Characterizing Electrical Panel Constraints of Residential Energy Retrofit Deployment at Scale

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ABSTRACT

Adding new electric appliances to a home can overload an existing electrical panel or exhaust its available breaker spaces. These constraints sometimes necessitate a costly panel or service entrance upgrade, but lower cost alternatives, such as low-power appliances and load control devices, can resolve the issue without full replacement. Understanding how often panel constraints arise improves cost estimation and planning for individual home improvement projects and helps utilities and program planners assess how panel constraints and the mitigation measures that address them affect grid and distribution capacity at scale. This study presents recent modeling capabilities in ResStock™ that characterize electrical panels across the U.S. housing stock and quantify panel constraints resulting from residential retrofits deployed at scale, including cold climate heat pumps and heat pump water heaters. By explicitly representing panel configurations and load calculations within ResStock, this work enables more accurate bottom-up estimates of upgrade costs and constraint frequency under a range of energy retrofit scenarios. The findings support scenario building for both homeowners and program planners, providing a foundational dataset for evaluating cost-saving pathways, informing mitigation strategies, and advancing energy affordability and consumer choice across the building and power sectors.

Introduction

Adding new electric appliances to a home often requires new branch circuits, which can overload the electrical panel or exhaust its available breaker space, leading to electrical panel constraints. The electrical panel, sometimes called a breaker box, regulates and distributes power across branch circuits that serve major appliances, lighting, and wall outlets. The service entrance, which carries power from the utility pole to the panel, can also become capacity constrained. Upgrading these electrical components can be costly and time-consuming, and together with their upstream effects on the distribution grid, they represent important considerations in home electrification and energy planning. Understanding how frequently electrical panel constraints occur and under what conditions can support electrification planning at multiple levels. At the customer level, frequency data can inform whether lower-cost mitigation measures, such as load control devices or low power appliances, are viable alternatives to full panel or service entrance replacement. At the utility and program level, this data can be incorporated into building stock models, such as ResStock™, to estimate how panel constraints may arise across the housing stock from widespread electrification to impact the grid and distribution capacity and evaluate the effectiveness of mitigation measures.

Existing research on residential panel constraints is limited by scarce panel data. National-scale studies have relied on surveys of a few hundred to a few thousand homes (Pecan St 2021; EPRI 2022; Meier and Gul 2024; Gul and Meier 2025), which often lack the equipment detail needed to correlate panel ratings with NEC load calculations. The National Electrical Code (NEC/NFPA 70) is the primary U.S. standard for safe electrical design and installation and provides guidance for sizing service and feeder loads. Detailed modeling has been confined to regional studies, such as Fournier et al. (2024), who used Los Angeles housing records to estimate the NEC version in effect when each panel was installed or when each home was renovated. To bridge these gaps, several studies have applied machine learning to extrapolate survey findings to broader housing stock datasets (Pecan St 2021; EPRI 2023; Quinn, Molar-Cruz, and Lindsey 2024). Murphy et al. (2025) extended this approach by applying trained models to detailed ResStock™ metadata to predict panel capacity and breaker space nationwide. In a study comparing Fournier et al. and Murphy et al.'s approaches (Less et al. 2024), both showed a similar distribution of electrical panel sizes for single-family housing stock in California.

This paper presents new panel constraint modeling built into ResStock, a U.S. housing stock model, drawing on Murphy et al. (2025) and related work between the National Laboratory of the Rockies (NLR) and Lawrence Berkeley National Laboratory (LBL). Rather than extrapolating from a few detailed models, ResStock performs bottom-up NEC load calculations across approximately half a million representative dwelling models. This study characterizes existing panels for both single- and multi-family housing across the U.S. and models constraints resulting from upgrade measures including cold climate heat pumps and heat pump water heaters, with the full dataset available on the Open Energy Data Initiative (OEDI). It also demonstrates use cases for scenario planning to help homeowners and program planners account for electrical upgrade costs and mitigation strategies.

Method

To characterize the range of electrical upgrade requirements associated with energy retrofit measures, we combined three components: ResStock, a national building stock modeling platform (Subsection 1); electrical panel characterization (Subsection 2); and code-based load calculations (Subsections 3 and 4). Together, these enable bottom-up modeling of electrical panel capacity and breaker space constraints. A capacity constraint occurs when calculated connected loads exceed the panel's service rating, requiring upsizing or mitigation. A space constraint occurs when the panel lacks sufficient breaker slots for new circuits.

The panel constraint modeling framework was developed in partnership with LBL under a 2023 U.S. Department of Energy project on affordable residential electrification that avoids electrical panel upgrades (Jin and Walker 2023). The capability led to panel metrics—both component loads and constraints using the load-based method—being published for the first time in 2025 in ResStock's dataset release.

1. Building Stock Modeling

ResStock is a U.S. national residential building stock model that uses statistical sampling to generate hundreds of thousands of synthetic housing models from housing characteristic distributions, with each model representing approximately 250 dwelling units across all 50 states

(Reyna et al. 2025). Drawing from the most recent census and housing survey data—including the Residential Energy Consumption Survey (RECS), the American Community Survey (ACS), and the Amercian Housing Survey (AHS)—these distributions capture detailed building parameters such as location, building type, floor area, vintage, envelope, and equipment, along with correlated demographic variables including household income and owner/renter status. Building parameters are then modified to simulate upgrade measures such as air sealing and heat pump water heaters. Using high-performance computing, models are simulated for a given weather year to produce realistic subhourly end-use time series, which are aggregated and analyzed for energy-related impacts including utility bills and peak load reduction.

Since 2021, ResStock has released annual open-access, national-scale datasets on OEDI to support energy planning and policy analysis at local, state, and federal levels. This study draws on seven electrification measures from the ResStock 2025 Release 1 dataset (Parker et al. 2025), which uses actual meteorological year (AMY) 2018 weather data. The remaining measures – envelope only improvement only, gas appliance upgrades, and like-for-like replacements – do not introduce new electrical loads and are therefore excluded.

Details of the energy measures evaluated are described in Table 1. The technical details column describes each upgrade's efficiency and performance ratings. The application column defines which housing segments are eligible — for example, ducted heat pumps apply only to homes with existing ducts, as non-ducted homes are more likely to upgrade to ductless systems. Measure applicability (the fraction of homes upgraded by each measure) is shown in **Error! Reference source not found.**.

Table 1. Energy measure description

Measure Name	Technical Specs	Application Criteria
Cold climate ducted air-source heat pump (ASHP)	**ASHP**: Variable-speed, Heating Season Performance Factor (HSPF2) 8.5, Seasonal Energy Efficiency Ratio (SEER2) 17.5, Coefficient of Performance (COP): 3.37 at 47°F, 1.98 at 5°F, HCR (Heating Capacity Ratio) 0.67, -15°F lockout, sized to max of heating or cooling load accounting reduced capacity at design temperature **Backup**: integrated electric resistance, sized to full heating design load	Ducted HVAC systems, multi-family units must have individual central AC or heat pump (HP) to ensure room for outdoor unit
Dual-speed geothermal HP	Two-speed compressor, variable-speed air handler, water-to-air, COP 4.0, Energy Efficiency Ratio (EER) 20.5, has vertical ground heat exchanger	Ducted HVAC systems, low-rise buildings (<8 stories) must have ground thermal conductivity > 0.8
Dual-speed geothermal HP with improved envelope	**GHP:** same as above **Air sealing:** 5 ACH50 **Attic insulation:** 2021 IECC prescription (R-49 for IECC climate zone 1 and R-60 elsewhere)	Applies to GHP target homes with poor baseline insulation/sealing

	Ducts: sealing to 5% leakage to outside, insulating to R-8	
Ducted ASHP with natural gas furnace backup	**ASHP:** single-stage, HSPF2 7.8, SEER2 15.2, HCR 0.50, 35°F lockout, sized to cooling load with some oversizing allowed for larger heating load per ACCA Manual J/S **Furnace:** 92% AFUE if in IECC climate zones 1-4 and 95% AFUE elsewhere	Ducted, non-shared HVAC systems with active natural gas access
Electric vehicle (EV) with level 1 charger	Typical EV, 120V slow charging, 1650W	Occupied units without level 1 charging
EV with level 2 charger	Typical EV, 240V fast charging, 7680W	Occupied units without level 2 charging
Heat pump water heater	240V, UEF ≥3.3, ≥45 gal/h first hour rating, efficiency varies slightly by tank volume	Units without existing solar thermal or HP water heaters

2. Electrical Panel Characterization

To measure constraint, we first characterized preexisting electrical panels across the housing stock in terms of service rating and breaker space headroom. Panel data is limited nationally, with surveys covering only hundreds to thousands of samples (Quinn, Molar-Cruz, and Lindsey, 2024; Meier and Gul 2024; Gul and Meier 2025), regional data concentrated in the Pacific Northwest (Murphy et al. 202l6), and some data not publicly accessible. To partly overcome these gaps, we applied machine learning models to survey data, generalizing trends from the Pacific Northwest while controlling for the overrepresentation of gas heating through direct segmentation. As documented in Murphy et al. (2026), this approach was used for single-family attached and detached dwellings. For multi-family buildings, panel attribute distributions were derived directly from the data due to insufficient samples for model training. For mobile homes, which lacked high-fidelity samples, we approximated distributions using single-family detached values.

Figure 1 and Figure 2 show how modeled panel service ratings are distributed across census regions and segments of building types and floor area bins, respectively. Nearly half of U.S. homes have 200A service panels or larger. The highest concentration of high-capacity panels is in the South, where air conditioning is widespread and all electric homes are more common, a pattern consistent with existing survey data (EPRI 2022; Meier and Gul 2024; Gul and Meier 2025). In the Midwest and Northeast, reliance on fuel-based heating reduces electrical demand, resulting in lower panel ratings overall. As shown in Figure 2, panel rating also tends to rise with floor area, largely because larger homes require bigger HVAC systems, along with more lighting and general receptacle loads. Single-family homes – including single-family detached homes, single-family attached homes, and mobile homes – tend to have higher panel ratings than multi-family homes – including high-rises, low-rises, and duplexes in stacked configurations – and have a stronger correlation to floor area, because they are more likely to have dedicated appliances—such as HVAC, laundry, EV chargers, and pools—that are typically shared or absent in multi-family buildings. Although not shown, newer homes tend to have higher electrical panel ratings, reflecting their larger size and greater ownership of electric space heating and cooling according to 2020 RECS.

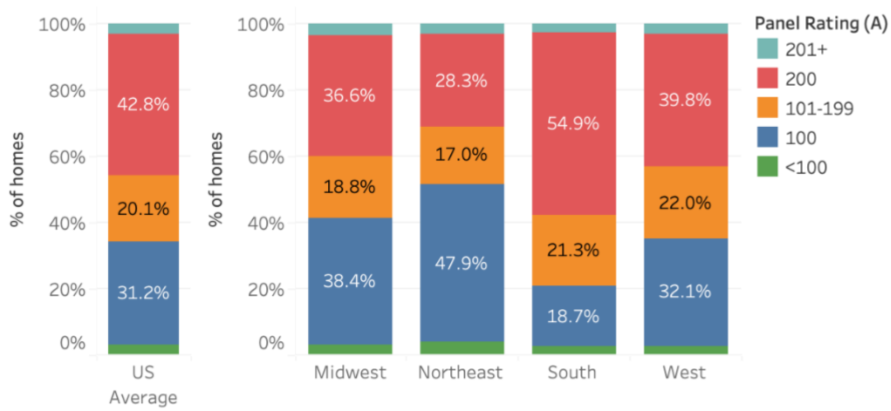

Figure 1. Distribution of modeled panel service rating by census region.

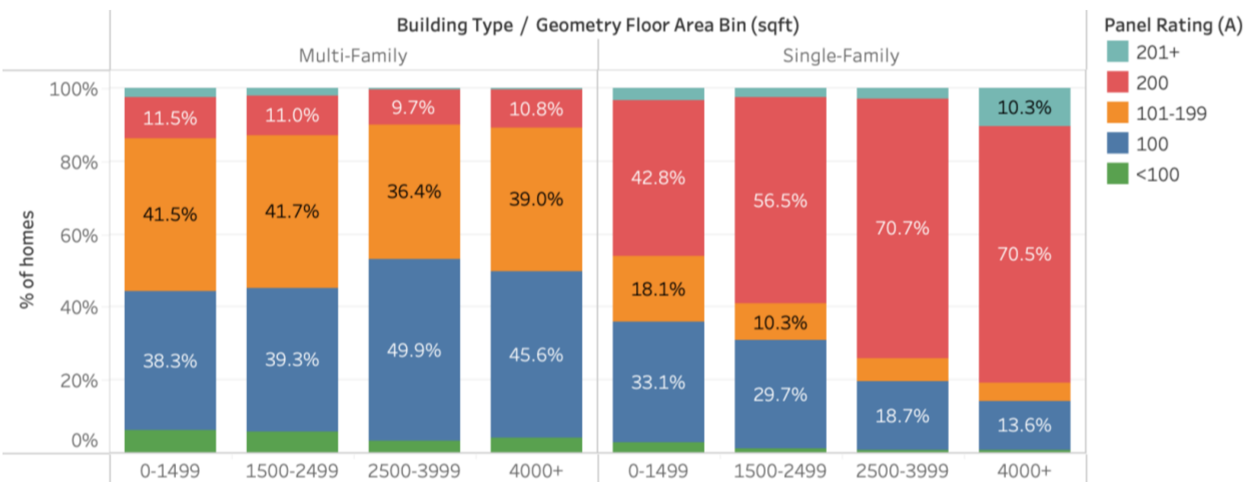

Figure 2. Distribution of modeled panel service rating by building type and floor area.

Figure 3 shows how modeled available breaker slot count is distributed across panel service ratings and building types. Overall, multi-family units have fewer open breaker slots than single-family homes as multi-family units tend to have lower power demand and a smaller footprint, making breaker space a premium. 35% of multi-family units do not have any breaker space available for a new circuit compared to 22% of single-family homes. The median multi-family unit has two open spaces compared to three for the median single-family.

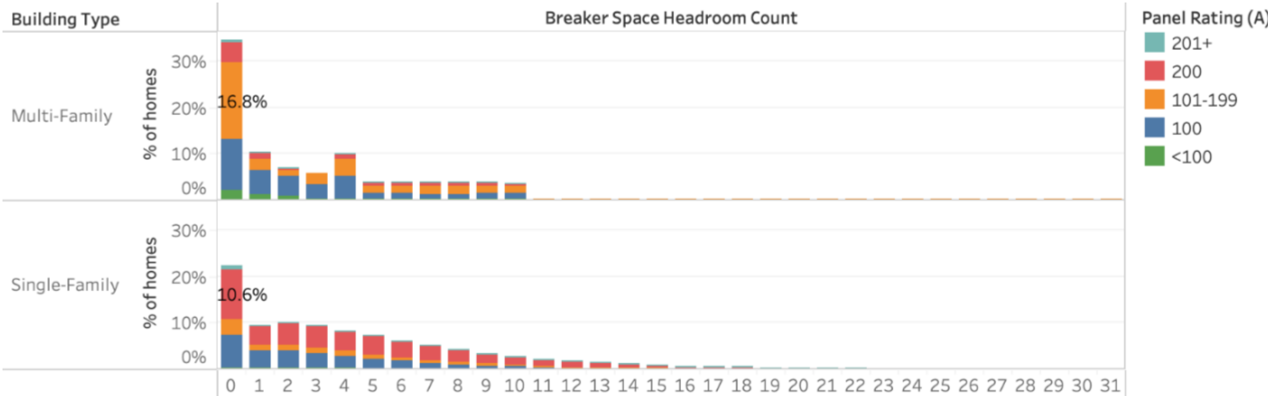

Figure 3. Distribution of modeled available breaker space count by panel service rating and building type.

3. Capacity and Load Calculation

To assess whether an existing panel can accommodate new loads, we performed two feeder load calculations according to 2023 NEC—load-based (i.e., standard method of NEC 220.83) and meter-based (i.e., optional method of NEC 220.87)—using housing metadata for each model. In both methods, a "load" refers to equipment power demand at full-load (steady-state) conditions, not the short-duration peak that occurs during startup. While the nameplate power rating of most equipment was looked up, we developed regression models relating power to design capacity for space heating and cooling systems. This was necessary because HVAC systems vary significantly in size, and ResStock does not model them in standard discrete increments. Further details are provided in Reyna et al. (2025), including power assumptions for HVAC and other modeled equipment in ResStock.

The load-based method (NEC Section 220.83) sums the loads of major appliances and required lighting and receptacle circuits using demand factors that estimate how much of the total load operates simultaneously. This calculation is performed after accounting for any new equipment added and old equipment removed. Table 2 details the specifics and provides a sample calculation.

Table 2. Load-based calculation

Type	2023 NEC 220.83	Sample Calculation
General lighting/ receptables	3 VA/sqft	• Floor area: 1,228 sqft Load: 3,684 VA
Kitchen circuits	Min. two branches at 1.5 kVA each	• Branches: 2 Load: 3,000 VA
Laundry circuits	Min. one branch at 1.5 kVA	• Branches: 1 Load: 1,500 VA
Major electric loads	• HVAC (larger of heating or cooling) • Water heaters • Clothes dryers (not already on laundry circuit) • Cooking ranges/ovens	• HVAC: New ducted heat pump with integrated electric backup sized to heating load: 17,998 W • Water heater: New heat pump: 4,500 W • Range oven: New electric: 12,000 W • Dryer: New electric: 5,760 W

	• All appliances "fastened in place, permanently connected, or located to be on a specific circuit"	• EVSE: New level 1: 1,650 W • Other connected: existing waste disposal, ventilation: 679 W
Total load calculation	Demand factors depend on HVAC load type: (a) If not adding new HVAC, sum: • All loads: 8 kVA + 40% remainder (b) If adding new HVAC, sum: • HVAC load: 100% • Non-HVAC load: 8 kVA + 40% remainder Capacity (A) = total load (W) / 240V	Demand factors: new HVAC, use part (b) Calculation with itemized loads above: • HVAC: 17,998 * 100% • Non-HVAC: 8,000 + 24,773 * 40% Total load: 35,097 W Total capacity: 147 A

As shown in Table 2, the demand factor is more conservative when new HVAC is added to the home. In this study, we treated HVAC measure upgrades (including replacement of electric resistance heating with air-source heat pumps) as new loads and therefore applied option (b) for their calculations.

The meter-based method (NEC Section 220.87) estimates existing total load from the prior year's metered peak power by scaling it up to 125%, then adds new loads at 100%. Because the code provides no guidance on how to treat removed or replaced equipment, we make the following assumptions. Removed loads are not subtracted. For new HVAC serving both heating and cooling, only the larger of the two loads is added. For new cooling only, the full cooling load is added if the preexisting HVAC load is cooling-dominant, or if it is heating-dominant but the new cooling load exceeds the preexisting heating load. The same logic applies in reverse for new heating only.

Table 3 details the specifics and provides a sample calculation according to 2023 NEC. The meter-based calculation is performed by taking the pre-upgrade modeled 15-minute electric peak as the existing load. The calculation is applied to occupied homes only due to otherwise unrepresentative electric usage from vacancy. We computed the meter-based metrics separately for this study as they are not yet available in ResStock.

The resulting load calculation yields the total adjusted electrical demand of the upgraded home, which can then be converted to amperage (by dividing load by 240V) and compared against the existing panel's service rating to assess capacity constraints. In the sample calculations, an existing 150A panel would have sufficient capacity under the load-based method (147A calculated) but would be considered constrained under the meter-based method (192A calculated).

Table 3. Meter-based calculation

Type	**2023 NEC 220.87**	**Sample Calculation**
Existing load	125% of 15-min metered peak from: • a one-year period • a representative 30-day period minimum	• Max demand: 3,402 W Existing load: 4,253 W
New loads	Any new load at 100%, no subtraction of removed load	• Load itemization shown in Table 2 Total new load: 41,908 W
Total load calculation	Total load = existing load + new loads Capacity (A) = total load (W) / 240V	Total load: 46,161 W Total capacity: 192 A

4. Breaker Space Calculation

The breaker space calculation involves two steps. First, we determined the rated breaker space count for each model's preexisting panel by summing available slots and slots occupied by existing connected loads and circuits, using housing metadata that includes panel breaker space headroom. Second, we recalculated total occupied slots for the upgraded home and compared this against the rated space count to assess breaker space constraints.

For breaker space assumptions, 120V equipment—such as lighting, receptacle circuits, L2 EV chargers, and dishwashers—was assumed to occupy one breaker slot each, while 240V equipment, which includes most major electric appliances, occupies two slots per circuit. Higher-power equipment may require multiple circuits. For space heating and cooling, the number of circuits was estimated based on component power ratings, assumed wiring configuration, and a maximum circuit capacity of 50A. Although slim and multi-pole breakers can reduce space requirements, these were not assumed in our calculations. Further details are provided in Reyna et al. (2025).

Results

To enable a comparison between the load-based and meter-based calculations, all the following results consist of only occupied dwelling units, which make up 88% of the stock or 483,334 models. 26% of the occupied homes are multi-family and 74% single-family. Each model represents nearly 254 dwelling units.

1. Available Capacity

Table 4 summarizes modeled available panel capacity before any upgrades, broken out by building type and load calculation method (Method Subsection 3). Most panels, especially those rated 100A or above, have substantial untapped capacity, with higher-rated panels offering more headroom. The median home has 67-88A of spare capacity (depending on method), compared to 77-96A for the average home. For single-family homes, median available capacity by panel rating using the load-based method is: -6A (<100A panels, indicating a pre-existing constraint), 31A (100A), 61A (101–199A), 113A (200A), and 183A (201A+). The meter-based method estimates are modestly higher: 16A, 60A, 85A, 133A, and 209A, respectively.

Multi-family units show slightly more remaining capacity than single-family homes within the same panel rating ranges, though this may reflect greater uncertainty in panel rating predictions for multi-family units rather than a true difference. The load-based method generally estimates higher connected loads and, therefore, lower available headroom, than the meter-based method, consistent with anecdotal findings. This suggests that fewer actual loads operate simultaneously than the prescriptive demand factors used for the load-based method assume.

Preexisting capacity constraints (i.e., negative available capacity) affect roughly 2% of homes and are a modeling artifact. Because panel ratings are estimated from housing characteristics rather than detailed equipment inventories with explicit nameplate ratings, some uncertainty is unavoidable. Unlike breaker space constraints, capacity constraints can appear in the model even without a physical limit being reached, since the calculated connected load is derived analytically rather than measured directly.

Table 4. Summary of modeled available capacity (A) by building type and load calculation method

		Load-Based					Meter-Based				
Building Type	**Panel Rating (A)**	**P25**	**P50**	**P75**	**Avg**	**Std**	**P25**	**P50**	**P75**	**Avg**	**Std**
All	All	42	67	115	77	48	62	88	135	96	53
Multi-Family	All	43	57	68	64	38	64	84	97	86	42
	<100	8	20	28	19	15	26	43	53	37	27
	100	37	47	61	47	15	65	80	88	73	22
	101-199	50	58	69	60	17	67	86	99	81	29
	200	126	133	142	134	14	132	155	170	145	37
	201+	182	191	201	191	14	200	218	231	212	27
Single-Family	All	41	84	120	82	50	61	94	143	99	56
	<100	-17	-6	6	-7	18	-3	16	31	11	29
	100	19	31	43	30	18	45	60	72	56	25
	101-199	47	61	75	60	23	64	85	102	80	34
	200	93	113	131	110	29	99	133	157	122	48
	201+	164	183	206	194	51	184	209	233	216	63

(P25: 25th percentile, P50: 50th percentile/median, P75: 75th percentile, Avg: average, Std: standard deviation)

A preexisting capacity constraint may reflect a genuinely overloaded panel—one that experiences frequent breaker tripping or flickering lights—but no empirical data on overloaded panels is available to validate these estimates. To focus the analysis on the incremental impact of each measure, we only counted models where the connected load increased to cause or worsen a capacity constraint. Models with a preexisting constraint were excluded unless the measure made that constraint worse. Finally, given the uncertainty in the underlying estimates, no additional safety factor was applied when comparing calculated capacity against the panel service rating.

2. Load and Breaker Space Increases by Measure

Figure 4 show the average increase in connected load and breaker space by measure and building type. Load changes are higher under the meter-based method than the load-based method because the meter-based method counts all new loads at 100%, while the load-based method applies tiered demand factors. For example, new EV charging loads carry a 40% marginal demand factor under the load-based method but are counted in full under the meter-based method. The load-based method also captures shifts in HVAC demand factors between baseline and upgrade scenarios (Table 2). For example, in a cooling-dominant home, the HVAC load is calculated as 40% of existing cooling load before a heat pump upgrade and 100% of the heat pump load after.

The primary driver of connected load increases for heat pump upgrades is whether electric resistance backup heating is included. Electric backup is typically sized to cover 100% of the heating load and is assumed to run simultaneously with the heat pump for supplemental heating, which can more than double the load added by the heat pump alone. For the average single-family home, a cold-climate ducted ASHP with electric backup increases connected load by 26–30 kW (depending on method), compared to just 4–7 kW for an ASHP paired with a gas furnace for backup. Geothermal heat pumps, which require no electric backup, fall in between at 11–15 kW. Where envelope improvements allow the geothermal system to be downsized, connected load drops further to 7–11 kW.

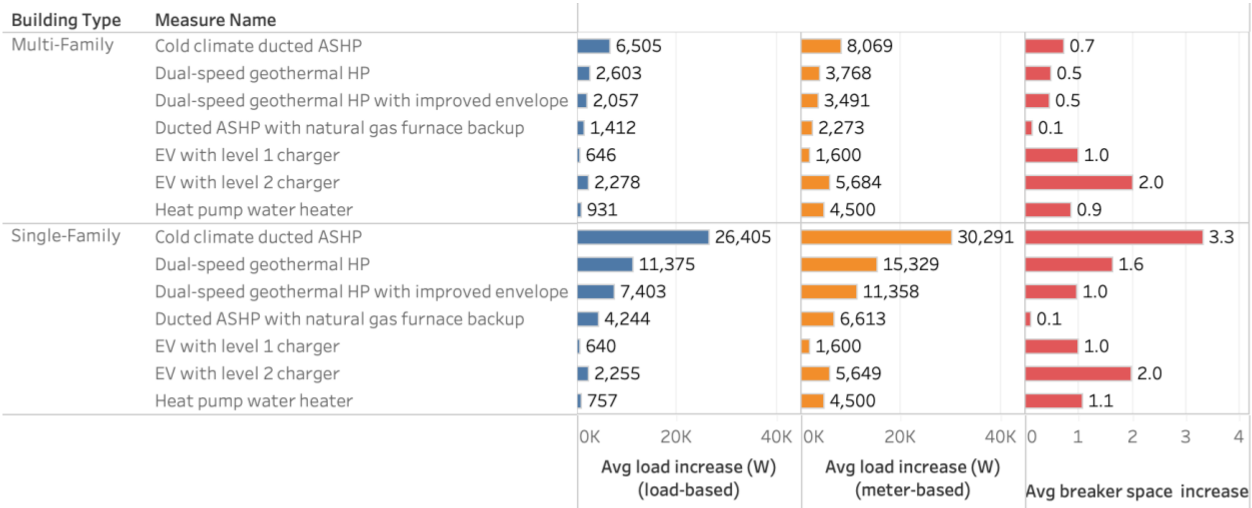

Figure 4. Average increase in connected load and breaker space *by measure and building type, based on load-based calculations.*

Breaker space impacts depend on both the circuits added for new equipment and the circuits freed when existing equipment is removed. Central AC occupies 240V circuits, fossil-fuel heating uses only 120V, and electric resistance heating can occupy multiple 240V circuits—all of which are freed when a heat pump replaces them, since heat pumps provide both heating and cooling. Both ASHPs and geothermal systems require a 2-pole 240V circuit for the outdoor unit. For the indoor unit, a system without electric backup needs only a 1-pole 120V circuit, while an ASHP with electric strip heat requires one or more additional 240V circuits, each assumed up to 50A. As a result, a cold-climate ASHP with electric backup adds 3.3 breaker slots on average, compared to 1.6 for a geothermal system and just 0.1 for an ASHP with gas backup—a figure so close to zero that the impact nearly cancels across the housing stock, with some homes seeing a net decrease, others no change, and the rest a modest increase. In homes with central AC and electric resistance heating, a heat pump without electric backup can even reduce occupied breaker space, since heat pumps draw less power than electric resistance.

In multi-family buildings, HVAC and water heating systems are sometimes centralized and unit-level systems tend to be smaller, so upgrades generally add less connected load and require less breaker space than in single-family homes. For EV charging, we assumed chargers are added directly to individual units (though in practice, multi-family EV charging is often shared and installed in parking structures with dedicated subpanels for billing and load management). An L1 charger adds one slot for a new dedicated 120V circuit; an L2 charger adds two slots for its 240V circuit.

3. Panel Constraints by Measure

Error! Reference source not found. summarizes the applicability of each measure (the share of homes it applies to) and the resulting panel constraint outcomes for those homes, with capacity constraints assessed using both the load-based and meter-based methods. For example, cold climate ducted ASHP applies to only homes with ducts – 65% of single-family homes and 11% of multi-family units. Of the applicable single-family homes, 57–58% (depending on method) are expected to face a capacity constraint and 39% a breaker space constraint. For multi-family units, 14–18% would be capacity constrained and 17% space constrained. This translates to over 55 million homes in total expected to face a capacity constraint from a cold climate ducted ASHP alone.

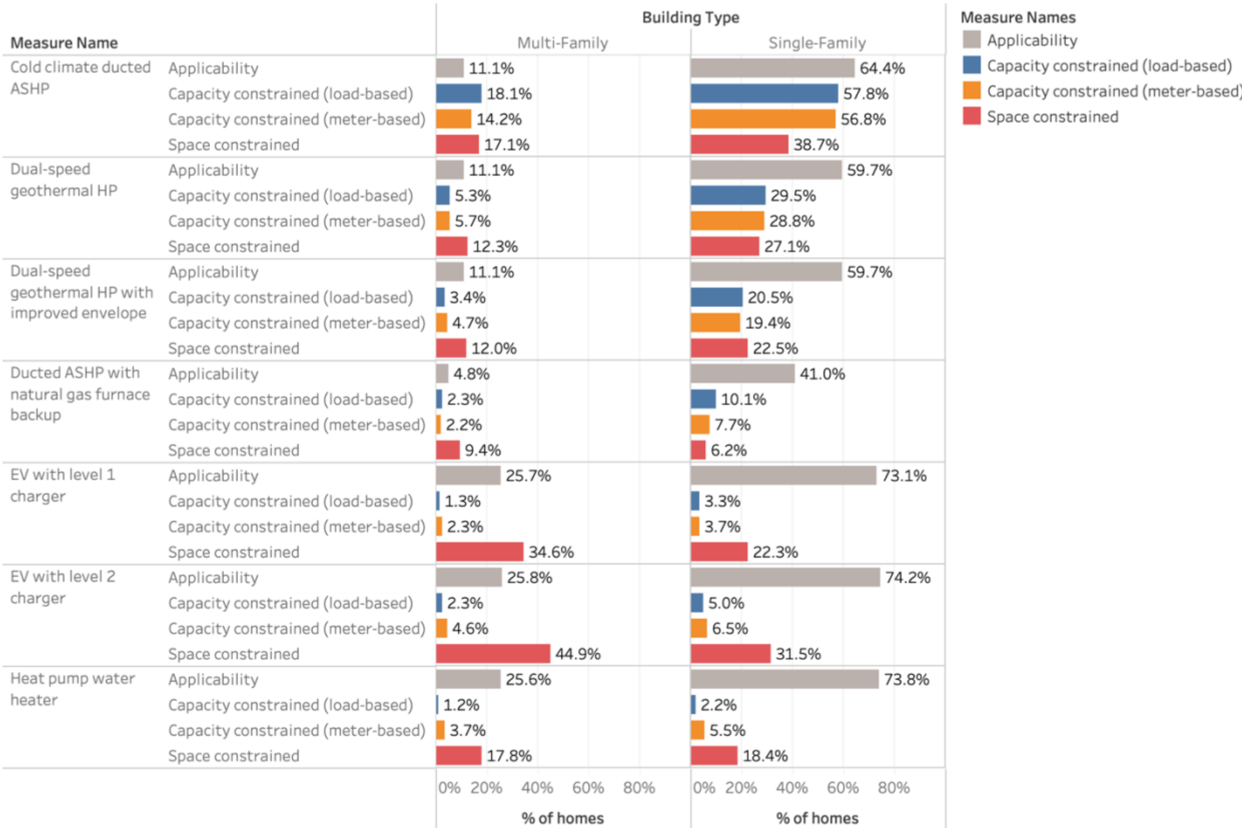

Figure 5. Measure applicability and portion of applicable homes that are constrained by capacity and breaker space.

The two methods produce broadly similar results. The load-based method tends to estimate higher capacity constraints for HVAC measures and lower constraints for non-HVAC measures (such as EV charging and water heating) than the meter-based method, which reflects differences in how each method applies marginal demand factors to HVAC versus non-HVAC loads. Across all measures, multi-family units are more likely to hit a breaker space constraint before a capacity constraint—a consequence of having fewer open breaker slots (Figure 3) but more capacity headroom than single-family homes (Table 4).

For HVAC and water heating upgrades, single-family homes face higher constraint rates than multi-family units, driven by their larger floor areas and greater number of bedrooms (which determine water heater sizing). Consistent with the connected load and breaker space trends discussed in Result Subsection 2, constraint rates are lower for heat pump measures that omit electric backup or that can be downsized due to envelope improvements.

For water heating and EV measures, breaker space constraints are more common than capacity constraints. For heat pump water heaters, 18% of homes are expected to face a breaker space constraint, versus only 1–6% facing a capacity constraint (varying by building type and method). For EV charging, 32% of single-family homes lack the two breaker slots needed for an L2 charger, while 22% lack even the single slot needed for an L1 charger, assuming a new dedicated circuit. Moving from L1 to L2 doubles the share of homes with a capacity constraint, from 3% to 6% of single-family homes, and 2% to 4% of multi-family homes.

Figure 6 shows the state-level distribution of homes with load-based capacity constraint, breaker space constraint, and overall panel constraints for the cold climate ducted ASHP measure, based on the load-based method. Capacity constraints range from 6% in Hawaii to 79% in Nebraska, space constraints from 5% in Florida to 67% in Vermont, and overall constraints from 20% in Hawaii to 86% in Vermont. The meter-based result (not showed) shows similar state-level distribution, with overall constraints from 17% in Hawaii to 83% in Vermont and Nebraska.

Constraints are concentrated in colder regions, where homes have historically relied on fuel oil or natural gas for heating and therefore tend to have smaller electrical panels. In the South, where high cooling demand has driven adoption of larger-capacity panels (as shown in Figure 1), fewer homes face constraints when upgrading from air conditioners to heat pumps. Along the Pacific Coast, mild temperatures reduce both heating and cooling demand, resulting in lower constraint rates as well.

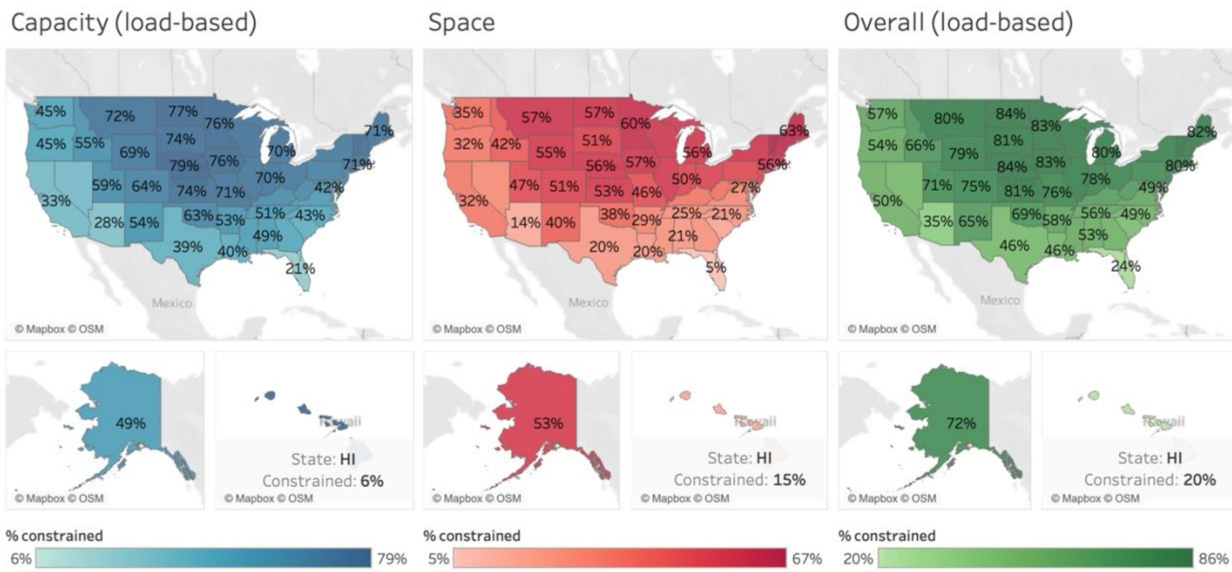

Figure 6. Proportion of homes with capacity, breaker space, and overall panel constraint across U.S. states for the cold climate ducted ASHP measure based on load-based calculations.

Discussion

1. Limitations and Insights

Several modeling limitations warrant consideration. Panel service ratings are estimated from limited housing characteristics using machine learning models rather than detailed equipment inventories, introducing uncertainty in panel characterization—a limitation shared by all studies in this area. The training data skews toward the Pacific Northwest, where gas appliances are more common; although the models address this by stratifying on heating fuel type, fewer data points for electrically heated homes make panel characterization less certain for those homes. The training data also covers only single panels, excluding subpanels and slim breakers — cost-effective options for adding breaker slots —which may cause the model to underestimate available breaker space. For non-HVAC appliances such as cooking ranges and dryers, nameplate ratings are fixed regardless of home size (e.g., an electric cooktop is assumed to be 12 kW), which may overestimate loads in smaller homes that likely have lower-capacity.

Finally, while ResStock is calibrated to state-level Energy Information Administration (EIA) energy and utility load research data, some end-use schedules do not coordinate with standardized annual energy calculations, which can produce unrealistic profiles for a small fraction of models. Additional limitations are documented in Reyna et al. 2025 and NLR's ResStock FAQ.

In general, fossil fuel-to-electric conversions increase load and breaker space requirements, while electric-to-fossil fuel conversions (not covered by this study) reduce them. For electric-to-electric upgrades, more efficient appliances do not necessarily have lower nameplate power ratings. Connected load can increase when redundant systems are required, such as electric backup added alongside an ASHP. Reductions occur when a high-power appliance is replaced by a lower-power one, such as an electric tankless water heater swapped for a heat pump water heater, or when other improvements allow a system to be downsized.

Heat pump sizing and backup configuration significantly influence constraint outcomes. High-performance cold climate heat pumps that maintain capacity at low design temperatures can be sized smaller, reducing both connected load and breaker space requirements. Configuring electric backup to operate only when the heat pump cannot—rather than simultaneously—further reduces these demands. Envelope improvements and advances in heat pump defrost technology offer additional opportunities to reduce backup sizing requirements.

While the measures modeled here stop short of full electrification scenarios, the findings are consistent with existing studies suggesting that tens to hundreds of millions of homes may face some form of panel constraint when converting fuel-based equipment to electric (Pecan St 2021; Quinn, Molar-Cruz, and Lindsey 2024). Both load calculation methods yield similar results, but the load-based approach is generally more robust. By accounting for the full load inventory and demand factors that approximate coincident peaks, it can subtract removed loads to produce more accurate net impact estimates. The meter-based method, by contrast, is harder to interpret consistently, requires accessible and representative metered data, and is impractical when loads are added incrementally—since the baseline peak must be re-metered over time. It also excludes vacant homes and those without metered data.

2. Applications and Opportunities

These results support several practical use cases. At the household level, they enable more complete electrification cost estimates by accounting for potential electrical upgrade costs and facilitate cost-benefit comparisons of mitigation strategies—such as low-power appliances or load control devices—to identify optimal pathways for adding electric loads. Tools like the Redwood Energy's Watt Diet Calculator and Pocket Guide to All-Electric Retrofits of Single-Family Homes illustrate this application.

Capacity constraints can be mitigated through various means—load shedding or circuit sharing devices, smart panels, low-power or smart appliances—without necessarily upgrading the service entrance. Many of these mitigation solutions also provide breaker space relief, e.g., low-power appliances do not require 240V dedicated circuits. Space constraint can also be addressed using slim multi-breakers, subpanels, or rewiring for circuit consolidation (Murphy et al. 2025).

At larger scales, the granularity of ResStock's modeled results enables city, regional, and national analysis of panel constraints, supporting technology adoption impacts, assessments of distribution grid adequacy, and population-level insights for product, policy, and incentive design. Panel replacement typically costs $2,000–$4,500, service upgrades $2,500–$20,000, and transformer upgrades $3,000–$30,000 (PG&E 2022), with costs running higher today due to inflation and in areas with elevated labor costs or contractor shortages. When combined with itemized costs, the panel constraint results can inform estimates of community-wide home improvement projects and broader upstream upgrade needs. The ongoing Delaware Valley Energy-to-Community project (funded by the U.S. Department of Energy) provides one example of these results being applied to inform electrical upgrade needs and costs at the regional level.

Finally, improving panel characterization and panel constraint modeling will require broader data collection and, critically, data sharing across organizations. Efforts by Pecan Street, EPRI, and the national labs remain siloed, exacerbating existing data gaps. Incorporating electrical panel information into nationally administered surveys, such as the EIA's RECS, the AHS, or the ACS, would meaningfully improve accuracy.

Conclusion

As new electric loads are added during a home improvement project, the electrical panel may lack sufficient capacity or breaker space to accommodate new circuits, becoming constrained and potentially requiring an upgrade. This study presents new electrical panel modeling capabilities in ResStock, built from foundational work between NLR and LBL and relevant results from ResStock's first dataset published with electrical panel results. The results enable city, regional, and national analysis of panel constraints, supporting technology adoption impacts, assessments of distribution grid adequacy, and population-level insights for product, policy, and incentive design. Understanding the frequency of electrical panel constraints can improve the costing and planning of home improvement projects by considering lower cost alternatives, thus supporting affordability and consumer choice. This knowledge also supports utility programs in assessing the potential strain these upgrades may place on the distribution grid.

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