A Comprehensive Survey of Electrical Panel Capacities in U.S. Single-Family Homes and Implications for Nationwide Electrification

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ABSTRACT

In the US, single-family homes are a major part of the housing sector. Achieving carbon neutrality by 2050 requires their electrification, transitioning from fossil fuels to electric alternatives. Central to this is optimizing electric panels for efficient electricity distribution within homes. It's crucial that these panels manage the increased electrical demand and integrate with modern energy management systems for safe and efficient home electrification. However, a data gap exists regarding electric panel capacities and the appliances they support. To better understand the current state of electric panels, a survey was conducted across US single-family homes using SurveyMonkey. The survey collected data on construction year, floor area, heating type, major appliances, and electric panel data, verified with photographs. However, out of 565 submissions, only 281 met our validity criteria, highlighting data accuracy challenges. The data reveals that 62% of homes have 200A panels, with an increase in 200A panels post-1960s and a decline in 100A panels post-2000. Larger homes, particularly those built after the 1960s, often have higher capacity panels. However, some smaller homes have 200A panels, while certain larger homes are equipped with 100A panels. A strong correlation exists between heating sources and panel capacities, with homes having higher panel capacities often opting for electric heating. In conclusion, house characteristics provide valuable insights into electric panel capacities, yet precise predictions remain challenging.

Introduction

To attain the global climate goals of carbon neutrality by 2050, reliance on renewable energy, enhanced energy efficiency, and prioritization of electrification are imperative. This shift towards electrification, especially in critical sectors such as transportation, industry, and buildings, is crucial for sustainability and emissions reduction (Gielen and Boshell 2021). In alignment with global efforts, the United States has also committed to achieving net-zero carbon emissions by 2050 (Horowitz 2021). A significant step forward is the Inflation Reduction Act (IRA) of 2022, landmark legislation that earmarks substantial funding and incentives to promote clean energy and energy-efficient technologies across various sectors, including buildings. Specifically, the IRA designates $8.8 billion for enhancing home energy efficiency and supporting electrification efforts, providing grants for state-led Home Efficiency Rebates programs aimed at encouraging homeowners to invest in energy-efficient improvements (DOE 2023).

Building electrification, a key element of this transition, involves the shift from fossil fuels to electricity for heating, cooling, and cooking in residential buildings. This encompasses several components, including space heating, water heating, clothes drying, stoves, and even heating systems for pools and spas. Transitioning to electric heat pumps from fossil fuel-based heating systems can reduce CO_2 emissions by 38–53%, with the potential for greater reductions as the electrical grid becomes cleaner (Pistochini et al. 2022). Moreover, replacing gas furnaces with electric heat pumps can achieve cost and carbon neutrality, particularly when updating from older, less efficient systems (Walker, Less, and Casquero-Modrego 2022). In special cases, electric resistance heating can be used as a substitute, but at the cost of much higher electrical demand. Electric heat pump water heaters (HPWHs) outshine both gas and conventional electric heaters in efficiency, potentially cutting evening peak load power by up to 90% and thereby reducing costs for both utilities and consumers (EERE 2019). These modern HPWHs typically include backup electric resistance heaters to maintain efficiency and reliability under colder conditions. The efficiency of clothes dryers is also improving, with heat pump technology surpassing the energy use of traditional models. A government initiative is now promoting the standardization of dryer efficiency, advocating for the adoption of ENERGY STAR-certified models, including heat pump dryers (EERE 2022). In the realm of cooking, induction cooktops offer superior energy efficiency over gas stoves, providing faster cooking times and precise temperature control. They are up to 85% efficient in transferring heat, compared to 32% for gas, and use significantly less energy (Bui 2023; Energy Star n.d.). Pool heating is also moving towards electrification with heat pump pool heaters. These heaters can achieve up to 700% efficiency, promising long-term savings despite their higher upfront costs (DOE n.d.). Another critical component of this transition is the adoption of electric vehicles (EVs), which present a cleaner alternative to gasoline vehicles by eliminating tailpipe emissions. As the electrical grid continues to incorporate more renewable energy, the overall impact of EVs will become even more positive, contributing to the goal of a net-zero carbon economy by 2050 (EPA 2021).

Despite ambitious goals and legislative support for achieving a net-zero carbon economy, technical and infrastructural challenges hinder the United States' rapid electrification. Many existing homes have electrical panels that are not adequately sized or equipped to handle the increased electrical load associated with electrifying various systems, such as heating, cooling, and cooking (Deziel 2023). Additionally, the internal wiring, including circuits and connections to the main electrical panel, may be outdated and incapable of safely handling the higher currents required by modern, electrified appliances, posing potential safety hazards or system failures. Furthermore, utility distribution systems often lack the capacity to manage the surge in demand that widespread electrification would bring.

Electrical panels, central to a home's power system, distribute electricity to circuits. The capacity of these panels is measured in amperes (A), determining the total electrical load they can support. When a panel's capacity is insufficient, it limits the ability to connect and use new, power-intensive devices. With the increasing electrical demands due to widespread electrification, upgrading to a panel with a higher amp rating is frequently necessary (Clean Energy Connection 2022). In estimating electric panel capacity for single-family homes, it is essential to consider a range of factors beyond the mere number and type of appliances. Key considerations include the likelihood of multiple appliances running concurrently, which can necessitate a higher capacity to avoid overloading, and future expansion possibilities for appliance addition or upgrades and new electric systems. Local climate is another significant factor, as it affects heating and cooling system use, which are major contributors to the electrical load. The energy efficiency of appliances also cannot be overlooked; modern, more efficient appliances can substantially reduce the overall electrical load. Furthermore, household size and lifestyle, particularly in larger or high-use households, may demand increased capacity. It's advisable to include a safety margin in the panel's capacity for unexpected surges or loads.

Additionally, adhering to the National Fire Protection Association's National Electric Code (NEC) guidelines ensures compliance with minimum standards for electrical systems, including panel capacities, crucial for safely managing peak demands (NFPA 2023).

Other studies in the U.S. regarding electrical panels have focused on specific regions or aspects. For example, Pecan Street's research examined single-family homes, primarily post-2007 constructions in Texas. This study's regional focus and emphasis on newer homes suggest its findings might not be broadly applicable to the entire U.S. (Merski 2021). The Technology and Equipment for Clean Heating (TECH) Clean CA surveyed installers of heat pump systems in single-family homes, concentrating on the need for electrical panel upgrades. This study provided insights into the frequency and cost of such upgrades, but again, it was limited to California (TECH 2022). These studies highlight the need for more comprehensive research that encompasses a wider range of homes across the U.S. to understand the correlation between house characteristics and panel capacity more accurately.

Recognizing the gap in data regarding the capability of residential electrical infrastructures to meet the demands of electrification, our research focuses on evaluating the electrical panel capacities of single-family homes across the United States. The objective of this study is to understand the relationship between house characteristics and panel capacity, specifically to determine how many single-family homes lack sufficient panel capacity for converting all gas appliances to electric. We initiated this study in August 2022 and are continuing to collect data from single-family homes nationwide. The Electric Power Research Institute (EPRI) conducted a similar study from August to October 2022, focusing on the current capacity of residential electric panels across the United States (EPRI 2022). In this article, we will discuss the methodology for collecting our preliminary data, address challenges encountered during analysis, results and compare these initial findings with those of the EPRI study.

Methodology for Understanding Electrification Readiness

We conducted a survey to better estimate the number of homes where panel capacity may be insufficient to electrify. We utilized SurveyMonkey in conjunction with Amazon Mechanical Turk to distribute our survey, focusing on single-family homeowners across the United States. This strategy allowed us to collect a diverse and comprehensive dataset, introducing randomness to our sampling method to improve representativeness. The anonymity of the survey ensured participant privacy and will facilitate the future public release of the dataset, setting our study apart from others. Participants were incentivized to provide accurate responses, enhancing data reliability.

Our survey was meticulously designed to capture essential aspects of single-family homes and their electrical infrastructures. The 12 survey questions were tailored to understand homes unique electrical panel requirements. We collected geographical data, including city, zip codes and state information, to account for regional variations. To assess the dynamics of energy use, participants provided information on their primary heating fuel, and the main electrical and gas appliances in their homes. Additionally, questions about the floor area, year of construction of the homes, and the main breaker rating were also included. A key aspect of our methodology to ensure the accuracy and reliability of the data, involved requiring participants to submit photographs of their electrical panel. This included an image showing the complete panel and another providing a close-up view of the Main Service Disconnect rating, allowing us to directly verify reported panel capacities.

Following the successful collection of 565 surveys via Amazon Mechanical Turk, our next step focused on thorough validation of this data. Our validation process employed specific techniques to ensure data authenticity. Reverse image searches were conducted to determine if the submitted panel pictures were available online, which would indicate fraudulent submissions. For metadata examination, we recognized that images downloaded from the internet often lack metadata, a clear sign of inauthenticity. In contrast, authentic submissions typically include metadata with timestamp correlating with the survey completion period. This metadata not only helps confirm the genuineness of submissions but also indicates that most images were likely taken with personal devices during the survey process. While it's possible to alter metadata, we considered it unlikely that participants would engage in such sophisticated tampering for the purposes of this survey. The survey submissions were categorized as 'good', 'uncertain', or 'error' based on the outcomes of our verification process. Those labeled as 'error' due to implausible main breaker ratings were deemed inaccurate and excluded.

After the initial validation process, we further scrutinized the remaining 'uncertain' and 'good' surveys. This involved addressing issues such as multiple submissions from the same respondent, and submissions with identical pictures but varying survey data. Anomalies, like submissions showing a large home with minimal appliances, were also examined for accuracy. We conducted a detailed cross-referencing of the labeled circuit breakers in the electric panels against the appliances listed in the surveys to spot inconsistencies. This rigorous approach led to the identification of 281 'good' submissions that were suitable for analysis. Additionally, at this stage of analysis, we also counted the total number of slots and empty slots present in each panel, as visible in the photographs submitted by the respondents. This step was vital in assessing the panels' current utilization and their capacity for future expansion.

To identify trends and correlations in the survey data in the exploratory analysis we utilized various visualization techniques to interpret the data effectively. This involved:

1. Analyzing electric panel capacities in single-family homes, highlighting the prevalence of different capacities and identifying trends over time.
2. Examining the relationship between electric panel capacities and home characteristics such as construction period and floor area.
3. Investigating how heating types influence panel capacities across various house sizes and construction years.
4. Exploring the distribution of empty slots in electrical panels to understand the potential for future expansions.
5. Comparing our findings with external studies, like the EPRI study, to validate our results and provide context.

This approach allowed us to draw meaningful insights from the data and understand the complexities of electric panel capacities in relation to home electrification readiness.

Results and Discussion

In this study, our primary objective was to explore the intricate relationship between single-family homes (considering characteristics such as area, location, appliances used, and age) and their electric panel capacities. Additionally, we examined the number of unused or spare slots in the panels, as these are crucial for potential upgrades and future electrification initiatives.

Descriptive Analysis

In our initial exploratory analysis of the survey responses, we aimed to uncover patterns, trends, and potential outliers within the data. Figure 1 illustrates the varying capacities of electric panels installed in single-family homes. It highlights that a significant majority, over 62.5%, are equipped with electric panels of 200A capacity or more, indicating a trend towards higher capacity installations. In contrast, approximately 29.5% of the homes have electric panels with capacities of 100A or less. A smaller segment, around 7.8% of the homes, have electric panel capacities ranging between 100A and 200A. This categorization highlights the varying electrical infrastructure across different households and aids in understanding the current landscape of electrical capacity in residential settings.

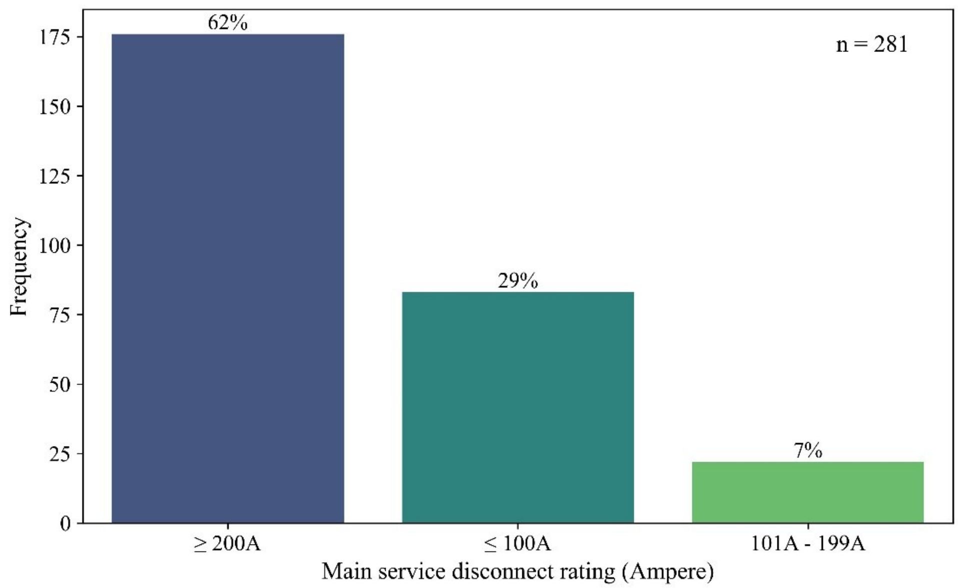


Figure 1: Distribution of electric panel capacities in single family homes

Figure 2 reveals trends in electrical panel capacities for single-family homes across different construction decades. It shows that homes built after the 2000s predominantly feature panels with 200A capacities, reflecting a shift towards higher-capacity installations in newer constructions. The period from 1960 to 2000 displays a mix of panel capacities, ranging from 100A to 200A, indicating a transitional phase in electrical infrastructure. Prior to 1960, panels with a capacity of 100A were more prevalent. This change in panel capacity over time is likely influenced by updates in building codes, advancements in electrical standards, and the evolving energy demands of households.

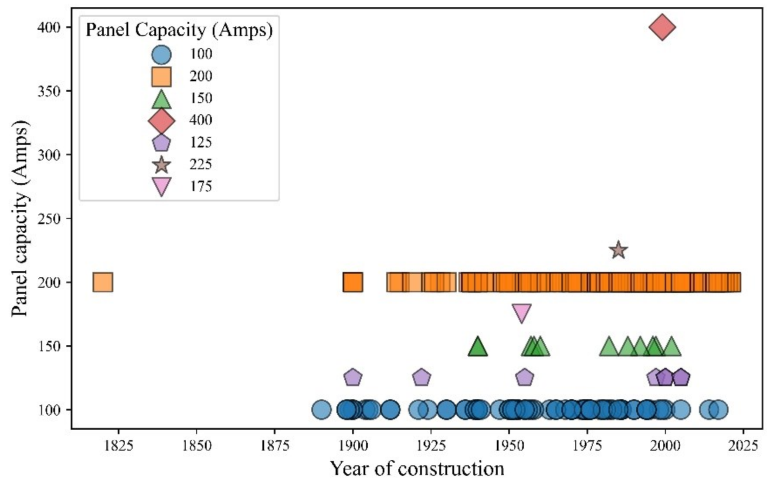


Figure 2: Trends in electric panel capacities relative to construction periods of single-family homes

The correlation between electric panel capacity and the floor area of a home is explored in Figure 3. The analysis reveals that homes less than 2000 square feet typically have 100A panels. However, the presence of 100A panels in some larger homes suggests that factors beyond mere size influence panel capacity, possibly including the age of the electrical installation or regional energy requirements. Panels with capacities ranging from 125A to 175A are generally found in homes larger than 1000 square feet, indicating a trend towards higher capacities in medium to large homes. Interestingly, while 200A panels are most common in larger homes, they are also present in a significant number of homes between 1000 and 2000 square feet, and even some homes under 1000 square feet have 200A panels. This indicates a complex relationship between home size and panel capacity, potentially reflecting a trend towards higher capacity panels irrespective of home size, influenced by modern energy demands or updates in building regulations.

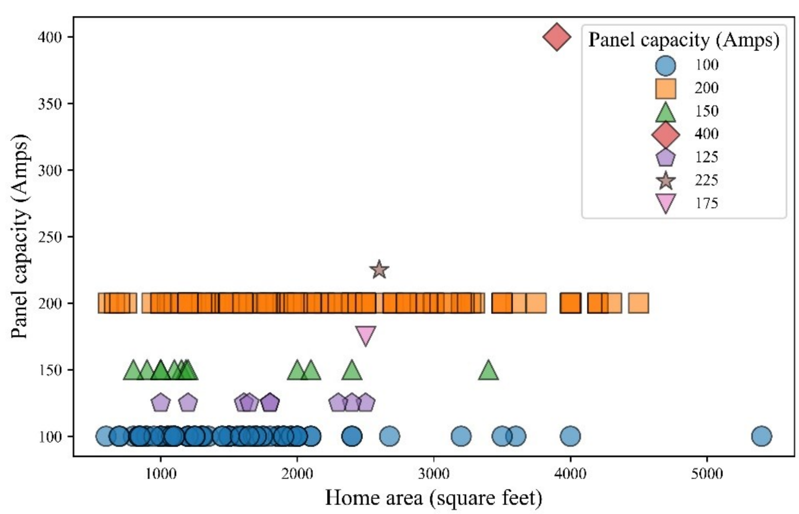


Figure 3: Relationship between approximate home floor area and electric panel capacity

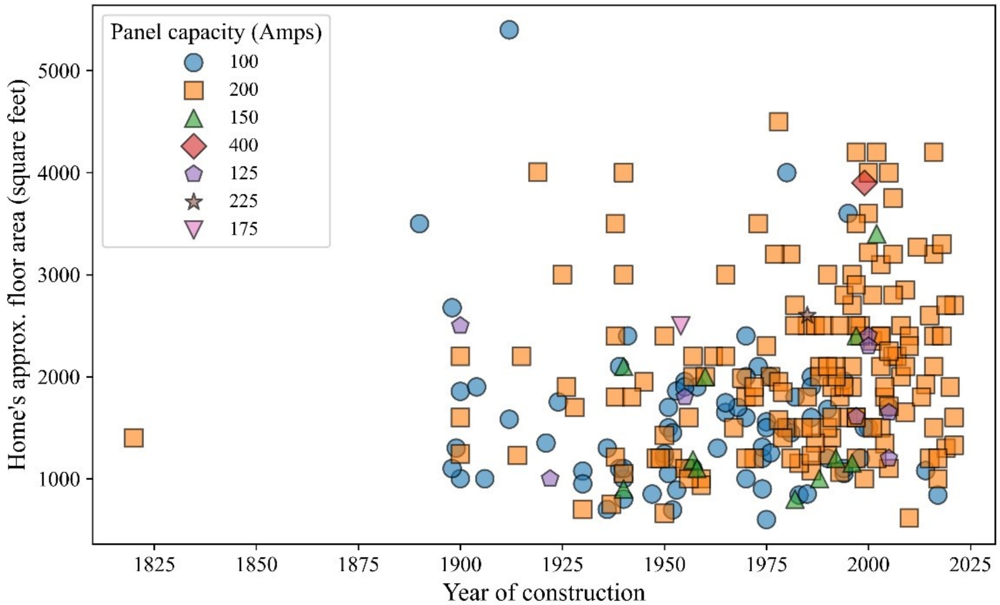


Figure 4: Comparative analysis of electric panel capacities, floor area and year of construction

Figure 4 illustrates the complex interplay between a home's floor area, electric panel capacity, and construction age, highlighting how electrical infrastructure choices have evolved over time. Newer homes, particularly those constructed after 1975, mostly feature 200A panels. However, instances of 200A panels in homes built before 1960 are also noted, suggesting retrofits or significant updates to older electrical systems. Homes equipped with 100A panels are generally smaller, typically under 3000 square feet, and were more commonly constructed before 1975. The period from 1975 to 2000 shows a diverse mix of 100A and 200A panels, with 100A panels mostly found in homes under 2500 square feet. This variance, including notable exceptions such as an older home with 200A panel capacity, indicates that factors beyond construction age and size—possibly including homeowner renovations or changes in building codes—can influence panel capacity. This analysis enhances our understanding of the relationship between home size, age, and electrical capacity, providing valuable insights for future residential electrical planning and policy development.

The influence of heating fuel type on electrical panel capacities across varying house sizes and construction years is depicted in Figure 5. It is apparent that homes equipped with 100A panels predominantly use gas heating, a trend that persists across all house sizes and construction years. In contrast, the capacities ranging from 125A to 175A, especially in homes built post-1975, show a distinct pattern where smaller homes frequently use electric heating while larger ones generally favor gas, indicating a varied preference based on house size. Moreover, older homes (pre-1960) equipped with 200A or higher capacities exhibit a notable preference for electric heating. This suggests that the demands of electric heating systems may drive the need for higher capacity panels. These intricacies highlight the complex interplay between heating preferences and panel capacities, which were not fully captured when only considering house age and size as shown in Figures 2-4. The correlation patterns observed here underscore the need to consider a broader range of factors, including heating type, when assessing the suitability of electrical infrastructure in residential settings.

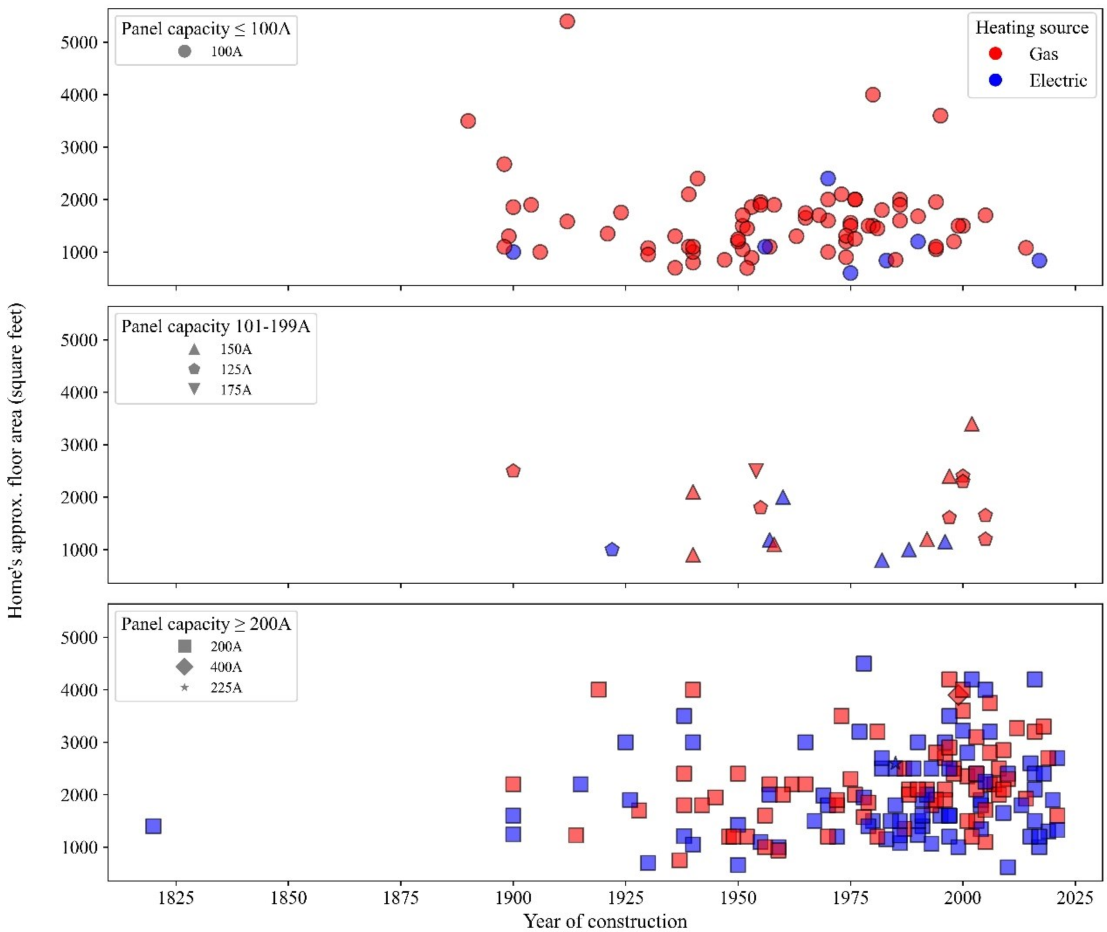


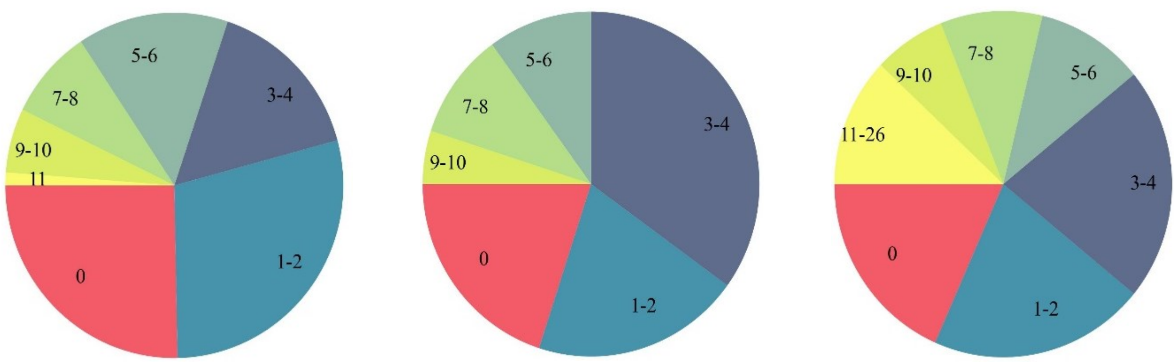
Figure 5: Comparison of electric panel capacities to home floor area, year of construction, and heating source preferences.

By examining the number of empty slots in electric panels, as shown in Figure 6, we gain insights into their potential for adding more circuits. Among panels rated at 100A and below, 25% have no space left for additional breakers, indicating they are fully utilized. Additionally, 55% of these panels have only 1 to 4 empty slots, suggesting limited capability for expansion. Panels with 5 or more empty slots are less common in this category, highlighting that smaller panels are often used to their full capacity.

Looking at panels with ratings between 100A and 200A, we see a different trend. About 35% of these panels have 3-4 empty slots, which is the most common situation in this group. It shows a bit more room for new circuits, but the capacity is still somewhat limited. Interestingly, 20% of these panels are completely full, with no empty slots. For panels rated at 200A or higher, the pattern changes again. Here, 18% have no space for more breakers. But there's a wider range in the number of empty slots available, from 1 to 26. Specifically, 22% have 3-4 empty slots and 12% even have between 11 and 26 empty slots. This shows there's more variability in how these larger panels are used and more potential for adding new circuits.

When we look at the number of available slots in panels of different ratings, it's important to consider the total number of slots available for circuit breakers in each panel category. Panels rated at 100A or less usually have around 19 slots, but this can vary from 10 to 32 slots. For panels with ratings between 100A and 200A, the average number of slots is slightly higher, about 21, with a range from 14 to 32 slots. The difference is more pronounced in panels rated at 200A or more. These usually have around 29 slots but can range widely, from 8 to 80 slots. This diversity in panel sizes shows the complexity involved in assessing available space for extra circuit breakers.

For instance, having 3-4 empty slots in a panel rated at 200A or above suggests a different scenario compared to a panel with a 100A rating or less, even if they have the same number of empty slots. In homes with 200A panels, a higher number of slots are already occupied, often indicating the presence of more electric appliances. As shown in Figure 5, most homes with 200A panels primarily use electricity for heating. Therefore, having 3-4 empty slots in these homes might be sufficient for their needs, considering they may not require many gas appliances to be converted to electric ones.



a: Empty slots distribution in panels rated 100A and below

b: Empty slots distribution in panels rated between 100A and 200A

c: Empty slots distribution in panels rated 200A and above

Figure 6: Distribution of empty slots across different electrical panel ratings.

In contrast, homes with 100A panels, which more commonly rely on gas, might find 2-3 empty slots to be inadequate. This is due to their already limited panel capacity and the presence of more gas appliances that may need to be switched to electric in the future. Additionally, the consideration for future needs, such as EV charging, adds another layer of complexity. Homes with 200A panels are likely more prepared for these advancements, given their larger capacity and existing configuration of electric high-demand appliances. This readiness for additional electrification efforts or future expansions is less pronounced in homes with 100A panels, highlighting the importance of not just the number of empty slots but also the panel's total capacity and the existing appliance configuration in evaluating a home's electrical system for future needs.

After comprehensive analysis of our data, as detailed in the preceding figures and discussions, we will now compare our study's findings with the results of the EPRI study. The EPRI survey, similar to our own, aimed to assess the readiness of residential electrical systems for the transition to all-electric homes, with a particular emphasis on integrating new electric technologies such as electric vehicles (EVs) and heat pump systems.

Our study underscores a correlation between the age of a building and its electric panel capacity. We found that homes built before 1960 are significantly more likely to have panels with capacities of 100A or less, at rates 5-9 times higher than those constructed after 2000. This trend is clearly depicted in Figure 8, aligning with the patterns observed in the EPRI study's Figure 7 (Lindsey 2023).

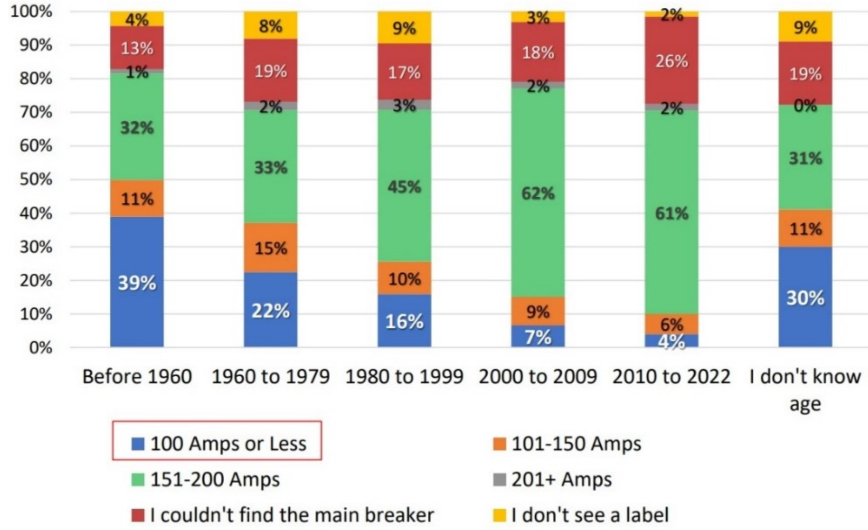


Figure 7: EPRI study panel capacity correlation with home age. Source: Lindsey 2023

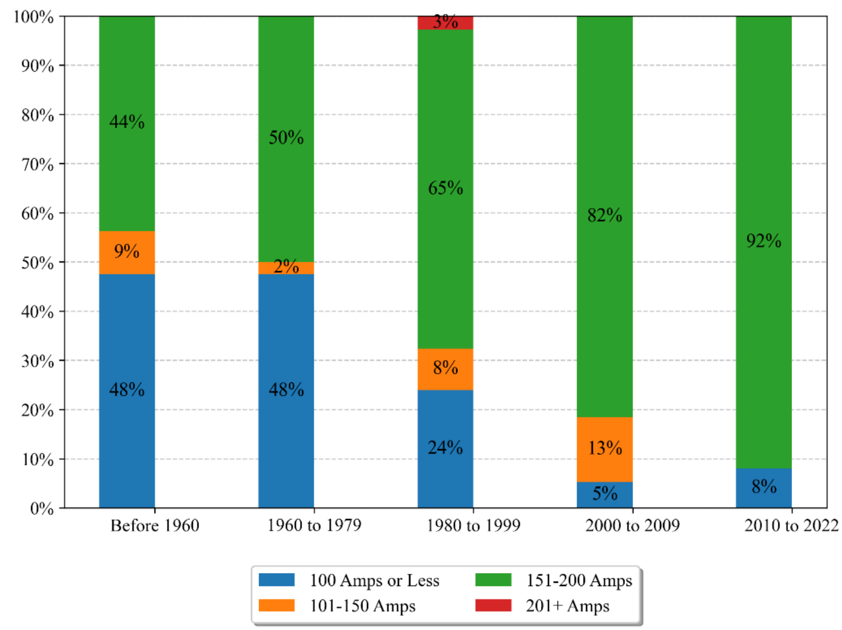


Figure 8:Panel capacity correlation with home age

Similarly, when examining the correlation between panel ratings and house size, the EPRI study concluded that smaller homes are more likely to be equipped with 100A panels. Our analysis also suppport these findings, showing a higher concentration of 100A panels in smaller homes as depicted in Fgure 8. However, upon a closer comparison, our data shows a higher prevalence of 100A panels in smaller homes compared to the EPRI study's findings.

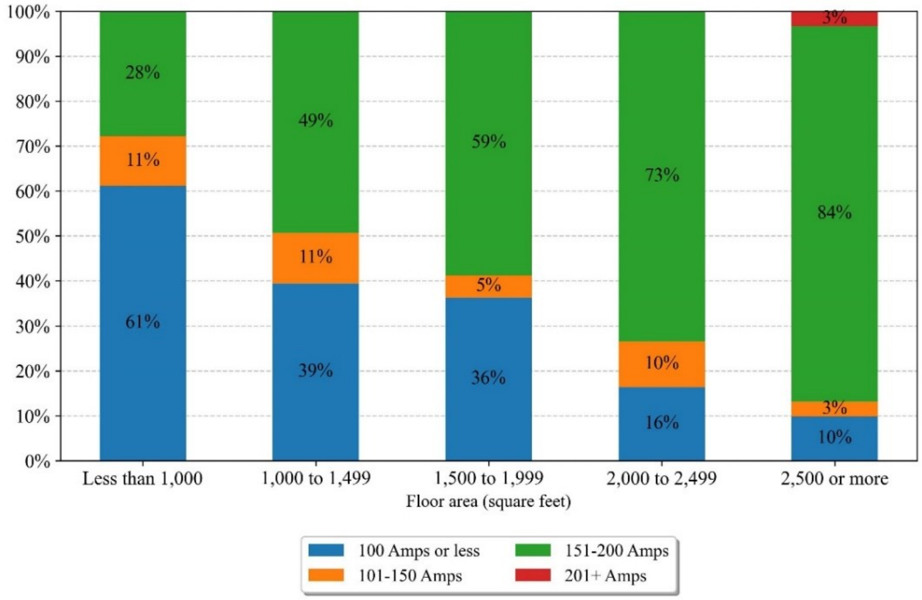


Figure 9: Correlation of home size and panel capacity

For instance, in our study, the proportion of homes under 1000 square feet with 100A panels was 59%, as opposed to EPRI's reported 37%. In general, our analysis revealed that smaller homes in our study more frequently had 100A panels than those reported by EPRI. Overall, our dataset showed that 29% of homes had 100A panels or less, which contrasts with 21% in the EPRI study (Lindsey 2023). This disparity might explain the variations observed in our study.

While we referenced the EPRI study through publicly available presentations slides, the inaccessibility of the full report limits our comparative analysis to summarized data, preventing a detailed point-by-point comparison. This constraint emphasizes the preliminary nature of our findings. Furthermore, understanding regional variances in electrical panel capacities is essential due to the impacts of local climates and building practices. As our data collection continues, we plan to expand our dataset and conduct a detailed geographical analysis. This future work will enhance our understanding of how regional factors influence residential electrification readiness across the United States.

Implications and Recommendations

The results indicate that newer homes tend to have larger electric panel capacities compared to older homes, especially those using gas heating, which may have insufficient capacities. This underscores the need for policies that facilitate the upgrading of electrical infrastructure in existing homes.

Financial incentives or subsidies for homeowners to upgrade their electric panels could ease the transition to electric appliances and heating systems. Specifically, considering the increasing adoption of electric vehicles, which significantly impact electrical load, our findings suggest a pressing need for homes to support higher-capacity panels to manage future demands.

Given the preference for gas heating in homes built before 2000, policy measures could target these older homes for electrification efforts. This might involve incentives for replacing gas heating systems with electric options, such as heat pumps, and for installing energy-efficient electric appliances.

The survey's findings could prompt policies that fund research and development efforts focused on making electrical upgrades more affordable and less invasive. This research could explore innovative technologies or methods for increasing the capacity of existing electrical panels without the need for complete replacements, thereby reducing the barriers to home electrification.

To ensure that new constructions are equipped to handle future electrification needs, policies could advocate for the standardization and modernization of building codes. These updated codes would require that new homes are built with electric panels of sufficient capacity to support a fully electric load, including electric vehicles charging, thus future-proofing new constructions against evolving energy needs. Implementing such policies could not only improve energy efficiency but also enhance property values and contribute to national goals for reducing carbon emissions.

Conclusions

While our survey-based approach enabled broad data collection from U.S. single-family homes, it's crucial to recognize the inherent limitations of self-reporting. The accuracy of data relies heavily on respondents' knowledge and honesty. Moreover, direct home audits, though more reliable, are impractical on a large scale due to logistical, financial, and privacy concerns.

Despite these challenges, our study provides critical insights into the readiness of U.S. single-family homes for the transition to a fully electrified, carbon-neutral future. Notably, we observed a significant trend towards higher-capacity (200A) electric panels in newer homes post-2000, which suggests a degree of preparedness for increased electrical demands, including the growing necessity to accommodate electric vehicle charging. However, the widespread presence of lower-capacity panels in older homes presents a substantial barrier, underscoring the need for targeted infrastructure upgrades.

The correlation between home size and panel capacity is complex and not directly intuitive. For instance, while some smaller homes surprisingly possess 200A panels, certain larger homes are equipped only with 100A panels. Additionally, the type of heating—electric vs. gas—significantly influences the panel capacity, with homes using electric heating often having higher capacities.

This varied landscape highlights the critical need for nuanced, well-targeted electrification policies that consider these diverse factors. Moving forward, it is imperative that policymakers and stakeholders address these disparities to ensure all homes, regardless of age or size, can support the shift towards sustainable energy solutions.

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