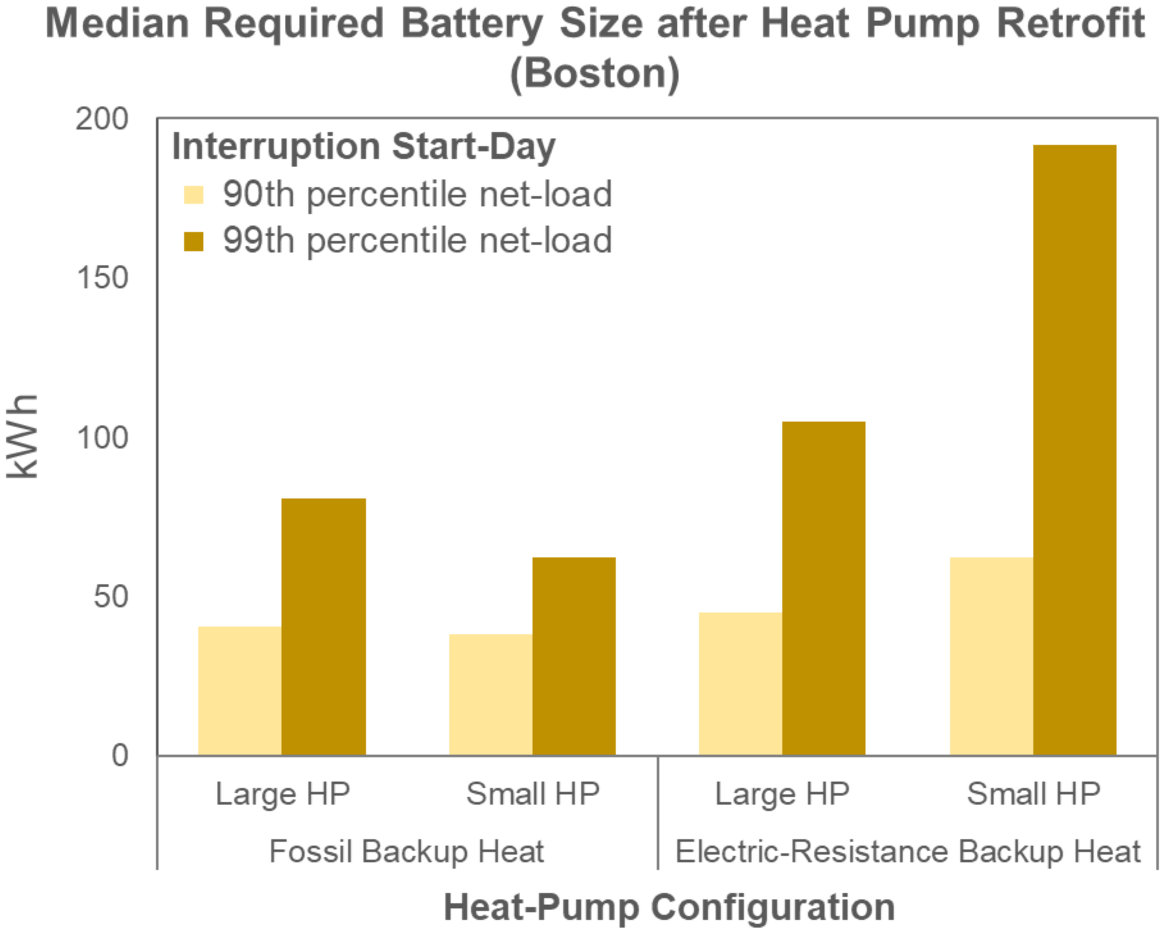


The "+all measures" bundle includes set-point adjustments, building envelope upgrades, and all electrification measures, including heat pumps.

Sensitivity to Heat Pump Configuration

And interdependence with interruption timing

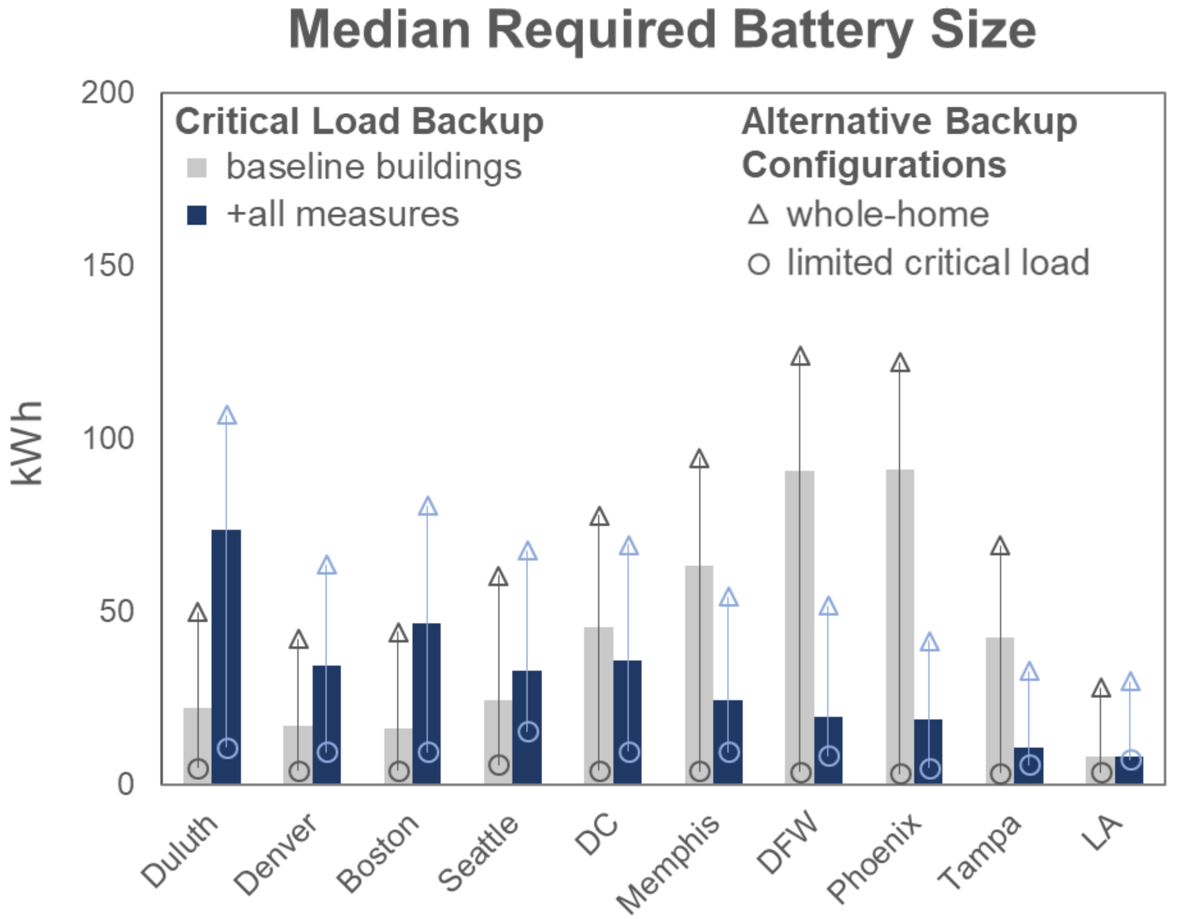
- Prior analysis assumes relatively large heat pumps with fossil backup heat (used only when heat pump is unable to meet heating load)
- Electric-resistance backup heat can significantly increase the amount of battery storage required for backup power, especially if planning for extreme (99th percentile) conditions
- Sensitivity is further amplified for small heat pumps, which more heavily rely on backup heat
- For Boston, as an example, the median required battery size under 99th percentile conditions varies from ~60-200 kWh depending on heat pump sizing and backup heating source
- Results for other regions on Appendix slide 59



Large HP is based on sizing to maximum load, while Small HP is based on sizing to maximum cooling load (ACCA Manual S/J standard). All results shown here include temperate set-point adjustments and building envelope efficiency upgrades.

Alternate Backup Load Scenarios

- The DER measures in this study principally impact heating/cooling loads, hence our focus on critical-load backup with heating and cooling
- However, in many backup power applications today, customers back up only a limited set of critical loads that exclude heating and cooling
- For limited critical load backup without heating and cooling, battery sizes are quite small (<15 kWh) across all locations, and are largely unaffected by the set of DER measures
- Whole-home backup requires about 30 kWh more storage, on average, compared to what is needed for backup of critical loads with heating and cooling; that difference is largely unaffected by the set of DER measures

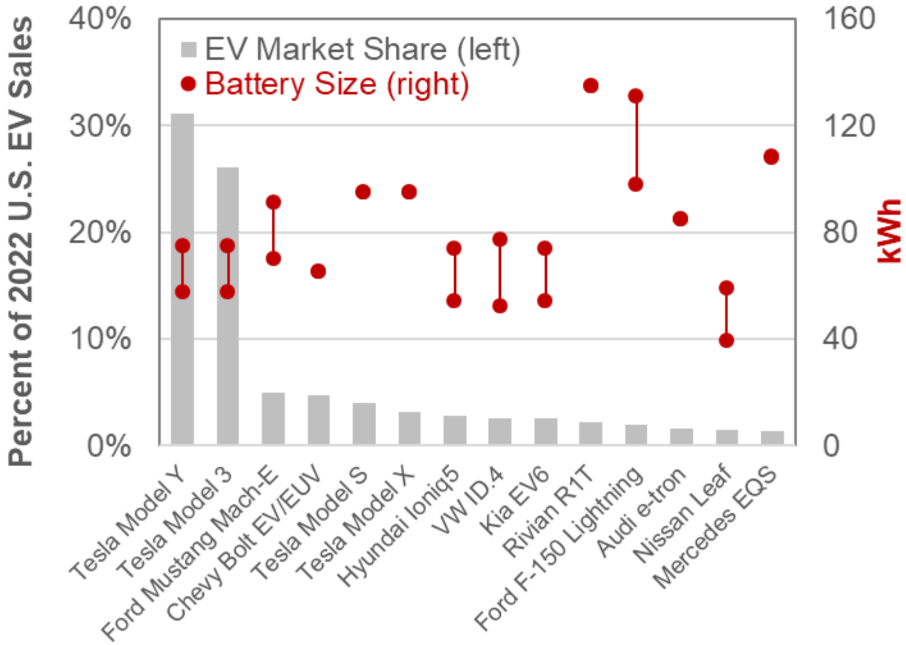


See methods section for definitions of the alternative backup configurations. The "+all measures" bundle includes set-point adjustments, building envelope upgrades, and all electrification measures, including heat pumps.

Side-Bar: *Bi-directional Electric Vehicle Charging as a Key Enabling Technology for PVESS Backup Power*

- EVs are an additional load that may need to be served, though driving and charging behavior may differ significantly from the norm during a long-duration power interruption (e.g., curtailment of normal daily routine, emergency needs, etc.)
- EVs are also a potentially large source of energy storage (see figure), as well as potentially a form of “transmission” if nearby public charging stations have power
- Our results suggest that bi-directional EVs could be important, if not essential, to enabling PVESS backup power of heating/cooling loads in a number of conditions:
  - Customers with heat pumps in cold-weather locations (though stationary storage may suffice in many cases)
  - Extreme cold weather events/locations and particularly long-duration interruptions (beyond 3 days)
  - Especially high-consumption households, even after efficiency measures have been implemented

EVs Battery Size and Market Share
(Top 90% of U.S. EV Sales in 2022)



Battery sizes are given as a range, if different model options are available. Data sources: https://ev-database.org/ and Kelly Blue Book EV Sales Report.

Conclusions

High-Level Summary

- Required battery sizing for PVESS backup power varies considerably across individual homes, and depends highly on the timing and duration of the interruption, and on the set of loads backed up
- Load flexibility (in the form of thermostat set-point adjustments) and building envelope efficiency upgrades reduce required storage sizing, especially for homes and regions with large cooling or electric heating loads
- The impact of heat pump retrofits on required battery sizing is complicated and varies:
  - In hot climates, efficient heat pumps can significantly reduce storage sizing by replacing inefficient A/C units
  - In cold climates, heat pumps significantly reduce storage sizing if replacing electric-resistance heat, but can significantly increase storage requirements if replacing fossil heat (albeit mitigated to some degree by efficiency and load flexibility measures)
  - Heat pump configuration also matters, particularly the source of backup heat (fossil vs. electric-resistance)
- Other forms of building electrification (e.g., cooking and water heating) generally have marginal impacts on backup battery sizing given their small energy demand

Conclusions

- Results demonstrate the value of pairing building efficiency upgrades, smart home controls, and (in mild winter climates) heat pump retrofits with PVESS in backup power applications; value comes in the form of reducing the amount of storage required and/or extending the range of interruption conditions over which a given system can provide backup power (i.e., more extreme weather and/or longer interruptions)
- Heat pumps in cold-weather climates can pose a challenge for PVESS backup power given the amount of storage required, though are a vast improvement over electric-resistance heating; retaining existing fossil-based heating systems for occasional use during power interruptions (as either the primary or supplementary source of heat) can mitigate this challenge
- Bi-directional EVs may be key to enabling PVESS backup power in certain circumstances—including cold-weather homes with heat pumps, and more generally for providing resilience against extreme weather and/or especially long-duration (>3 day) power interruptions

Areas for Further Research

- Evaluation of PVESS backup power performance for typical short-duration, but unpredictable, power interruptions (planned for 2024)
- Backup of home medical equipment and/or single-room space conditioning
- Socio-economic dimensions (e.g., value and capabilities of PVESS backup power for low-income and vulnerable populations)
- Economic evaluations (e.g., comparing PVESS costs to customer value of lost load, diesel generators, and/or conventional grid hardening measures)
- Empirical validation of how customers use PVESS for backup power, and how systems have actually performed
- Comparative analysis of PVESS backup capabilities in neighborhood/microgrid configurations
- Impacts of climate change on PVESS backup performance and value
- Potential value of over-sizing PV systems and/or adding PV to stand-alone storage to enhance backup power capabilities

Appendix

Appendix Contents

- Distribution of heating technology types in the baseline building stock
- Further details on heat pump modeling and representation
- PV system sizing and roof area constraints
- Seasonal distribution in the timing of interruption events
- Impact of battery power constraints on required battery sizing
- Supplementary sensitivity results for interruption duration
- Alternate load flexibility measure: pre-cooling/pre-heating with curtailed PV
- Alternate measure sequence: Impact of set-point adjustment if implemented after heat pump retrofit
- Alternate measure sequence: Impact of building envelope measures if implemented after heat pump
- Waterfall chart for all regions
- Comparison of TMY results to results using actual meteorological year (AMY) data from 2011-2021
- Additional details on AMY results showing distribution in interruption event years
- Sensitivity to heat pump configuration for all locations
- Sensitivity to heat pump efficiency

Heating Fuel Breakdown in Baseline Building Stock

Location	Electric Resistance	Heat Pump	Fossil	Other or None
Boston	3%	0%	96%	1%
DC	16%	11%	73%	0%
Denver	12%	3%	84%	2%
DFW	36%	18%	46%	0%
Duluth	11%	1%	83%	5%
LA	12%	1%	86%	0%
Memphis	22%	11%	67%	0%
Phoenix	41%	26%	33%	0%
Seattle	20%	5%	74%	1%
Tampa	57%	35%	8%	0%

Note: Percentages may not sum to 100% due to rounding

Heat Pump Modeling Details

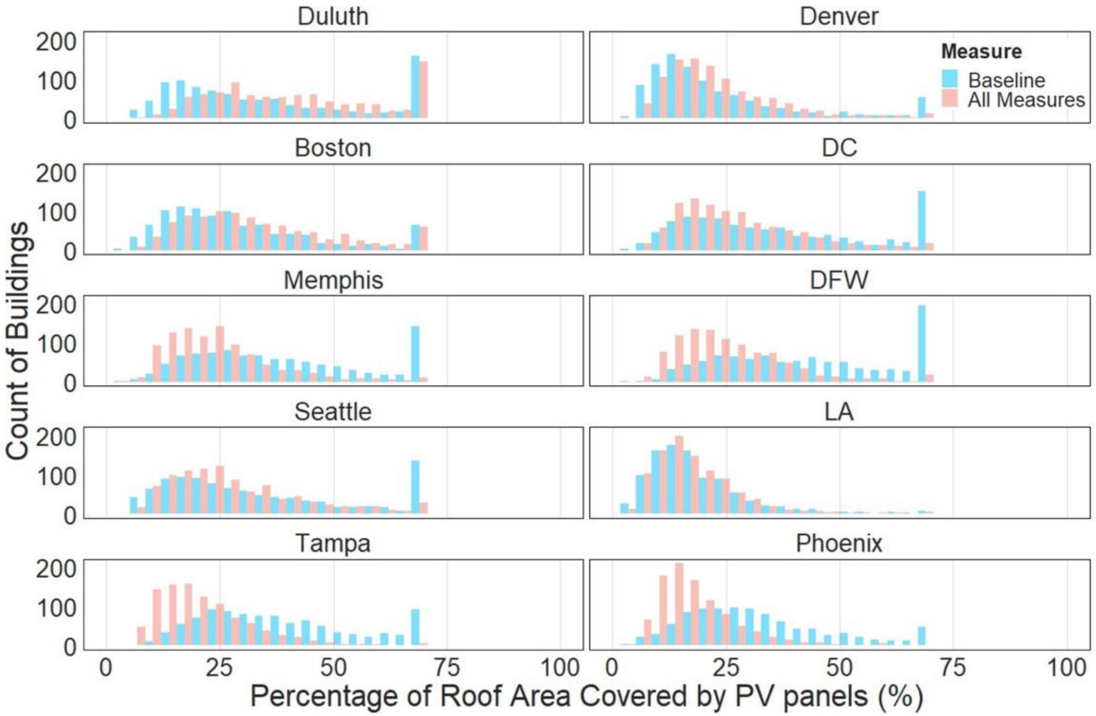
- Homes in our sample are either ducted, with a centralized system, or ductless. This distinction has implications for heat pump efficiency and our approach to simulating fossil backup.
- Efficiency Scenarios
  - Low efficiency: ≤ SEER 15, 9 HSPF (ducted and ductless homes)
  - High efficiency: SEER 24, 14 HSPF (ducted homes); SEER 29.3, 14 HSPF (ductless homes)
- To simulate a fossil backup heat pump system, we either drop all electric backup consumption (ductless homes) or reduce backup heating electric consumption to furnace fan demand (ducted homes). This represents an idealized control scheme that assumes the fossil backup system would have similar operational timing to an electric resistance backup system.
- We size heat pumps either to meet the annual max-cooling load via ACCA Manual S/J standard (which allows oversizing in some conditions) or to meet the overall max-load of the home
  - In mild winter locations, this has no impact, a both conventions yield the same size
  - Cold weather locations have significant heating needs, leading to large heat pump sizes in the max-load scenario
  - Even in max-load scenarios, back-up heat from either a fossil or electric resistance device is needed, though its usage is significantly lower than compared with the max-cooling scenario

PV System Sizing and Roof Area Constraints

- PV system sized to meet each customer’s annual consumption, subject to available roof area
- Simplified roof constraint imposed by assuming that only 70% of total roof area available for PV
  - In reality, this percentage may be smaller for some homes due to shading, poor roof-plane orientations, obstructions, etc. (though those homes are also less likely to install PV)
- As shown in the figure, the roof area constraint rarely binds (10-15% of homes for some locations, in the baseline, and typically much less often once measures are applied to the baseline)
- Though there is a wide distribution, the majority of the modeled PV systems take up less than half of the total roof area

PV Sizing Distributions

(Percent of roof area covered)

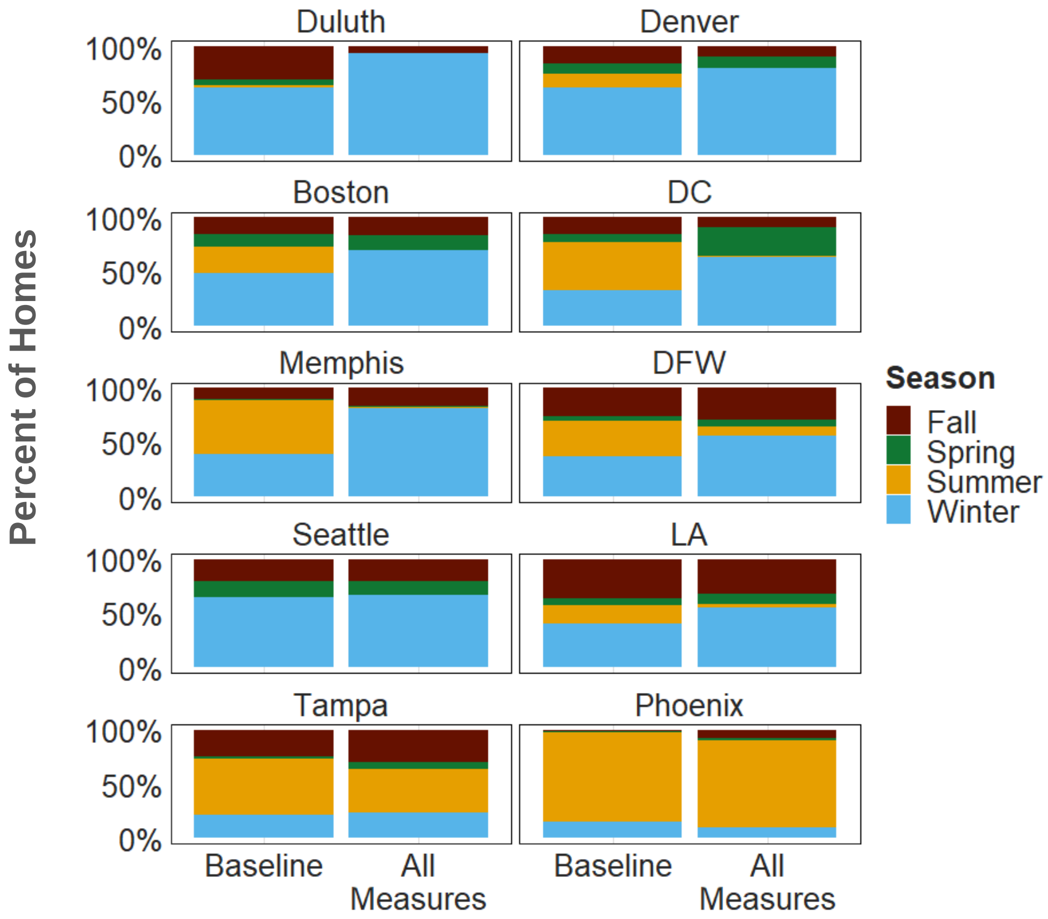


The two distributions shown here correspond to the PV sizes for the baseline building stock and for the scenario with all measures (load flexibility, building envelope efficiency, heat pump, and other electrification) applied to the Baseline building stock.

Seasonal Distribution in the Timing of Interruption Events

- ☐ Throughout most of the analysis, interruption events begin on the 90th percentile net-load day
- ☐ As such, interruptions tend to occur during winter months in cold regions and during summer months in hot regions, though variation exists across homes
- ☐ Some of that variation reflects differences in heating type (e.g., winter peaking homes in Memphis and DFW likely have electric resistance heating)
- ☐ Heat pump retrofits (included in All Measures) shift peak loads from cooling to heating months in most regions (esp. pronounced for DC, Memphis, DFW)
- ☐ Phoenix and Tampa are the only areas where peaks continue to be driven by cooling loads, even after heat pump retrofits

Seasonal Distribution in 90th Percentile Net-Load Day Across Homes in Each Location

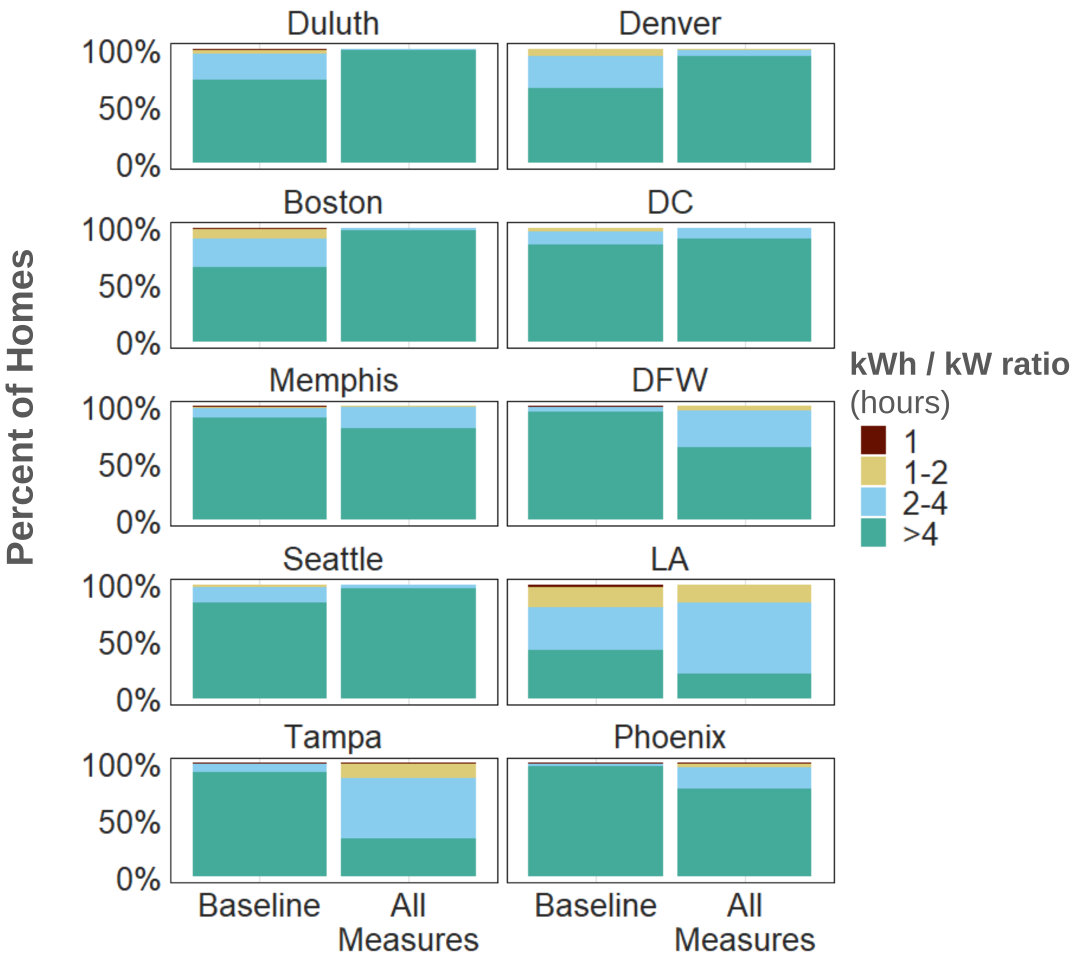


Implied Battery Power Requirements

- Battery dispatch model constrains the max kW discharge/charge to the kWh energy storage capacity (effectively assuming a 1-hour duration battery)
- The figure shows the distribution in required storage duration across all simulated homes and locations
- As shown, the kW constraint rarely binds (i.e., a negligible share of systems with 1-hour duration)
- Most systems have ratio >4 hours, suggesting that energy needs dominate the battery sizing decision for backup power
- Results indicate that typical 2-hour duration residential batteries on the market today would have sufficient power capabilities (kW), given the required amount energy storage (kWh) found in our analysis

Distribution in required storage duration

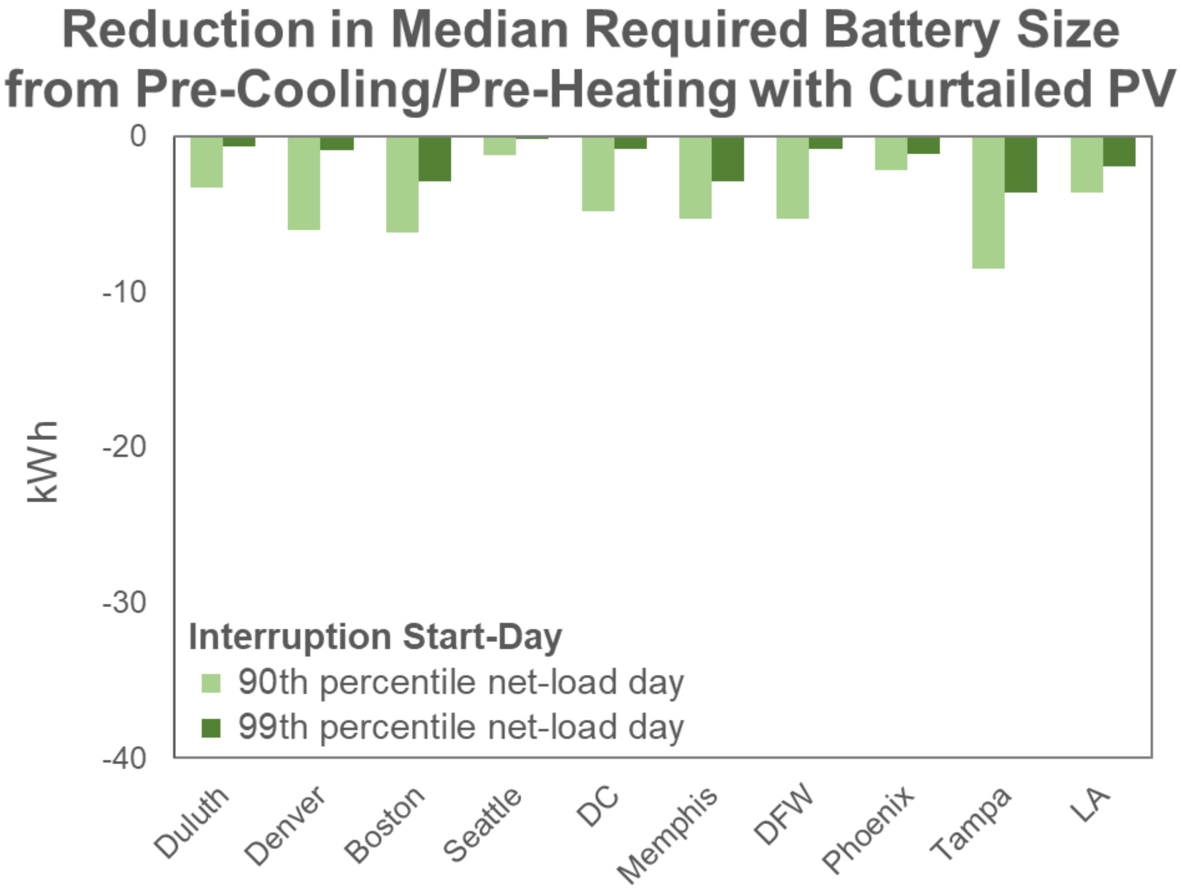
(kWh capacity / max. kW charge or discharge)



Impact on Battery Sizing from Pre-Cooling/Pre-Heating with Curtailed PV (an idealized upper bound)

- We bound the potential impact on battery sizing by considering a case where curtailed PV is fully utilized for pre-cooling/pre-heating with no thermal losses (i.e., simplified and optimistic)*
- Impacts are generally small due to limited quantity of curtailment PV, which in turn is due to large batteries and constraints on PV sizing
- Reduces median required battery sizes by 1-8 kWh across locations for interruptions on the 90th percentile net load day (vs. 1-25 kWh from thermostat set-point adjustments)
- Impacts are even smaller under more extreme weather conditions, due to higher loads and less curtailed PV available

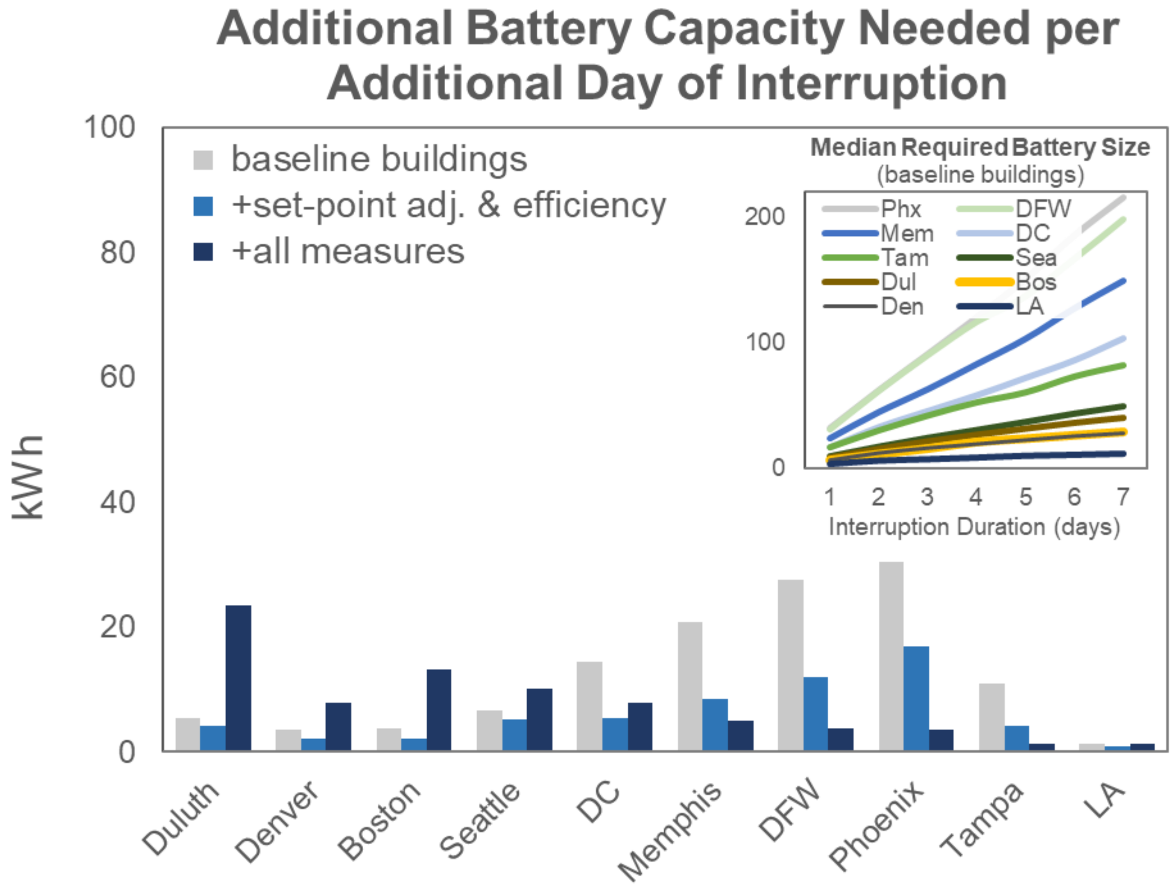
* *To develop a more precise estimate would have required a fundamentally different modeling framework than used in this study*


Reduction in Median Required Battery Size from Pre-Cooling/Pre-Heating with Curtailed PV

Values represent reductions from the baseline building stock. No other measures are assumed beyond the use of curtailed PV for pre-cooling/pre-heating. The representation of pre-cooling/pre-heating is highly simplified and over-states the likely impact.

Sensitivity to Interruption Event Duration (Supplementary)

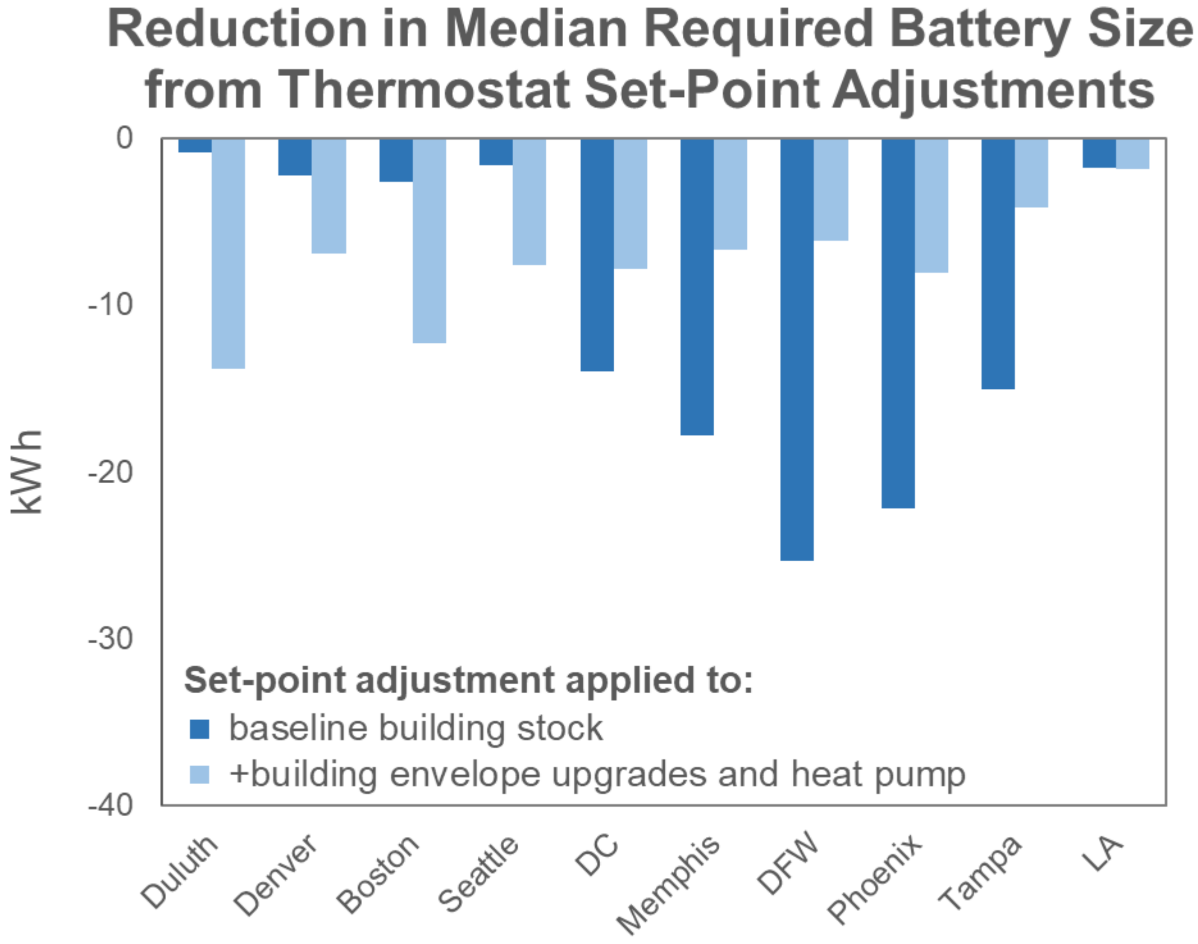
- Required battery sizing scales more-or-less linearly with interruption duration (see insert), as daily PV generation typically is not enough to fully replenish the battery, so initial SoC gets drawn down over the course of the event
- Amount of additional battery capacity needed for each additional day of interruption ranges from 1-31 kWh/day in the baseline stock
- Efficiency, load flexibility, and (in mild winter climates) heat pumps reduce that sensitivity
- In cold locations, electrifying space heating tends to have the opposite effect, increasing sensitivity to interruption duration



Values plotted are calculated from the median required battery sizes for interruptions ranging from 1-7 days in each location. The "+all measures" case includes set-point adjustments, building envelope upgrades, and all electrification measures, including heat pumps.

Alternate Measure Sequencing: Impact of set-point adj. if implemented *after* envelope efficiency and heat pump measures

- Earlier results show how set-point adjustments applied to the baseline building stock have limited impact on battery sizing in cold-weather regions with predominantly fossil heating (Duluth, Denver, Boston, Seattle)
- Set-point adjustments become more impactful in those locations once heat pumps are installed: i.e., 8-14 kWh reduction in median battery size, compared to 1-3 kWh when applied to the baseline building stock
- In contrast, in hot-weather locations, impact of set-point adjustments are considerably lower (though still meaningful) once heat pump and building envelope measures are installed: 4-8 kWh reduction in battery sizing vs. 14-25 kWh

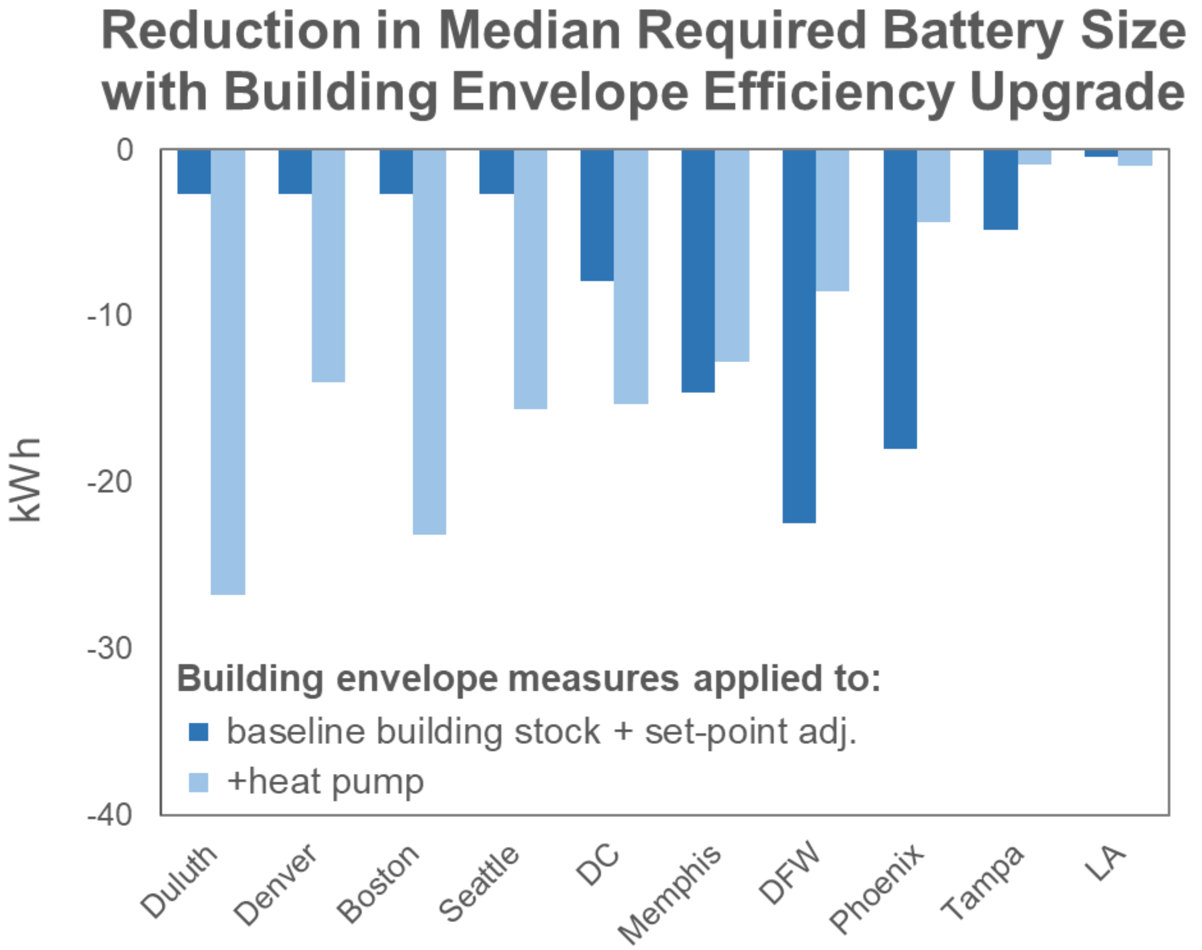


Heat pump measure assumes all homes retrofitted with high-efficiency heat-pump, sized to maximum load, with fossil backup heat.

Alternate Measure Sequencing: Incremental impact of envelope upgrades if implemented *after* heat pump retrofit

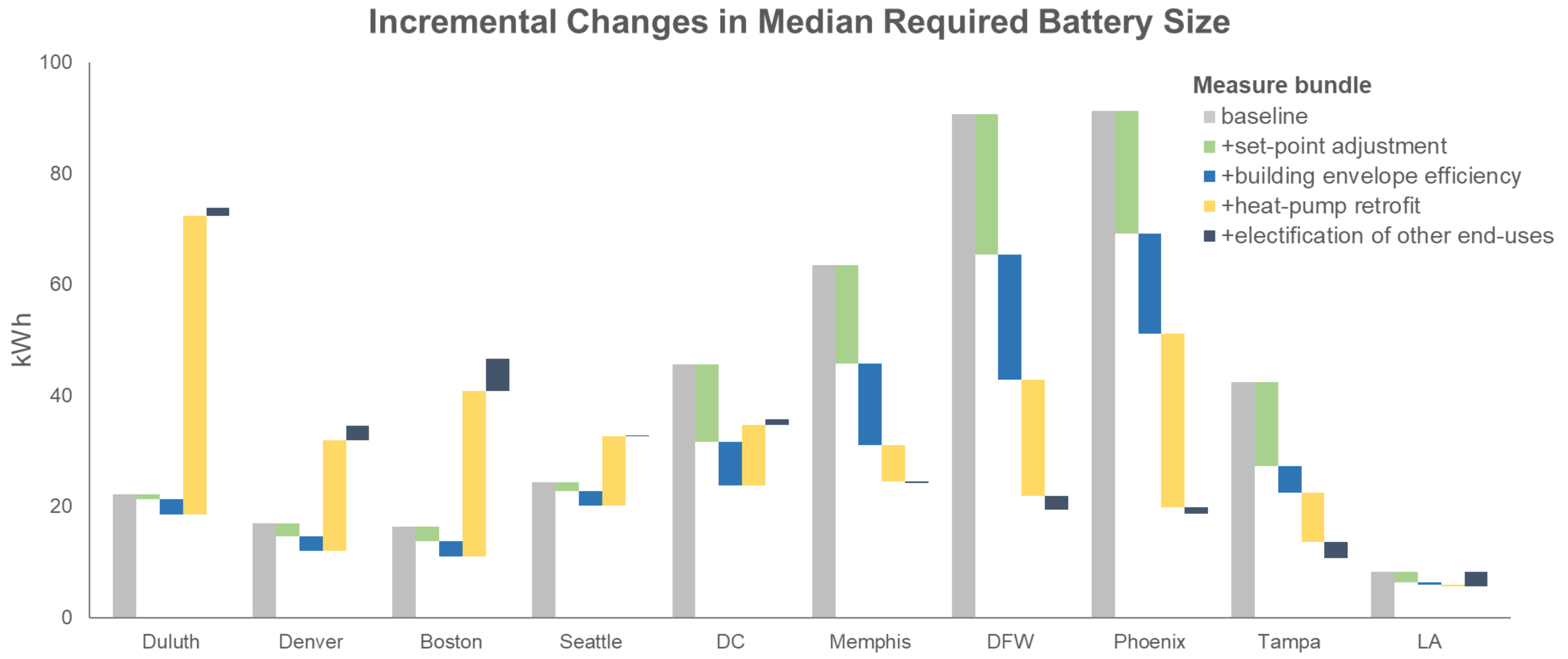
A similar story as on the previous slide, but even more pronounced:

- Earlier results show how envelope efficiency upgrades have limited impact on battery sizing for homes in cold-weather regions with predominantly fossil heating
- Impacts of envelope upgrades are significantly larger in those regions once heat pump retrofits are installed: i.e., 14-27 kWh reduction in median battery sizing vs. 3 kWh for baseline heating tech.
- The opposite is generally true in warmer locations where heat pumps often replace inefficient A/C and electric-resistance heating



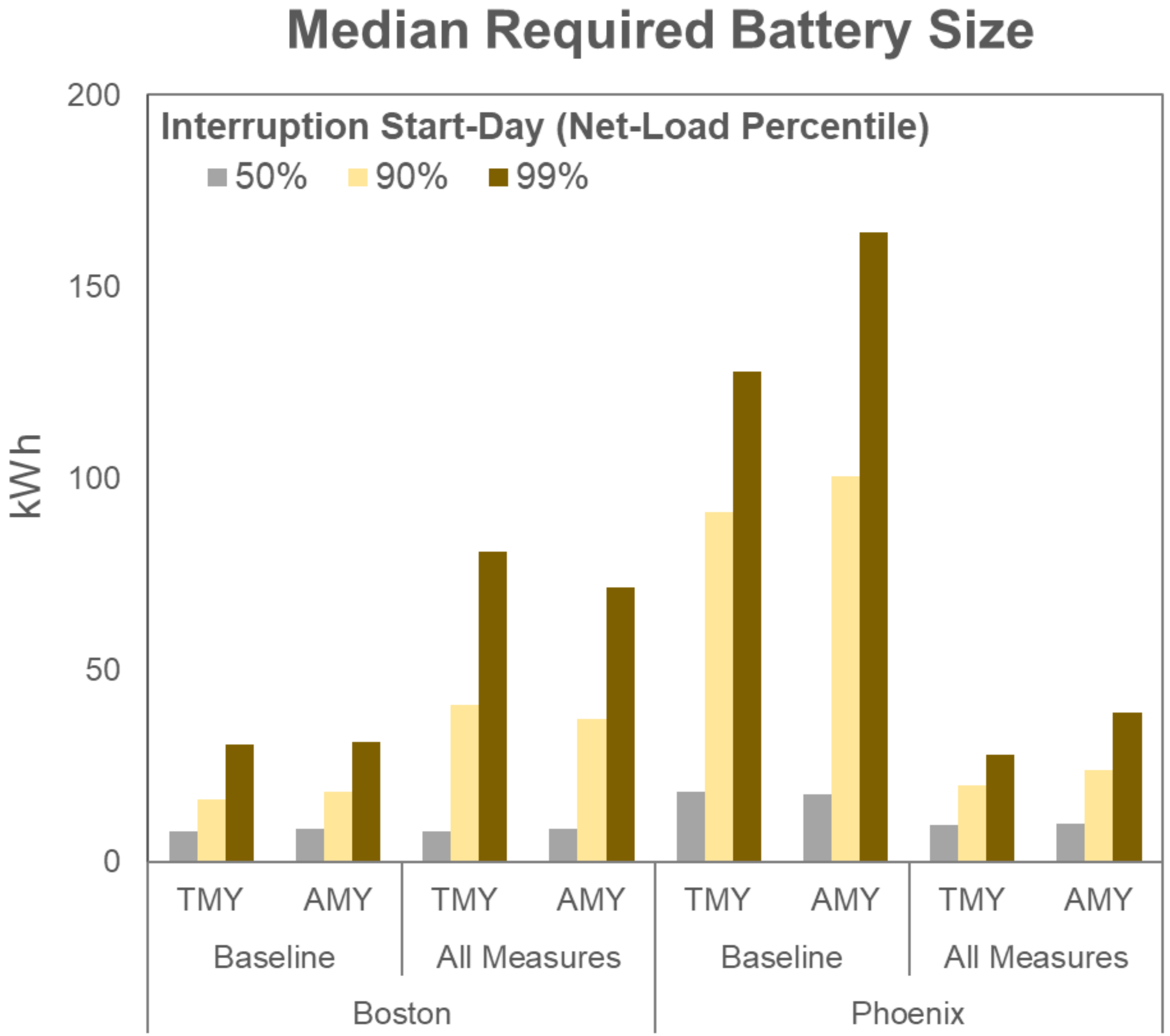
Heat pump measure assumes all homes retrofitted with high-efficiency heat-pump, sized to maximum load, with fossil backup heat.

Incremental Changes in Battery Sizing as Measure Bundles Are Sequentially Added: All Locations



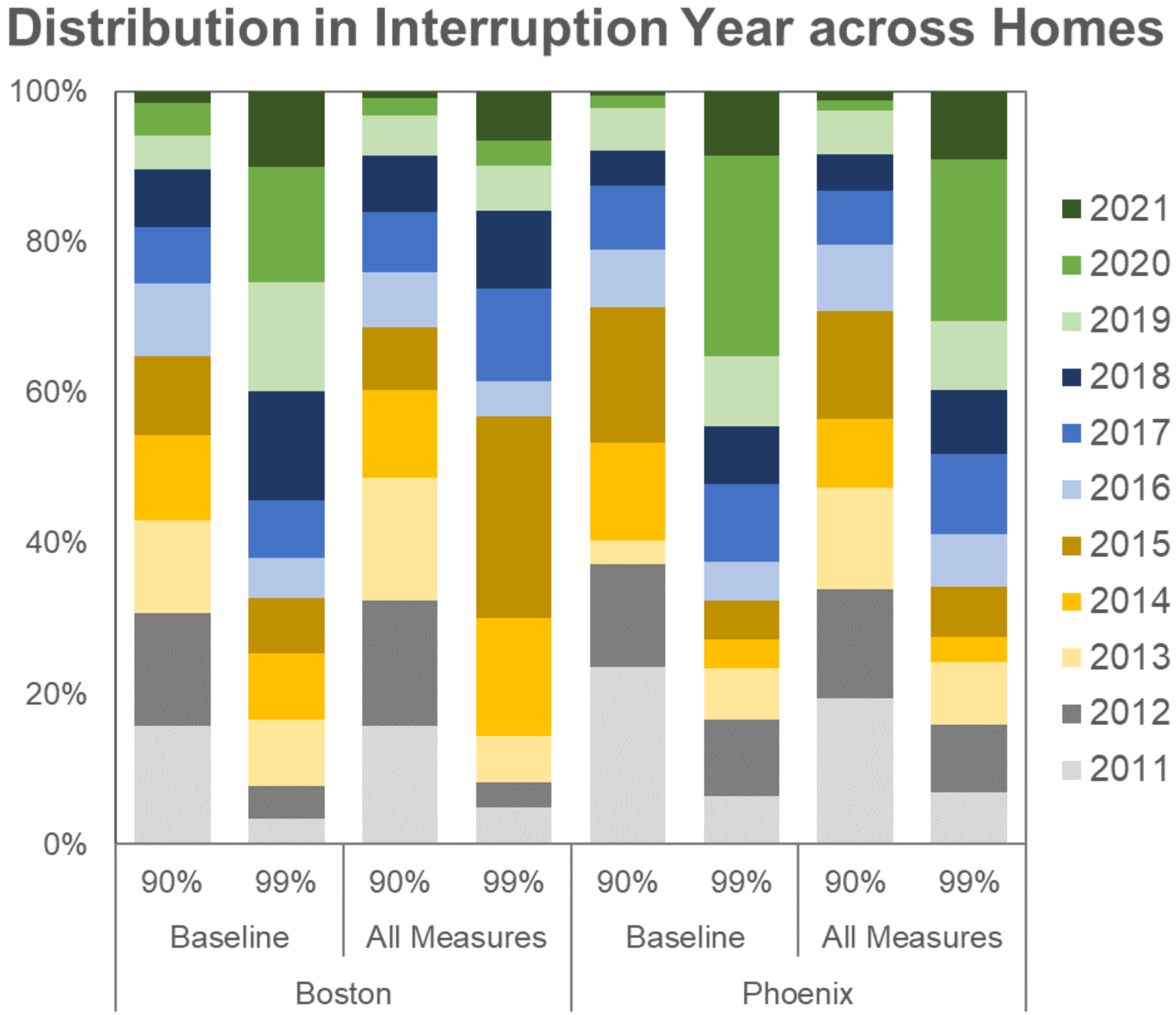
Comparison of Results using Actual Meteorological Year Weather Data from 2011-2021

- For Boston and Phoenix, we replicated our analysis using actual meteorological year (AMY) data from 2011-2021, to assess if TMY data understates the impact of extreme weather
- The results for Phoenix do, indeed, show larger required battery sizes when using AMY data, for interruptions starting on either the 90th or 99th percentile net-load day (no difference for 50th)
- Results for the Boston-All Measures case show the opposite trend (TMY sizing > AMY sizing)
- On balance, results illustrate the potential importance of using actual historical weather data for PVESS backup power sizing, though changing climate poses a challenge in any case

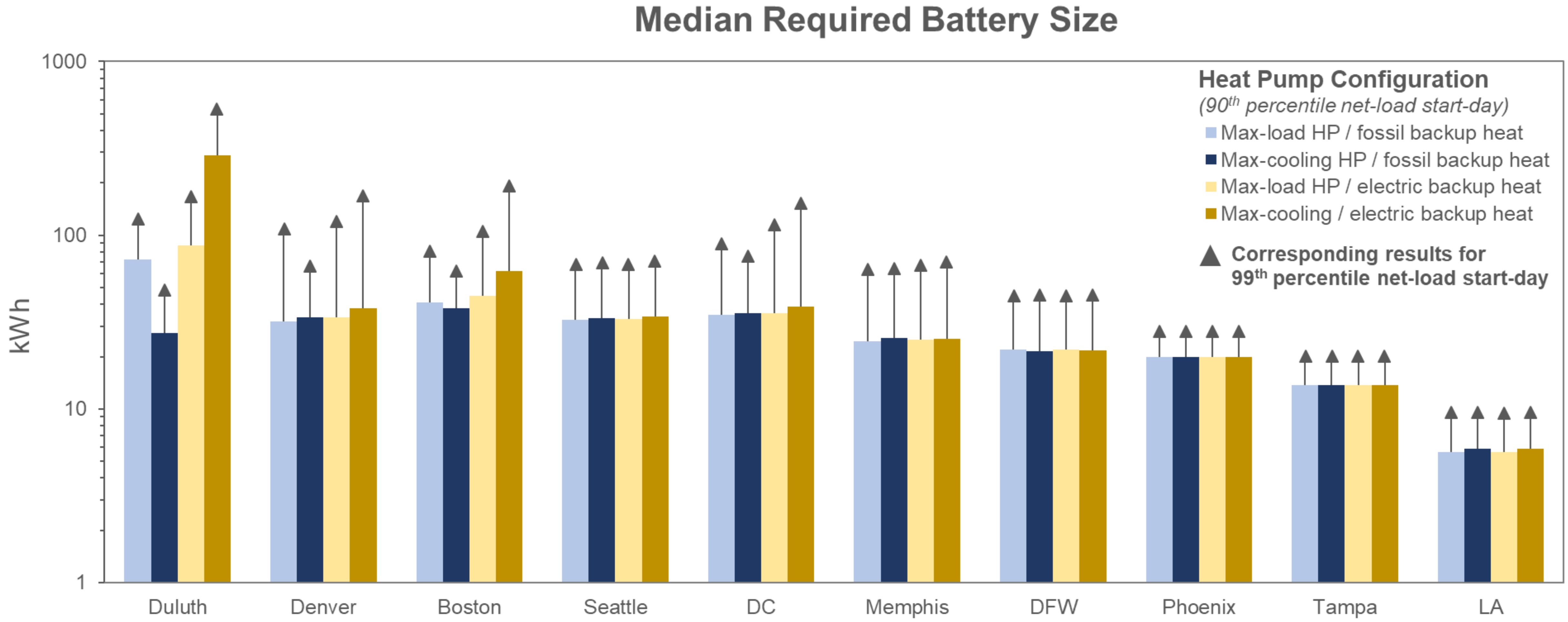


Interruption Year in AMY Analysis

- AMY analysis selected interruption start-day based on the net-load percentile over the entire 11-year historical weather period
- In general, the interruption event year varies greatly across homes (i.e., no single year dominates the results), even for the 99th percentile net-load case



Sensitivity to Heat Pump Configuration: All Locations

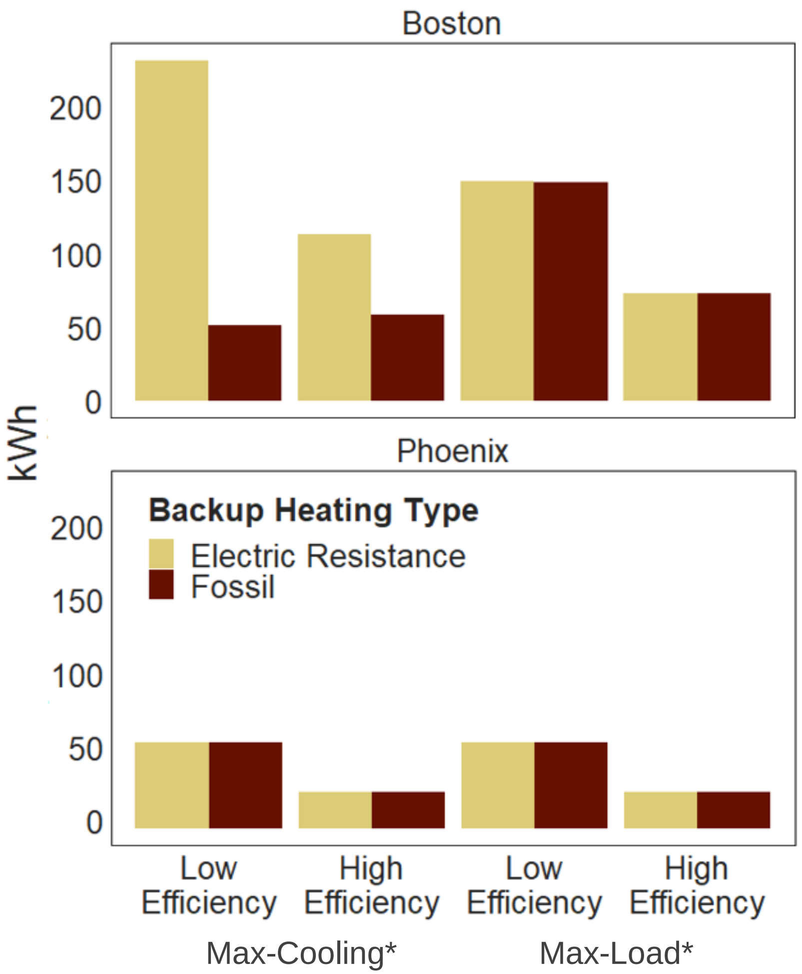


Max-load HP is based on sizing to maximum load, as generally assumed throughout the analysis, while Max-cooling HP is based on sizing to maximum cooling load (ACCA Manual S/J standard). For cooling-dominated regions, these two sizing conventions are equivalent. All results include temperate set-point adjustments and building envelope efficiency upgrades.

Sensitivity of Battery Sizing to Heat Pump Efficiency

- In cold-weather regions, heat pump efficiency can strongly impact required battery sizing in the cases of:
    - Large (e.g., max-load) heat pumps that serve all/most heating demand
    - Small heat pumps (e.g., max-cooling) with electric-resistance backup heat, where higher efficiency HPs reduce run-time of backup heating
- In hot-weather regions, impact of heat pump efficiency on battery sizing is akin to the effects air-conditioning efficiency; larger impacts the greater the cooling demand

Median Required Battery Size



*Heat pump sizing in Phoenix is the same for max-cooling and max-load

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