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Authors

Gul, Sadia

Meier, Alan

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Assessing electrification readiness in U.S. single-family homes based on a nationwide survey of electrical panel capacities

Sadia Gul [a,*], Alan Meier [b]

[a] Energy and Efficiency Institute, University of California Davis, Davis, CA, 95616, USA
[b] Department of Environmental Science and Policy, University of California Davis, Davis, CA, 95616, USA

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ABSTRACT

Electrification of residential buildings is a key strategy for increasing the use of renewable energy sources. Central to this transition is understanding the capacity of existing electrical infrastructure—specifically electrical panels—to safely and effectively manage increased electricity demands from electrification technologies. However, comprehensive nationwide data on electrical panel capacities in U.S. single-family homes is currently lacking. To address this gap, we conducted a nationwide survey of single-family homes, collecting detailed data on electrical panel capacities, breaker slot availability, major electric and gas appliances, electrical panel models, and home characteristics such as construction year and floor area. Photographic documentation was used to verify electrical panel data and appliance information.

Results show that approximately 60% of surveyed homes have electrical panels rated at ≥200 amperes (A), indicating that a significant portion of the existing housing stock can accommodate additional electric loads. However, 31% of homes possess panels rated at ≤100 A, potentially restricting their ability to adopt new electric appliances without significant upgrades. Panel capacities positively correlate with both home size and construction year, with newer and larger homes generally better suited for electrification. Homes with higher-capacity panels tend to have fewer gas appliances, reflecting a gradual shift toward electric technologies. Conversely, homes with lower-capacity panels frequently rely on multiple gas appliances, highlighting substantial electrification challenges.

Additionally, approximately 3% of surveyed homes had potentially hazardous electrical panel models, emphasizing important safety considerations in the residential electrification process. Our findings underscore the need for targeted policies, financial incentives, and infrastructure investments designed specifically to address infrastructural and safety barriers, particularly in older and smaller homes, to support equitable and efficient electrification across the U.S. residential sector.

1. Introduction

Electrification involves transitioning from fossil fuel-based systems to electrically powered alternatives, which can enable greater integration of renewable energy sources. In residential buildings, electrification entails the adoption of electrical technologies for space heating, water heating, clothes drying, cooking, and, in some cases, pool or spa heating. This transition to electric appliances not only reduces greenhouse gas emissions but also enhances energy efficiency and can lower operating costs, particularly when paired with efficient technologies, favorable electricity rates, or renewable energy sources. For instance, modern electric heat pumps offer high operational efficiency and are more cost-effective than traditional heating systems in many U.S. regions (Walker et al., 2022), and induction cooktops also achieve significantly higher heat-transfer efficiency than gas stoves (Bui, 2023). Moreover, as electric vehicles (EVs) gain popularity, the resulting increase in household electricity demand further underscores the need for robust electrical infrastructure. This transformation requires a thoughtful approach to ensure that homes are equipped to efficiently manage the increased electrical load.

In the United States, local and national incentives and regulations have been developed to accelerate electrification, such as tax credits for energy-efficient home improvements and EV purchases (Offutt, 2024). States such as California, New York, and Massachusetts have set

* Corresponding author. Energy and Efficiency Institute, University of California, Davis, 95616, USA.
E-mail address: gul@ucdavis.edu (S. Gul).

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ambitious building electrification and decarbonization targets, highlighting the urgency of ensuring homes can support increased electrical loads.

Single-family dwellings, which constitute around 68% of the U.S. housing market (over 84 million units) (U.S. Energy Information Administration, 2020), face unique challenges in this energy transition. Unlike multi-family or commercial buildings, which may share energy systems and have standardized needs (Multifamily Building Study Pilot: Methods, 2022), single-family homes are individual units with diverse electrification requirements. Many were constructed under older building standards, and may lack adequate electrical capacity to support modern high-demand appliances and systems (Quinn et al., 2024). A critical component of this electrification process is the residential electrical panel, which distributes power to all household systems. Understanding and addressing panel capacity limitations is essential for guiding infrastructure upgrades, maintaining grid stability, and reducing the environmental impact of the residential sector.

Electricity reaches homes through a structured network: high-voltage transmission lines from power plants minimize losses over long distances, with voltage step-down occurring at regional substations and local transformers. As illustrated in Fig. 1, electricity enters individual homes via service wires connected to the electric meter, which measures consumption. Power then flows to the home's main electrical panel, or breaker box.

Electrical panels distribute power throughout the home, with each circuit corresponding to designated areas or appliances. The panel's capacity, rated in amperes (A), dictates the total electrical load a home can safely support, typically indicated by the main service disconnect switch as shown in Fig. 2. Each circuit breaker acts as a safety device, interrupting the flow of electricity when demand surpasses safe limits to prevent overloads, fires, and other electrical hazards. As household electrical demands grow, due to the addition of high-demand appliances or EV chargers, new circuits can be installed, provided there is sufficient panel capacity. Typical residential electrical panel capacities range from 100 A to 200 A. Homes with insufficient capacity may require costly panel upgrades, underscoring the importance of accurate initial assessments.

Panel capacity assessments are guided by the National Electrical Code (NEC) (National Fire Protection Association, 2022a), which outlines requirements for residential electrical installations, including detailed calculations for determining the required panel capacities. Following NEC guidelines, load calculations must account for both continuous and non-continuous loads, including safety margins for potential load increases or surges. Specifically, NEC Article 220 provides methods and examples for standard and optional residential load calculations. Adhering to these standards ensures efficiency, safety, and compliance in electrical systems, minimizing the risk of overloads.

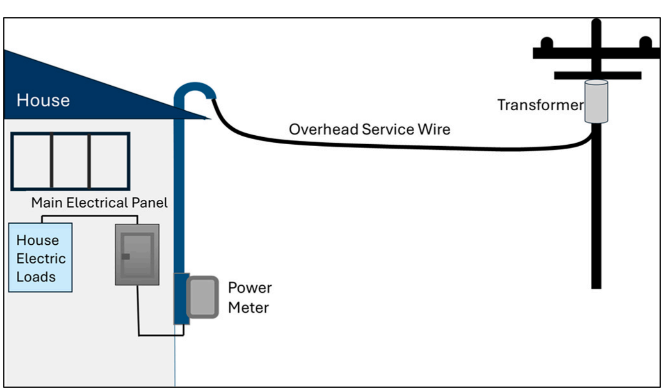

Fig. 1. Illustration of electricity flow from the local transformer to home components, highlighting service wires, electric meter, and main electrical panel.

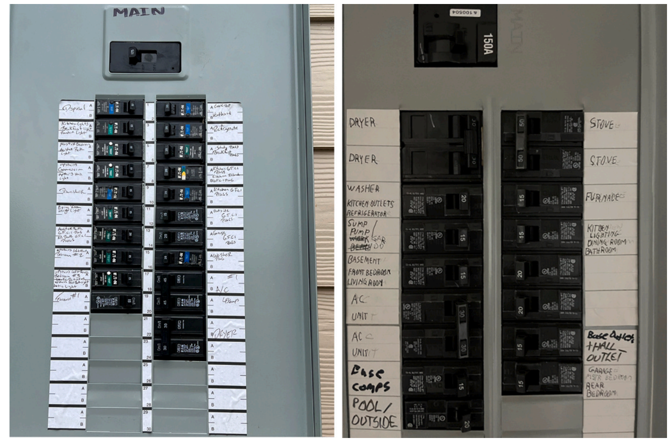

Fig. 2. Residential electrical panel displaying labeled circuit breakers. The main breaker, rated at 150 A, is located at the top-right corner.

A quantitative understanding of existing electrical capacities in U.S. homes is crucial for informing electrification policies, as it directly influences both technical feasibility and costs. Currently, comprehensive nationwide data on residential electrical panel capacities is limited. Previous studies have attempted to infer national electrification readiness from small region-specific samples. Pecan Street's research (Merski, 2021) examined panel capacities in single-family homes, concluding that while many residences could transition fully to electric appliances without panel upgrades, homes with capacities under 200 A might need significant upgrades. They estimated that approximately 35-45 million homes could transition without panel upgrades, whereas up to 48 million might require upgrades. However, as the sampled homes were predominantly newer and located in Texas, these findings may not accurately represent older properties or broader regional variations across the U.S. housing stock.

Similarly, a Massachusetts study by Guidehouse (Golino et al., 2024) revealed significant disparities in readiness for additional electrical loads, emphasizing the critical role of electrical service capacity in supporting heat pumps, EV chargers, and advanced cooking appliances. The analysis highlighted that many homes have structural potential for electrification, but roughly half of the sampled homes had 100 A panels, with 85% of these already near or exceeding capacity after adding major electric appliances. A California-based study by Opinion Dynamics found that older homes frequently require electrical panel upgrades to accommodate modern heat pump systems, especially during retrofits (TECH, 2022). Additionally, research by the Commonwealth Edison Company (Home Infrastructure Upgrades to Enable, 2023) showed that two-thirds of its customers had limited panel capacities (≤100 A), supporting only partial electrification without substantial infrastructural upgrades. Another California study by Fournier et al. (2024) quantified existing electrical service panel capacities, indicating that many homes may need panel upgrades to facilitate comprehensive electrification, with disadvantaged communities disproportionately affected due to smaller panels.

The Electric Power Research Institute (EPRI) conducted a large-scale online survey across the United States to assess the residential electric panel capacities, subsequently applying predictive modeling to estimate the proportion of homes needing panel upgrades for full electrification. Although their presentation slides outline key results, such as the prevalence of smaller panels and potential upgrade requirements, a comprehensive, publicly available report detailing their methods and findings is lacking, limiting independent validation (Quinn et al., 2024; Lindsey, 2023). Their survey found that over 20% of single-family homes have panels rated at 100 A or smaller, most of which would need upgrades for full electrification. Similar electrification barriers may exist in other countries that rely on fossil fuels for heating, but these barriers have not yet been documented. In summary, existing research indicates that while a considerable number of U.S. single-family homes may already support full electrification, a substantial portion, especially older homes with 100 A panels or smaller, may face significant capacity constraints.

Building upon these findings, our research provides a robust dataset of 348 rigorously validated survey responses, each accompanied by photographs of electrical panels (Meier and Gul, 2024). This enabled independent verification of panel ratings and examination of circuit breaker labels. Additionally, we examined breaker ratings for major appliances in homes with panel ratings below 200 A to assess current load distribution, and identified the presence of two potentially hazardous panel models. We then applied Spearman's rank correlation to explore relationships between panel capacity and home characteristics such as age, floor area, and reliance on gas appliances. Overall, this study offers new insights into the state of residential electrical infrastructure and its readiness for electrification.

2. Methodological framework for assessing electrification readiness

2.1. Survey design and distribution

To estimate the number of single-family homes in the United States with potentially insufficient electrical panel capacity for electrification, we conducted a nationwide survey targeting single-family homeowners. The survey, designed in SurveyMonkey and distributed through Amazon Mechanical Turk (MTurk), included 12 targeted questions focused on household and infrastructure characteristics relevant to electrification:

- **Location data (Q1-Q4):** Respondents identified their home type (detached or attached) and provided ZIP code-level geographic information.
- **Home characteristics (Q5–Q6)**: Approximate construction year and floor area were collected, as both factors influence electrical demand.
- **Fuel use and appliances (Q7–Q9):** Participants reported primary heating fuel and major gas and electric appliances, which are essential for assessing a home's electrification needs.
- **Electrical panel information (Q10–Q12):** Respondents uploaded two photographs of their electrical panel: one full view and one close-up of the main disconnect, and reported the main breaker rating.

The survey was intentionally concise to reduce participant burden and improve response quality, while still capturing the key variables necessary to assess electrification readiness.

2.2. Data collection process

The survey was available on MTurk from August 2022 to July 2023. Participation was voluntary and restricted to single-family home residents in the U.S. No personally identifiable information was collected, and participants were compensated up to USD $8.00 for completing the survey. Instructions emphasized accurate reporting and the submission of original photographs.

While MTurk facilitated broad geographic reach, potential demographic and geographic biases may exist due to self-selection and platform limitations. Demographic data was not explicitly collected, thus limiting our ability to quantify these biases directly. However, we assessed sample representativeness by comparing home construction period and floor areas with Residential Energy Consumption Survey (RECS) benchmarks.

A total of 565 initial survey responses were collected via MTurk, supplemented by additional responses from university-affiliated networks. Each submission included survey responses and two photographs of the electrical panel.

2.3. Data validation and cleaning

Given the risk of fabricated submissions (e.g., internet-sourced electrical panel images) via online platforms, we implemented a multi-step validation process:

1. **Reverse image search:** Used to verify image originality.
2. **Metadata review:** Analyzed photo metadata (e.g., timestamps, device info) for consistency with survey timing. Authentic images typically had metadata consistent with the survey completion timeframe and demonstrated evidence of being captured by personal devices. Images lacking metadata were flagged as potentially inauthentic. Given the average survey completion time of approximately 8 min, the opportunity for respondents to manipulate images was limited.
3. **Consistency checks:** Survey responses were cross-referenced with visible information in the photographs. According to the National Electrical Code (NEC 408.4(A)), circuit breakers must be clearly labeled (National Fire Protection Association, 2022b). Breaker labels visible in photographs were compared with listed appliances in survey responses to detect inconsistencies.
4. **Validation question**: A validation question about the amperage rating of the main service disconnect was included to assess participant accuracy and familiarity with their electrical system. Responses that fell outside typical amperage ranges were flagged as potentially inaccurate and excluded.

After validation, 348 responses were retained for analysis. Their geographic distribution is shown in Fig. 3, overlaid with Building America Climate Zones (Antonopoulos et al., 2022). While the dataset demonstrates broad geographic coverage, regional data density remains limited, which restricts the reliability of region-specific or climate-specific conclusions. Ongoing data collection will enable more robust regional analyses in future research.

2.4. Data analysis

2.4.1. Exploratory approach

We used visualization techniques to explore trends and relationships within the survey data. Specifically, we analyzed the distribution of electrical panel capacities in single-family homes to assess their prevalence and identify potential trends over time. We also explored associations between electrical panel capacity and home characteristics, such as the construction period and floor area. In addition, we examined the types and prevalence of gas appliances used in homes, providing insight into current energy use and infrastructure readiness. Lastly, we assessed the number of empty breaker slots in panels to evaluate their potential for accommodating additional electric loads.

2.4.2. Statistical analysis

To quantify the relationships identified through exploratory analysis, we performed Spearman's rank correlation tests using Python's **scipy.stats** module. This non-parametric method evaluates the strength and direction of monotonic relationships between two variables. The following variable pairs were analyzed:

Electrical panel capacity relative to:
o year of construction.
o total floor area.
o number of gas appliances.
o total number of breaker slots and number of empty slots.

For each test, we established a null hypothesis (H_0) stating that no monotonic relationship exists between the variables, and an alternative

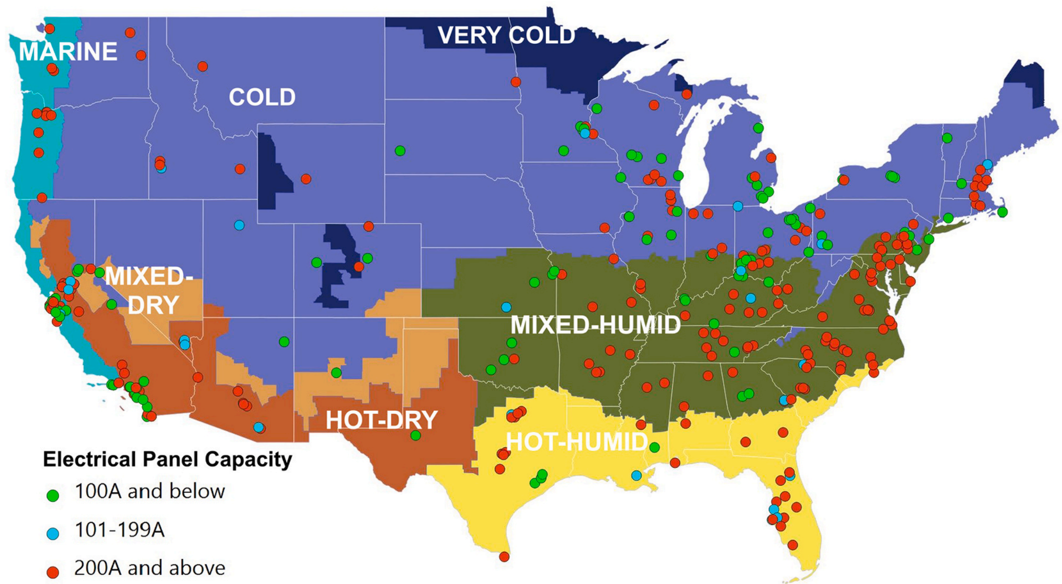

Fig. 3. Geographical distribution of validated survey respondents across the United States.

hypothesis (H_1) suggesting the presence of such a relationship. A significance level (α) of 0.05 was used. A p-value below 0.05 indicated rejection of the null hypothesis, signifying a statistically significant relationship.

3. Results and discussion

3.1. Dataset expansion and comparison with external, representative sources

Building on our previous investigation (Meier and Gul, 2024), we expanded the dataset by incorporating additional responses. We also performed further data cleaning and verification, resulting in a 24% increase in valid submissions. This expansion enhances the reliability of our findings and supports a more comprehensive analysis of residential electrical infrastructure across the United States.

To assess the representativeness of the expanded dataset, we compared key home characteristics, specifically building vintage and floor area, with data from the Residential Energy Consumption Survey (RECS) (U.S. Energy Information Administration, 2023a; U.S. Energy Information Administration, 2023b). Our analysis indicates that the distribution of construction periods in our dataset closely mirrors national trends, thereby strengthening the generalizability of our findings. For example, homes built before 1950 comprise 18.7% of our sample, comparable to 17.4% in RECS. Similarly, homes built between 1970 and 1979 represent 14% in both datasets, and those constructed between 2000 and 2009 account for 15.3% compared to 13.4% in RECS (Fig. 4). This alignment suggests that our dataset adequately captures the diversity of construction periods within the U.S. housing stock.

However, our sample differs somewhat from RECS with respect to

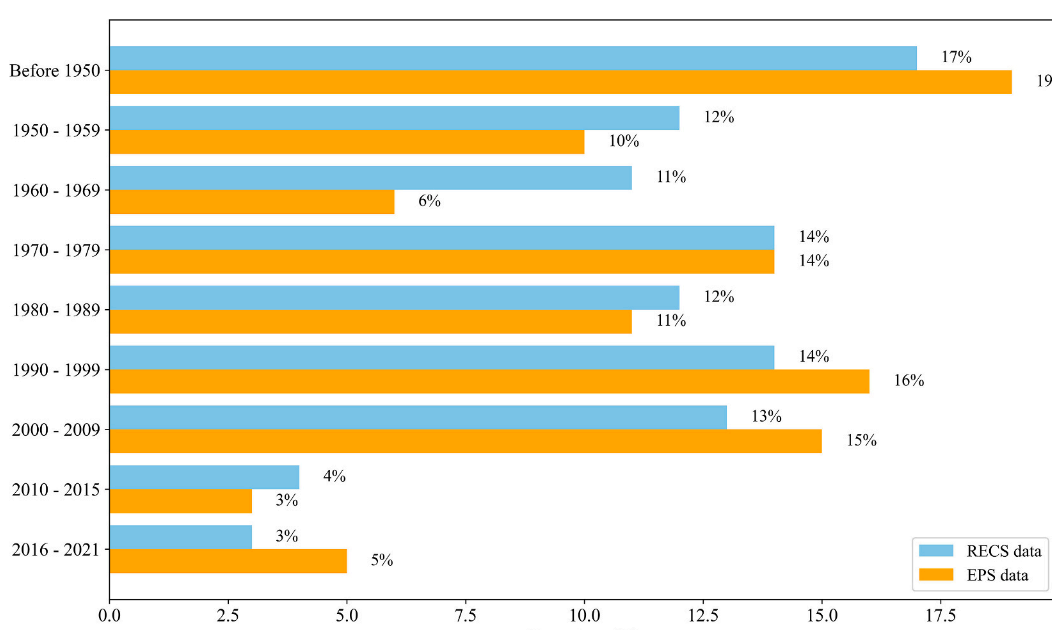

Fig. 4. Construction period distribution: Electric Panel Survey (EPS) vs RECS data (Note: Percentages are rounded to the nearest whole number for clarity).

home size (Fig. 5). Homes with floor areas between 1,000–1,499 square feet (approx. 93–139 m^2) and 1,500-1,999 square feet (approx.139-186 m^2) are overrepresented, comprising 24% and 29% of our dataset, respectively, compared to 16% and 20% in RECS. Conversely, larger homes ($\geq$ 3000 square feet, approx. 279 m^2) are underrepresented, making up 13% of our sample compared to 17% in RECS.

These differences introduce some sampling bias; however, our dataset still captures a diverse range of home sizes, supporting robust analysis of electrical panel capacities. The overrepresentation of homes between 1,000–1,999 square feet (approx. 93–186 m^2) may bias the observed distribution of panel capacities toward lower-capacity panels. Therefore, findings related to electrification readiness should be interpreted with caution in light of this limitation. Nevertheless, the close alignment in construction period distribution strengthens confidence in our analysis of the relationship between building characteristics and panel capacity.

3.2. *Distribution of electrical panel capacities*

Our analysis reveals important insights into electrical panel capacities in single-family homes, a key factor influencing electrification readiness. Fig. 6 shows that 60% of surveyed homes are equipped with 200 A panels, reflecting the increased prevalence of higher-capacity panels, possibly due to modern building codes and increased electrical demands. However, 31% of homes have panels rated at 100 A or less, highlighting potential barriers to electrification without infrastructure upgrades. An additional 9% of homes have intermediate capacities (101 A and 199 A), such as 125 A, 150 A, and 175 A panels, representing a transitional segment that may offer some, but limited, capacity for further electrification.

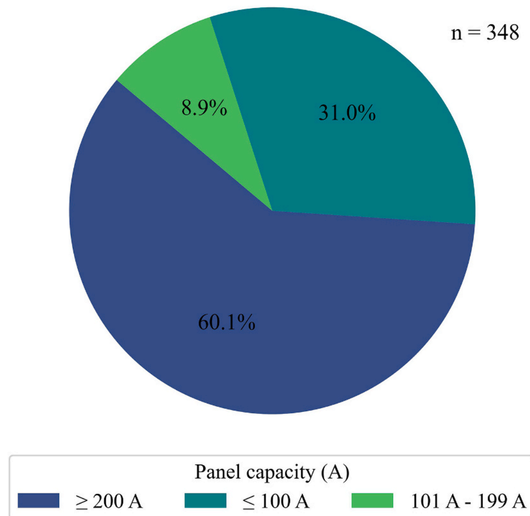

Fig. 6. Distribution of electrical panel capacities in single-family homes.

3.3. *Relationship of panel capacities to year of construction and floor area*

To better understand how electrical panel capacities vary across different housing characteristics, we examined their relationship with construction year and floor area.

3.3.1. *Panel capacities by construction year*

Homes built after 2000 predominantly have 200 A panels (over 80%), reflecting the standardization of higher-capacity systems in more recent construction (Fig. 7). In contrast, fewer than 20% of these newer homes have panels rated at 100 A or lower, suggesting these homes are better prepared for electrification. However, even newer homes may face limitations if their breaker slots are fully occupied.

Older homes display greater variability in panel capacities. Among homes built before 1960, 46% still have panels rated at 100 A or less, whereas 43% have been upgraded to 200 A, reflecting significant retrofitting efforts. From 1960 to 1999, the prevalence of 200 A panels increased gradually from 40% to 66%, corresponding with evolving electrical standards and appliance usage.

These trends indicate a gradual shift toward higher panel capacities over time, driven by increasing household energy demands and changes in building codes. However, many older homes, particularly those that have not been upgraded, may still require electrical panel upgrades to support full electrification.

3.3.2. *Panel capacities by floor area*

Fig. 8 illustrates the relationship between home size and panel capacity, showing that larger homes typically have higher-capacity panels to meet greater energy demands.

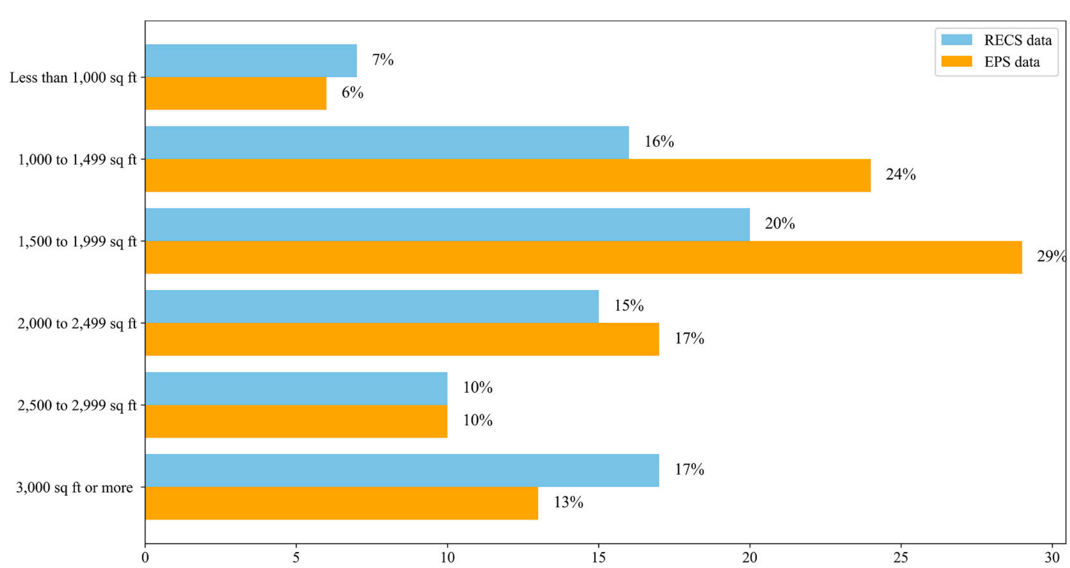

Fig. 5. Floor area distribution: EPS vs RECS data
(Note: Percentages are rounded to the nearest whole number for clarity).

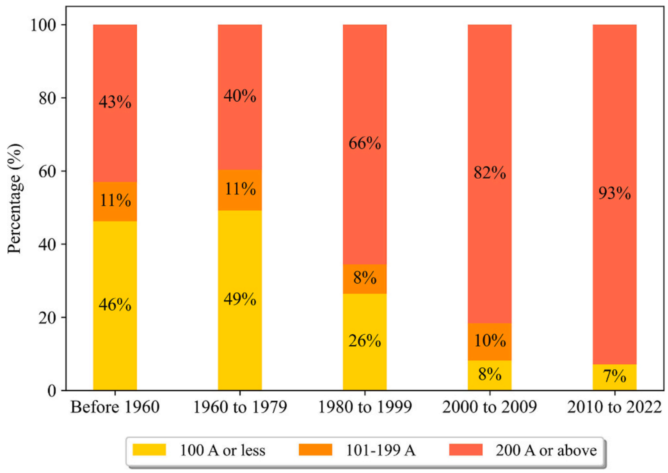

Fig. 7. Percentage distribution of homes electrical panel capacities across various construction decades.

- **Homes >2,500 square feet (approx. 232 m^2)**: 81% have 200 A panels, 15% have panels rated between 101 A and 199 A, and only 4% have 100 A or lower.
- **Homes 2,000–2,499 square feet (approx. 186–232 m^2)**: 71% have 200 A panels, 20% have ≤ 100 A panels, and 9% fall in the 101 A and 199 A range.
- **Homes 1,500–1,999 square feet (approx.139–186 m^2):** 53% have 200 A panels, 40% have ≤ 100 A panels, and 7% have mid-range capacity panels.
- **Homes < 1,000 square feet (approx. 93 m^2):** 65% have 100 A panels, 26% have 200 A panels, and 9% have mid-range panels.

While larger homes generally have higher-capacity panels, the presence of 200 A panels in smaller homes suggests that factors beyond home size, such as air conditioning use, construction year, building codes, and future energy considerations, also influence panel capacity.

Fig. 9 integrates panel capacity with construction year and floor area, highlighting the interdependence of these variables. Homes built after 2000 consistently feature 200 A panels across all size categories, while pre-1980 homes show greater variability, with lower-capacity panels more common in smaller homes.

Although newer and larger homes are typically equipped with higher-capacity panels, variation across the housing stock underscores the need for individualized assessments. Notably, older or smaller homes with 200 A panels likely reflect proactive retrofitting, whereas homes still using 100 A panels are more likely to require electrical upgrades to support electrification technologies. These findings emphasize the importance of evaluating multiple factors, not just panel amperage, when assessing a home's electrification readiness.

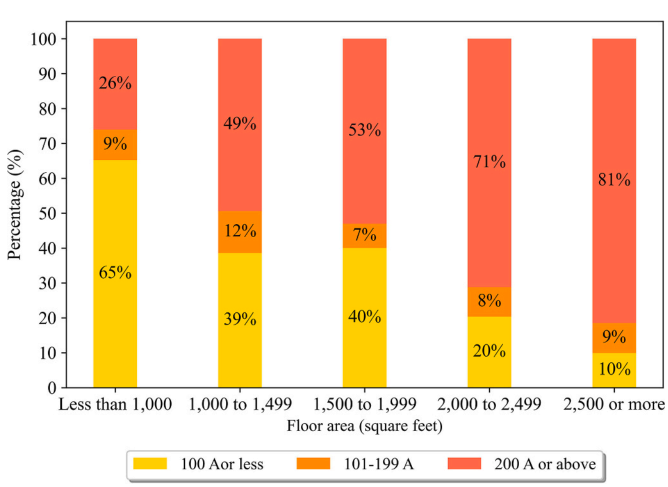

Fig. 8. Distribution of electric panel capacities for different floor area categories.

3.4. Spare breaker slots across panel ratings

To further evaluate electrification readiness, we analyzed the availability of empty breaker slots, which are critical for adding new electric circuits. Photographic documentation enabled accurate counting of the circuit breaker slots. However, some uncertainty remains due to subpanels that may not have been visible in the images.

Fig. 10 presents the distribution of spare breaker slots by panel rating using a box-and-whisker plot. Each box represents the interquartile range (IQR), with the edges marking the 25th (Q1) and 75th (Q3) percentiles. The median is marked by a line within each box, and whiskers extend to values within 1.5 times the IQR. Outliers beyond this range are shown as individual circles.

The analysis reveals significant variability in available slots across panel types:

- **Panels rated** ≤ **100 A** generally have limited capacity for expansion, with a median of 2 empty slots and a range of 0–11 slots. This limited availability suggests that many of these homes may struggle to accommodate new circuits without panel upgrades.
- **Panels rated between 101 A-199 A** offer moderate expansion capacity, with a median of 3 empty slots and a range from 0 to 16 slots.
- **Panels rated** ≥ **200 A** show the highest capacity for additional circuits, with a median of 4 empty slots and ranges extending up to 26 slots.

These results emphasize that both the panel's amperage rating and the physical availability of breaker slots are important factors in determining a home's readiness for electrification. Notably, some 200 A panels had no available slots, illustrating that higher amperage alone does not guarantee adequate expansion capacity.

3.5. Impact of gas appliances

The presence of gas or electric appliances in a home significantly influences both the availability of breaker slots and the feasibility of transitioning to a fully electric system. Since gas appliances typically do not require dedicated high-amperage electrical circuits, homes with more gas-powered systems often have more available breaker slots for future upgrades.

We collected data on six common gas appliances: gas water heaters, gas furnaces or boilers, gas stoves or ovens, gas clothes dryers, gas fireplaces, and gas pool or spa heaters. Fig. 11 shows the percentages of each gas appliance type across surveyed homes. The distribution reflects typical residential energy use patterns in the United States, where natural gas has historically been preferred for heating and cooking due to its affordability and widespread availability. Gas furnaces, boilers, and water heaters are the most common appliances in surveyed homes. This highlights key challenges in electrification, as replacing these appliances with electric versions will also require sufficient panel capacity and breaker availability.

To assess how the number of gas appliances influences breaker slot availability, we segmented homes based on both the number of gas appliances and their electrical panel capacity. Fig. 12 presents the results using a box and whisker plot, where each box shows the interquartile range (IQR) and the median number of empty breaker slots.

- **Homes with** ≥ **200 A panels:** These homes maintain a relatively stable median number of empty breaker slots, typically between three and six, regardless of the number of gas appliances. This

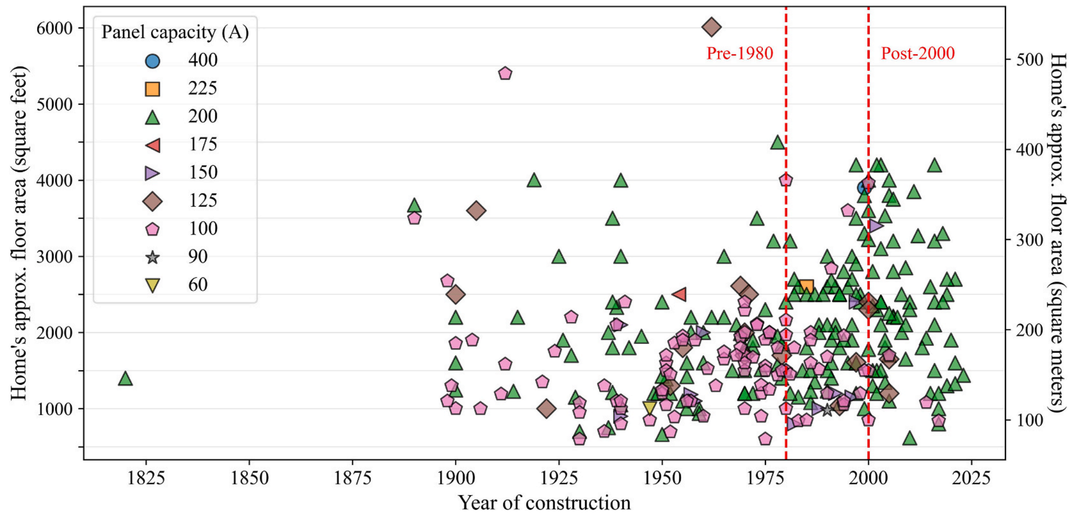

Fig. 9. Correlation among electric panel capacities, floor area, and year of construction.

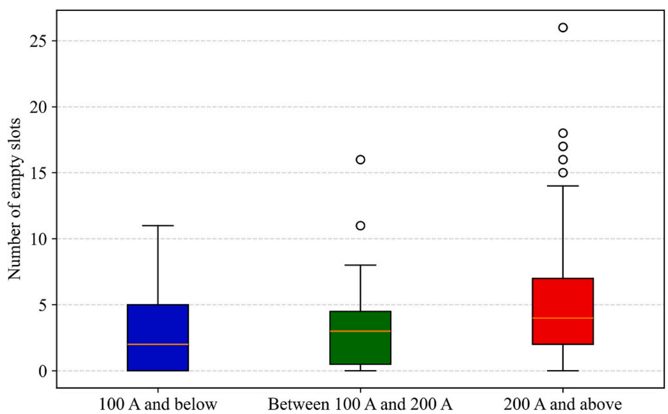

Fig. 10. Distribution of empty slots across different electrical panel ratings.

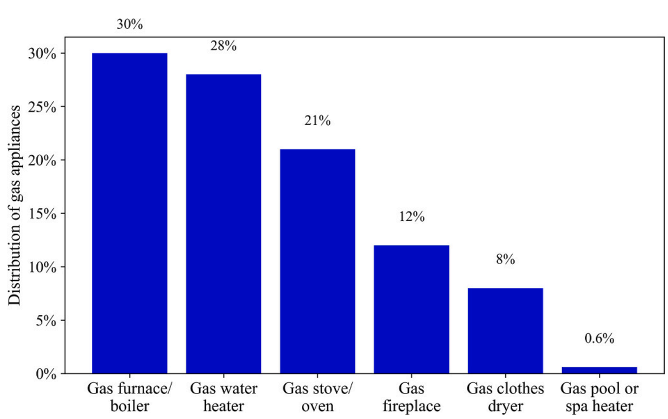

Fig. 11. Distribution of different gas appliances used in single-family homes.

consistency suggests that higher-capacity panels provide flexibility for electrification without requiring substantial electrical upgrades.

- **Homes with ≤ 100 A panels:** These homes show greater variability and generally fewer available slots, especially as the number of gas appliances increases. Interestingly, fully electric homes in this category show a higher median of five empty slots, possibly due to more efficient use of circuits or lower overall electrical load. However, as the number of gas appliances increases, the median number of empty slots drops to two or three.
- **Homes with panels between 101 A and 199 A:** These homes exhibit moderate capacity for circuit additions, with median empty slots typically ranging from two to five.

Overall, the trend indicates that homes with higher-capacity electrical panels offer greater adaptability for electrification, whereas lower-capacity panels, especially in homes with multiple gas appliances, may face significant limitations.

3.6. *Assessment of circuit breaker labels in electrical panels*

Proper labeling of circuit breakers is a fundamental safety requirement and an important factor for evaluating a home's current and future electrical capacity. According to the National Electrical Code (NEC 408.4(A)), all circuits must be clearly and legibly identified to indicate their specific loads. Proper labeling allows occupants, electricians, and inspectors to quickly and accurately identify circuit breakers, thus enhancing electrical safety and maintenance efficiency.

Our survey revealed substantial variability in labeling practices, as illustrated in Fig. 13. Some panels were fully labeled, others were partially labeled, and many lacked labeling entirely. Fig. 14 quantifies these observations:

- Among the 257 submissions depicting entire panels, only 28.8% had all circuit breakers labeled.
- Of the 91 submissions showing partial panels, only 15.9% were fully labeled.

Definitions used in Fig. 14:

- **Labeled**: Entire panel is visible, and each circuit breaker is labeled.
- **Not labeled**: Entire panel is visible but none of the circuit breakers are labeled.
- **Partially labeled**: Entire panel is visible but only some circuit breakers are labeled.

The low rate of complete labeling presents challenges for accurately assessing panel usage and the feasibility of adding new circuits. The lack of proper labeling is a potential safety hazard, especially during maintenance or emergencies. For instance, incomplete or incorrect labeling may cause delays in repairs or increase the risk of electric shock if a circuit is mistakenly assumed to be turned off.

These findings highlight the importance of enforcing standardized labeling practices during panel installation or upgrades, as they are

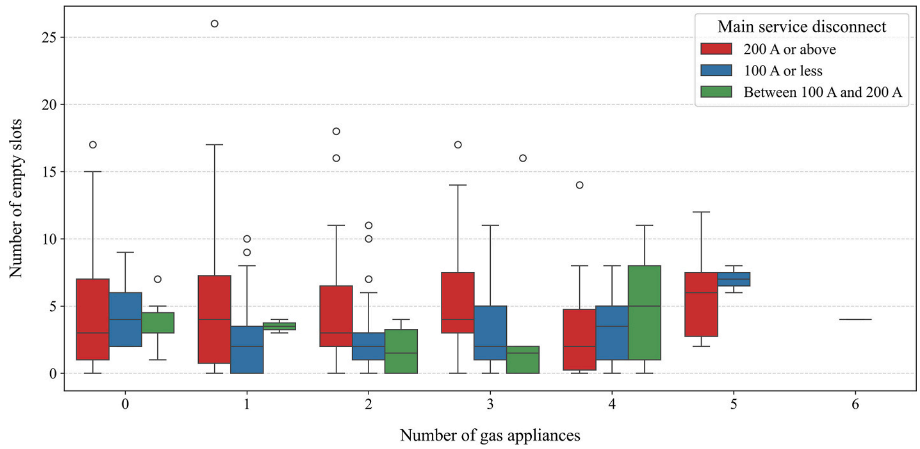

Fig. 12. Impact of number of gas appliances on empty breaker slots across panel ratings.

essential for ensuring safety, improving maintenance efficiency, and enabling better planning for future electrification needs.

3.7. Circuit breaker ratings for electric appliances

To assess how existing appliances use electrical panel capacity, we analyzed the amperage ratings of circuit breakers for common electric appliances. This analysis was limited to fully labeled panels in homes with panel capacities below 200 A, as these homes are more likely to face constraints in accommodating additional loads required for electrification. Table 1 summarizes the observed breaker ratings for key appliances.

Based on the data presented in the table, the following patterns in appliance electrical requirements are observed:

Central air conditioning units exhibit the greatest variability, with breaker ratings ranging from 20 A to 50 A (which typically requires 240V), reflecting differences in home size, climate conditions, and cooling requirements.

Appliances such as water heaters, ranges, ovens, and dryers show less variability in breaker sizes, suggesting more standardized power requirements across homes.

Electric resistance heating, observed in only one case, required a 60 A breaker, underscoring its substantial electrical demand.

These findings suggest that while many appliances have consistent load requirements, the electrical demand for air conditioning varies significantly based on home-specific factors such as size and regional climate. The limited number of fully labeled panels in our dataset constrains the generalizability of this analysis, but still provide useful insights into appliance-specific load implications for panel capacity planning.

3.8. Safety assessment of electrical panels

Although visual survey data cannot substitute for a professional electrical inspection, the identification of certain panel models, such as Federal Pacific Electric (FPE) Stab-Lok and Zinsco, can indicate potential safety concerns. FPE panels with Stab-Lok breakers, are known for failing to trip during overload conditions, posing a heightened risk of electrical fires (What to do if You). Similarly, Zinsco panels have a history of breaker malfunctions, including melting and fusing, creating fire risks (Dwellinspect Arizona - The Shocking Truth).

In our dataset, approximately 3% of homes had these high-risk panel types, specifically, six homes with FPE panels and three homes with Zinsco panels. Their presence, though limited in number, highlights the importance of including panel safety assessments in electrification planning. Proactive replacement of these outdated panels is essential not only for ensuring occupant safety but also for supporting the reliability and resilience of future all-electric systems.

Fig. 13. Variability in Circuit Breaker Labeling. These panels show the range of labeling practices found in our survey.

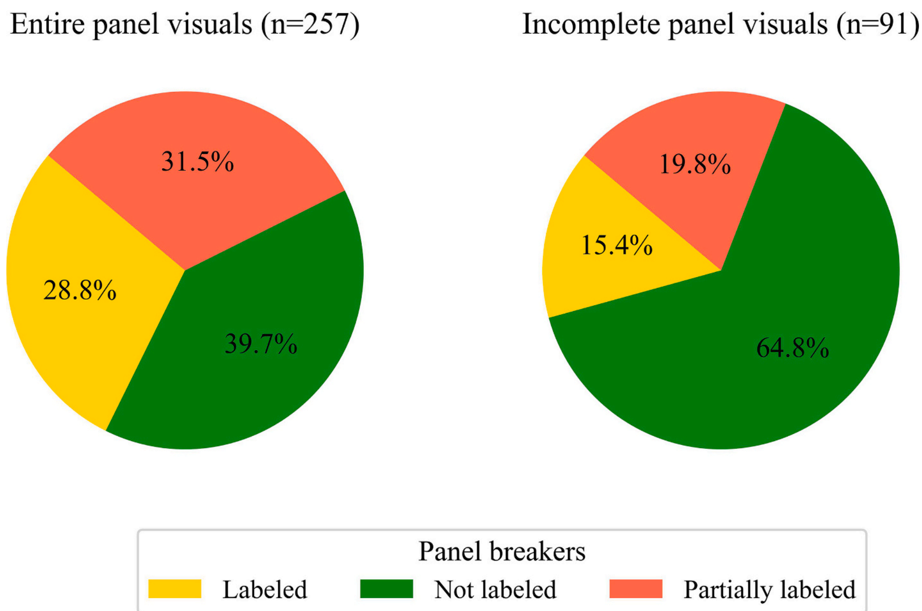

Fig. 14. Distribution of circuit breaker labeling completeness in electrical panels.

3.9. Correlation between electrical panel and home characteristics

To quantitatively evaluate the relationships observed in earlier sections, we conducted a Spearman's rank correlation analysis. Fig. 15 presents pairwise correlation coefficients among key variables related to electrical infrastructure and home characteristics. To evaluate the statistical significance of the observed correlations, hypothesis tests were conducted with the null hypothesis assuming no monotonic association exists between variables. A p-value < 0.05 was used to indicate statistically significant relationships. The key findings are:

- **Electrical panel capacity and its correlations with other variables**:
  - o **Year built**: Significant positive correlation ($\rho = 0.38$, $p < 0.001$) suggests that newer homes tend to have higher-capacity panels.
  - o **Floor area**: Positive correlation ($\rho = 0.34$, $p < 0.001$) indicates that larger homes are more likely to have higher-capacity panels.
  - o **Number of gas appliances**: Negative correlation ($\rho = -0.23$, $p < 0.001$) indicates that homes with higher-capacity panels tend to have fewer gas appliances.
  - o **Total and empty breaker slots**: Significant positive correlations with both the total slots ($\rho = 0.53$, $p < 0.001$) and the number of empty slots ($\rho = 0.19$, $p < 0.001$) show that higher-capacity panels are associated with more total and available breaker slots.
- **Total breaker slots and floor area**: Positive correlation ($\rho = 0.33$, $p < 0.001$) supports the finding that larger homes have panels with more slots.
- **Year built and number of gas appliances**: Negative correlation, though not statistically significant ($p > 0.05$), suggests that newer homes might be equipped with fewer gas appliances.
- **Number of empty slots**: Positive correlation with total number of slots ($\rho = 0.38$, $p < 0.001$), but no significant relationships were observed with other variables ($p > 0.05$).

Table 1
Circuit breakers current ratings for various appliances based on labeled breakers in the electric panels.

Appliances	Breaker ratings (A)
Central air conditioning units (Double-Pole breakers)	20, 25, 30, 35, 40, 50
Range (Double-Pole breakers)	40, 50
Oven (Double-Pole breakers)	30, 40, 50
Cooktop (Double-Pole breakers)	20, 30
Dryer (Double-Pole breakers)	30
Water heater (Double-Pole breakers)	20, 25, 30
Electric resistance space heating (Double-Pole breakers)	60
Well/Pool pump (Double-Pole breakers)	20, 30
EV charger (Double-Pole breakers)	40
Furnace	15, 20

The positive correlations between panel capacity and factors such as floor area, construction year, number of spare slots, and total slots indicate that newer and larger homes are generally equipped with higher-capacity panels that offer more breaker space and room for expansion. Conversely, negative correlation with the number of gas appliances suggest that homes more reliant on gas tend to have lower electrical demand and therefore typically lower panel capacities. The lack of a significant correlation between home age and gas appliance use implies that, while newer homes may be shifting away from gas, this trend is not yet consistent across the broader housing stock.

3.10. Cost implications of electrical panel upgrades

The cost of upgrading residential electrical panels varies widely based on factors such as geographic location, labor rates, and permitting requirements. A California-focused study (Fournier et al., 2024) reports average upgrade costs ranging from \$2,500 to \$5,000 per home.

Our analysis of panel slot availability (Fig. 10) indicates that homes with 100 A or smaller panels typically have limited remaining capacity (median of two empty breaker slots). This constraint persists across most of these homes, suggesting that a substantial share of these homes will require panel and service upgrades.

To account for variability in retrofit feasibility and housing characteristics, we estimate that 50–75% of homes with 100 A or smaller panels, equivalent to approximately 16–23% of all U.S. single-family homes, may ultimately require service upgrades. With an estimated 84 million single-family homes nationwide (including both detached and attached units), this translates to approximately 13–19 million potential upgrades.

We estimate the total investment for necessary panel upgrades ranges from \$32 billion to \$96 billion. These estimates highlight the

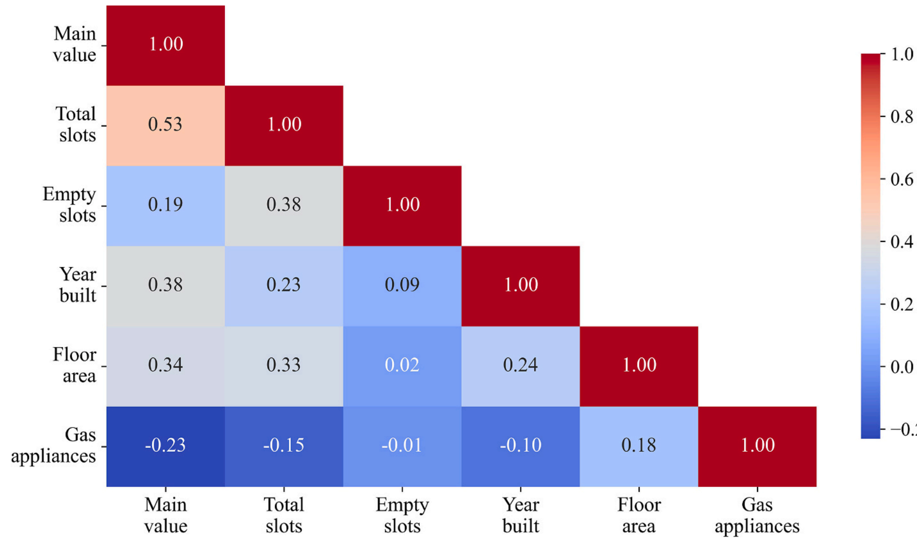

Fig. 15. Each cell shows the Spearman correlation coefficient between property features, with the adjacent color scale highlighting the correlation strength. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

potential scale of infrastructure investment required to support widespread residential electrification and emphasize the need for further research.

4. Limitations and future research

Although our survey-based approach successfully captured a diverse sample of U.S. single-family homes, several limitations should be acknowledged:

- **Sampling bias**: Using online platforms such as MTurk may introduce sampling bias, as respondents may not fully represent the general population in terms of demographics or geographic distribution. This limitation may result in the underrepresentation of certain regions and associated differences in housing characteristics and electrical infrastructure. In addition, the overall sample size (348 validated responses) limits the confidence of some findings, particularly for underrepresented regions and climate zones. Ongoing data collection will help improve the robustness of future analyses.
- **Lack of actual electricity consumption data**: This study did not incorporate household electricity usage data, which limits our ability to assess how electrical panel capacity aligns with real-world demand. In practice, household loads are often lower than code-based estimates due to the diversity of appliance usage. Future work incorporating measured consumption data and exploring load management technologies could provide a clearer understanding of when service upgrades are truly necessary.
- **Limited panel labeling**: Substantial variability and incompleteness in circuit breaker labeling limited the depth of our load analyses. Future studies should adopt improved data collection protocols that emphasize comprehensive photographic documentation of main panels, subpanels, and complete breaker labeling to enhance the accuracy of assessments of existing electrical loads and capacity.

To strengthen future analyses, we plan to implement targeted sampling strategies based on geographic regions. This will support more detailed regional analyses by climate zone and allow for a better understanding of how climate variability influences electrification readiness.

5. Conclusion

This study provides a comprehensive assessment of the electrification readiness of U.S. single-family homes, focusing on electrical panel capacities, breaker slot availability, and the prevalence of gas appliances. Our findings show a significant portion of newer and larger homes are equipped with panels rated at $\geq$ 200 A and have sufficient breaker slots to accommodate additional electric loads. However, many older and smaller homes face challenges due to lower-capacity panels ($\leq$ 100 A) and limited expansion capacity. These trends are further supported by correlation analysis, which shows strong associations between panel capacity and a home's construction year, floor area, and gas appliance use.

The study also quantifies the presence of known, unsafe electrical panels (approximately 3%). These panels pose fire and reliability risks, reinforcing the need to consider panel safety, not just capacity, during electrification planning.

In addition to capacity-related concerns, the study highlights a commonly overlooked issue: poor labeling of circuit breakers. We found that labels on individual circuits in electrical panels are often incomplete and sometimes incorrect. This lack of accurate labeling is potentially hazardous and can hinder both repairs and upgrades. Improving labeling practices should be considered an essential part of broader electrical upgrade efforts.

Our work contributes insights into residential electrical infrastructure, which will enable better targeted electrification programs. Future research should build on these findings by incorporating detailed load calculations, exploring regional variations and comparison to metered energy consumption data.

CRediT authorship contribution statement

Sadia Gul: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Alan Meier:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author used ChatGPT to improve the grammar and language. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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