Electrical Panel Constraints of Residential Energy Retrofits Deployed at Scale

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Abstract

Adding electric appliances can overload home electrical panels, causing costly upgrades. Lower-cost mitigations like smart load controls can bypass these constraints. This study introduces new ResStock™ modeling that characterizes U.S. electrical panels and quantifies constraints from large-scale retrofits, including heat pumps (HPs). By integrating panel configurations and bottom-up National Electrical Code (NEC) load calculations, this work delivers congruent estimates of constraints and upgrade frequencies. These findings offer homeowners and utilities a foundational dataset to evaluate cost-saving pathways, target mitigation strategies, and accelerate affordable residential energy retrofit deployment.

Introduction

The Challenge:

- Adding electric appliances (HPs, Electric Vehicles (EVs)) can overload electrical panels or service entrances, and exhaust available breaker spaces
- Traditional panel or service upgrades are costly and time-consuming

The Knowledge Gap:

- Existing studies are limited in scope (small-scale surveys) or region (e.g., LA county) and often lack the detail needed to fully model panel constraints
- This study uses bottom-up NEC load calculations integrated directly into a national building stock model to evaluate panel constraints across various energy retrofits

Method

Data Source:

- Used ResStock national-scale datasets (hosted on OEDI), which contain ~550,000 statistically representative U.S. homes (1 per ~250 dwelling units)
- Focused on electrical panel outcomes for occupied units and relevant upgrades from the 2025 data release (simulated with 2018 weather data)

Panel Metadata: Baseline panel service ratings and available breaker spaces were predicted using housing metadata (NLR-LBL collaboration).

NEC Standards: Evaluated load calculations and breaker space requirements for each retrofit according to the 2023 NEC:

- Section 220.83 (Load-based calculation)
- Section 220.87 (Meter-based calculation)

Limitations & Insights

Data and Model Uncertainty:

- Panel capacities were estimated using ML models (in which data also skewed toward the Pacific Northwest) rather than direct inventories, introducing baseline uncertainty (e.g., 2% homes with a preexisting capacity constraint)
- ML models excluded subpanels and slim breakers, which may underestimate available breaker space
- Fixed nameplate ratings (e.g., 12 kW cooktops) may overestimate panel loads in smaller homes
- Energy-focused simulation protocols offer lower-fidelity dwelling-unit load profiles, which may impact the baseline for meter-based calculations

Equipment Sizing is Key: High-performance heat pumps and envelope upgrades reduce constraints by allowing smaller HVAC sizing, minimizing backup heater requirements, and lowering peak loads.

NEC Calculation Robustness: Load-based calculations are more robust than meter-based ones because they account for removed loads, are occupancy-agnostic, and do not require metered data.

Results

- Most panels (≥ 100A) have significant headroom: a median of 67-88A, an average of 77-96A unused (which generally scales with panel size)
- For 240V retrofits (e.g., EV charging, HP water heaters), physical breaker space limits are more common than capacity constraints
- Electric auxiliary heating can increase HP panel load. High-performance HPs, envelope upgrades, and sizing/configuration strategies can minimize this load and required circuits
- Constraints are clustered in colder regions where a historic reliance on fossil fuels has left homes with smaller baseline panels

Scan me for data!

Table 1. Energy measure description

Measure Name	Technical Specs	Application Criteria
Cold climate ducted Air Source HP (ASHP)	ASHP: variable-speed, HSPF2 8.5, SEER2 17.5, HCR (Heating Capacity Ratio) 0.67, -15°F lockout, sized to max of heating or cooling load accounting for reduced capacity at design temperature Backup: integrated electric resistance, sized to full heating load	Ducted HVAC systems, multi-family units must have individual central AC or HP to ensure room for outdoor unit
Dual-speed geothermal HP	Two-speed compressor, variable-speed air handler, water-to-air, COP 4.0, EER 20.5, has vertical ground heat exchanger	Ducted HVAC systems, low-rise buildings 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) Ducts: sealing to 5% leakage to outside, insulating to R-8	Applies to GHP target homes with poor baseline insulation/sealing
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 Furnace: 92% AFUE if in IECC climate zones 1-4 and 95% AFUE elsewhere	Ducted, non-shared HVAC systems with active natural gas access
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, hybrid/electric tank, UEF ≥3.3, FHR ≥45 gal/h, efficiency varies slightly by tank volume	Units without existing solar thermal or HP water heaters

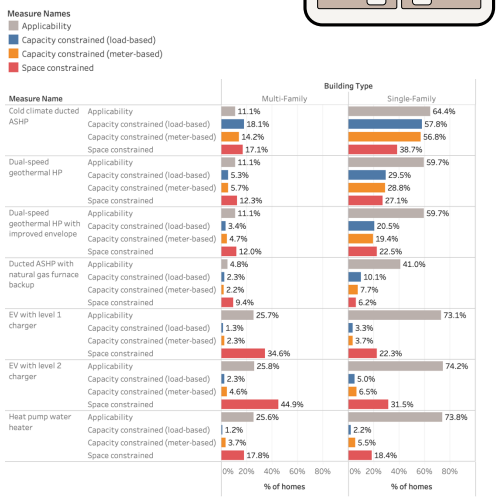

Fig 2. Measure applicability and portion of applicable homes that are constrained by capacity and breaker space.

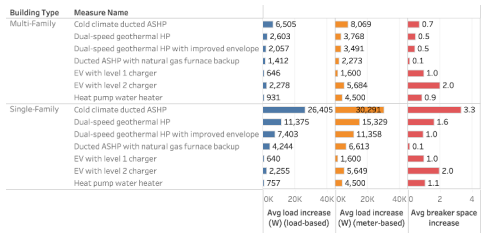

Fig 1. Average increase in connected load and breaker space by measure and building type, based on load-based calculations.

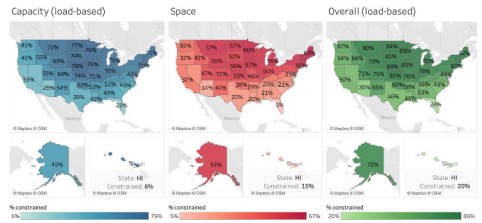

Fig 3. Proportion of homes with capacity, breaker space, and overall panel constraint across U.S. states for the cold climate ducted ASHP measure based on load-based calculations.

Notes:

- Only models where the load increased enough to cause or worsen a capacity constraint were counted
- No safety margin was applied to load calculations
- Breaker space requirements depend on circuits added and freed during equipment changeout

Applications & Future Work

Solution Pathways:

This granular ResStock dataset containing panel outcomes helps stakeholders evaluate upgrade costs and mitigation strategies

- *Customer level:* Directs when low-cost mitigation can bypass full replacements.

Constraint Type	High-Cost Traditional Upgrade	Low-Cost Smart Mitigation
Capacity (Amperage)	• Service entrance / panel upgrade *(Est: $2,500 – $20,000+)* • Grid transformer upgrade *(Est: $3,000 – $30,000+)*	• Smart panels & load shedding devices • Circuit-sharing switches • Low-power/smart appliances (avoiding 240V lines also offer space relief)
Breaker Space (Slots)	Main panel replacement *(Est: $2,000 – $4,500)*	• Slim multi-breakers / tandem breakers, subpanel installation, Circuit consolidation & rewiring

- *Utility level:* Evaluates incentive programs, quantifies how widespread retrofit adoption impacts the distribution grid and capacity

The Case for Data Sharing: Current panel research remains siloed (Pecan Street, EPRI, national labs).

Call to Action: Integrating electrical panel questions into national surveys (e.g., RECS, AHS) is critical to improving future stock modeling.

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