It’s All About the Envelope: Prioritizing Envelope Upgrades for Electrification of Cold Climate Homes

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ABSTRACT

Building decarbonization via electrification on a clean grid is the most promising climate solution proposed to date for the building sector. In cold climate zones, building electrification will be driven in large part by moving from natural gas space heating to cold climate heat pumps (CCHPs). CCHPs are commercially available today, including economical cold climate air source heat pumps (ccASHPs). But there’s one big problem—wide-scale adoption of ccASHPs will dramatically increase winter peak electricity demand, even with the highest efficiency ccASHP products. Furthermore, cold climate space heating loads will drive unprecedented electric system peaks during the lowest periods of renewable generation and are likely to overwhelm existing distribution systems. This scenario is avoidable by coupling electrification with building envelope upgrades to reduce peak heating loads.

This paper presents a model, built from home energy audit and research data sets, that quantifies the above challenges. Results demonstrate how weatherization efforts coupled with additional high-performance envelope upgrade measures can prepare the building stock for electrification and show the benefit these measures can bring to future utility operations. Much of this envelope upgrade work is cost-effective, according to conservative cost-benefit testing and program successes to date, and is coupled with substantial non-energy benefits. However, persistent market barriers have made scaling of envelope retrofit work challenging for decades, suggesting additional policy support is required. Lessons learned from previous policy experience, combined with new technology and administrative support, create exciting potential for this decarbonization climate solution.

Introduction

Building electrification powered by a high-penetration renewable electricity supply is a leading strategy for lowering or eliminating more than one-third of national emissions.[1] In cold climates, the largest end-use load in typical residential buildings is space heating. Electrifying space heating can more than double the electricity use and peak demand of a home. There are three fundamental strategies to mitigate the barriers associated with electrifying single-family space heating systems in cold climates. These strategies are improved HVAC efficiency, local storage, and load reduction.

[1] Building sector energy use resulted in 36% of national emissions in 2020 (EIA 2021).

Theoretically, a ccASHP with a power draw of 7 kW and a coefficient of power (COP) of 2 at -22°F could provide 48 kBtu/hr of capacity to meet space heating design loads[2] for a single family home without auxiliary heat. To the best of our knowledge, these systems do not yet exist. But they may in the future, with vapor compression cycles better optimized for heating performance through the use of new refrigerants and operating strategies. While this would enable ccASHPs to become the primary and only heating system for a majority of single-family homes, it would still represent a space heating peak load nearly triple that home's existing cooling peak.

Ground source heat pumps (GSHPs) present another option, and they are available. These systems can be sized to meet design loads and do so at COPs of 4 or greater. Hence, GSHPs can supply capacity and maintain peak loads that are fairly similar to current cooling-based peaks. However, due to their high costs and drilling requirements, GSHPs are an unlikely solution for the majority of the existing building stock. Another option is air-to-water heat pumps with storage. These systems require buffer storage tanks and radiant emitters, and are currently also cost prohibitive for most of the market. Battery storage could also be considered to directly power part or all of the electric space heating equipment during design conditions. However, based on peak space heating requirements (Table 1) and current ASHP efficiencies, battery capacities of 100–200 kWh would be required to meet peak loads over 8- to 24-hour periods. Recharging during extended periods of cold weather would be a problem for all storage, and the capacity would be relatively expensive because it would only be necessary for a few cycles per year.

The final fundamental strategy for mitigating capacity limitations and peak load demands of ASHPs in cold climates is load reduction. Space heating loads are driven by heat transfer through the building envelope. Historically, measures that moderately reduce these losses are called weatherization. More extensive building envelope improvements are possible through larger whole-home projects such as deep energy retrofits, passive house retrofits, or panelized retrofit technologies. While building envelope improvements are among the oldest and most successful energy efficiency strategies, their role in enabling a decarbonized cold climate building stock is underemphasized compared to ASHP deployment. As a pure efficiency approach, envelope improvements provide a mechanism for cost recovery by lowering annual heating and cooling energy needs. Furthermore, envelope upgrades bring many other non-energy benefits including improved comfort, improved resilience, avoided cost of HVAC capacity, and avoided costs of other strategies or supply-side investments to the grid. The remainder of this paper will focus on envelope upgrades as a strategy to enable and enhance cold climate building electrification efforts.

Methodology

This paper extends results from a recent project that studied the cost-effectiveness of residential building envelope improvements as a means to reduce natural gas consumption for space heating in Minnesota homes (Quinnell 2021). In that project, residential energy audit and research data sets unique to Minnesota were combined to estimate space heating loads in

[2] Design load is the space heating capacity required from a heating system (kBtu/hr) for a building to keep setpoint (70°F) at its winter design temperature (99.6% of the coldest temperature).

Minnesota homes as a function of building typology and performance characteristics. Following a process used for a national building stock assessment (Wilson 2017), these data were transformed into a data model that preserved correlations between variables and then sampled appropriately to provide a set of 5,000 parameter combinations to represent single-family homes in Minnesota built before 1990. The analysis here is limited to these older homes due to insufficient data on newer construction; nonetheless they represent 70% of the single-family building stock in the state. Basic building geometries were developed from these data following standard stick-frame construction assumptions. Space heating loads were estimated using the heat load factor method (ASHRAE 2021) on all major building components. In that project, weatherization program data were also used to estimate the weatherization costs and outcomes featured here. That project also estimated the costs of envelope retrofit projects including continuous exterior insulation (CEI) and replacement windows as a function of those building characteristics and RSMeans construction estimation data. In this paper, this data set representing older single-family homes is compared against ASHP performance specifications obtained from the Northeast Energy Efficiency Partnership ASHP Product list (NEEP 2022) and manufacturer specifications to determine the suitability of current heat pumps to meet design loads in these Minnesota homes.

Results

Space Heating Loads

Space heating loads in climate zones 6 and 7. Minnesota straddles climate zones 6 and 7, where winter design temperatures are below zero and heating degree days exceed 7,500. Heating requirements across the state vary, as depicted in Table 1, where heating data are presented for four cities across Minnesota that are roughly representative of the state's four quadrants (NW, NE, SE, SW). Winter design temperatures (99.6%) range from -11°F to -22°F for these four cities, and heating degree days range from 7,700 to 9,700. The temperature also drops below the design temperature regularly. The frequency and duration of these events should impact heating system selection—brief periods below these temperatures will eat into capacity safety factors, whereas longer periods may require more heating capacity. In Table 1, we can see how the severity of these below-design-temperature events varies from region to region. Average outside temperatures remain below the winter design temperatures for periods lasting 8–47 hours. The difference between design temperature and the coldest sustained outside temperatures is most apparent in the Twin Cities, where the heat island effect may mean warmer temperatures generally, but the area is still subject to extreme cold weather events. Lastly, the table includes the number of single-family homes in these regions built before 1990. About 70% of the single-family homes in the state are located in the Twin Cities area, highlighting the importance of considering the extreme weather, which can exceed average design loads for up to two days.

Table 1. Minnesota heating climates.

Location	Winter design temp (°F)	TMY3 HDD	Longest sustained period below design temperature	Single-family homes built <1990
Thief River Falls (NW)	-22	9,700	16 hr	132k
Duluth (NE)	-17	9,000	9 hr	84k
Minneapolis/ St. Paul (SE)	-11	8,400	47 hr	812k
Worthington (SW)	-11	7,700	19 hr	127k

Design loads on single-family homes. Years of collecting single-family residential data via residential energy audits for utility efficiency programs and research projects enables the estimation of design loads for single-family homes in this region. We compiled these data to understand the distribution of and correlations between building characteristics (e.g., cladding, age, size, type) and performance data (e.g., R-values of walls, windows, foundation, and attic as well as air leakage). From these data, we developed a building envelope model, assuming conventional stick-frame construction details, and calculated design loads under conditions given in Table 1. This enables us to understand how design loads will vary as a function of both the weather and the building characteristics throughout the state. These design loads are summarized in Figure 1 for homes built before 1990. This date serves as a reasonable demarcation for what we refer to as pre-energy code homes.

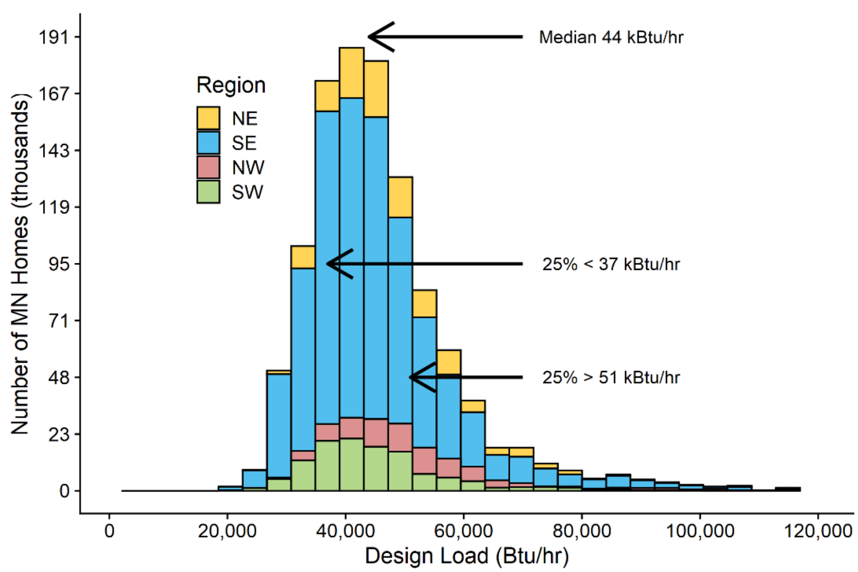


Figure 1. Winter heating design loads for Minnesota homes built before 1990.

Heating design loads are presented in Figure 1 as a stacked histogram, where each color represents each region listed in Table 1. For all Minnesota homes built before 1990, the median design load is 44 kBtu/hr and the average design load is 46 kBtu/hr. These loads occur at different temperatures depending on location in the state. About 25% of homes have design loads below 37 kBtu/hr and 25% of homes have design loads above 51 kBtu/hr. These loads need to be met by space heating systems that can deliver this capacity while operating at outdoor temperatures of -11°F to -22°F. In practice, some of this load will be mitigated by internal gains, occupancy, and other behavioral factors, but this estimate reflects conservative design calculations.

Typical residential component-level heating loads for climate zone 6 and 7. It is no mystery that old buildings are leaky and underinsulated. A new characterization study looking at a national typology for decarbonizing the U.S. building stock identified the largest drivers for heating loads, with infiltration taking the lion's share of heating loads (Reyna et al. 2021). For Minnesota's pre-1990 single-family building stock, we identify walls, closely followed by air leakage (infiltration) and windows, as the most significant factors for space heating loads, as shown in the boxplot in Figure 2. In many respects these data point to the successes of prior envelope work to lower air leakage and add attic insulation to this building stock. However, the outliers on these audit data demonstrate the extent to which completely uninsulated attic and wall assemblies as well as single-pane windows remain across the building stock and drive very large space heating loads. Even the median building, which includes some proportion of previously weatherized homes, has a combined median space heating load though walls, air leakage, and windows of 761 therms/yr.

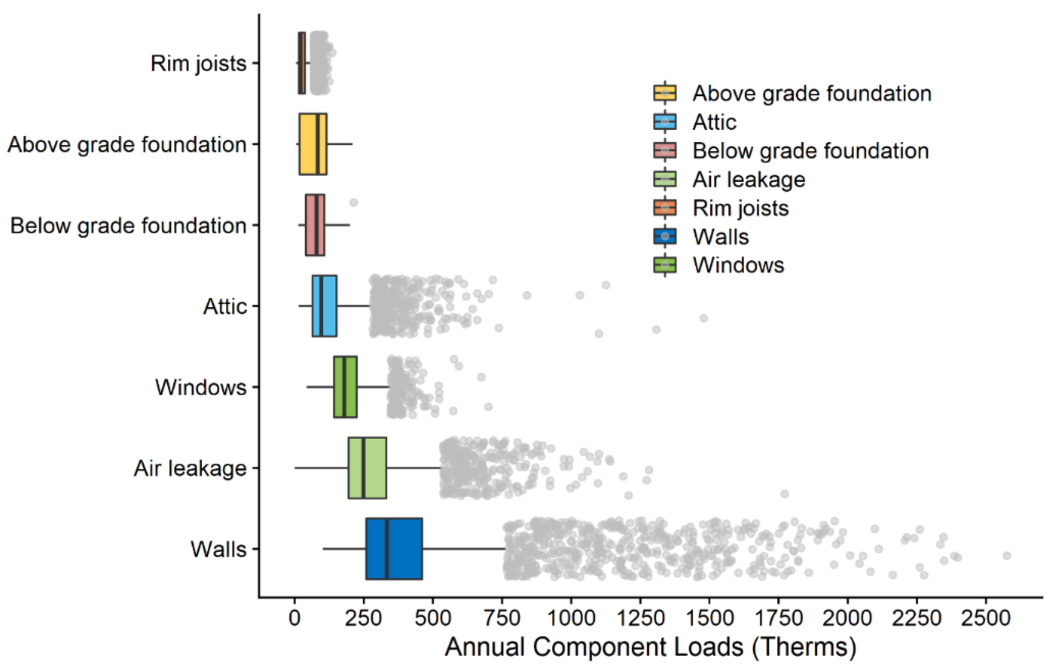
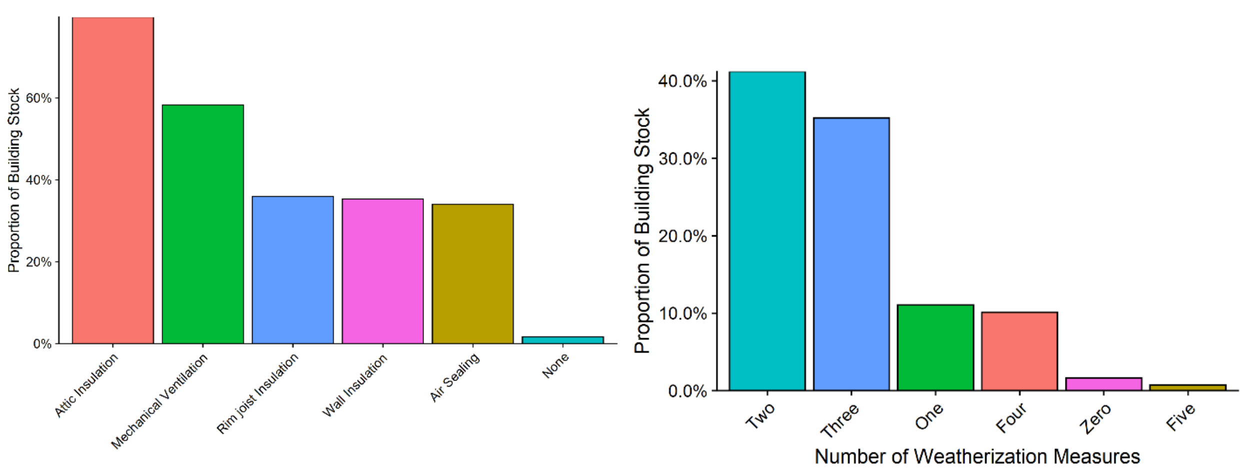


Figure 2. Component level loads for pre-1990 Minnesota single-family building stock.

Prioritizing Envelope Upgrades

Weatherization. ASHPs are the most widely used and available measures of electrification, which is the most seriously viable strategy for building decarbonization when paired with carbon-neutral energy production. The industry-wide employment of ASHPs as a heating source is warranted due to the wide market availability. This technology is financially viable despite the higher upfront costs compared to electrically resistive heating. Envelope upgrades, including basic weatherization measures, are an invaluable companion for ASHP measures through reduction of the costs of electrification for consumers via energy savings, equipment downsizing, as well as reducing loads on grid, and distributed energy resources, including grid-interactive efficient buildings.

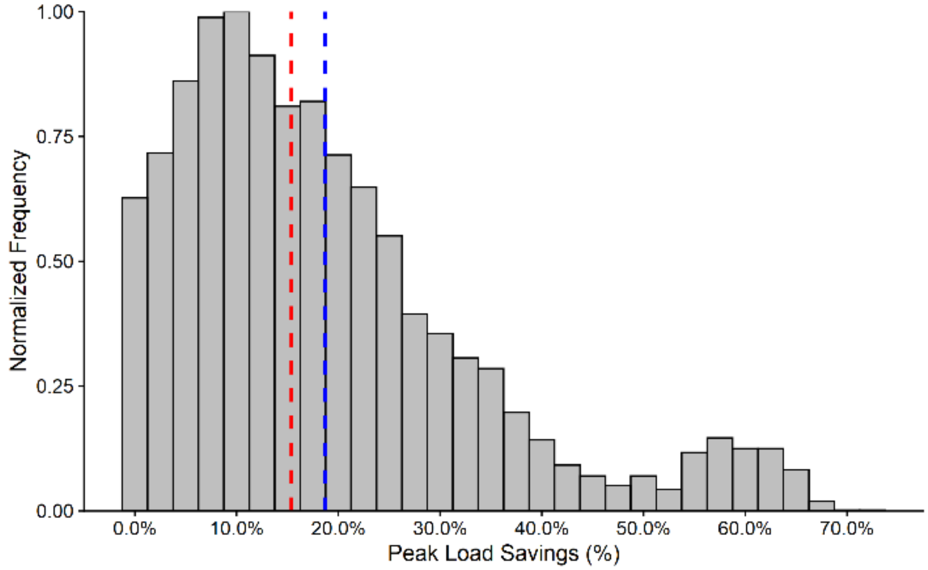
Most homes built before 1990 require weatherization upgrades to reach basic minimum performance standards that have been part of evolving energy code for decades. Using the space heating model and weatherization program data, the weatherization needs for old building stock are presented in Figure 3. The following measures are applied to the building stock, based on each building's existing performance characteristics. Air sealing work is performed on buildings with leakage rates exceeding the average leakage rate of 1.08 CFM_{50}/ft^2 and assumed to reduce overall infiltration by 15%. Dense pack insulation is added to wall cavities with existing wall insulation R-values less than R-8 $ft^2{\cdot}°F{\cdot}hr/Btu$ to bring them up to R-11 $ft^2{\cdot}°F{\cdot}hr/Btu$ and assumed to reduce infiltration by 10%. Attic insulation is added for buildings with average attic R-value less than 21.2, or 50 $ft^2{\cdot}°F{\cdot}hr/Btu$, depending on the insulation plane, up to those criteria values with assumed infiltration leakage reductions of 10%. Rim joist insulation of less than R-4 $ft^2{\cdot}°F{\cdot}hr/Btu$ is insulated up to level of R-10 $ft^2{\cdot}°F{\cdot}hr/Btu$ and infiltration is reduced by 5%. Continuous mechanical exhaust is added when infiltration supplies less than 50% of the International Energy Conservation Code 2012 ventilation requirements. These weatherization measure descriptions are in line with current weatherization program recommendations and outcomes.



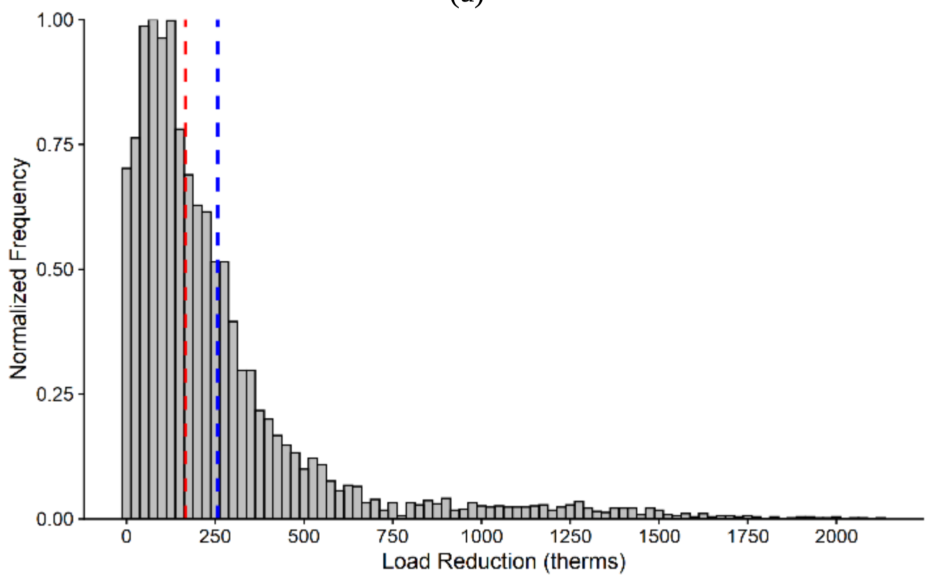
(a) (b)

Figure 3. Applicability of weatherization measures to (a) the existing (<1990) building stock and (b) the number of weatherization measures per building weatherization project.

Overall, about 98% of the existing homes built before 1990 need at least one measure described above, 41% of existing homes need two weatherization measures, 35% need three measures, 10% need four measures, and less than 1% of building stock need all five measures. The most needed weatherization measure is attic insulation at 80%. However, about half these buildings have already had existing attic insulation added to R-30 ft2·°F·hr/Btu or higher. The second most needed measure is mechanical ventilation at 58% because ventilation is often needed after adding attic insulation, wall insulation, or air sealing. For existing homes, rim joist insulation is needed in 36% of homes, wall insulation is needed in 35%, and air sealing is needed in 34%.



(a)



(b)

Figure 4. (a) Weatherization peak load reduction and (b) absolute annual energy savings. Blue and red dashed lines are average and median quantities, respectively.

Peak design load reduction and annual energy savings from weatherization are estimated for this building stock in Figure 4. While peak load reductions of 40% to 60% are possible in much of the building stock, the average reduction is 19%, and median reduction is 15%—these results are in line with average weatherization outcomes. In many cases these weatherization outcomes yield over 1,000 therms of annual energy load reduction for homes with uninsulated walls, attics, and single-pane windows. Average and median savings, however, also remain quite high (257 and 167 therms/yr, respectively) for the building stock when brought to the uniform envelope standards described earlier. These weatherization outcomes were previously estimated to be cost-effective for participants with natural gas heated homes (Quinnell 2021) according to Minnesota's Department of Commerce BENCOST framework (MN Commerce 2021).

Beyond weatherization. Historically, weatherization measures represent the suite of building envelope improvement measures that can be completed noninvasively and cost-effectively. However, these measures represent only the basic steps to bring existing buildings up to a minimally acceptable level of efficiency. Buildings weatherized to the standards presented here will still result in space heating loads that are relatively higher than those of buildings constructed in the last few decades. Consequently, additional envelope upgrades are likely required to bring heating loads in many old buildings down to the corresponding levels seen in new construction. Two such measures are considered here. Even after cavity filling walls to R-11 $ft^2\cdot°F\cdot hr/Btu$, more heat is lost through walls than any other building component. Continuous exterior insulation (CEI) remains one option for further improving the insulation value of walls, while minimizing thermal bridging through the building's structural elements. Additionally, many existing homes, if not an outright majority, have windows that are beyond end of life. Although most Minnesota homes have received window upgrades in their lifetime (from single pane to double pane), current code-minimum double-pane windows offer improvement by about a factor of two over older double-pane windows. These measures, on top of a weatherized building stock, can further improve the prospects of electrification while minimizing the peak load impacts to the grid.

ASHP capacity limitations. Maximum heating capacity is generally only relevant in winter design conditions because loads (and capacity requirements) are smaller at warmer outside temperatures. Figure 5 underscores this capacity challenge by comparing the capacities of different space heating systems as a function of outside air temperature. About 18 kW of resistance heat will output 60 kBtu/hr at all outside temperatures. A 60-kBtu/hr condensing furnace will supply around 55 kBtu/yr at all outside temperatures. Consequently, these conventional systems can meet median design loads and have around 25% surplus capacity, which can be deployed below design conditions, perform setback and recovery, or enable increased setpoint temperatures.

This flexibility does not extend to heat pumps currently available in the market, all of which struggle to provide heating capacity at and below the stated design temperatures. Capacity curves from four heat pump models are provided in Figure 5 to illustrate this limitation. A 5-ton reference heat pump is provided as an example of a relatively high performance, market-leading, variable-speed ccASHP. Three other high-end heat pumps, selected for their capacity maintenance at low outside temperatures, are also shown. Performance data are optimistically extrapolated to assume COP of 1.2 at -25°F in all cases because performance data are sparse to non-existent at very cold temperatures. The reference unit provides relatively good performance under most conditions—however, it lacks enhanced vapor injection and loses capacity and performance rapidly below 5°F. The reference unit provides about 75% of its capacity (40 kBtu/hr) at 5°F, decreasing to below 20 kBtu/hr at relevant design temperatures.[3] The other units have some improved capacity maintenance due to enhanced vapor injection technology in their compressors and preserve more of their nameplate capacity at design conditions. However, these units still struggle to maintain capacity, with all of them falling to 60% to 80% of nameplate capacity at climate zone 6 and 7 design conditions.

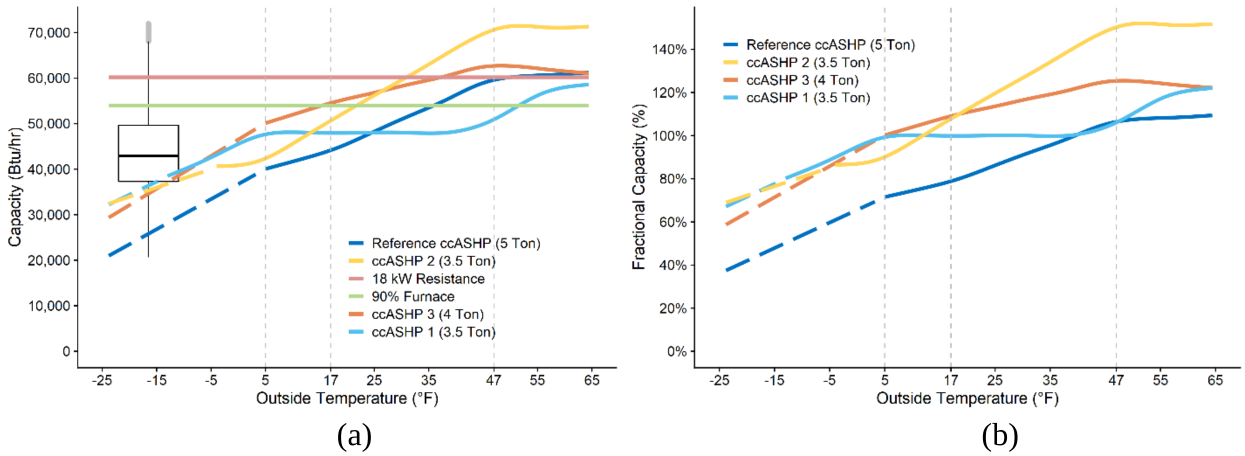


Figure 5. (a) Capacity (Btu/hr) of select heating systems compared to boxplot of MN single family loads; and (b) capacity (%) relative to nameplate capacity at 47°F (right). Dashed lines incidate extrapolated performance data.

These capacity curves introduce a major barrier to space heating electrification in climate zones 6+. The best current ASHP systems cannot meet design load in a majority of single-family homes in these climate zones. Furthermore, they don't have any spare capacity for cold weather events that exceed design loads, or the ability for recovery or demand response in these cold conditions. Based on the loads in Figure 1, we can calculate the proportion of single-family homes (built prior to 1990) that can meet their design load with the four heat pumps shown in Figure 5. Today's best heat pumps (ccASHPs 1–3) can meet the design condition in just 24% to 31% of older Minnesota homes as shown in Figure 6. The 5-ton reference heat pump is insufficient in over 96% of older Minnesota homes. The best residential systems available today are incapable of meeting design loads on the majority of single-family homes in climates with design temperatures below -10°F, and upsizing or specifying multiple units for this purpose is likely to increase costs dramatically.

Consequences of envelope improvements on space heating electrification. The consequences of building envelope measures on the fraction of older building stock that can meet winter design loads with ccASHPs in Minnesota are shown in Figure 6. Basic weatherization, weatherization with added R-10 CEI, and weatherization with CEI and replacement windows all increase the fraction of building stock that can meet heating load with best-in-class residential ccASHPs. Basic weatherization nearly doubles the fraction, from 24%–31% to about 59%–67%, of single-family homes that can electrify space heating with a best-in-class ccASHP. Adding CEI and

[3] This extrapolation is for demonstration purposes only; in practice, this machine will lock out below an outside air temperature of -4°F.

replacement windows increases this fraction to 81%–85%. Building envelope upgrades even enable the reference ccASHP to meet winter design loads in nearly half (46%) of these older homes.

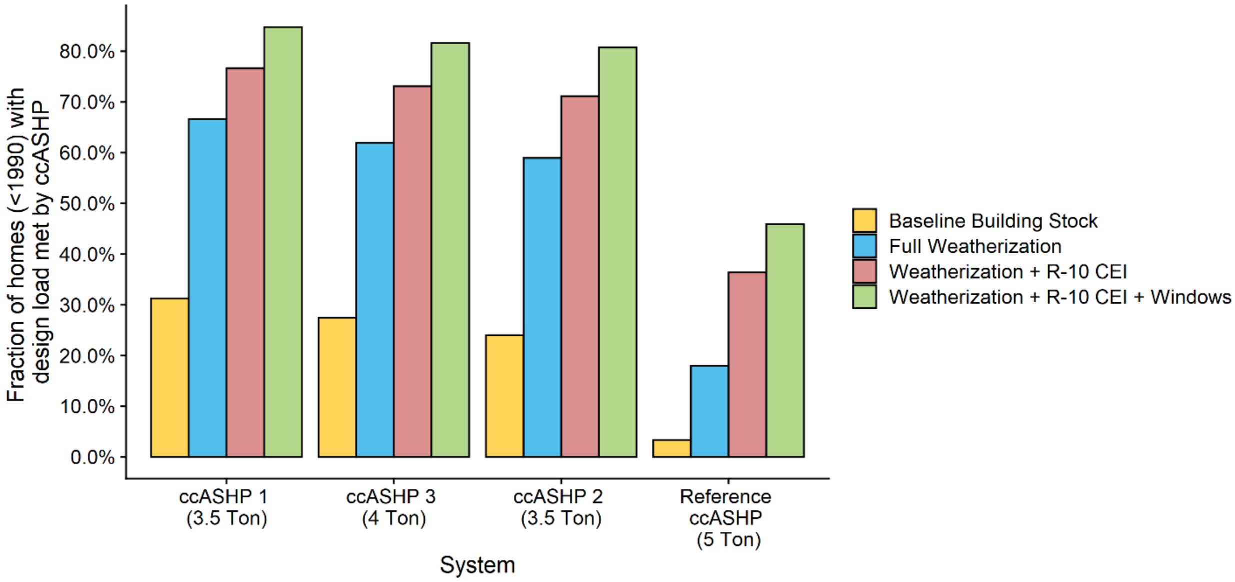


Figure 6. Fraction of homes built before 1990 that can have design loads met by the heat pump under full weatherization, CEI, and window measures compared to the baseline building stock.

Overcoming capacity limitations. For homes that cannot meet load with an ASHP, the current and most viable decarbonization approach is to provide supplemental capacity via electrical resistance elements that run in series with a heat pump to increase capacity. Many manufacturers sell relatively low-cost cased plenum heaters (i.e., electric heat kits) that can be attached downstream of the A-coil heat exchanger. These electric resistance heaters are available in a large range of capacity, typically 5–20 kW. At a COP of 1, these units provide 17–68 kBtu/hr of heating capacity to supplement insufficient ccASHP capacity at low outside temperatures. However, with that COP of 1, large power input is necessary, adding to peak load. The strategy for capacity and performance is to operate any ccASHP as long as its COP is greater than 1. Then the net system, even with supplemental electric resistance, will retain some efficiency benefit. For example, a 5-ton ccASHP using 6 kW at a COP of 1.2 will provide 25 kBtu/hr of heat at -22°F. For a building with a design load of 44 kBtu/hr, this ccASHP is 19 kBtu/hr short on capacity, which can be provided by 5.9 kW of electric resistance heat. Thus, at this design condition, the system will draw 11.9 kW of power (about 50A) at a net COP of 1.1. Due to the heat pump, the system runs about 10% more efficient than a pure electric resistance system. So, there is always an efficiency benefit of running a heat pump when its COP exceeds 1. One advantage of plenum heaters is that they are very cheap, only about 5% to 10% of the cost of a ccASHP. Subject to electrical service and panel limitations, these systems can also be oversized without much performance loss. For example, to meet a 44 kBtu/hr design load from just a plenum heater would require 13 kW of resistance heat. Unsurprisingly, this is about 10% greater power than the ccASHP-plus-electric-resistance combo. The major limitation is that this electric resistance system will always operate at a COP of 1, whereas the ccASHP can operate at a COP 1.2 and up to 5 in mild weather. Nonetheless, oversizing plenum heaters is a fairly easy way to supplement ccASHP capacity as necessary to optimize performance, while also providing sufficient backup capacity to operate without a heat pump.

Given the loads presented in Figure 1 and the ASHP capacity curves in Figure 5, we can calculate the auxiliary electric resistance that is necessary to supplement ccASHP capacity for pre-1990 single-family homes in Minnesota. This required electric resistance capacity depends on the design load of the home and individual heat pump specifications. For the four heat pumps discussed, the distribution of electric resistance heating requirements is given in Figure 7. Median auxiliary electric resistance is 2.6 to 2.8 kW for ccASHPs 1–3 and 4.4 kW for the reference heat pump. Consequently, peak power draw to meet design loads in pre-1990 single-family loads is 8.6 to 9.6 kW and largely invariant across the different heat pump types due to very similar performance at the coldest temperatures and relatively minor efficiency benefit over electric resistance. The colder design temperatures in northern Minnesota require approximately 2 to 3 kW of extra resistance heat compared to southern Minnesota due to deteriorating ccASHP performance below -10 °F. We also call attention a potential overestimate of the performance and capacity of heat pumps at these temperatures based on the extrapolation used here. Consequently we are still yet to fully appreciate the magnitude of auxiliary electric resistance necessary for today's best heat pumps and the impacts on peak load.

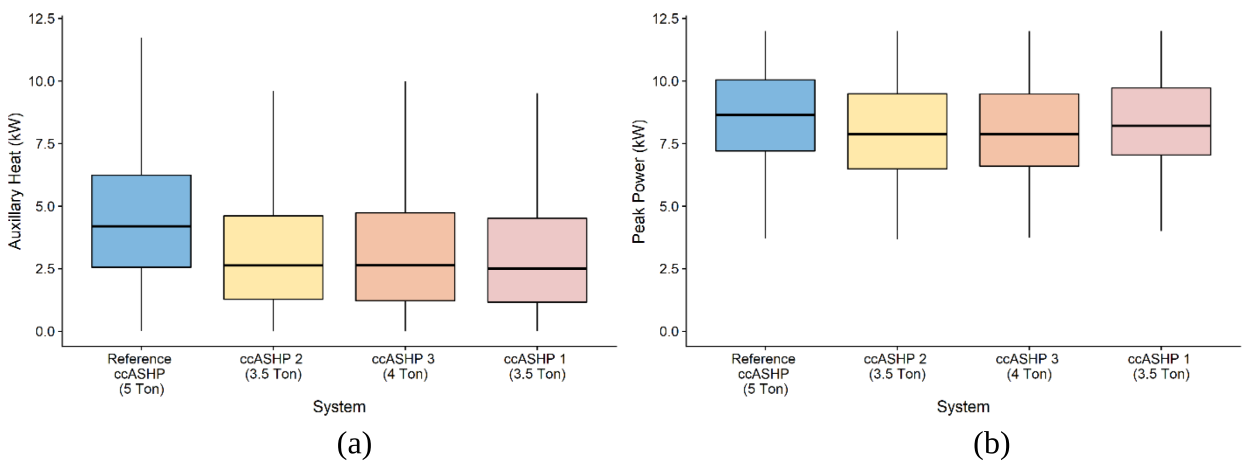


Figure 7. (a) Auxiliary electric resistance heating requirements for Minnesota homes built before 1990 and (b) Peak power (combined ASHP and auxiliary) draw at design load.

The relationship between building envelope improvements and peak load is shown in Figure 8. Median peak loads drop 2 to 2.5 kW and range between 6.3 to 7.2 kW when the baseline stock is fully weatherized. Exterior insulation and replacement windows drop peak loads by another 1 kW, yielding a net peak load reduction of about 32% to 37%. Such reductions of peak load will have a dramatic impact on grid capacity investments for fully electrified and decarbonized space heating in cold climates.

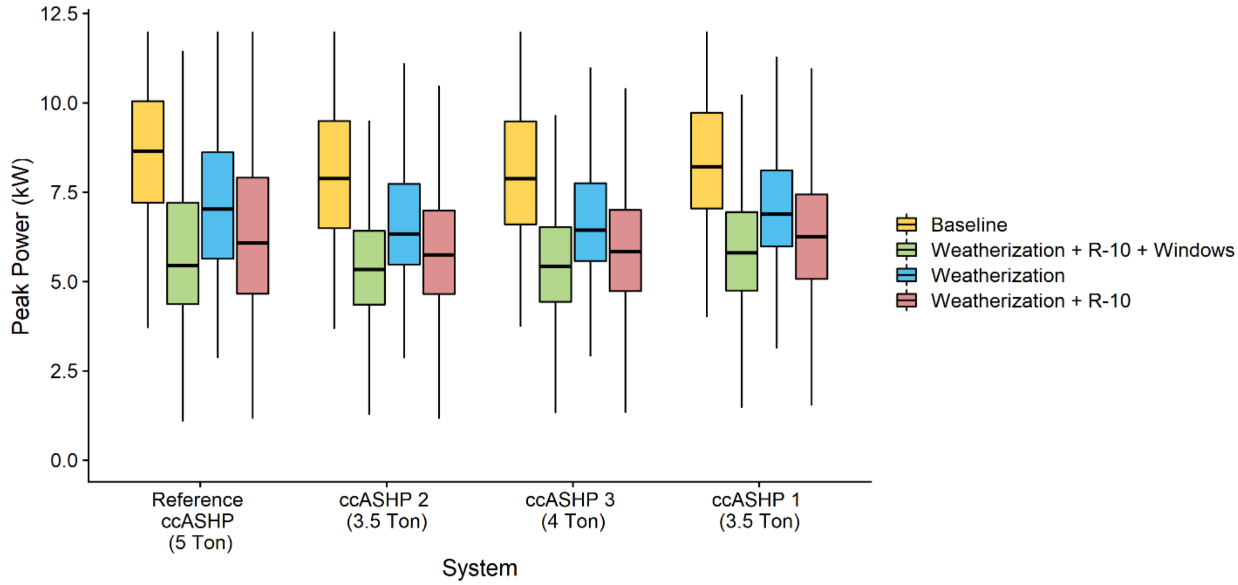


Figure 8. The change in peak load statistics in the older Minnesota single-family building stock under various envelope improvement measures.

Policy Implications

Prior barriers to envelope work (including weatherization). Infiltration has been identified as the largest contributing factor to home heating across all climate zones (Reyna et al. 2021), and this work demonstrates that infiltration is only slightly behind walls as the largest heat loss mechanism in pre-1990 Minnesota homes. Addressing these leaks has been a long-standing effort for both new and existing structures. Government-funded weatherization assistance programs initiated in 2009 made funding available for low-income properties to undergo energy assessments and improvements. These funds were administered through non-profits, local governments, and community action associations. This effort, applied to only partial segments of the building stock, was able to make an economic and societal impact for underserved communities across the country. This kind of program support can provide performance improvements for a larger portion of the building stock, particularly those cold 6+ climates addressed in this study. The benefit can be magnified through displacement of fossil-fired space and water heating if the building envelopes are improved sufficiently to reduce heating loads in order to allow electrification without unreasonable escalation of peak loads. The lessons learned by identifying the effective channels and networks for administering this kind of weatherization funding can be brought to bear in future efforts. Programs like this can create a cascade effect of new technology implementation. LED bulbs, once novel, became mainstream as a highly effective, quick payback energy conservation measure. Implementation expanded once utility programs supplemented LED bulb use in weatherization projects. Retailers began offering direct rebates to support the endorsement of state and local entities. Evidence that a lucrative and growing market for energy efficient technologies existed with LED light bulbs, ENERGY STAR® appliances, water-efficient toilets, and flow-limiting devices for hot water that led to increasing penetration into the available inventory of buildings ripe for retrofit. It's more difficult to improve a building envelope than it is to screw in a light bulb or replace a refrigerator, but that same approach can yield results in reaching a greater portion of the building stock by providing deep building envelope improvements.

Lessons learned from previous policy factor permutations. There is federally funded work ongoing to inform where and how existing technology deployment can be cost-effective. Programs such as ENERGY STAR, and Zero Energy Ready Homes provide information that consumers and business can rely on to make informed, energy-conscious decisions. This includes understanding how deeper building envelope retrofits can mitigate some of the challenges for electrification transitions. The benefits ancillary to deep building envelope improvements undertaken include improved resilience during grid interruptions, internal air quality improvement through protective technologies, and enhanced longevity of structures undergoing retrofit. Through research, case study, and demonstration of existing technologies, the path to increased participation by private, local, state, and federal entities is made less steep and more attractive in these efforts that will accelerate decarbonization.

Potential for accelerating decarbonization through envelope work. Deep energy retrofit envelope improvements, while not modest in terms of cost, carry relatively low risk in terms of efficacy, and can be considered technology- and policy-agnostic. Modeling data and case studies show substantial savings from retrofits of continuous insulation and window improvements on existing structures. Improvements like these will be effective in reducing energy consumption, and carbon output, even if they are not associated with any other very high efficiency equipment improvements. These measures are equally as effective for reducing the load for an existing 10-year-old furnace as they are at reducing the necessary installation sizing and operating requirements for a new system. New installations of all varieties will benefit from envelope improvements. The net impact of envelope + space-conditioning system solutions will be favorable for potential future advanced hybrid technologies, and for installation of high-efficiency cold weather heat pumps. Because there is some level of implementation risk with new equipment technologies, it is important to take a measured approach in deployment. Envelope improvements pave the road for advanced space conditioning technologies. While that measured technology deployment is underway, envelope improvements can proceed at full speed, getting a necessary head start for ramp up of effective new technology solutions.

Conclusion

The results from the examination of the energy and peak load impacts of improving building envelopes in climate zones 6 and 7 suggest that envelope upgrades should be prioritized in electrification and decarbonization efforts. Addressing load reduction is the path to responsibly electrify buildings at scale and offer truly viable options without massive investments in energy production to meet electrical loads that would nearly triple compared to current needs. While a full analysis of further grid loading should be conducted, this falls outside the scope of the discussion of this paper. It is, however, reasonable to assume that the current grid services could not handle peak loads if buildings are merely electrified, and a future lower carbon resource mix greatly magnifies this challenge. Although some viable options for dual-fuel and advanced heat pump designs are possible, these typically do not fully electrify the building, or tend to be cost prohibitive. Failure to recognize the very different grid needs for fully electric space heating compared to the much lesser needs of dual-fuel approaches may lead to suboptimal capacity investments that ultimately stifle future efforts to fully decarbonize space heating systems in cold climates.

Weatherization efforts should be expanded to a wider range of existing buildings. Basic weatherization efforts performed over the last decade have shown promise in energy reduction measures with minimal investment. Typically these measures have been widely deployed to disadvantaged areas and low-income households. Our assertation is that this should be deployed to a wider range of buildings, which can be identified through a number of methods with grid services, audit data, or end-use profiling.

Envelope upgrades have been a difficult upgrade and further research and field validation are needed. Although the advanced methods presented above offer a path forward with further load reductions, the upfront costs tend to come with a level of "sticker shock" to the consumer. Further research and advanced building construction approaches should be explored to further reduce retrofit costs to the envelope. Addressing these cost barriers would allow these types of retrofit opportunities to a wider range of building owners, which allows for a more resilient building stock and a smaller peak load impact to the grid when electrification efforts are deployed.

Equipment-based upgrades are widely accepted, but envelope upgrades are trailing and further programmatic support is needed. ccASHPs are one of the most exciting and widely deployed measures for electrification and decarbonization, but bring several issues that need to be considered. Without successfully reducing peak loads, electrification and decarbonization measures stand to overtax the grid, and viability is reduced when considering these measures on a regional scale. This leaves only two real solutions in the space: massive upgrades to production and grid services, or coupling envelope upgrades into the suite of retrofit measures when considering building electrification. While the former is important in considering the aging grid, the latter offers an approach that can be addressed in a case-by-case basis during electrification operations. While the current costs for envelope upgrades are high in comparison, further research and development of advanced building construction, panelized construction, and creative retrofit approaches can offer further cost mitigation. Further programmatic support that bolsters envelope upgrades stands to address these issues, but these efforts continue to fall behind equipment-based measures.

Grid utilization of renewable energy sources is on a trajectory to improve. Replacement of appliances at the end of useful life with fossil fuel-burning options now will lock in a large portion of residential energy with no way to benefit from future local or grid generated renewables. Strategic planning for two impactful outcomes borne from the single effort of building envelope improvements is both wise and necessary to meet significant decarbonization challenges. Enhancement of residential building envelopes facilitates the penetration of electrical space and domestic hot water heating appliances into a high potential market. This effort supports aggressive carbon goals set by state and federal entities, and it ensures that until the electrification infrastructure gap is bridged, energy use is attenuated on the path to a potentially more impactful solution.

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References

ASHRAE. 2021. ASHRAE Handbook Fundamentals. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta. 2021.

EIA. 2021. "In 2020, the United States produced the least CO_2 emissions in nearly 40 years." U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=48856

MN Commerce. 2021. *2021-2031 Minnesota Department of Commerce Conservation Improvement Program BENCOST Framework with approved inputs for 2021-2023 triennium.* https://mn.gov/commerce/industries/energy/utilities/cip/cip-guidance-policy-documents/

Northeast Energy Efficiency Partnership (NEEP). 2022. NEEP's Cold Climate Air Source Heat Pump List. Lexington, MA. https://ashp.neep.org/

Quinnell, J.A. 2021. Exploring High-Performance Envelope Retrofits: The next step in single-family building weatherization. Technical Report prepared for Minnesota Department of Commerce Division of Energy Resources. Grant #158619. St. Paul, MN. December 2021.

Reyna, J. et al. 2021. U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings. Part 1: Residential Buildings. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-81186. www.nrel.gov/docs/fy22osti/81186.pdf.

Wilson, E. et al. 2017. Energy Efficiency Potential in the U.S. Single-Family Housing Stock. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-68670. www.nrel.gov/docs/fy18osti/68670.pdf.