Peak vs Panel: Insights from Submetering LMI Electrifications

Benjamin King, Center for Energy and Environment
Madhu Bhargava, ComEd
Samantha Hill, PhD, Center for Energy and Environment

ABSTRACT

Electric panel capacity and service limitations are significant barriers to whole-home electrification retrofits, particularly for low- and moderate-income (LMI) households. A single electric panel and service upgrade can cost upwards of $10,000, potentially doubling the cost of electrifying the most energy-intensive load in the average home: the heating and cooling system. These high costs place electrification out of reach for many. Yet, panel upgrade decisions are often based on conservative assumptions, not real-world data. This paper provides a detailed analysis of how whole-home electrification (WHE) retrofits impact electric peak loads in cold climate homes. High-resolution submetering in twenty single-family homes is used to quantify peak panel loads and the individual contributions and coincidence between major appliances including heat pumps, water heaters, dryers, and stoves. Observed peak loads are also compared to the estimates commonly used for service sizing and upgrades. Observed peak loads are found to be significantly lower than NEC estimates across all sites monitored. NEC-estimated median was 175 amps while the field monitored median was 87 amps with 240-volt service. There is evidence that WHE is possible with 100-amp panels, but current estimate methods don't support it. This study offers timely insights for program designers, utilities, and policymakers working to expand electrification equitably by providing real electric usage data for cold climates homes.

Introduction

Whole-home electrification (WHE) retrofits are a strategy for homeowners to reduce energy use, save on utility bills, and lower environmental impacts. For most homeowners, WHE requires replacing appliances including HVAC systems, hot water heaters, dryers, and stoves. While total site energy use often decreases after WHE, electricity use can increase significantly. Electric usage encompasses both total electric energy consumption and the peak electric load, which is the average electric power or energy usage rate during a short time interval. The expectation of increased peak loads after WHE often leads to electrical service and/or panel upgrades during WHE projects. The median price of a panel and service upgrade was $10,500, and the cost of a panel-only upgrade was $4,870 for homes in this study. The high price of these upgrades can be a barrier for WHE projects as previously identified (Less 2024). This is especially important to low- and moderate-income (LMI) customers who are more sensitive to cost increases and the electrification programs that aim to maximize savings with their available funding.

A panel upgrade is the full removal and replacement of a building's main power breaker and electrical distribution panel. This is done to increase the peak load capacity and/or increase the breaker spaces in the panel. A service upgrade is the replacement of a building's exterior power supply lines, which sometimes also requires a utility meter replacement and almost always requires an accompanying panel upgrade. Existing panels are sized to their existing service capacity or less, so a panel upgrade is generally required to use additional capacity provided by a service upgrade. In contrast, some panel upgrades can be completed without a service upgrade if the existing panel capacity is less than the existing service capacity. This is useful if the existing service capacity is sufficient for WHE, but not the panel. Ultimately, every home needs to be independently assessed to determine if the panel, service, both, or neither are limiting factors for electrification.

Local electric codes govern and define electrical capacity rules and requirements. In most of the United States, local codes align with a recent version of the National Electric Code (NEC) (NFPA 2023, Article 220). One aspect of this code is to ensure that the expected peak load of all circuits does not exceed the rated peak capacity of a home's electrical service and panel. Electric service lines, meters, and panels all have maximum safe load ratings. If typical electric demand in a home regularly exceeds these limits, breaker trips will occur and safety may be compromised from excessive wear. Peak load estimates are used to design for expected power use and avoid these issues.

Electricians often perform a peak load estimate in accordance with NEC article 220 (NFPA 2023, Article 220), which provides a method for calculating minimum panel capacity using appliance rated power, home size, and estimated coincident load factors. Local regulators may also supersede the NEC methods with their own requirements. Different calculation methods can result in different recommendations depending on the details of a home, further complicating an already complex electrification process. This paper quantifies real world peak electrical loads in recently electrified homes and compares them to the estimate methods most frequently used to qualify panel and service upgrades. The data presented here can inform electrification strategies that avoid costly electrical infrastructure upgrades. Emerging methods of avoiding or delaying upgrades include choosing appliances with lower peak electric loads, load management devices, smart panels, and on-site energy storage systems. These are later discussed in the context of the real-world data gathered for this study.

Methodology

The end-use energy monitoring described here is one component of a larger field study that monitored appliance-level loads and heat pump performance at 20 single-family homes that completed income-qualified electrification projects through their utility's LMI electrification program. Recruitment and monitoring were conducted by Center for Energy and Environment (CEE) independently of the LMI WHE program as a voluntary paid research opportunity. Homeowners were not required to modify their systems or behavior in any way to participate. Optional interventions included notification when electric appliances needed repair and assistance with contacting contractors for service. All study sites had heat pumps with electric resistance backup, heat pump water heaters, electric dryers, and a mix of electric resistance and induction ranges.

Data about electric appliances and upgrades performed at homes was collected from contractor invoices and on-site observations by CEE researchers. Contractor invoices for most sites listed model numbers of the newly installed appliances and often specified total costs related to electrical upgrades although they rarely clarified whether a panel or service upgrade was performed as part of that electrical work. To verify the work completed, images were collected of the new appliances and their nameplates for later comparison to invoices. Photos were taken of the electric panel, electrical mast, and electric meters for comparison to pre-electrification inspection data available at most sites. Review of these photos helped determine if the panel or service had been upgraded.

Panel capacity and breaker spaces occupied were also documented for the old and newly installed panels from those photos. Three sites did not have documentation of the previous panel, but these were documented as panel and service upgrades by the contractors' invoices, and it was assumed that they were 100- to 200-amp upgrades. All other sites were verified through observation by research staff. Most sites received panel and service upgrades from 100 to 200 amps as shown in Table 1.

Table 1. Electrical panel and service upgrade prevalence for monitored sites

Upgrade	Sites	Context
No upgrade	2	Had existing 200A panels
Service only	0	It is not expected that service would be upgraded alone
Panel only	1	Upgraded from 100A to 200A with existing 200A service capacity
Panel + service upgrade	17	16 were 100A to 200A upgrades. One site had an existing 200A panel replaced, possibly for safety.

High-resolution electric consumption data for major appliances was collected using an eGauge Core submeter. The appliances monitored included heat pumps (HP), electric resistance (ER) backup heat units, heat pump water heaters (HPWH), electric dryers (dryer), and induction stoves (stove). These appliances required independent 240V breakers that allow for individual appliance monitoring except for the air handler, which shares the electric resistance circuit. The submeter collected electric consumption data for each circuit on both split phases every second. Lower-resolution whole-home energy use data was obtained from the electric utility's advanced metering infrastructure (AMI) data for each site. AMI monitors total energy use at the meter and reports energy consumption in 30-minute increments for the entire monitoring period.

Approximately one year of end-use and advanced metering infrastructure (AMI) energy consumption data was collected for 20 monitored sites. The end-use dataset provided 15-minute consumption summaries for the five major appliances, while the AMI dataset recorded whole-meter electricity consumption at 30-minute intervals. To account for loads not captured in the major end uses, the difference between the total AMI consumption and the sum of the measured end uses was calculated and designated as "other" consumption, representing non-major loads such as lighting and plug loads.

Because the target temporal resolution for the analysis was 15 minutes, the AMI-derived "other" consumption was interpolated from 30-minute to 15-minute intervals. This approach was based on the observation that "other" loads generally constituted a relatively small share of total consumption and exhibited less short-term variability than the major appliance loads. Accordingly, the "other" consumption for each 30-minute AMI interval was assumed to be evenly distributed across the two corresponding 15-minute intervals. For example, for the 1:00–1:30 interval, the sum of the measured end-use consumption was subtracted from the AMI total, and the resulting difference was defined as the "other" load. This value was then divided equally between the 1:00–1:15 and 1:15–1:30 intervals and added to the end-use loads in each period. This interpolation step was necessary due to the coarser temporal resolution of the AMI data. As a result, the reconstructed 15-minute panel level load profile represents the combination of directly measured end-use loads and an estimated allocation of "other" based on AMI data.

Analysis

Panel Space Constraints

One possible motivation to upgrade an electrical panel is to accommodate more breaker spaces. This may have been a factor for some panel replacements at the study sites. For example, any site using more breaker spaces in their new panel than were available in their old panel may have chosen to upgrade at least in part to obtain more breaker spaces. Insufficient breaker space may be a motivation for these panel replacements, but additional breaker spaces can usually be added via a subpanel addition, tandem circuit breakers, or circuit consolidations. Each of these options is expected to be lower cost than a full panel replacement. However, these strategies do not offer safety improvements to the existing panel, which may be recommended for achieving the latest standards. Similarly, safety improvements are also a primary motivator for replacing fuse boxes with modern circuit breaker panels whenever new electrical loads are added, no matter the number of spaces or existing service capacity.

Among the 18 sites with panel upgrades, one originally had a fuse panel, and three had no documentation available to confirm the number of preexisting breaker spaces available. Breaker space capacity changes between the preexisting and new panels could not be compared for those four sites. Of the remaining fourteen sites, twelve used more breaker spaces after WHE than their original panels had. The breakdown of post-WHE breaker space use relative to preexisting panel capacity is shown in Figure 1. Performing a panel upgrade solely to provide additional breaker space is often not a cost-efficient practice because cheaper alternatives exist. However, since new panels potentially offer more convenience, reliability, and safety, a lack of available breaker spaces could motivate panel replacement.

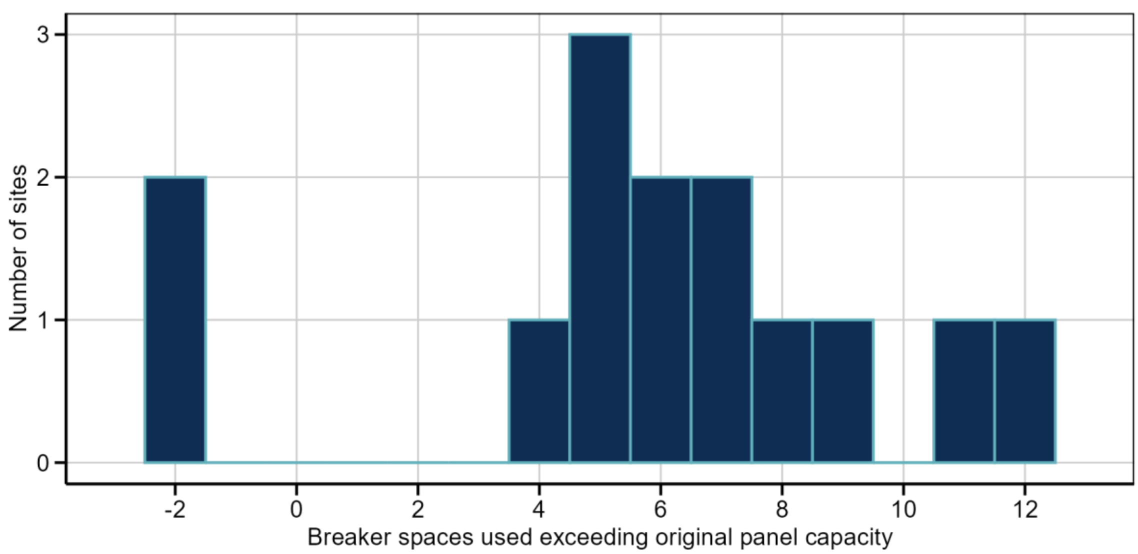

Figure 1. Frequency of sites with panel and service replacements that required additional breaker spaces for electrification. The “-2” indicates the original panel had two more spaces than were used for electrification.

Service Constraints

The individual circuit breakers of a panel do not impact its peak load rating. Instead, the load ratings of the panel's main breaker and/or the exterior service lines constrain peak load capacity. Good electric design requires peak service capacity to exceed the peak demand, a variable that must be estimated because it depends on many hard-to-predict factors like occupant behavior. The peak load estimates that likely drove most of the service and panel upgrades for the homes studied here were not available from project implementers, so we assume peak demand was estimated in accordance with the most widely used approach, the NEC Standard Method (NFPA 2023, Article 220).

All the study homes had similar electrical appliances installed, including 3- or 3.5-ton cold climate heat pumps with 10-kW electric resistance backup units. Most homes also had induction stoves, standard electric dryers, and 240-volt hybrid heat pump water heaters. Images of these appliances' labels verified their electrical requirements. Post-install electrical panel circuit labels were used to identify any other major appliances and the number of small appliance circuits. WHE program records provided floor area data for each site. Together, this data enables load estimates in accordance with NEC article 220 standard methods (NFPA 2023, Article 220). This method uses peak major appliance loads, estimates for small appliance loads, and demand factors to estimate the peak electric load a panel will supply. An example of one such load calculation is shown in Figure 2.

CEE completed load estimates and later compared these to observed peak load data for 17 of the 20 observed sites. Three sites were excluded from the load estimate and monitoring analysis because site characteristics distinguishing them from the cohort. One site had an electric car, which meant meter consumption readings were not representative of panel loads during high solar hours. The other two sites removed were part of a duplex and experienced odd load behaviors. These coincidently were the three sites that had existing 200-amp panels prior to electrification. The remaining sites are all single family-homes, that had panels upgraded to 200-amps. The distribution of estimated peak loads for the study cohort is shown in Figure 3.

	Qty	VA	Contribution [VA]
General Lighting			
Floor area (3 VA/sqft) [sqft]	2338	7014	
Small appliance circuits (min. 2@1500VA)	2	3000	
Laundry Circuit (min. 1500VA)	1	1500	
DF = 3000VA @ 100%, then 35%			5979.9
Fixed Appliances			
Microwave(est. 1500VA)		1500	
Dishwasher (est. 1200VA)		1200	
Garbage Disposal (est. 900VA)		900	
Waterheater (est. 5000VA)		5000	
Other		0	
DF = 75% if 4 or more			6450
HVAC HP+ER			
HP Compressor		8640	
Blower Motor		540	
Electric Resistance		10000	
DF = HP@100% and ER@65%			15680
Other			
Range (est. 8kVA)		8000	
Dryer (min. 5kVA)		5000	
DF = 100%			13000
Add 25% largest motor			
HP Compressor (22A @ 25%)		1320	
DF = 100%			1320
Peak Load Estimate			
Minimum Panel [VA]			**42430**
Minimum Breaker [Amp 240V]			**177**

Figure 2. Sample peak load estimate using NEC article 220 standard methods. The minimum panel/service rating for this home is 177 amps.

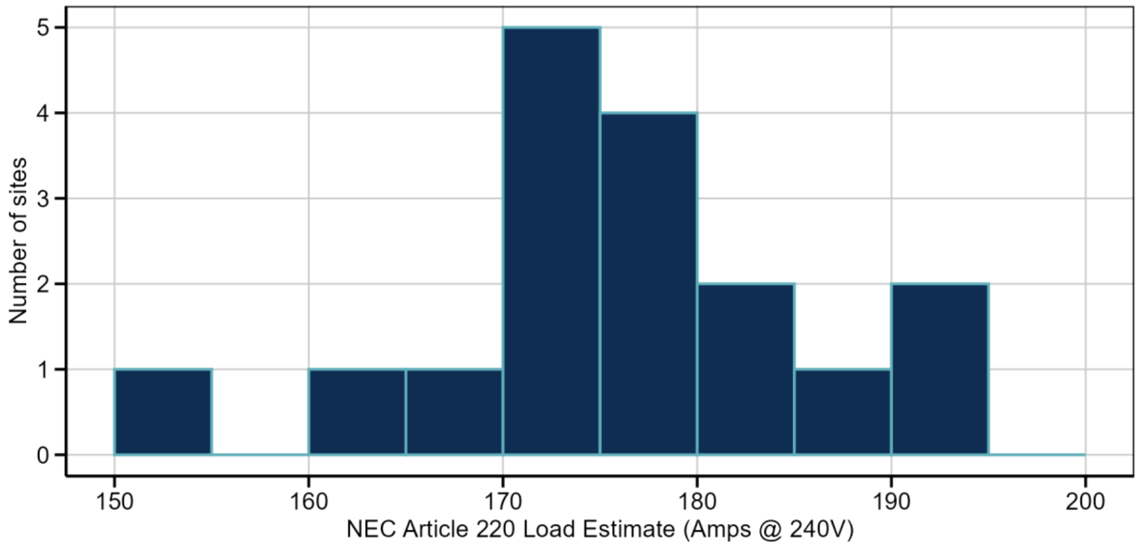

Figure 3. Distribution of peak load estimates for cohort sites in units of service amps at 240V

NEC article 220 standard method load estimates for the homes in this study were between 150 and 200-amps at 240V. Service needs to be sized in excess of the NEC estimate, and standard service equipment sizes include 100, 150, and 200 amps. Because estimated loads are more than 150 amps, 200-amp panels appear necessary to support the projected peak loads at these sites. Accordingly, all studied homes had 200-amp service and panels at the end of their WHE projects. Eighteen of the twenty panels in this study were upgraded and service upgrades from 100-amps to 200-amps were also completed at seventeen of those sites. In twelve of the fourteen cases where prior panel breaker space was known, the fully electrified home used more breaker spaces than were previously available. Regardless, the high peak load estimates are likely the leading cause of panel and service upgrades at these sites rather than breaker space constraints. Increasing the number of breakers does not definitively require a new panel and certainly does not require a service upgrade. Further, whenever a new panel is needed for service capacity reasons, it is easy to default to a panel with more circuits than strictly necessary to reduce planning and installation time.

Observed Peak Loads

Electric service and panel upgrade decisions are typically made with the information discussed in the previous two sections. To evaluate these methods, we used power monitoring to compare actual peak demand to the previously estimated peak load. Continuous monitoring data was collected for all the homes in this study for approximately one year. The exact monitoring time and measured peak loads for each home is detailed in Table 2. The 15-minute peak load is the average electrical power measured over a continuous 15-minute interval and is most relevant to compare to NEC methods. NEC article 220 is a complete method for estimating future peak panel loads by using appliance power ratings and coincidence factors. NEC article 220.87 has an alternative method that uses the power ratings of planned appliance upgrades plus the peak 15-minute monitoring load from utility AMI usage data multiplied by 125%, if at least one year of AMI data is available (NFPA 2023, Article 220.87). This peak load calculation can only be completed for existing systems and is often used to determine remaining load capacity for the addition of new circuits. To align measured load data with NEC article 220.87, further mentions of observed peak load will be the 15-minute average peak load multiplied by the 125% multiplier. This will be referred to as NEC article 220.87 observed minimum panel capacity and is represented in amps. Peak power measurements presented in kilowatts are the actual measured value without the 125% multiplier. Figure 4 compares the NEC article 220 standard method load estimates to the NEC article 220.87 observed minimum panel capacities calculated from monitoring data.

Table 2. Peak 15-minute average panel level load, NEC article 220.87 minimum panel capacity from monitoring data, and NEC 220 load estimates for each site

Site	Monitored	15-Min Peak	NEC 220.87	NEC 220
Units	Days	kW	Amp	Amp
sf017	412	26.7	139.3	166.4
sf034	410	23.6	123.0	181.0
sf010	376	19.0	99.1	175.9
sf103	402	18.3	95.3	191.5
sf022	371	18.3	95.3	172.8
sf117	356*	18.1	94.4	177.2
sf024	392	17.1	89.0	175.4
sf021	361*	16.7	87.0	173.6
sf108	386	16.7	86.9	171.9
sf043	383	16.4	85.6	193.7
sf086	376	16.0	83.3	162.7
sf051	397	14.6	76.3	175.1
sf104	360*	14.5	75.8	171.3
sf020	295*	13.7	71.5	174.3
sf037	373	13.3	69.1	183.7
sf018	281**	13.1	68.3	152.9
sf015	366	12.8	66.8	186.8

* Denote sites with less than one year of monitored data. This peak load calculation is not in strict compliance with NEC Article 220.87 methods (NFPA 2023, Article 220.87). ** Denotes that the site did not have a clothes dryer, so expected loads are lower than sites with this appliance.

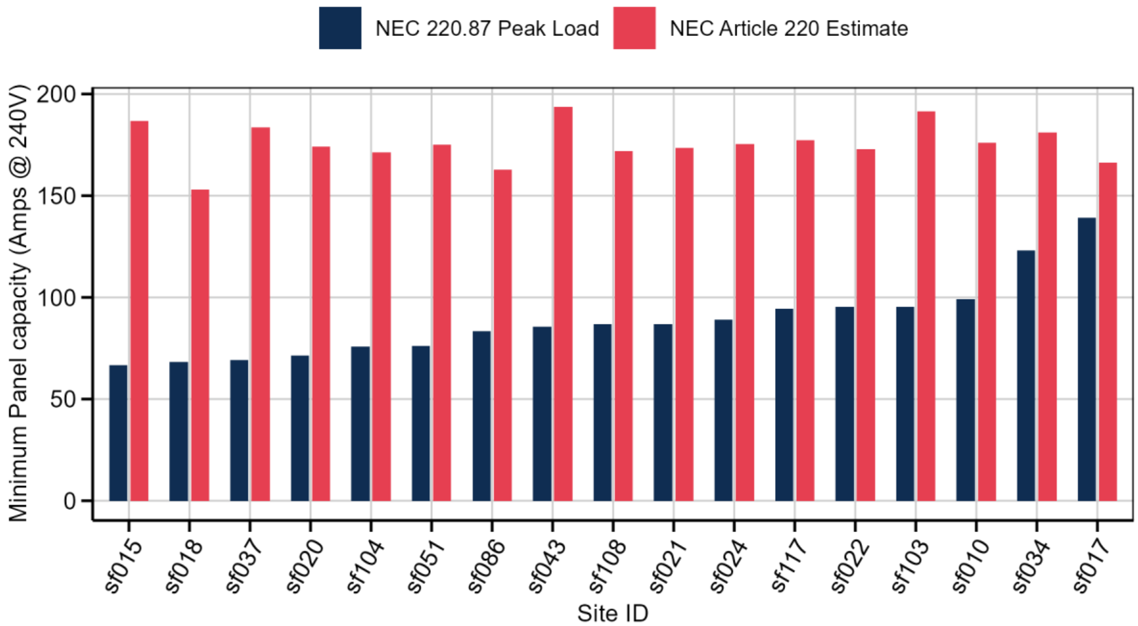

Figure 4. Comparison of estimated peak electric load using NEC article 220, and NEC 220.87 observed minimum panel capacity.

The observed minimum panel capacities after WHE are significantly lower than NEC article 220 standard method estimates for all sites. The median site's observed NEC article 220.87 minimum panel capacity was 87 amps. Of 17 sites, 15 sites had observed peak loads below 100 amps, the most common preexisting service capacity in the studied homes. Retrospectively, this suggests that there are opportunities to size service for whole home electric retrofits lower than NEC article 220 standard estimates. However, these monitored peak loads could only be calculated a year after the retrofits occurred. Therefore, this finding alone cannot influence upgrade decisions.

In the context of 100-amp panels being prevalent across the existing midwestern housing supply, the frequency of peak loads exceeding the capacity of a 100-amp panel are of specific interest. Table 3 identifies the frequency and duration of observed loads exceeding the capacity of a 100-amp panel. A 100-amp panel and service connection requires that the monitored load does not exceed 80 amps at 240-volts (19.2 kW). Accordingly, we evaluated a 100-amp panel/service as exceeded when an 80-amp, 240-volt (19.2 kW) or greater average load occurs in a 15-minute or longer continuous monitoring interval.

Table 3. Frequency and length of events with electric loads exceeding the capacity of a 100A, 240V panel (19.2 kW or more for 15 minutes or more) during the time monitored

Site	Unique events	Max event time (hr)	Total time (hr)
sf017	10	0.5	2.75
sf034	1	0.25	0.25

Peaks beyond the capacity of a 100-amp panel are rare and short at these homes. Monitored load exceeded 19.2 kW for a maximum of 0.5 continuous hours across a year of data from 17 sites. The site with the most events only exceeded the capacity of a 100-amp panel/service for 0.03% of the time monitored. The short and infrequent nature of these peaks suggests that load reduction or management devices on just a few of the largest electric loads could minimally impact occupant experience, while still delivering enough peak savings to meaningfully reduce service requirements.

To provide context for which appliances could be targeted for load reduction or management, Figure 5 shows the prevalence of each appliance's use during peak events with loads exceeding the capacity of a 100-amp panel for all the study sites. The peak power shows the distribution of appliance level load during events where the appliance was on and panel capacity was exceeded. Heat pumps and high-stage output electric resistance backup heaters (10kW) operated during all peak events, while dryers and HPWH electric resistance backup operated during approximately half of peak events. The stove was notably never in use during an observed peak event, but note that the dataset is small. Additionally, the coincidence of appliance operation during each site's 15-minute interval with the highest electrical consumption can be observed in Figure 6. Heating loads contribute the most to the peak load at almost every site.

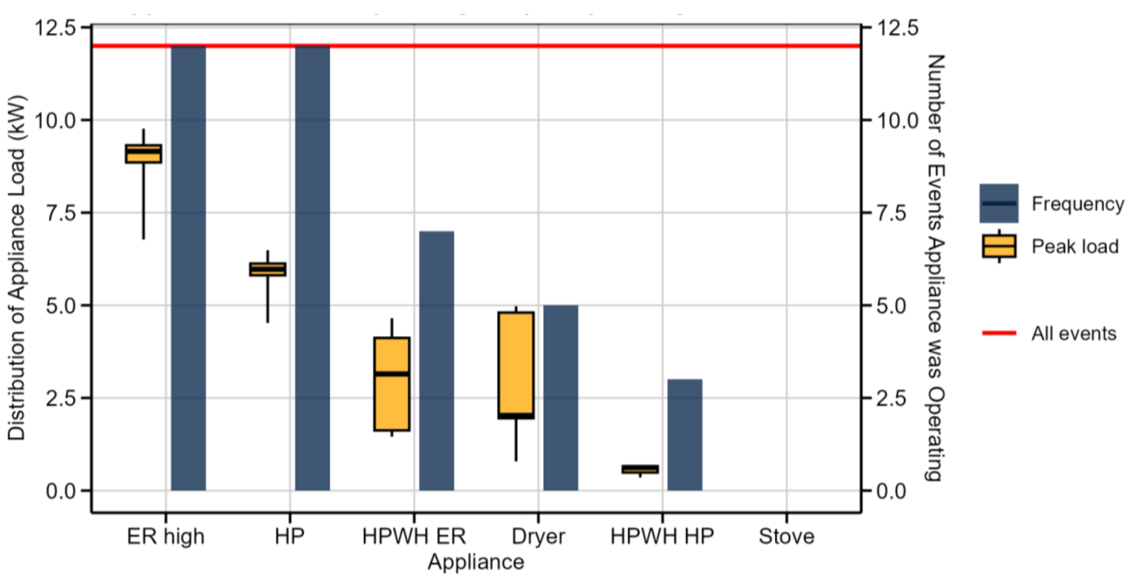

Figure 5. Frequency of appliance usage during each 15-minute interval with power exceeding the capacity of a 100A, 240V panel (19.2 kW or more for 15 minutes or more), and distribution of appliance level power consumption during events

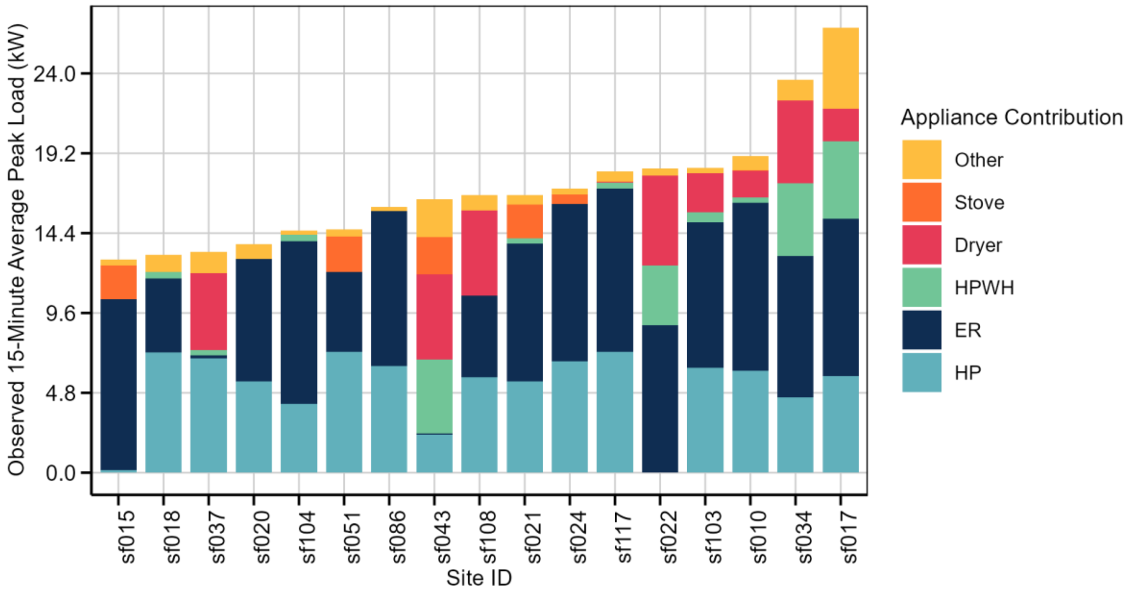

Figure 6. Appliance level load during peak 15-minute monitored electric load interval for each site

Observed Peak Appliance Loads

The operating behaviors of unique appliances can be better understood from continuous sub-monitoring at the circuit level. As previously mentioned, all the appliances in this study were similar in brand and model between sites, but there were a few occasions where appliances were not replaced if they were already electric or did not exist. Those exceptions are not included in the appliance-level analysis that follows. Appliance operating power consumption, and time of day density-normalized distributions were computed from one-minute average data for each site and appliance. The distribution of individual appliance power consumption and use by time of day was summarized with histograms in Figure 7. To generate the histograms showing all sites' data in Figure 7, each site's appliance distribution of power usage (or time-of-day usage) was first converted to a relative-frequency distribution. These relative frequency distributions were then averaged across all sites. This procedure ensures that each site contributes equally to the final composite distribution, independent of differences in monitoring duration.

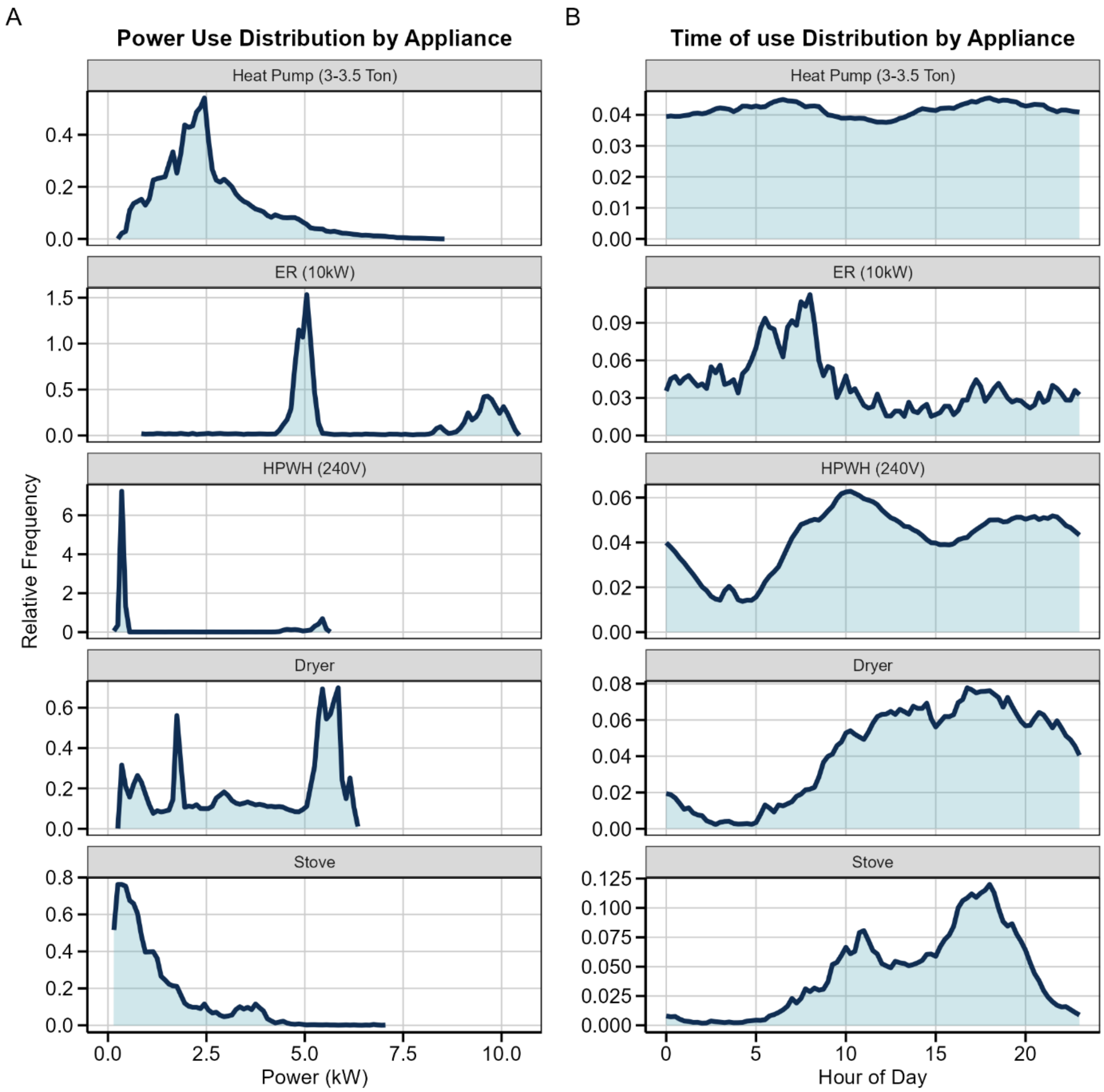

Figure 7. (a.) Distribution of appliance level operating power. (b.) Distribution of appliance level operating time of day. Threshold power values were used to establish appliance use. The threshold was set at 1 kW for ER to eliminate air handler energy use. However, the ER power distribution does include the coincident air handler power, which is comparatively small at less than 250 watts.

In this study, all homes had a 3-or 3.5-ton, cold climate, variable speed heat pump with a two-stage 10 kW backup electric resistance unit. The heat pumps can vary their power consumption between approximately 1 and 7 kW, depending on load and outdoor air temperature. In Figure 5, the median heat pump power during peak events was observed at the high end of this range (6.0 kW), but Figure 7 shows the heat pumps rarely consumed that much power. The wide power distribution of the heat pumps indicates effective, variable capacity performance, and the concentration of power draws below 2.5 kW suggests most of the heat pump operating hours are spent in an efficient, low-power consumption mode. Heat pump operation is also spread more evenly across the day than any other appliance load. In contrast, the electric resistance units operate exclusively at two power levels, 5 and 10 kW, due to the units' two-staged design. The electric resistance is also more likely to be operating in the morning than any other time of day. Morning backup heat use in all electric systems is associated with setback recovery. This occurs when the thermostat setpoint is lowered overnight, then increases on schedule in the morning. Heat pumps can't always deliver the sudden increased load immediately, resulting in backup heat turning on.

The other three monitored appliances trended toward afternoon and evening use. The stoves and dryers operate at a variety of power levels while HPWHs almost exclusively operate around 0.4 or 5 kW. The lower 0.4 kW power draw by the HPWH, which was by far the most prevalent, occurs when the heat pump operates without electric resistance. The 5 kW power level occurs when the backup electric resistance heats in conjunction with the heat pump.

Alternative appliance choices can directly reduce the peak power used by appliances. There are heat pump only models of both HPWH and dryers, but inclusion of electric resistance backup is common to provide faster heating or drying capabilities than a heat pump could deliver on its own. Common 120V heat pump hot water heaters have nameplate maximum power rating of approximately 500 to 1,000 watts compared to 5,000 watts for the hybrid unit. Similarly, a heat pump dryer has a maximum nameplate rating of approximately 800 watts compared to approximately 6,000 watts for an electric unit. These options could be considered for reducing peak loads.

Upgrade Avoidance

Monitored peak electric loads are low enough at most sites (15 of 17) that 100-amp electric panels and service would have been sufficient for WHE, though NEC calculations ultimately support all sites receiving 200-amp service as part of their electrification project. Panel sizing decisions cannot be made prior to electrification projects with post-electrification usage data, so we investigated if other site characteristics correlated with measured peak loads falling near or far below NEC capacity calculations. We looked for correlations between observed peak load and building floor area, Manual J heating load estimates, and building age, but no trends were found. All sites had similar appliances and HVAC equipment, so variation in peak load between sites did not result from appliance choice, either. Occupancy is known to impact some appliances' usage profile, but that data is not available for this sample.

Despite being able to confirm that many homes need only 100-amp service to fully electrify, we can't find indicators that reliably predict which homes would or would not need to upgrade to larger service. Monitoring data shows that actual peak demand is the result of just a few major appliances running coincidently. Heat pumps, electric resistance backup heat, water heaters, and dryers can all independently use more than 5 kW of electric power and significantly impact the peak demand when operating simultaneously. Existing peak load estimates use demand and safety factors to estimate coincidence factors for appliances across large populations. However, the coincidence of these appliance loads is challenging to predict because user behavior varies and ultimately dictates the patterns of appliance use.

Peaks result from high-load appliances operating coincidentally, so strategies to reduce peak demand can either reduce maximum appliance power or limit which appliances can run together. First, the maximum power consumption of an appliance can sometimes be reduced by choosing alternative models. Heat pump water heaters and dryers are available that have maximum electric usage ratings 80% lower than the models installed in this study. Second, appliances with large loads can be controlled with load management devices so they can't run simultaneously. This is often done using a device that cuts appliance power when total panel load exceeds a set threshold. There are also energy storage solutions that can store thermal energy for use while electric energy consumption is high or appliances with built-in batteries to reduce appliance peak loads. These strategies reduce the maximum possible electric load on the panel.

Each appliance will be impacted differently by these strategies. The maximum power consumption of a heat pump or electric resistance heater is difficult to reduce if it is already properly sized to the home's heating load. Similarly, preventing the operation of a stove or clothes dryer will be frustrating to occupants. Appliance-level peak load and coincidence data informs which actions will have the most significant impact on peak loads. Figure 5 indicates that load management on the stove would not have impacted any of the peak events, while load management on electric resistance heat would have reduced loads for all the events.

An alternate WHE strategy was modeled for the 17 homes by estimating the impact of using 120-volt heat pump water heaters and a load management device controlling the HVAC systems electric resistance backup heat. The water heater replacement was based on the availability of similarly priced units with significantly lower peak power due to a lack of electric resistance backup. A load management strategy was chosen for the electric resistance heat since it is the largest individual appliance electric load, and it can be disabled in most systems without turning off the heat pump. Modeling was performed using 15-minute interval appliance consumption data. Delivered energy was conserved by postponing operation or having the unit run for longer to deliver the same energy as was measured.

This model demonstrates that changes to WHE strategies can reduce the peak load of a building. After performing this model, no peaks were observed in the modeled data set for any site exceeding the capacity of a 100-amp panel (19.2 kW), shown in Figure 8. This is one example of how peak loads can be reduced by changing appliances and controls. However, it is important to note that the modeled changes might cause hot water to run out or short periods during which the building's heating system is unable to meet the setpoint temperature.

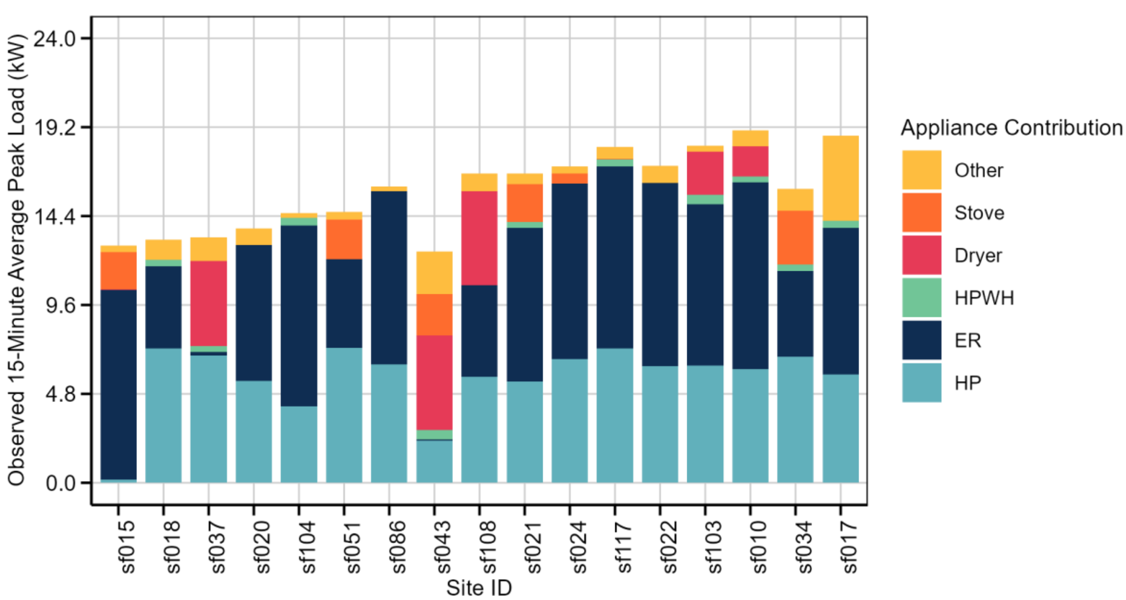

Figure 8. Appliance-level load during peak 15-minute monitoring interval for modeled peak load reduction at each site

Model results suggest that program changes would have allowed all sites to be electrified without upgrading the existing 100-amp panels, but NEC article 220 estimates for peak load would still exceed 100 amps in the model conditions. An NEC article 220 standard method load estimate (NFPA 2023, Article 220) was performed similarly to that in Figure 2, for this alternative model where the electric resistance backup heat is a load-managed appliance that does not contribute to the estimated peak load. The 120-volt heat pump water heater was also incorporated using its reduced nameplate maximum load. The resulting minimum panel and service capacity for a median house in the study was still 123 amps. This is larger than the capacity of the desired 100-amp panel that modeled data suggests would pass an NEC article 220.87 load test after installation and monitoring. At this time, retrospective monitoring data suggests that WHE with 100-amp panels and service would be possible with limited design changes for this cohort, but NEC standards do not allow these findings to be applied in a way that reduces upgrades.

Conclusion

In this study, 18 of the 20 homes received panel upgrades as part of their WHE projects. All the sites completed WHE with 200-amp service. NEC article 220 minimum panel capacity estimates supported this design decision as all estimates exceeded 100 amps, with the median estimate being 175 amps. However, monitoring data produced a median observed minimum panel capacity of 87 amps after electrification occurred, which was significantly lower than estimates used to make upgrade decisions. The finding that measured loads often do not exceed the capacity of existing 100-amp panels (15 of 17 sites) means many sites could have avoided upgrades, saving projects thousands of dollars. However, since upgrades can't be avoided using monitoring data that is only collected after an upgrade is complete, these findings alone are unable to provide a solution for avoiding all unnecessary panel and service upgrades.

The sites in this cohort had similar appliances, but different observed peak loads. Occupant behavior appears to be a likely driver, as indicators like Manual J, home size, and home age were not found to accurately indicate which sites' peak loads would exceed the capacity of a 100-amp panel. Instead, the peak electric load of each site is impacted by coincident operation of a few major appliances. Sub-monitoring of each major electric appliance identified which were frequently used during peak events that exceeded the capacity of a 100-amp panel and service. Heat pumps, electric resistance backup heat, and heat pump water heaters all operated during at least half these events and can consume more than 5 kW of electricity.

Restricting the peak power or coincidence of electric resistance backup in the heating system or in the heat pump water heater has the most potential to reduce the maximum peak load at the studied homes. Field data showed that peak loads exceeding the capacity of a 100-amp panel were short and infrequent. This suggests that load reduction or management devices on just a few of the largest electric loads could minimally impact occupant experience, while delivering enough peak savings to meaningfully reduce service requirements. Modeling the use of 120-volt heat pump water heaters and load managing electric resistance backup heat while using field monitoring data for other loads indicates that none of the sites would have exceeded the capacity of a 100-amp electric panel with those modifications. However, NEC peak load estimates in that scenario would still exceed 100-amps and result in service upgrades. Future work should focus on aligning load estimate methods with the field monitoring results of this study and validating electrification solutions that guarantee peak loads do not exceed existing panel capacities for WHE projects without sacrificing comfort.

References

Less, D., I. Walker, S. Murphy, and E. Fournier. 2024. *Electrical Service Panel Capacity in California Households with Insights for Equitable Building Electrification*. Washington, DC: ACEEE.https://www.aceee.org/sites/default/files/proceedings/ssb24/pdfs/Electrical%20Service%20Panel%20Capacity%20in%20California%20Households%20with%20Insights%20for%20Equitable%20Building%20Electrification.pdf.

NFPA (National Fire Protection Association). 2023. *NFPA 70 (National Electric Code)*. Quincy, MA: NFPA. www.nfpa.org/codes-and-standards/nfpa-70-standard-development/70.