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Community Scale Impacts of Sizing Dual Source Cold Climate Heat Pumps

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Abstract

Beneficial community electrification is critical to the US energy transition and decarbonization movement. It also requires careful design and analysis to execute properly. This process often includes retrofitting heating systems with heat pumps and requires special consideration in cold climates. This study examines the effects that heat pump sizing methods and switchover temperatures have on the energy consumption and energy costs of cold-climate air source heat pumps. We found that heat pump sizing methodology has a large effect on the resulting number of unmet hours, while switchover temperature has smaller effect on the same outcome. We also observed that a large difference in unmet hours/comfort can be made with minimal changes in energy bills.

Introduction

Community electrification is vital for the US energy transition and decarbonization movement. With space heating accounting for 42% of the energy use in the residential sector, space heating plays a prominent role in this transition regarding energy use, carbon emissions, and energy burden/costs (EIA 2023). Existing homes' space heating is typically decarbonized with Air Source Heat Pump (ASHP) retrofits, which can reduce heating carbon emissions but require special consideration in very cold climates where even specialized cold-climate ASHPs (ccASHPs) might require backup heating. Thus, it is important to conduct a careful design and analysis process in these climates prior to retrofit. In many neighborhoods, current electric home infrastructure and electric distribution systems might not be able to accommodate the additional load of electric backup resistors. Thus, dual source systems might be a solution for electrifying existing communities in cold or very cold climate zones where communities are being electrified all at once.

The performance of a dual source ccASHPs is dependent on various design factors, two of which are the heating capacity (usually expressed in kBtu/hr) and the switchover temperature (the temperature below which, backup or additional heating is produced by natural gas instead of electricity). This switchover temperature set point affects both the amount of natural gas consumed by the home and the number of hours for which an ASHP might not be able to meet loads. The combination of these two adjustable factors in heat pump design makes for a unique design problem that requires both field measurements as well as simulations to cost-effectively size heat pumps for residential neighborhoods. Thus, this work is part of a more extensive study that is retrofitting and partially electrifying a home park in Lake County, Colorado. In particular, this paper uses a new community modeling framework to analyze the effect of dual source cold climate heat pump sizing and switchover temperature on the energy cost and comfort perceived in a residential community. We expect that an optimal heat pump sizing exists between the current auto-sizing (which automatically sizes for cooling load) and maximum load sizing methodologies.

Background

ASHP cost-optimizing studies state that homes in the majority of U.S. climate zones could benefit from replacing their current air conditioner with an ASHP at the end of its life, while maintaining their furnace to work in tandem as a dual source system (Modi, Culligan, and Rauschkolb 2020). The recommendation for preservation of original furnaces is due to the generally lower COP of ASHPs at very low ambient temperatures in cold or very cold climate zones, which are unaccounted for in the current HSPF (Heating Seasonal Performance Factor) performance metric (NEEP 2018). These studies have also confirmed that, for certain electricity rates, the breakeven cost will be reached for homeowners who switch to ASHPs (Modi, Culligan, and Rauschkolb 2020).

Sizing of Heating, Ventilation, and Air Conditioning (HVAC) systems is a critical step to ensure that a satisfactory level of occupant comfort is maintained. The importance of this step is further emphasized by the fact that HVAC systems are the largest end-use consumer of electricity in residential buildings (EIA 2015).

Previous studies show that while oversizing of equipment increases energy consumption, it does not greatly improve the comfort of occupants and in some cases leads to lower comfort levels (Obrien, Abdelalim, and Gunay 2019; Takemura 2023). While oversizing of equipment can lead to unnecessary energy usage, undersizing can lead to unacceptably large quantities of unmet hours (or overuse use of backup/supplemental heating), poor occupant comfort, and even health risks (Lima, Ferreira, and Leal 2020). This concept also applies in warmer climates where heat pumps can be evaluated by the number of unmet cooling hours. In a techno-economic analysis of heat pump sizing in 3 cities in the United States with cooling-dominated climates, researchers found that, in some cases, undersizing led to lower energy consumption when a smaller heat pump could not keep up with cooling requirements. This, however, leads to unacceptably high numbers of unmet hours (Nelson et al. 2019). The maximum allowable number of annual unmet hours is 300 (ASHRAE 2022). This standard and these possible outcomes leave a clear goal to reduce the number of unmet hours while being conscious of energy consumption.

One study attempts to improve the way that we optimize the sizing of heat pumps by including the use of a correction factor K to account for humidity changes, and ultimately reduce air source heat pump design day temperatures by an average of $2.8°C$ (Li et al. 2023). Another study finds inconsistencies in current modeling methods of ASHPs (Underwood, Royapoor, and Sturm 2017) when performing parametric analysis based on field data to improve the compressor modeling accuracy of current heat pump models. This study concluded that a meaningful gap exists between field heat pump data and manufacturer performance data. However, field data matches well with comparisons to a heat pump tested in a laboratory setting. This finding reveals that sizing heat pumps using laboratory measurements is insufficient for making correlations to field applications. Other heat pump models have experimented with climate-based techniques that can improve annual efficiency by up to 19% by more precisely sizing the heating/cooling systems (Madonna and Bazzocchi 2013).

Ground/Air source heat pump long-term simulations have found that this tandem ground and ASHP method may be best suited to operation in cold climates where current air source heat pumps struggle to maintain comfortable indoor temperatures (Milanowski, Cazorla-Marín, and Montagud-Montalvá 2022). In addition, some free cooling modes addressed a small percentage of the annual energy demand.

Other studies have combined the ASHP with solar photovoltaic/thermal panels in a dual source Solar Assisted Heat Pump (SAHP) system, which provides solar heat to stored water. The heat pump can then extract heat from either stored water or external air. Results show this type of system could be suitable for application to multi-residential applications (Croci, Molinaroli, and Quaglia 2017). Other studies have coupled ASHP with Phase Change Materials (PCMs) to improve efficiency and reduce sizing requirements. When using combined air/ground source heat pumps, the addition of PCMs for heat storage always improved the operating performance of the systems (Bottarelli and Gallero 2020). However, this literature review found little to no previous work on the analysis of dual-source cold-climate ASHPs on very-cold climate zones.

There are a number of methods that can determine the appropriate size for a home's heating needs. Starting with the standards used for sizing heat pumps in actual construction projects, Manual J and S are commonly used. Manual J is used to estimate heating and cooling loads for a particular building, while Manual S is used to choose the appropriate equipment for that load rating (ACCA 2016). The current Manual S was not designed for cold climate heat pumps and is being updated as a result. This causes common undersizing for heating in very cold climates when using Manual S (Davis 2022).

BEopt (NREL's residential building energy optimization software) allows for HVAC auto-sizing using two methods for HVAC equipment: The Air Conditioning Contractors of America (ACCA) heat pump sizing methodology allows for the selection of HVAC equipment that meets requirements for heating, sensible and latent cooling, and blower airflow (Davis 2009). The MaxLoad heat pump sizing methodology in BEopt sets the size of the HVAC system by considering the maximum demand load required to meet heating or cooling loads. In the early stages of this study, we determined that the ACCA feature leads to large numbers of unmet hours that are often unacceptable to ASHRAE guidelines and likely uncomfortable for residents. Thus, this study focuses on analyzing the impact of sizing methodologies on various outcomes of electrified HVAC systems that will be used in this community.

Simulation Methods

This study uses BEopt (version 3.0.1.0) and URBANopt (version 0.10.0) to compare and assess different heat pump test cases. BEopt allows users to input specific housing characteristics and obtain an optimally efficiency design before simulating a full community (DOE 2013). In BEopt, limited options are available for sizing of heating/cooling equipment, with the two options being ACCA and MaxLoad. The ACCA method uses Manual J while the MaxLoad method sizes for the maximum predicted HVAC loads (NREL 2022a). BEopt-generated Home Performance eXtensible Markup Language (HPXML) files are inputs to the URBANopt community simulations as shown in Figure 1. The Urban Renewable Building and Neighborhood optimization (URBANopt) software runs on the backbone of OpenStudio and EnergyPlus to simulate communities of buildings and interface with other software products such as REopt and OpenDSS to predict other outcomes (NREL 2022b).

We obtain building geometry, year built, envelope and HVAC specs from publicly available data. However, energy assessments on the test case community will later update these input parameters. The first set of outputs from these processes are the default URBANopt results which outline the energy demand from each building broken down by end-uses. The secondary outputs from URBANopt are temperature reports, including all indoor zone temperatures.

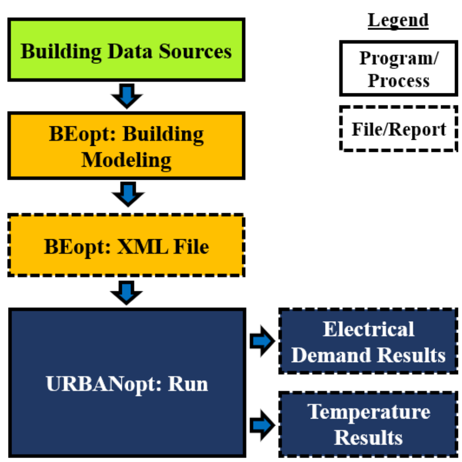

Figure 1: Project software and information workflow beginning with data source inputs and ending with the desired results categories

Community Details

Our analysis uses a case study community located in Lake County, CO at about 10,000 ft above sea level in IECC climate zone 7 (very cold). Figure 2 shows the full year of outdoor temperature data used which was pulled from a Typical Meteorological Year (TMY) version 3 dataset (OneBuilding.org 2023). This particular location can benefit from dual-source heat pumps to supplement electric heating with natural gas heating. Figure 3 shows outlines of the analyzed home-park community that consists of 28 manufactured homes, which range in age from the 1960s to 2000s. While this particular study focuses on only manufactured homes, this framework could be applied to residential housing of any type. All existing homes in this community currently use natural gas furnaces and have no central cooling which has caused resident complaints of uncomfortably warm indoor temperatures in the summer. In addition, the local electrical distribution infrastructure cannot handle a complete transition to electrical heat pumps if all houses are to use electrical heating simultaneously. Thus, the focus is on dual-source heat pumps.

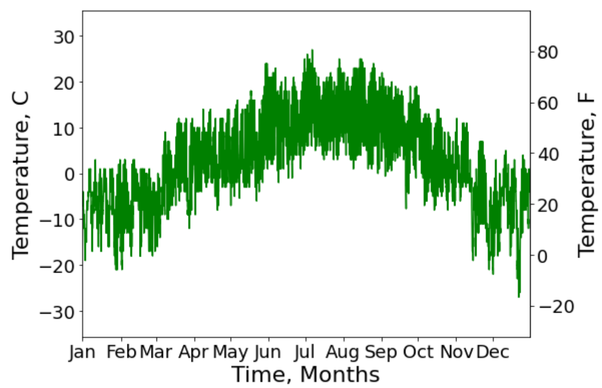

Figure 2: Plot of annual outdoor temperature by hour from TMY3 file in Lake County, Colorado

Simulated electrification also includes replacing natural gas water heaters with Heat Pump Water Heaters (HPWH) or electrical resistance water heaters and gas stoves with electric ones. The choice between HPWHs and electrical resistance water heaters will depend on space constraints due to the larger diameter of HPWHs. This model assumes that HPWHs will fit in every house. In addition, all retrofitted stoves are assumed to be heated by electrical resistance and not induction.

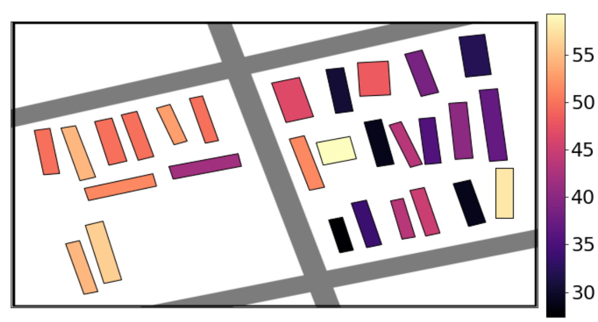

Figure 3: Analyzed 28 home community map shaded by default ACCA heat pump size (in kBtu/hr) and -5°F switchover temperature in BEopt

We gathered building and HVAC information from various sources to model the building characteristics of the studied community:

- Geojson.io: Building geometries and geospatial coordinates through tracing
- Lake County Tax Assessor's Website: Year built
- Zillow: Building configurations
- LBNL Linear Regression Study: Air leakage constants. This model considers inputs including year built, foundation type, attic type, and floor area (Chan, Joh, and Sherman 2013).
- Manufactured Home Construction and Safety Standards: All other needed information such as wall, ceiling, and floor insulation specifications.

Heat Pump Modeling

BEopt models ASHPs and other HVAC systems by matching the performance of lab measurements of over 400 systems from 5 different manufacturers to COPs and SEER ratings. Performance curves were then interpolated from the data gathered from each SEER rating (Cutler et al. 2013). The specific BEopt ASHP selected for the retrofitted case is the highest available "SEER2 20.9 and 8.9 HSPF2, Gas Backup" option that should closely match the model that will be used in the field retrofit. While this study does not compare to the baseline (before retrofit) model, the baseline HVAC assumes natural gas furnaces with 80% AFUE.

Sizing Analysis and Comparison Process

The ASHP sizing and comparison consists of 15 test cases that include 5 heat pump sizes and 3 switchover temperatures. This is done with the following 7 steps:

1. Create BEopt baseline models for each of the 28 buildings in the case study community and size each home following ACCA sizing and MaxLoad sizing methodologies for a total of 2 test cases. These default sizing choices are shown in Figure 4 for each building.

2. Export BEopt HPXML files for each home.

3. Create 3 other models for each building interpolating from the MaxLoad sizing method as a benchmark. Those 3 new sizings were 0.5*MaxLoad, 0.75*MaxLoad, and 1.25*MaxLoad. A Python script reads in the two benchmark HPXML files and then edits the heat pump heating capacity and backup heating capacity. Aside from those heating capacities, the HPXML files remain unchanged from their originals. At this point, we have 5 HPXML files for each building model.

4. Edit the switchover temperatures to make 3 variants of each existing case: 0°F, -5°F, and -10°F (-17.7°C, -20.5°C, -23.3°C) using a Python script. With these edits, we have a total of 15 community test cases. In total, we ran and processed each of these 15 test cases for all 28 buildings using the URBANopt CLI. We specified all building attributes using the HPXML files created with BEopt.

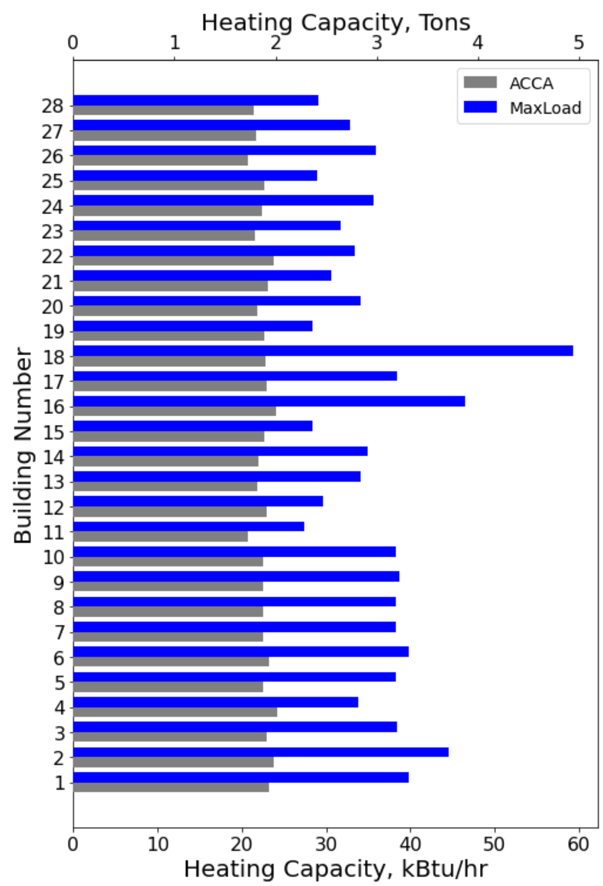

Figure 4: ASHP sizing results for all 28 homes using BEopt methodologies (ACCA and MaxLoad) for heat pump capacity with -5°F (-20.5°C) switchover temperature

5. Add two additional measures to modify the URBANopt default process to:
   a. Add the indoor temperature variable to the EnergyPlus output results .sql file using "add output variable".
   b. Add these results to a .csv file by using the measure "create csv output".

The combination of these two measures allowed us to view the indoor temperature in each zone of the buildings and to track unmet hours.

6. Calculate unmet heating hours for each test case by counting the hours where zone temperature lies outside the setpoint range.

7. Calculate energy savings and associated costs using the annual average cost of natural gas for the state of Colorado (15.33 \$/MCF) to calculate gas costs. For electricity costs, we used an annual average cost factor for Lake County, CO (0.1421 \$/kWh).

Results and Discussion

We analyze and compare both sizing methodologies at the individual building and the aggregate community level due to the large variance in auto-sizings of HVAC equipment between different homes in this community.

Building Results

Figure 5 shows the number of unmet heating hours (gray and blue bars) and respective HVAC size (maroon diamonds) for the three switchover temperatures (0°F, -5°F and -10°F) and five sizes (ACCA to 1.25*MaxLoad) for a total of 15 test cases for a single building in this community. This analyzed building has a floor area of 1300 ft^2 and was built in 1979. Figure 5 shows that as the heat pump heating capacity increases, the resulting unmet hours decrease. For this specific building, a capacity of around 0.75 to 1 times MaxLoad results in unmet hours below by ASHRAE standards (<300 unmet hours/year).

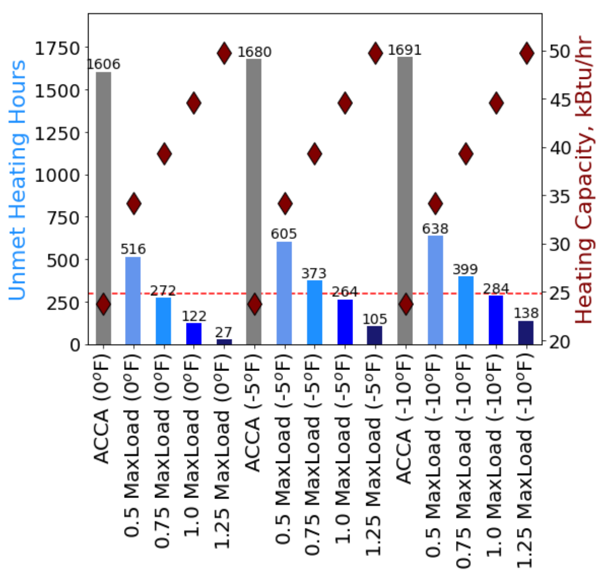

*Figure 5: Unmet heating hours (bars) and heat pump sizing (diamonds) of each ASHP sizing methodology case (0°F, -5°F and -10°F) and five sizes (ACCA to 1.25*MaxLoad) for a 1979 home in the test community*

When we raise the switchover temperature, we reduce the number of unmet hours; however, this beneficial change comes at the cost of increased natural gas consumption and subsequent carbon emissions. Figure 6 shows the annual natural gas consumption for each of the same 15 test cases (right axis, maroon bars) and the unmet hours (left axis, gray and blue bars). This bar graph shows natural gas intensity decreases as switchover temperature decreases, and a less drastic change when adjusting sizing methodology.

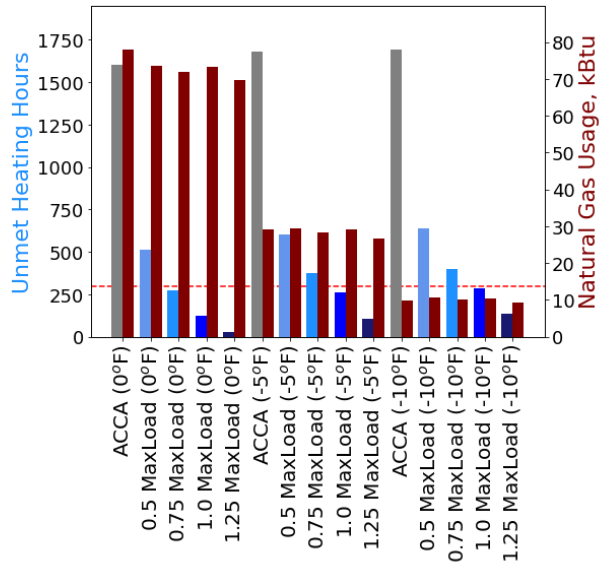

Figure 6: Unmet hours (blue/gray bars) and annual cumulative natural gas consumption in kBtu (maroon bars) for each ASHP sizing and switchover temperature

Figure 7 shows stacked graphs of the monthly combined electrical and natural gas bills expected for an average home in this community. This shows monthly energy bills remain within \$135±5 or ±1.75% for all test cases. Figure 7 zooms in on the natural gas portion of Figure 8 to show the small differences between each of the cases that are not visible in Figure 7. This shows that an increase in comfort can be achieved with minimal changes in monthly energy costs. Figure 7 also exhibits an unusual decrease in energy costs for each of the three 1.0 Maxload cases. This consistent reduced cost could be a result of uncertainty of the model. However, it is possible that this trend suggests the existence of a minimum cost performer near the Maxload sizing case.

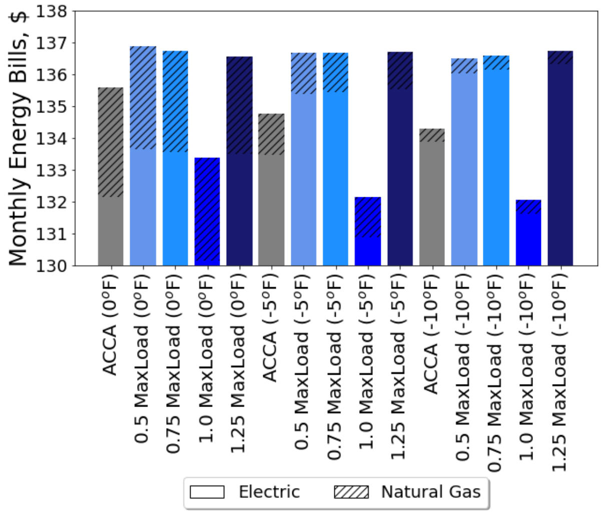

Figure 7: Average monthly energy bills for electricity (solid) and natural gas (hatched) zoomed into area of interest with respect to y-axis cost. Note that the y-axis does not begin at zero

Natural gas bills showed a higher percentage change when compared to electrical energy bills. Figure 8 shows expected natural gas monthly bills for each analyzed case. All monthly values are less than $4. This visualization also emphasizes that natural gas energy consumption and natural gas energy bills are much more sensitive to changes in switchover temperature than heat pump sizing.

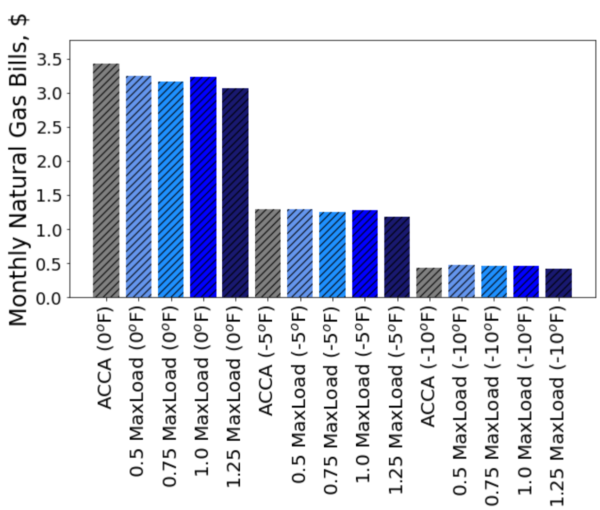

Figure 8: Monthly average natural gas energy bills for each ASHP sizing method

Figure 9 shows predicted indoor air temperature for the main living zone of a home produced by URBANopt, for 5 of the 15 test cases (switchover temperature of -5°F) over the course of the entire year. This figure shows that the winter temperatures in a cold climate without proper sizing can drop below 50°F (10°C) which is 21°F (11.6°C) below the heating setpoint. On the contrary, all heat pump sizings can meet cooling loads in this region as all indoor temperatures did not rise above the cooling setpoint of 76°F (24°C).

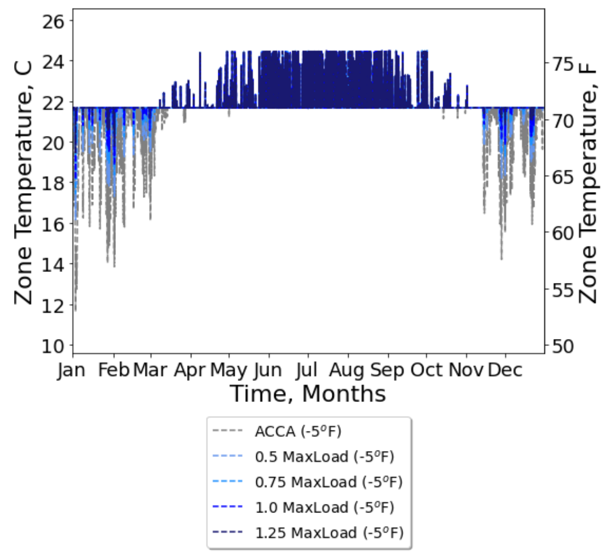

Figure 9: Annual indoor zone temperature profile by hour for each sizing methodology and the -5°F switchover temperature

Figure 10 shows the same data as Figure 9 but for only two particularly cold days of winter when the outside temperature ranges from -7°F to 30°F (-21.6°C to -1.1°C). Many of the sizings have a noticeable number of unmet hours in this span of time. A main takeaway from this plot is the points at which distinct sizings (line colors) will diverge due to differences in switchover temperatures (line patterns). This is especially prominent at the bottom of Figure 10 where the ACCA cases for -5°F and -10°F switchover temperatures diverge when the outdoor temperature drops below -5°F.

When comparing these indoor temperature profiles with outdoor temperature we can observe the point at which the -5°F and -10°F switchover cases diverge due to the switch from electrical power to natural gas backup furnace. Furthermore, Figure 10 shows the relationship between indoor and outdoor temperature for this same time window. The outdoor temperature line (shown in green) shows that subzero °F temperatures were reached during this period.

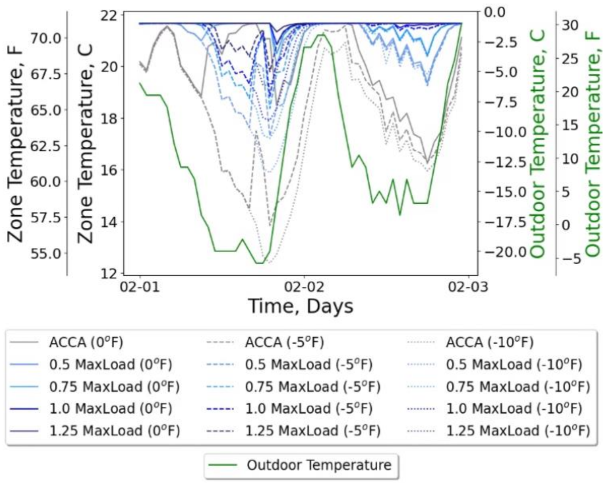

Figure 10: Zone temperature profile by hour for each heat pump sizing at 0°F, -5°F and -10°F switchover temperatures for two winter days

In this case, it is useful to view both zone temperatures and heating energy usage for a specific time period, as in Figure 11. This time period has an outdoor temperature which crosses through the switchover temperature of 0°F. At this temporal point, the electrical heating energy drops, and gas heating replaces it. This prevents the indoor temperature from dropping as far as it would without supplemental natural gas heating.

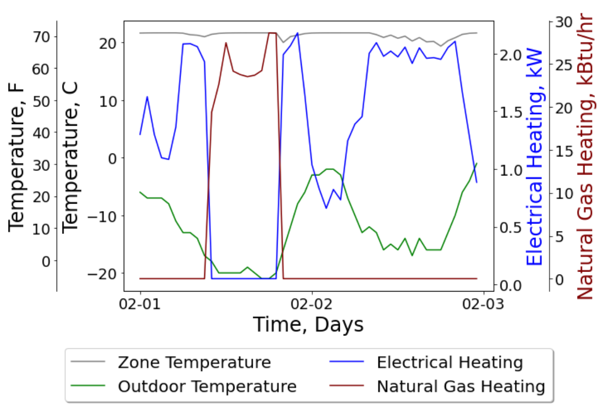

Figure 11: Indoor/Outdoor temperatures, electrical heating, and natural gas heating values of a single house (ACCA 0°F switchover temperature) for two days in February

Community Results

Figure 12 shows average the community daily winter electricity demand profile for the -5°F switchover temperature. The case with more aggressive heat pump sizing methods leads to higher morning and lower evening electrical demand peaks, while the least aggressive sizing method incurs the highest midday trough.

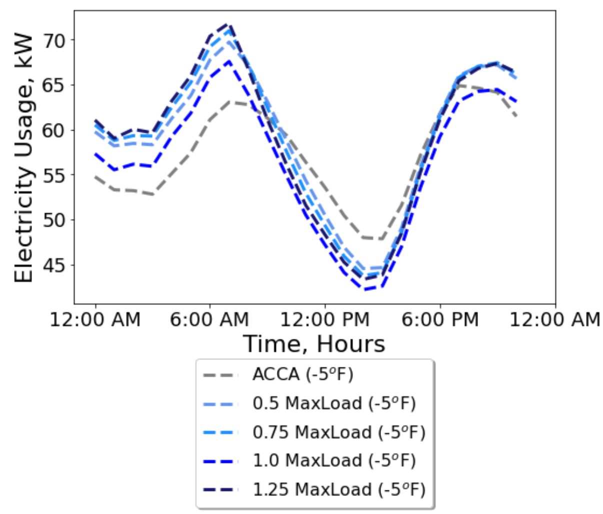

Figure 12: Winter community electrical demand averaged for the -5°F switchover temperature

This comparison of electrical energy use is further compared through the use of the violin plots in Figure 13. The general profiles of each of the ACCA cases match closely, as do the MaxLoad cases with minor changes in the maximum distribution points.

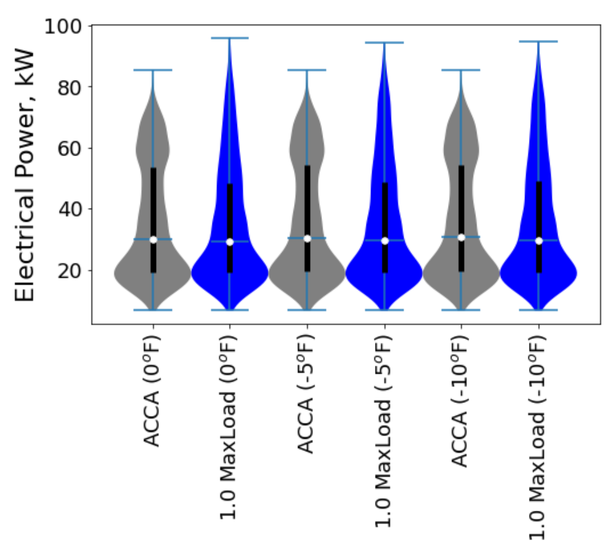

Figure 13: Violin plots of electricity consumption for ACCA and MaxLoad sizing at 0°F, -5°F, and -10°F switchover temperature

Figure 14 shows a box plot of heating capacity sizing between all homes at a switchover temperature of -5°F. ACCA tends to select a lower size by an average of 37%

and as much as 61% compared to MaxLoad. For this specific community the MaxLoad sizing was sized an average of 156% the size of the ACCA method.

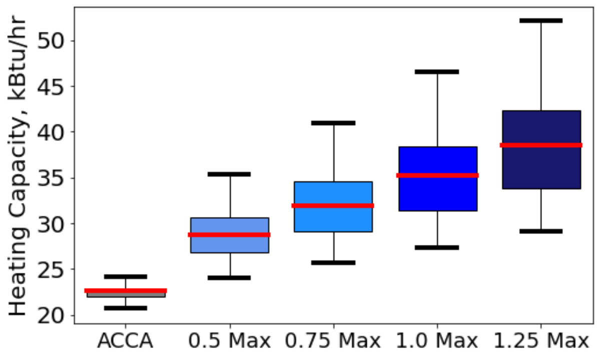

Figure 14: Box and whisker plot for variance in heating capacity sizes between the 28 buildings in the test community

Figure 15 shows a box plot of variance in unmet hours for all analyzed homes. All ACCA scenarios produced unsatisfactory results of more than 300 unmet hours. Figure 15 also reveals that the median unmet hours level (shown as a solid red line) is below the benchmark level of 300 hours (shown as a dotted red line) for the 0.75 Max, 1.0 Max, and 1.25 Max cases. While this median level is below the ASHRAE threshold, a high proportion of both the 0.75 Max and 1.0 Max cases lie above that threshold.

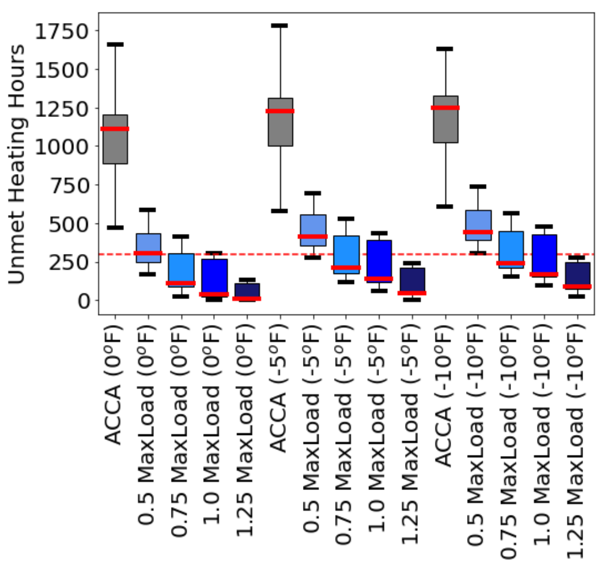

Figure 15: Box and whisker plot of variance in unmet hours per year for all 28 buildings and each heat pump sizing case

Conclusion

This study analyzes the effects that ASHP sizing methodology and switchover temperature have on community scale electrification energy costs and comfort through the simulation of a small community. Based on analysis of this data at the building-level, heat pump sizing methodology has a large effect on the number of unmet hours, while switchover temperature has smaller effect on the same outcome. We also observed that a large difference in unmet hours/comfort can be made with minimal changes in energy bills, meaning that the correlation between cost and comfort is not always strong. However, this analysis does not account for the initial cost of equipment. Also, even though the change in overall cost was not greatly affected by either of the chosen parameters, the cost of natural gas alone was largely dictated by the switchover temperature.

Unfortunately, none of the methods tested here proved to be optimal in all cases. Future work will study the possibility that more refinements between the 0.75 MaxLoad and 1.0 MaxLoad sizings would yield a more optimized result in terms of unmet hours. In addition, more analysis on the effect of initial cost of these HVAC systems and their effect on payback period is needed. In the end, this framework will also evaluate the benefits of adding solar PV and in-home battery energy storage systems. These results will be compared with field data that is currently being collected. Ultimately, we hope that this work can be used to inform government entities on the benefits that result from the electrification of low-income homes. Lastly, we believe that an investigation into the reasoning behind the ACCA methodology undersizing is required.

Acknowledgment

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