HVAC Heat Pump Upgrades and their Impact on Household Maximum Power Demand

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ABSTRACT

Millions of US households will undergo electrification of space heating using heat pump technologies in the coming decades. It is critical to understand how these new loads will impact household maximum electricity demand. Past work on this topic has addressed the upstream distribution system and has generally relied upon modeling of loads. These efforts have largely ignored the household electrical infrastructure behind the meter and have rarely used empirical metered data. This study used measured electricity use from several data sources representing thousands of existing US dwellings to characterize the changes in household maximum electrical demand associated with the installation of HVAC heat pumps in existing dwellings. Sub-metered data in 957 dwellings was used to estimate the impacts of heat pumps on maximum demand. Smart meter data for 9,093 Vermont dwellings that installed cold climate heat pumps was used to directly observe the change in maximum demand pre- and post- heat pump installation. The results show that heat pumps generally add less than their rated electrical demand to household maximum demand, but that in small minorities of homes, heat pumps add close to 100% of their rated electrical demand. We evaluate current and proposed heat pump demand factors (100% and 50%) for use in NEC service load calculations, and we show that using the proposed values for demand factors produces adequate load calculations, and that safe treatment of heat pumps in electrical load calculations does not require using overly conservative values currently in the electrical code.

Introduction

Adding significant electric loads to all the existing homes in the US has the potential to require considerable additional expense at both the home infrastructure and grid infrastructure levels. Replacing home electrical service infrastructure, such as electric service panels and/or conductors, has a large range of costs from $1,000-$30,000 (Less, Casquero-Modrego, and Walker 2022) and time delays of several months (Pena et al. 2022). These costs and time delays are significant barriers to home electrification. The impact of new electrical loads on grid demand is critical in determining both the costs and timing of grid infrastructure upgrades, such as local transformers and substations. Replacing grid infrastructure has costs that are currently unknown, but likely to be significant. These costs will be borne by ratepayers in the form of rate increases and higher bills–as has been seen in California, with very large rate increases to cover infrastructure costs. It is essential to determine if and when this new infrastructure is needed.

Current practice when adding HVAC heat pumps to existing homes is to perform service load calculations according to the National Electric Code (NEC) and to add the new equipment to the existing loads already in the home. Both sections of the 2023 NEC that address existing dwellings–220.83 and 220.87–both treat newly installed HVAC equipment at 100% of its nameplate power rating. Some argue that this leads to an overestimation of load and can contribute to unnecessary service panel replacements and potential grid upgrades. This study examines the actual changes in whole dwelling maximum power demand when adding HVAC heat pumps to see if this treatment at 100% of nameplate is realistic and appropriate.

Grid Estimates of Heat Pump Demand Impact

Past efforts have evaluated the impacts of electric space heating on maximum demand, but these have almost exclusively focused on grid impacts, rather than household impacts. Grid impacts are relevant for assessment of transformer upgrades or the need for additional power generation, whereas household maximum demand is critical for evaluating the adequacy of household electrical infrastructure, including service conductors and service panels. Many past assessments are not based upon detailed metering of heating system demand, but rather use statistical models to estimate that demand based on outdoor temperature and other conditions.

For heat pump grid impacts, much existing literature is based on simulations, regression modeling, or population-wide analyses. Yet, we identified some research that has used actual whole dwelling or heat pump sub-metering data sources to estimate grid loads. In sum, these papers suggest that heat pump loads on the grid are sub-additive and substantially less than the power ratings of the individual appliances. None of the papers cited below analyzed heat pump data with a focus on dwelling electrical infrastructure implications. A cold-climate air source heat pump study of 43 homes (Cadmus 2022) found that measured heat pump heating loads during the coldest seven hours of the year averaged only 40% of installed system heating output capacity, with a maximum of 81%. This indicates substantial potential for load diversity over the seven hour peak. Cadmus also reported on the sub-metered electrical demand of the installed heat pumps, with maximum hourly demand averaging 2.52 kW per 1,000 ft^2 of floor area, and average demand of 0.88 kW/1,000ft^2 during utility peak periods (5-7pm December-February). However, the results do not address impacts of the heat pumps on household maximum demand, which is relevant for household electrical infrastructure. A study of over 13,000 homes in Arizona used hourly household demand data to model differences in electricity consumption between homes with and without heat pumps (Liang, Qiu, and Xing 2022). The differences changed with time of day, with a peak at 8 a.m. The average increase in household demand at this peak was 0.68 kW with a 95% confidence interval peak of about 0.75 kW. A study in Germany (Schlemminger et al. 2022) metered a network of 38 homes with water-to-water heat pumps connected to shared solar thermal hot water system. Nominal heat pump compressor power was either 1.9 or 3 kW, and all systems additionally had a 6 kW backup heat in a small hot water storage tank. Heat pump load curves based on 10-second metering data showed an average maximum of around 1.8 kW per household. Relative to a standard whole home load profile used for German dwellings, the average household load curve for the heat pump dwellings had marginally lower maximum demand (0.1-0.2 kW). A United Kingdom (UK) study of 700 heat pumps (Love et al. 2017) with power consumption recorded every two minutes and aggregated to 30-minute intervals calculated a metric they termed “After Diversity Maximum Demand (ADMD)”, which accounts for the noncoincident operation of multiple heat pumps. This noncoincidence ensures their combined power demand is sub-additive relative to the maximum demand of each heat pump. Love et al. sequentially assessed the aggregate impact of different numbers of heat pumps operating together to illustrate this sub-additive effect. One heat pump had a maximum demand of 4 kW. This aggregated maximum demand drops off sharply as more heat pumps are included in the calculation. It is cut in half (to 2 kW) with 40 heat pumps included, and it reaches a stable value of 1.7 kW after including roughly 100 heat pumps in the calculation. This paper also found that the heat pump loads did not occur at the same time as existing heating loads or at the current grid peak. Both of these results have implications for estimating grid impacts, as the new heat pump loads were highly sub-additive. The authors pointed out that this is a critical issue for modeling studies that assume new loads simply add to the current peak.

Methods

This paper builds on these previous studies using larger numbers of homes over longer time periods, and with a focus on household rather than grid-level demand. We used several large data sets representing a range of US climates to focus the examination of the demand impact on individual residences. The study includes both direct pre-post comparisons of metered demand, as well as a synthetic retrofit approach using only post-installation heat pump metering data.

The data sets include a mixture of total residence demand data and sub-metered heat pump data. Total demand data was used to demonstrate how observed dwelling maximum demand changes after heat pump installation. Detailed end-use sub-metering data was used for disaggregation of the heat pump and total home loads. NEC service load calculations are performed in order to assess the appropriateness of current 100% demand factors for heat pumps relative to a proposed value of 50%.

Data Sources

Three sources of electricity data were used for the analyses reported in this paper. Vermont Energy Investment Corporation (VEIC) reported dwelling maximum demand values derived from smart meter data before and after incentivized installation of cold climate heat pumps. Two other sources reported end-use sub-metering data (Pecan Street Dataport and the Northwest Energy Efficiency Alliance (NEEA) End-Use Load Research (EULR) project). These data sets include major end-uses in each residence, including measurements of domestic hot water, space heating and cooling, and other consumer appliances.

VEIC Heat Pump Program Data. This data set was retrieved from project partners at the VEIC, who run energy efficiency programs for the state of Vermont. One such program is an incentive program for the installation in residential buildings of cold climate heat pump equipment rated to meet the NEEP criteria for low-temperature performance. The VEIC team shared monthly dwelling maximum demand derived from both 15-minute and 60-minute smart meter data for periods of at least one year before and after the recording of a heat pump installation. Typically, each dwelling provided 6-years of monthly maximum demand data, with varying numbers of years in the pre- and post-install periods. VEIC also provided data identifying the make and model numbers of the installed heat pump equipment. For data privacy purposes, we otherwise were provided with no dwelling information (e.g., building type, floor area, appliances), other than that they are located in the state of Vermont. The data required substantial cleaning and filtering of cases that lacked complete and adequate information. After cleaning, data from 9,093 households was retained for our analysis.

Pecan Street Dataport. The Pecan Street Dataport[1] has been sub-metering end-uses in occupied dwellings for the better part of a decade using standardized equipment and protocols in Texas (1,409 dwellings), California (136 dwellings), New York (122 dwellings), Colorado (58 dwellings), and a handful of dwellings in other states. The data was purchased through a licensing agreement between LBNL and Pecan Street and is not publicly available. These data are not nationally or regionally representative, rather they represent a sample of convenience. The data are recorded on a 1-second time-step, but for this work, data were aggregated to 15-minute average interval data. Dwellings in the Pecan Street dataset include anywhere from 1 to 10-years of data, with an average duration of 4.1-years. After data quality review, a total of 776 residences were included in our analysis.

NEEA EULR. The Northwest Energy Efficiency Alliance (NEEA) has run residential building stock assessment (RBSA) studies several times over the past two decades, which are intended to provide a statistically representative sample of the region's housing stock. These efforts include the retrieval of metering data and structured professional energy audits of households to document features, appliances, etc. The most recent RBSA included an additional sub-metering effort in select dwellings that included specific electric end-uses, including HVAC heat pumps and resistance electric furnaces, heat pump and electric resistance water heaters, electric vehicle chargers, etc. This data collection was termed the End-Use Load Research (EULR) study. 15-minute sub-metering data of each circuit in every dwelling are made publicly available by NEEA online. Dwellings include anywhere from 1 to 3.5-years of data, with an average duration of 2.7-years. After data quality review, a total of 181 sub-metered dwellings were included in our data analysis.

The end-use sub-metering data sets (Pecan Street Dataport and NEEA EULR) use different load naming conventions, which required development and mapping of a standardized load name schema for this work. In the NEEA EULR dataset, some heat pump loads were identified as ducted or ductless, and we included that sub-category in our load name schema as "Central Heat Pump (Ducted)" or "Central Heat Pump (Ductless)". However, these details were not available for the majority of heat pump loads, and these were identified more generically as "Central Heat Pump", which contains a variety of technology classes, including varying efficiency levels, compressor speeds, and ducting configurations.

The Pecan Street Dataset only identified sub-metered loads as a "compressor", without differentiating between cooling-only and heating and cooling appliances. End uses with the "compressor" designation were assigned to the "Central Heat Pump" category if the maximum observed load ever exceeded 0.5 kW during the hours of midnight to 6 AM in the months of December and January. The 0.5 kW threshold was chosen to eliminate operation of crankcase heaters, while capturing heating operation. This approach identified 58% of the 781 compressors

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[1] https://www.pecanstreet.org/dataport/

in the Pecan Street data as “Central Heat Pumps” and the remaining 42% were labeled as “Central Cooling”.

Table 1 and Table 2 summarize the sub-metered data examined, with the intent of characterizing the saturation of electric appliances and combinations of electric appliances in the metered dwellings. Table 1 shows the count and frequency of individual electric end uses, and Table 2 shows the combination of various electrified end uses (e.g., space and water heating) inside individual residences. The Pecan Street Dataport dwellings have fewer electric appliances than the NEEA EULR dwellings, particularly for water heating and clothes drying. The NEEA EULR dwellings are highly electrified, with over half of dwellings using electricity for space and water heating, clothes drying and cooking. It cannot be confirmed if these dwellings are “all-electric”.

Table 1. Summary of electric end-uses in sub-metered dwellings.

Source	Electric End-Use Count and Frequency*					Total
	Space Heating	Space Cooling	Water Heating	Clothes Drying	Cooking	
NEEA EULR	137 (76%)	49 (27%)	125 (69%)	165 (91%)	154 (85%)	181
Pecan Street	444 (57%)	286 (37%)	148 (19%)	406 (52%)	398 (51%)	776
All	581 (61%)	335 (35%)	273 (29%)	571 (60%)	552 (58%)	957

Table 2. Summary of combinations of electric end-uses in sub-metered US dwellings.

Source	Combined Electric End-Use Count and Frequency*			Total
	Space Heating And Water Heating	Space Heating And Water Heating And Clothes Drying	Space Heating And Water Heating And Clothes Drying And Cooking	
NEEA EULR	114 (63%)	111 (61%)	105 (58%)	181
Pecan Street	106 (14%)	53 (7%)	42 (5%)	776
All	220 (23%)	164 (17%)	147 (15%)	957

*Note: Not all residences have the same mixture of electric end use loads. Frequency represents percentage of total number of residences for each end use.

Calculation Methods

For each HVAC heat pump load considered in this analysis, we derive three pieces of information: (1) the change in whole dwelling maximum demand associated with installation of an HVAC heat pump in an existing dwelling; (2) the maximum observed demand of the HVAC heat pump equipment; and (3) the demand factor, which is the first value divided by the second value. A primary assumption is that the maximum observed heat pump demand can be used as a proxy for the nameplate rating, with a value that is less than or equal to the nameplate. The demand factor then relates the fractional contribution of the nameplate rating to the dwelling maximum demand. To illustrate, if a heat pump rated at 5 kW is added to an existing dwelling, and the dwelling maximum demand is observed to increase by 2 kW in the post-upgrade period, the resulting demand factor for the heat pump is 40% (2 kW / 5 kW). Notably, using the maximum observed demand for the heat pumps is likely to produce over-estimates of the demand factors compared with using the actual nameplate power ratings of the heat pumps. This is because the nameplate values almost always exceed in-situ demand. Nevertheless, this approach provides our best estimate given that common HVAC equipment databases (e.g., AHRI or NEEP) list appliance power levels at various conditions and do not list nameplate electrical ratings.

In the Vermont homes, actual upgrades occurred and new heat pump equipment was installed. The date of installation was recorded and used to divide the metering data into pre- and post-upgrade periods. The change in dwelling maximum demand associated with the heat pump installation was calculated as the maximum demand from the post-installation period minus the maximum demand in the pre-installation period. The pre- and post-installation periods were defined in two different ways: (1) comparing the years immediately before and after installation, and (2) comparing the mean maximum demands of the pre- vs. post-upgrade periods. For each heat pump installed in a Vermont dwelling, the maximum observed demand of the equipment was derived by matching the equipment model number to the NEEP ccASHP database, and then identifying the maximum power recorded across all of the NEEP rating conditions. This was sometimes, but not always, the coldest ambient condition. For those dwellings adding more than one heat pump unit, the maximum equipment power values were summed for the dwelling. These data give a direct estimate of the impact of heat pump installation on existing dwelling maximum demand; however, they also include some important uncertainties. One important issue is year-on-year variability in dwelling maximum demand based on weather and occupancy patterns, which makes isolating the impact of a new heat pump uncertain. Another important uncertainty is the lack of household information for these VT homes. For example, the data provided does not include pre-upgrade heating fuel type, presence of air-conditioning or information about the addition or removal of other electric loads.

In the end-use sub-metering dwellings (Pecan Street and NEEA EULR), no actual retrofits or upgrades occurred; new heat pump equipment was not installed. Estimating the effect of adding heat pumps required development of a “synthetic retrofit” analysis that evaluates the dwelling maximum demand with and without the sub-metered load under consideration. This is achieved by subtracting the sub-metered heat pump demand from the whole dwelling demand at each time-step. This gives two whole dwelling demand time-series, one with and one without the heat pump equipment included. We then calculate the maximum whole dwelling demand for each of these two time-series, and the change in whole dwelling demand associated with the heat pump is simply the dwelling maximum with the heat pump minus the dwelling maximum without the heat pump. The maximum observed demand of the heat pump equipment was derived by identifying the maximum 15-minute real power for the sub-metered heat pump over the entire monitoring period. This “synthetic retrofit” approach has pros and cons. Unlike the Vermont data, it provides a very controlled way to assess the impact of a heat pump retrofit, because all other loads in the home remain fixed, and only the heat pump load is included/excluded from the whole dwelling demand. A limitation is that this approach fails to capture the electricity demand that would have occurred without the heat pump in place (e.g., the power demand of the air handler for a natural gas furnace). In this sense, the approach is conservative and attributes the largest possible change in dwelling demand to the heat pump, because it neglects the contribution of these ancillary electrical loads.

Results

Vermont Cold Climate Heat Pumps

The majority of Vermont homes added either one (65%) or two (24%) heat pump units, and five units or less were installed in 99% of dwellings. Some buildings in this dataset were multi-family, and these sometimes reported installing 10 or more heat pumps (up to 60). Figure 1 shows the distributions of heat pump rated demand from the NEEP database and the change in dwelling maximum demand associated with the installation of cold climate heat pumps in Vermont dwellings. The typical household added 3.6 kW of heat pump to their dwelling. The median change in whole dwelling maximum demand after installation of heat pumps was dramatically less than that–only 0.20 kW–with roughly equal numbers of homes increasing and decreasing their maximum demand after installing a cold climate heat pump. Based on these values, the distribution of calculated heat pump demand factors is shown in Figure 2. The current treatment in NEC service load calculations is for new heat pumps to add 100% of their nameplate power rating. The median demand factor for these VT heat pumps was 5% (0.20 kW / 3.6 kW). The 75th percentile demand factor was 31% and the 90th percentile demand factor was 69%. Some extreme cases with demand factors greater than one or less than negative one were also observed and are discussed below.

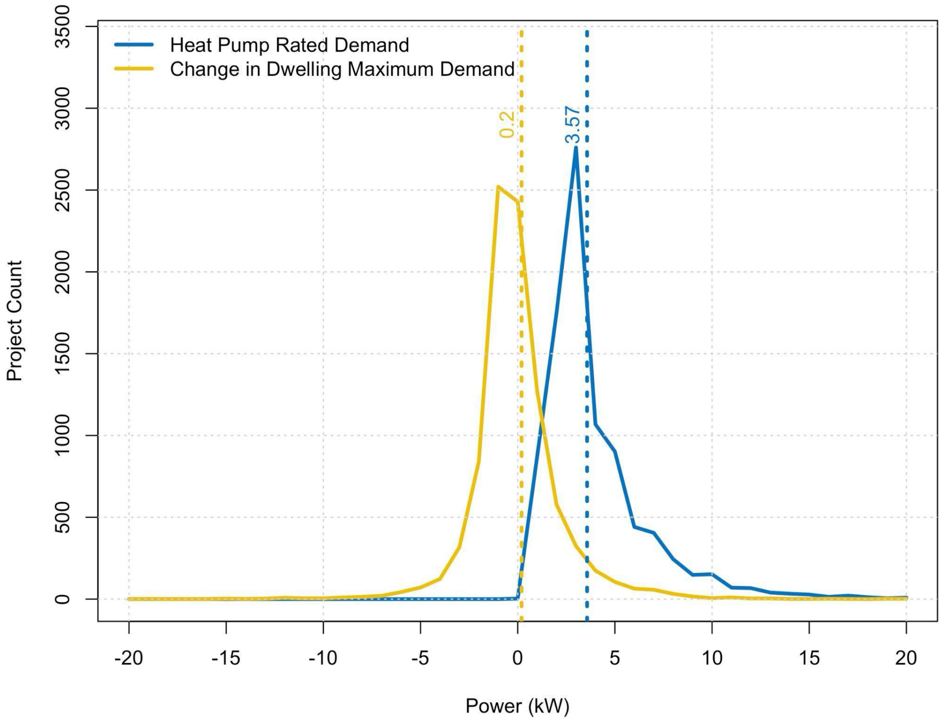

Figure 1. Distribution of heat pump rated demand and change in dwelling maximum demand for 9,093 cold climate heat pump installations in Vermont. Vertical dashed lines and data labels represent median values.

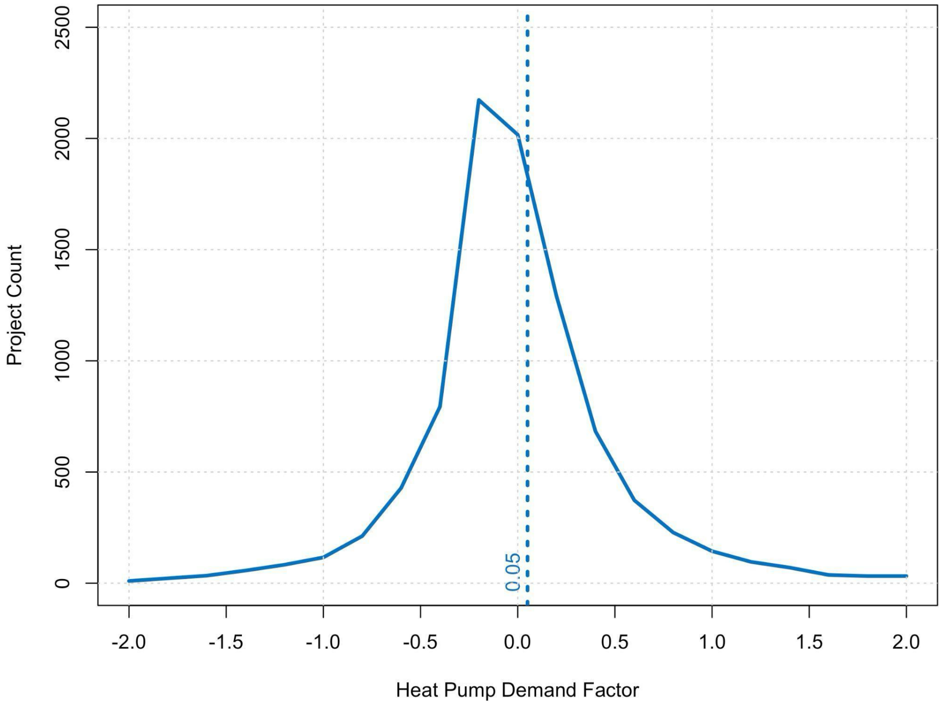

Figure 2. Distribution of heat pump demand factors for 9,093 cold climate heat pump installations in Vermont. Vertical dashed line and data label represent median value.

As noted in the Methods section, VEIC did not record or share detailed information about the dwellings being upgraded, and this lack of information contributes to uncertainty in our results. For example, we do not know about other large electrical loads in these dwellings, such as resistance electric water heating, clothes drying or cooking. Similarly, we do not know if the cold climate heat pumps were installed alongside other back-up heating sources (e.g., wood stoves, fuel-fired heaters or strip heat), if the heat pumps served as heating for the entire dwelling, or whether dwellings had mechanical cooling pre-heat pump installation. Finally, we do not know if electrical service upgrades occurred in conjunction with these heat pump installations.

Two issues are especially apparent: (1) in almost half of the dwellings, the dwelling maximum demand goes down after installing an electric heat pump, and (2) in about 8% of dwellings, the dwelling maximum demand increases by more than the rated power of the new heat pump (i.e., a demand factor > 1). Decreases in dwelling maximum demand may have occurred in dwellings with air conditioning or electric resistance space heating in the pre-retrofit condition. When these loads were removed and replaced with a high efficiency heat pump, maximum demand may actually have been reduced. Increases in dwelling maximum demand in excess of the rated power of the heat pumps were much rarer, but could be the result of new electrical loads not tracked by the heat pump program (e.g., resistance backup heat, electric vehicle charging, water heaters, cooking, etc.). Natural year-on-year variation in maximum demand is also likely to have impacted our estimates of demand factor. Based on the pre-upgrade periods, we observed a median ratio of maximum-to-minimum yearly demand of 1.18 (or roughly 1-2 kW for the same household).

The results shown above represent the changes recorded in whole dwelling maximum demand based on the values for individual years immediately before and after the date recorded for the heat pump installation. We also performed this analysis using the mean whole dwelling maximum demand from the multi-year pre- and post-heat pump installation periods. We found largely similar results, with somewhat higher estimates for added load (median 0.36 kW vs. 0.20 kW) and demand factor (median 9% vs. 5%).

Electrical Load Calculations and Panel Replacements. To estimate the effect of different demand factors on predicting the need for panel replacements we performed NEC 220.87 calculations combining the measured pre-heat pump demand with the ratings from the NEEP database for the added heat pumps to estimate post-heat pump demand. We evaluated if those panel replacements were necessary or not, based on the observed actual metered demand in the post-heat pump period. We do not know the panel ratings of the Vermont homes, nor do we know if panel replacements occurred as part of the heat pump upgrades. This analysis relies on NEC load estimates to identify the minimum panel ratings that would be required by code, and to use this information to identify homes that shift from requiring less than 100A to requiring more than 100A of service.

We calculated NEC 220.87 loads for the pre- and post-heat pump periods as follows, using demand factors of 100% and 50%:

- **Pre-heat pump load**: pre-heat pump dwelling maximum demand x 125%
- **Post-heat pump load**: pre-heat pump dwelling maximum demand x 125% plus the heat pump rated demand times the demand factor

To determine if a home needed a panel replacement, we use a threshold of 100A (24 kW) for the panel replacement decision, because this is a common panel rating in existing dwellings where panel replacements might be needed to accommodate a new heat pump load. Notably, this threshold of 24 kW would shift if power factor was substantially less than one, as could be the case if the dwelling maximum demand were dominated by inductive loads, for example. Based on the threshold of 24 kW, homes fell into one of three categories:

- **Remain at 100A**: Pre-heat pump load <= 24 kW and Post-heat pump load <= 24 kW
- **Remain at 200A**: Pre-heat pump load > 24 kW
- **Replace 100A with 200A:** Pre-heat pump load <= 24 kW and post-heat pump load > 24 kW

The fractions of homes in each category are tabulated using the 100% and 50% demand factors in Table 3. The 100% value is the current assumption in the NEC for new loads, and the 50% value is a proposed value for treating new loads in dwellings, including new heat pumps. The vast majority of homes do not require panel replacement according to this analysis. Using a 50% demand factor leads to fewer 100A panel replacements. Across the population of 9,093 dwellings, the 50% demand factor reduces the number of apparent panel replacements by 3.9% (355 homes).

Table 3. Tabulation of apparent panel replacements across the Vermont dwellings.

Panel Status	100% Demand Factor (current)	50% Demand Factor (proposed)
Remain at 100A	91.8%	95.8%
Remain at 200A	2.7%	2.7%
Replace 100A with 200A	5.5%	1.6%

The 50% demand factor leads to fewer apparent panel replacements compared with the current assumption in the NEC of 100%. The actual metered demand can be used to assess potential concerns about the 50% demand factor resulting in homes not replacing panels but subsequently exceeding panel capacity and tripping their main breaker. The metered post-heat pump data can also be used to estimate the number of unnecessary panel replacements. To investigate this, the actual metered demand from the post-heat pump period was used to differentiate between the following categories:

- **Unnecessary panel replacements:** Homes with panel replacements where the actual post-heat pump maximum dwelling metered demand was <= 24 kW.
- **Necessary panel replacements**: Homes with panel replacements where the actual post-heat pump maximum dwelling metered demand was > 24 kW.
- **Missed panel replacements**: Homes that remained at 100A where the actual post-heat pump maximum dwelling metered demand was > 24 kW. If these homes actually had

100A panels, they might experience an overload condition or trip a main breaker on rare occasions.

These determinations are tabulated using the current 100% demand factor and the proposed 50% demand factor in Table 4. Treating heat pump loads at 100% provides little value in identifying potentially hazardous homes, and it can substantially increase upgrade costs by requiring 3.6-times as many unnecessary panel replacements. In this analysis, 98% of panel replacements are deemed unnecessary when using the 100% demand factor, and 96% are deemed unnecessary when using the 50% demand factor. Across the entire population of homes, the number of panel replacements that actually appear necessary are small, from 0.07% to 0.11%. Missed panel replacements are the potentially hazardous situations that we want to avoid, and these are similarly very rare across the population of all homes (0.14% and 0.19%) and are not very sensitive to the demand factor assumption. In fact, doubling the demand factor for heat pumps identities only 0.04% additional cases (4 out of 10,000 homes). NEC service load calculations are not perfect and will occasionally incorrectly classify certain homes, but the choice of heat pump demand factor appears to be of minimal impact in this determination.

As noted above, the Vermont dataset lacks information about non-heat pump loads and it includes natural year-on-year variability in demand. In fact, some homes in this dataset increased their maximum power demand by more than the installed heat pump power rating (i.e., demand factors were greater than one), including all of the dwellings categorized as "Missed panel replacements". This could occur either as a result of uncontrolled year-on-year variability in demand, or as the result of new loads that were added that we are not aware of (e.g., backup heat, electric water heating). Therefore our estimates likely over-predict the "missed panel replacements" category and the impact of the 50% rather than 100% demand factor may have even less impact on this outcome.

Table 4. Categorization of Vermont heat pump homes according to necessity of panel replacements.

	100% Demand Factor (current)	50% Demand Factor (proposed)	Difference in Demand Factors
Unnecessary panel replacements	5.42%	1.50%	3.92%
Necessary panel replacements	0.11%	0.07%	0.04%
Missed panel replacements	0.14%	0.19%	-0.04%

End-Use Sub-Metering Heat Pumps

Table 5 shows tabulated values for the synthetic retrofit analysis of 681 air handlers, 554 heat pumps and 374 central cooling systems derived from the end-use sub-metering homes in the Pecan Street Dataport and NEEA EULR datasets. Unlike the VT heat pumps, these results are not impacted by year-on-year variability in peak demand or by the addition or subtraction of loads we cannot account for. Instead, they represent heat pump demand impacts under highly controlled conditions. The median maximum 15-minute demand of individual heat pumps was about 3 kW, except for ductless systems that added just under 2 kW. The median change in whole dwelling maximum demand attributable to these heat pumps varied from 1-1.5 kW, with ductless systems contributing only 0.40 kW. The resulting heat pump demand factors were about 60%, with ductless demand factors being only 24%. As with the VEIC data, the variability in results was large. Figure 3 shows the distributions of demand factors for the different types of heat pump. Three-quarters of the heat pump demand factors are less than 75%. Again, ductless systems had a much lower distribution of demand factors, which may be due to the presence of variable speed compressors. Across all heat pumps, few had very high demand factors: five heat pumps (0.3%) showed a demand factor of 100% and 52 heat pumps (3%) had demand factors of 95% or greater.

Table 5. Median end-use values tabulated according to standard load names schema.

Load Names	Number of Systems	Load Maximum Demand (kW)	Change in Whole Dwelling Maximum Demand When New Load is Added (kW)	Demand Factor for New Load Being Added
Air Handler	681	0.70	0.46	62%
Central Heat Pump	456	2.99	1.52	59%
Central Cooling	374	2.80	1.13	44%
Central Heat Pump (Ducted)	54	2.88	1.50	59%
Central Heat Pump (Ductless)	42	1.85	0.40	24%

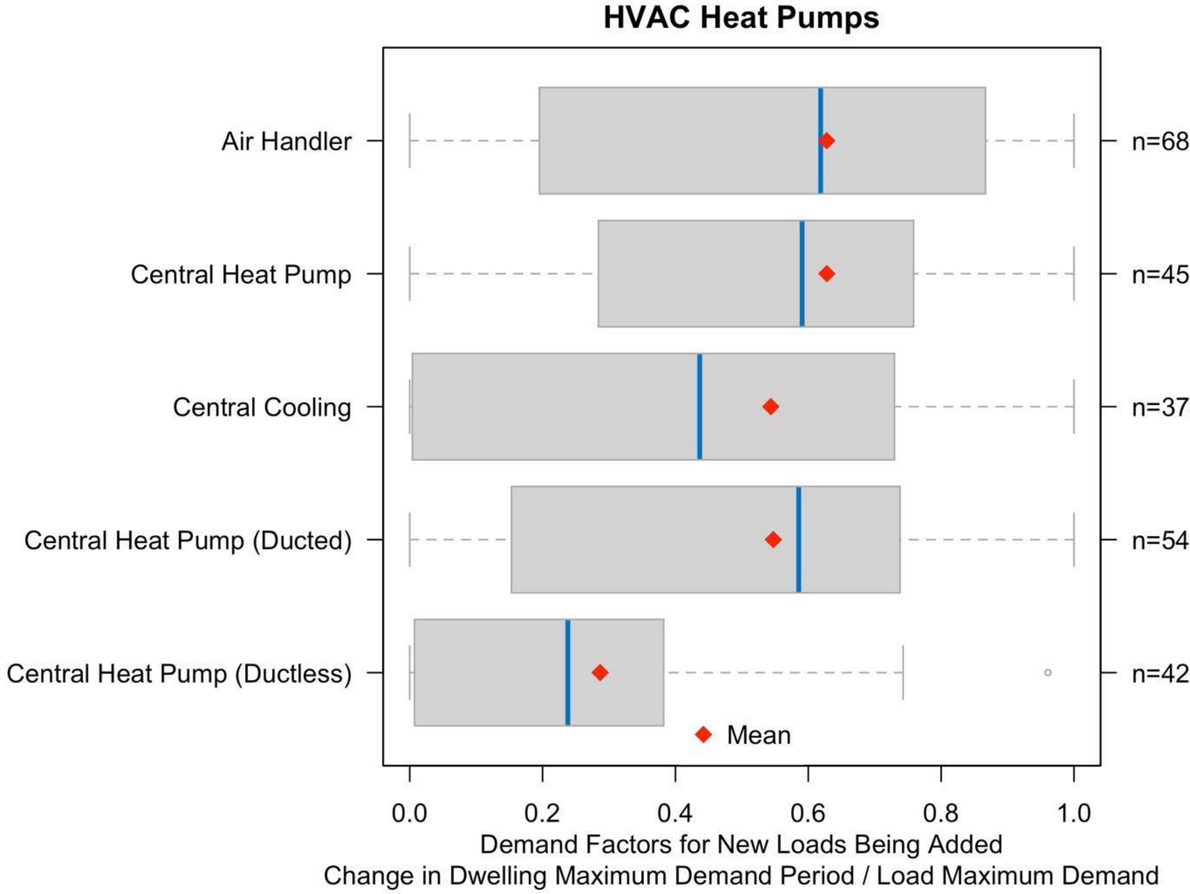

Figure 3. Distribution of demand factors for new HVAC heat pump loads being added to existing sub-metered US dwellings, disaggregated by equipment type. Blue vertical lines show the median and red diamonds show the mean. Gray boxes show the interquartile range (from 25-75th), and the whiskers extend to the data limits, except for outliers that are more than 1.5 times the IQR from the median.

Discussion

In this evaluation of thousands of HVAC heat pump installations from across the US, it is clear that while variable within and across data sources, the installation of heat pumps in existing dwellings contributes less to dwelling maximum demand than their nameplate ratings or peak application demand data suggest. Data from a Vermont heat pump retrofit program showed a very small median demand factor of only 5%, with roughly half of dwellings decreasing maximum demand after heat pump installation, and a small minority of others increasing maximum demand by more than the new load introduced by the heat pump. We speculate that contributory factors to this low demand factor could be swapping electric resistance heat for heat pumps, changes in other large electric loads, presence of other heat sources in the homes, and year-on-year variability in maximum demand. These specifics are unknown for these homes. In another synthetic retrofit setting where we could fully account for other home loads, median heat pump demand factors were much higher–roughly 60%. Both of these data sources suggest demand factors well below 100%.

For individual homes considering the need for increased electrical service, the variability in these results is concerning. At least some individual dwellings in both data sets experienced demand factors in the range of 90-100%. Currently, NEC service and feeder load calculations in Sections 220.83(b) or 220.87 account for new HVAC added to existing dwellings at 100%. Our results suggest that this treatment is unwarranted, because the vast majority of dwellings have much lower actual demand factors. Based on our results, we have proposed treatment of new HVAC heat pumps at 50% in the NEC for existing dwelling service load calculations. This proposition is supported by the following three arguments.

First, the NEC includes many conservative assumptions that when taken together reduce the risk of under- or over-estimating any individual load's contribution to the dwelling service load. For example, in 220.83, the first 8 kW of connected load is treated at 100% and any remaining connected load is treated at 40%. The 40% value surely under- or over-estimates individual loads in a home, but the default 8 kW reduces the risk of getting any single large load wrong. Similarly, in the 220.87 calculation, maximum demand observed from metered data is padded with a 25% safety factor, which again limits the risk of under-estimating any individual load's contribution. We evaluated these ideas by performing 220.87 NEC load calculations on the 9,093 Vermont homes, and we assessed the impact of accounting for the HVAC heat pump loads at both the 100% and 50% demand factors. We found that using the higher demand factor had very marginal impacts on the ability to identify dwellings truly in need of panel replacement, and that the higher demand factor led to 3.6-times as many unnecessary panel replacements. The high cost of panel replacements and the low marginal ability to identify problematic homes supports using the 50% demand factor in NEC calculations.

Second, diversity for residential loads is quite high, and overall loads are sub-additive to the dwelling peak. Furthermore, the diversity amongst loads increases with the number of loads connected, making coincident operation even less likely as more appliances are electrified. We evaluated this across all branch circuits in all of the sub-metered dwellings, and we observed that never were more than four loads on during the peak for the home at or near 100% of their maximum demand. This diversity means that when heat pumps are operating, at most only three other loads are also on. This observed limit on the number of active circuits is not included in load calculations. Instead, this needs to be accounted for by using demand factors for heat pumps that are less than 100%. Notably, credit for load diversity is allowed for larger numbers of clothes dryers (Table 220.54), cooking appliances (Table 220.55) and multi-family dwelling units (Table 220.84(B)). Additionally, high performance multi-speed heat pumps are not simple on-off devices that are at maximum capacity or zero capacity. Instead, they modulate to partial capacity in response to thermal loads, further contributing to load diversity. This allows for more headroom for other residential appliance loads. It is possible that a lower demand factor would be appropriate for multi-speed systems.

Finally, the demand factors observed from both of our analyses are likely to be biased high, because we rely on the maximum observed demand of the heat pumps as a surrogate or proxy for the nameplate power ratings used in NEC load calculations. These maximum observed demand values are commonly less than the nameplate ratings of the equipment. In fact, it appears that most heat pumps never use their nameplate rated power, even under extreme cold temperature conditions. For example, the typical 3-ton heat pump installed in the VT program had a maximum rated demand from NEEP testing of 3.6 kW based on laboratory test conditions. In comparison, an ad hoc review of nameplate ratings for residential heat pumps suggests that a 3-ton heat pump is most likely to have a 50% higher nameplate rating of 5.4 kW. Using these two values results in very different demand factors. For example, a heat pump with a reported demand factor of 50% from our analysis might have added 1.8 kW to whole dwelling maximum demand (1.8 / 3.6 = 50%), whereas the same heat pump would have a demand factor of only 33% if the actual nameplate value was used (1.8 / 5.4 = 33%).

Conclusion

Electrical service load calculations in the NEC treat new HVAC heat pumps in dwellings at 100% of their nameplate electrical rating. Based on our analysis, these assumptions are unnecessarily punitive to heat pump deployments with regard to electrical service requirements. In-situ monitoring of heat pumps suggest they rarely if ever reach their rated power demand. Furthermore, our analysis of thousands of HVAC heat pumps deployed across the US suggests their loads are substantially sub-additive in existing dwellings, contributing less than their nameplate ratings to dwelling maximum demand. We found median observed demand factors of 5% and 60% using two different measured data sets. However, small numbers of homes had high demand factors of 90-100%. We argue that using lower estimates of demand factor in NEC load calculations is appropriate for whole dwelling demand assessments, because demand is diverse amongst end-uses and other conservative assumptions in the code limit the risk of incorrectly accounting for any individual load. We tested these arguments by performing NEC load calculations on the Vermont dwellings, and we found little benefit in terms of predicting necessary panel replacements using a 100% vs. 50% demand factor assumption. These demand factors were based on the maximum observed demand of the heat pump equipment that was about one-third less than the nameplate power ratings that would normally be used in load estimates.

Future work should evaluate real-world retrofits under more controlled conditions by tracking the presence and removal of other large electrical loads in the dwellings. More work is also required to characterize the impacts on the distribution grid of adding heat pumps to existing homes. The grid impacts are distinct from the issue of dwelling maximum demand, which is often not coincident with the grid peak periods. Load diversity on the grid is a key question for future investigation.

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