Implications of Electrifying Residential Space Heating in Cold Climates with Heat Pumps, Envelope Improvements, and Thermal Storage

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ABSTRACT

Most greenhouse gas emissions stem from operational carbon emissions, which includes emissions from using fossil fuels in heating and cooling. US Energy Information Administration data show that in the United States, approximately 47% of households rely on natural gas as the main heating fuel. Electrification of heating is a primary consideration in deep decarbonization in buildings, but electrification of existing homes heated with natural gas will increase costs more than replacing gas furnaces with new gas devices. Furthermore, replacing existing gas furnaces would increase the energy burdens for some vulnerable populations. To assess the effect of electrification on energy burdens in cold climates, this paper explores how thermal energy storage (TES) and high-performance envelopes improve conventional and cold climate heat pump performance in five climate zones, particularly during the coldest times of the year. This paper also examines the effects on energy usage and peak demand, utility costs, and carbon emissions. This paper makes recommendations to policy makers regarding the use of TES and high-performance envelopes to support the equitable transition to building decarbonization by electrification.

Introduction

The United States has a goal to decarbonize the electric grid by 2035 and achieve a net-zero economy by 2050 (US White House 2021). Buildings will play an integral role in achieving decarbonization objectives by eliminating the burning of fossil fuels for space heating, water heating, and cooking appliances. In 2015, 69% of energy for space heating was provided by natural gas (EIA 2015). This percentage is even higher in colder climates where space heating and water heating equipment typically use natural gas, fuel oil, or propane (Billimoria et al. 2018). For example, only 7% of homes in both New York and Michigan were all-electric (AGA 2015). Furthermore, homes in cold climates comprise only 34% of homes in the United States yet consume about 60% of all fossil fuels for home heating.

Electric heat pumps (HPs) are well suited to assist in building decarbonization efforts by replacing natural gas furnaces. HPs use electricity to transfer heat from outside air into indoor spaces to provide space heating, and they can run in reverse to provide space cooling, like a

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conventional air conditioner. However, the lower temperature threshold in colder climates makes HPs less efficient, and replacing furnaces with HPs in colder climates can lead to increased utility bills. Policy-driven electrification will increase energy costs by approximately 38%–46%, potentially exacerbating the energy burden on vulnerable populations (AGA 2015). The adoption of HPs in cold climates has thus been slower than in warmer regions.

Researching ways to improve the efficiency of HPs in cold climates is crucial for mitigating the effects of increases in electricity demand and consumption for heating. Strategies that would have significant economic effects on both energy supply and demand include peak load management and flexibility using thermal energy storage (TES) and high-quality, smart, and efficient building envelopes (Best and Sinha 2021).

This paper presents original modeling work on the effect of TES integrated into HP adoption, as well as high-performance building envelope strategies regarding carbon emissions and electricity system peaks in cold climates. The findings are discussed in the context of system configurations and controls for TES needed to encourage policies (Carlock et al. 2021, Penttinen et al. 2021, Kaufman et al. 2019, Takahashi et al. 2020) that support the equitable transition of heating decarbonization in buildings. The future goal is to develop a framework that will inform electrification policies across the United States as HPs, TES, and high-performance envelope measures are used as a building electrification tools in cold climates.

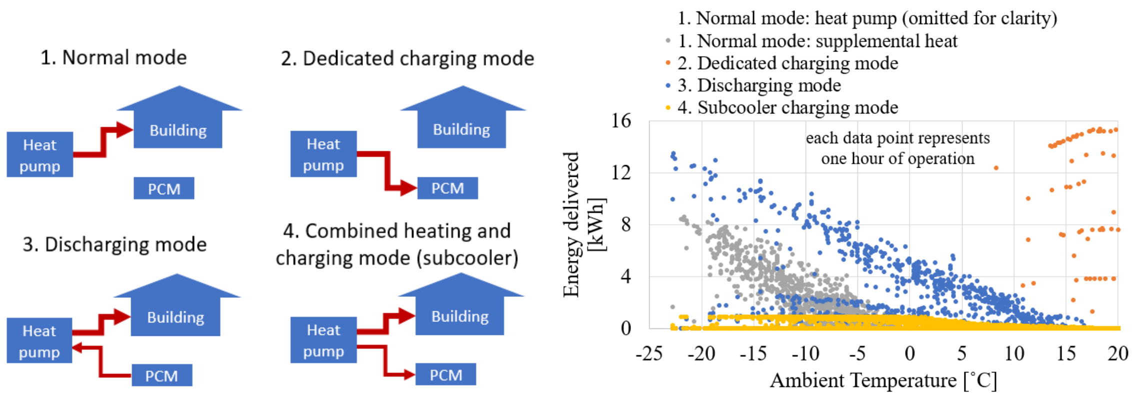
Modeling and Analysis Methodology

To assess the effect of electrification on utility burdens in cold climates, the authors modeled four types of equipment in two types of residential building vintages in five climate zones. The buildings and equipment were modeled with and without efficiency measures to evaluate the effect of enhanced equipment and enhanced envelope on energy utility burden. The following sections detail the equipment and envelope modeling.

Equipment Modeling Approach

EnergyPlus 9.5 is a computer program that many researchers and designers use to simulate buildings with HPs to evaluate their energy performance. To simulate cold climate HPs (CCHPs) integrated with TES, a custom EnergyPlus version was compiled. EnergyPlus uses performance curves to represent HP operations under a wide range of ambient and indoor conditions, which are bi-quadratic curves as a function of indoor and outdoor temperatures. Part-load performance is considered by inputting the degradation coefficient to a part-load correction curve. EnergyPlus can model variable-speed or multispeed cooling and heating coils with rated capacities, coefficients of performance (COPs), and air flow rates for individual speeds.

In addition to the variable-speed HP, the authors developed a new feature to model HPs integrated with TES. Figure 1(a) shows the four operating modes modeled in this work. In discharge mode, the HP draws heat from a PCM storage tank through a refrigerant evaporator in the tank and discharges heating energy to an indoor space via the condenser coil. The dedicated charging mode uses the outdoor air source and discharges all the heating capacity to the PCM tank. The combined heating and cooling (subcooler) charging mode splits part of the heating capacity by using the refrigerant coil in the PCM tank as a subcooler. The indoor coil still supplies 90% of the heat to the indoor space, and the subcooler stores the remaining 10% capacity in the PCM tank. The subcooler charging mode is assumed to have the same operation efficiency as the main space heating mode without the subcooler.



(a) (b)

Figure 1. (a) The four operating modes modeled in this work. (b) The delivered energy among the multiple working modes in the heating season in Indianapolis, Indiana.

To visualize this control strategy, Figure 1(b) illustrates the delivered energy among the multiple working modes during the heating season in Indianapolis, Indiana. The dedicated charging mode tends to work at ambient temperatures of >10°C when there are no space heating calls. The subcooler charging is always active when there is a space heating call. Supplemental heating is typically called when the ambient temperature is below –5°C. At low ambient temperatures, the discharging capacity can surpass the resistance heat use, indicating the potential to reduce supplemental heat use and decrease power consumption.

The authors modeled a three-speed HP, which has three discrete capacity levels at 50%, 67%, and 100%. The conventional HP case was sized to meet the cooling load at the 100% capacity level. The CCHP case was sized to meet the cooling load with the compressor middle stage (67%), reserving 33% capacity for enhanced heating and reduction of supplemental heating use at low ambient temperatures. This is a typical strategy for a CCHP. The rated heating COP is 4.1 at the low stage, 4.0 at the middle stage, and 3.8 at the high stage.

When charging the PCM, the high side PCM temperature is constant, and the COP and capacity vary as a function of the ambient temperature. The rated charging COP is 4.0 at 47°F (8.3°C) ambient temperature and 70°F (21.1°C) PCM tank temperature. Because the PCM source temperature and indoor return air temperature are nearly constant in the discharging mode, the discharging COP can be assumed to be constant (i.e., 6.0).

The authors selected EnergyPlus models of US Department of Energy (DOE) prototype single-family homes with slab foundations in Indianapolis, Indiana—representing a northern climate—to assess HPs integrated with TES via building annual energy simulations. The three-speed HP was auto-sized to match the building design cooling load at the middle speed. The indoor heating set point was 70°F (21.1°C).

To operate the TES with the HP, the authors adopted a control based on the weather forecast. The logic is explained as follows.

- Based on the weather forecast, predict a temperature range (0%–100%, from lowest to highest temperature) in the next 24 h.
- Run mode 3 (discharge) when the TES is not fully discharged, the hourly ambient temperature is below 2% (coldest time), and the building is calling for space heating.
- Run mode 4 (combined space heating and subcooler charging) when there is a space heating call and the TES is not full.
- Run mode 2 (dedicated charging) when there is no space heating call and ambient temperature is 80%–100%.
- Run mode 1 (normal) all other times when responding to a space heat call.
- Supplemental resistance heat turns on to match the remaining building load if not met by the HP.

The PCM storage tank was sized to support up to a 4 hour discharge operation. However, at low ambient temperatures, the HP is always called for space heating, which means that only about 10% of total heating capacity is available for charging. As a result, the TES may not always be fully charged before discharging.

Envelope Modeling Approach

To study these HP configurations in multiple building types, EnergyPlus models of DOE prototype residential buildings for single-family detached homes were used in this study. Two scenarios were considered for building envelopes: (1) a pre-1990 house with no insulation in wall cavities and on the floor and minimum insulation in the attic and (2) a house with improved windows, added insulation, and improved airtightness to meet the International Energy Conservation Code (IECC) 2021 requirements. Table 1 shows the envelope details for two scenarios.

Table 1. Envelope details for pre-1990 and IECC 2021 buildings

Vintage	Insulation			Windows, U-factor/solar heat gain coefficient	Air change per hour at 50 Pa pressure
	Walls	Ceiling	Floor		
Pre-1990	None	3.35 m^2.K/W)	None	2.84 W/m^2.K / 0.6	10
IECC 2021	IECC 2021			1.7 W/m^2.K / 0.33	3

Cases Simulated: Combined Equipment and Envelope Measures

As shown in Table 2, every combination of the four HVAC types, five climate zones, and two building vintages were simulated for a total of 40 scenarios. The higher the numeric value of a US climate zones, the colder the climate. The letter “A” designates a moist climate, and the letter “B” represents a dry climate.

Table 2. Simulation matrix of equipment, climate zones, and envelope types

HVAC types	Climate zones (representative cities)	Building vintages
1. Gas furnace (gas, 80% fuel efficiency)	1. 5A (Buffalo, New York)	1. Pre-1990
2. Traditional HP	2. 5B (Denver, Colorado)	2. IECC 2021
3. CCHP	3. 6A (Rochester, Minnesota)	
4. CCHP+TES, discharging TES at 2% lowest ambient temperature at a COP of 6.0.	4. 5B (Great Falls, Montana)	
	5. 7 (International Falls, Minnesota)	

Methodology for Scaling Results from One Building to All Buildings in a Climate Zone

To project these single-building savings to cold US climates, floor area or building multipliers are required. National Renewable Energy Laboratory's (NREL's) ResStock team used 133.1 million residential buildings (American Community Survey 2016), climate zone designations (ASHRAE STD169-2016), and spatial definitions (US Census 2012) to provide building count breakouts for residential buildings by climate zone (Fontanini 2021). These numbers were modified because 67% of residential buildings are single-family homes (American Community Survey 2016), resulting in an estimated 89,225,278 single-family US homes with cold climate zone breakouts, as shown in Table 3.

Table 3. Number of single-family residential buildings estimated for each sub-climate zone

Climate zone	5		6		7		Total
No. households	23,645,234		6,319,559		810,879		30,775,672
Sub-climate zone	5A	5B	6A	6B	7A	7B	
No. households	20,241,82	3,403,409	5,490,477	829,081	709,252	101,628	

The annual heating energy use was scaled by the number of single-family homes in each climate zone and summed for each climate zone to estimate the regional (i.e., climate zones 5–7) total. The monthly heating demand (i.e., heating electricity use for peak hours each month) was summed over the year and scaled by the number of single-family homes in each climate zone, resulting in an aggregated annual demand value that represents the total demand value for this region. The heating energy use was used to calculate emissions, and the heating energy use and heating demand were used to calculate the regional cost. Site energy use was used for these calculations rather than source energy use because this study focused on the individual building level rather than the utility. Also, the spatiotemporal variability of the grid mixes over the region and course would vary greatly, and there is uncertainty as to how these mixes will shift over time. This is important because generation and transmission losses can increase the electricity needed to meet the load necessary from a utility perspective.

Results and Discussion

Lower-income individuals tend to live in older, less energy-efficient housing in contrast to higher-income individuals (Frausto 2021, Rosenthal 2014). Lower insulation levels and lower efficiency heating systems are common among older homes. Also, older homes are more prevalent in the colder areas of the United States (EIA 2015).

The following sections show how electrification in cold climates can affect energy usage, peak demand, utility costs, and carbon emissions.

Heat Pump Performance

Figure 2 illustrates the overall heating COP and the amount of supplemental resistance heat consumed in various scenarios. In the figure, "CCHP+TES@DisCOP6" means the CCHP integrated with a PCM storage tank, and the discharging COP is 6.0, a realistic value regarding the compressor efficiency. "CCHP+TES@DisCOP12" is the best-case scenario, which would correspond to circulating the heat from the PCM to directly heat the zone with a small temperature difference via a large surface area (e.g., underfloor heating). The TES integration can reduce electric resistance heat use and thus improve the total seasonal heating COP. In the following analyses, the discharging COP of 6.0 was used.

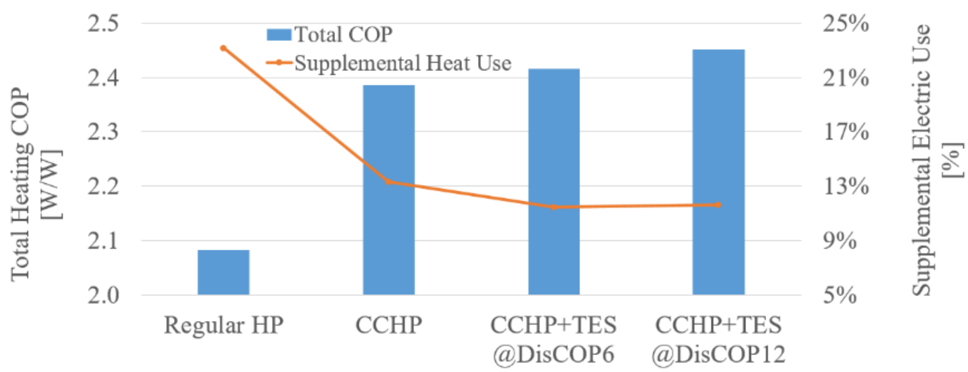


Figure 2. Seasonal heating COPs increase and resistance heat use percent decreases for CCHP and TES.

Energy and demand

Figure 3 summarizes the annual heat energy uses of various equipment types in the five climate zones for the single-family home vintages of pre-1990 and IECC 2021. Compared with the regular HP, the CCHP can reduce total electricity consumption by up to 20%. The CCHP+TES operation resulted in slightly lower annual energy consumption than the CCHP. The improved envelope of the building with IECC 2021 construction decreased the total energy consumption the most, resulting in a 50% annual electricity reduction in the five climate zones compared with a conventional HP in a pre-1990 building.

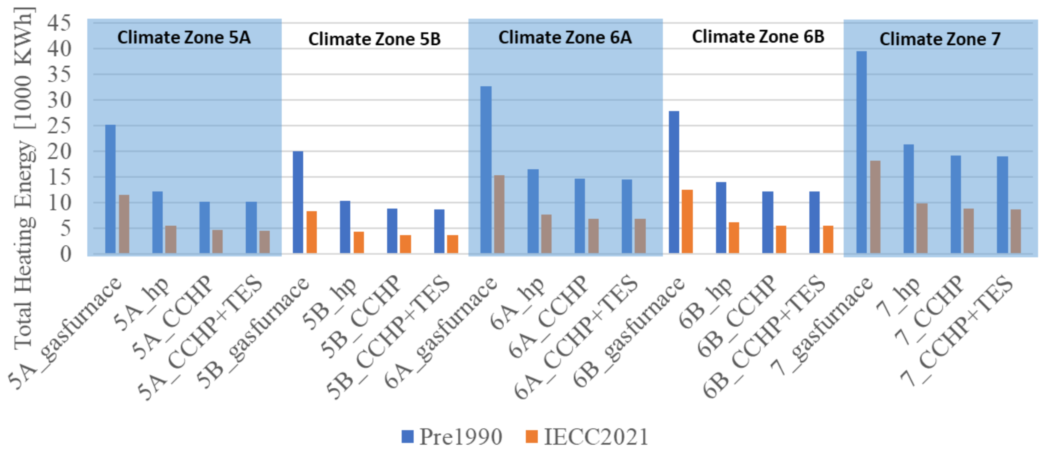


Figure 3. Annual heating energy use is reduced by CCHP and TES.

Figure 4 presents the peak power reductions in peak load hours (hourly ambient temperature below 2%) during February in a pre-1990 single-family home in Region 5A. It comprises four scenarios: (1) regular HP, (2) CCHP, (3) CCHP+TES with quick discharge to obtain source energy from the PCM tank during the first peak hours, and (4) CCHP+TES with slow discharge to average the TES energy use in all the peak hours for 1 day and meet the remaining load with the air source HP. CCHP+TES with slow discharge will require an advanced predictive control to schedule the TES energy release via weather forecast and predicted load. The CCHP reduces the peak power consumption by 5%–10% because of its higher efficiency and less supplemental resistance heat use. The CCHP+TES with slow discharge could reduce the peak power consumption by up to 40%.

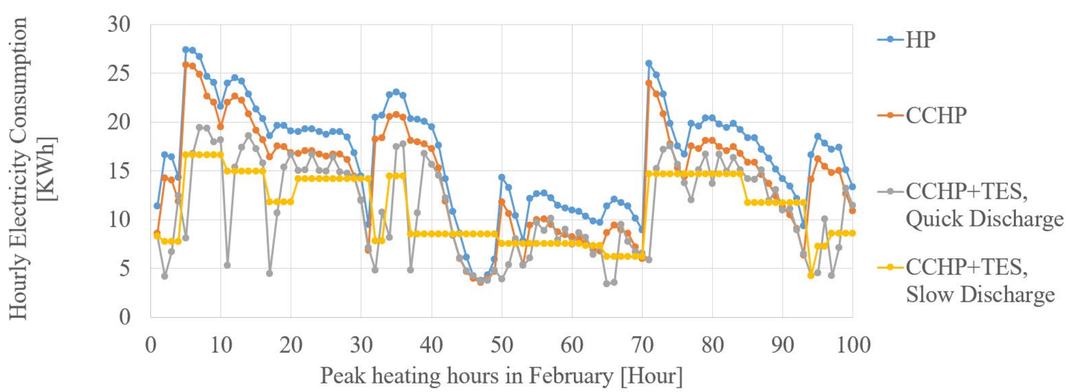


Figure 4. Reductions in peak power are achieved by CCHP and TES.

The effect of TES is significant when extra HP capacity is available, as seen in climate zone 5A. In the coldest climate zone (zone 7), all the HP's capacity is often needed to meet building demand. This leaves very little capacity for TES charging, thereby decreasing the effect of TES. Because fewer than 5% of single-family homes are in climate zone 7, this TES shortcoming is limited.

The hourly average heating load for the two vintages and three heating options for climate zone 5A is shown in Figure 5. The benefits of envelope improvements from pre-1990 constructions to the IECC 2021–compliant buildings are clear in Figure 5. The effect of envelope improvements is substantial when there is a large indoor and outdoor temperature differential. A high-performance envelope reduces peaks when CCHPs perform at their lowest efficiency. Even with the combination of high-performance envelope and TES, more must be done to bring significant benefits to the market in terms of reducing peak consumer demand and utility costs. Controls are critical, especially in the coldest months in cold climates, for experiencing the potential benefits of TES. Figure 6 also shows that the TES can lower the peak from 5 a.m. to 9 a.m. daily.

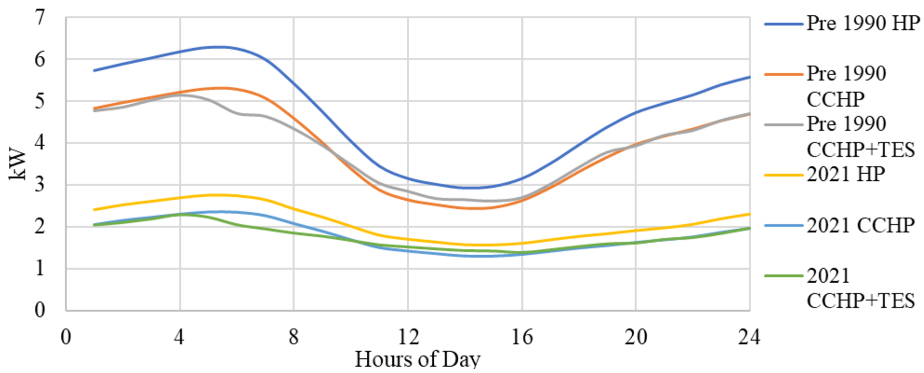


Figure 5. Average heating electricity use during peak hours in climate zone 5A is lowest with CCHP+TES.

Utility Cost

Assuming that the utility costs are the 2021 national residential averages, 13.72 cents/kWh for electricity (EIA 2022a) and 4.99 cents/kWh for natural gas (EIA 2022b), Figure 6 shows that a better envelope can reduce the heating bill by up to 40% in cold climate zones 5a–7. Using the 2021 utility rates, regular HPs will cause higher utility costs than natural gas furnaces, and the CCHP options result in slightly lower heating costs. Electrification of space heating paired with envelope improvements achieve much lower utility costs.

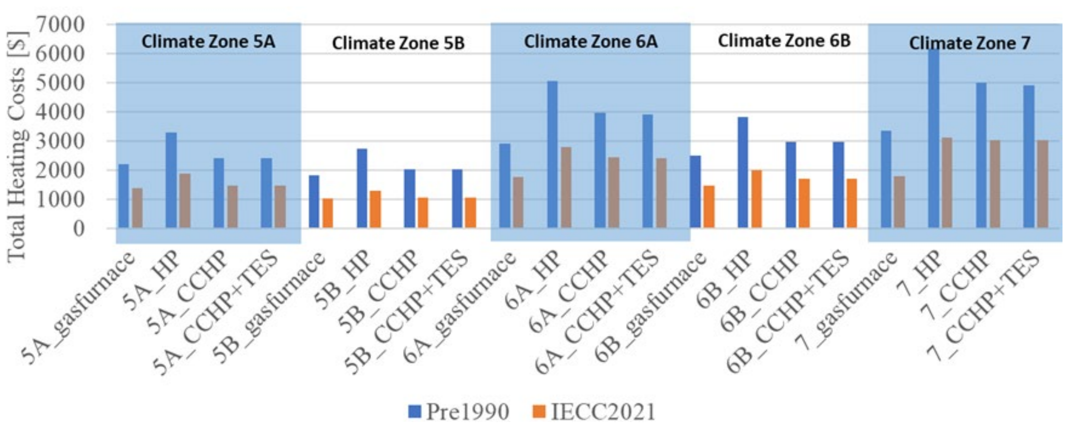


Figure 6. Annual heating energy cost.

Although most single-family homes currently do not include a demand charge, demand charges may become more widely used in the residential sector as electrification expands. Figure 7 illustrates the potential demand savings of the TES system if a monthly peak demand charge of $16.82/kW (NREL 2017) were used. This demand charge is an estimate based on US commercial buildings because widespread residential demand charges are unavailable in the United States. The TES system offers annual heating demand savings of up to 46% compared with the CCHP system without TES (climate zone 5A, 2021 vintage). These are significant demand savings, even without the control strategy determined by the peak load. If the TES were charged before the monthly peak and discharged during the peak hour, then the demand savings could be even larger. The lack of TES heating demand savings for climate zone 6A is a result of the control strategy and not necessarily aligned with the peak electricity use of each month. This adjusted control strategy could be evaluated in future analyses.

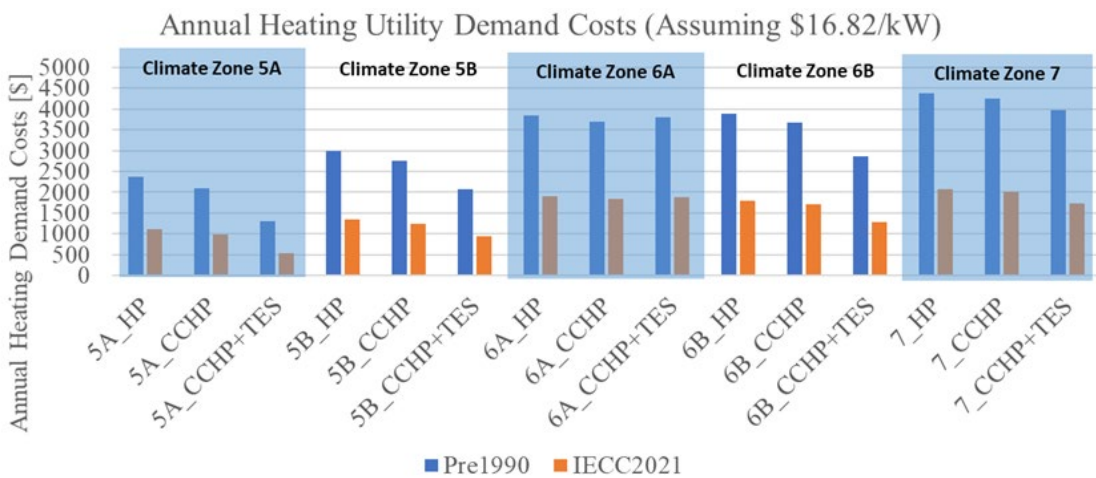


Figure 7. The annual demand cost is lowest with CCHP+TES.

Because future utility rate structures could include a demand charge and a consumption rate, lower utility costs due to pairing envelope improvements with TES have overarching implications in terms of energy bill savings. This is particularly important in low-income US households where energy burdens are higher. Low-income households spend three times more of their income on energy costs than the median spending of households that are not low income. Additionally, the second greatest percentage of households with high energy burdens are located in climate zones 5A, 5B, 6A, 6B, and 7 (Drehobl et al. 2020).

Carbon Emissions

The authors also assessed the effects on CO_2 emissions of various envelopes and heating options: 1 kWh electricity will produce 417 g of CO_2, and natural gas combustion in a furnace will produce 181 g of CO_2 to generate 1 kWh of thermal energy (EIA 2022c) (approximately 2.3 times less than CO_2 emission per kilowatt-hour of electricity). The higher emissions associated per kWh of electricity are mitigated by the high coefficient of performance of HPs, typically around 2– 4 kWh of heating provided per kilowatt-hour of electricity consumed. As the grid continues to decarbonize, the CO_2 emissions' benefits of electrification will improve. For current national averages, Figure 8 shows that in warmer climates (zones 5A and 5B), the CCHP and CCHP+TES still reduced the carbon emissions relative to the gas furnace heating.

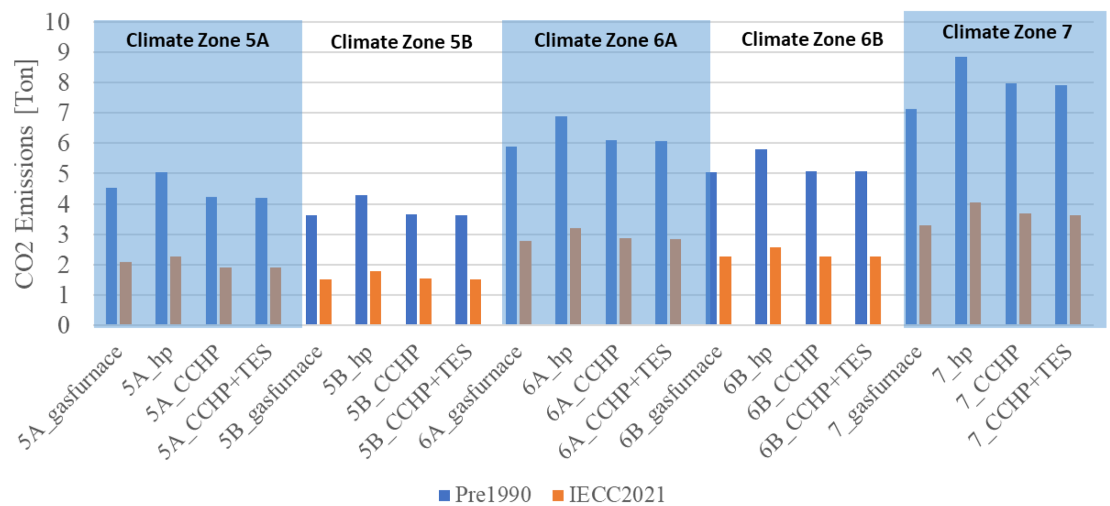


Figure 8. Heating season carbon emissions are lowest for CCHP+TES, except in the coldest climate zones.

The United States has made significant progress decarbonizing the electricity sector in recent years, and the grid continues to become cleaner. A Rocky Mountain Institute analysis (McKenna et al. 2020) shows that as of 2020, replacing a gas furnace with an HP would reduce carbon emissions in 46 of the 48 states (99% of US households).

Efficiency improvements in CCHPs are crucial to the decarbonization and electrification of buildings. Although the CCHPs in climate zones 5B, 6A, and 7 emit more emissions than gas furnace at these emissions rates, a less than 2% decrease in electric emissions per kilowatt-hour would result in CCHP emissions savings for climate zones 5B and 6A, and a 9% decrease in electric emissions per kilowatt-hour would result in CCHP emissions savings for climate zone 7. Thus, even small improvements to grid CO_2 emission rates result in significant savings when using the CCHP.

Regional Effect

The annual heating demand and heating energy use for each HVAC type, vintage type, and climate zone were scaled by the number of single-family homes in each climate zone. Estimated emissions and costs were calculated based on the heating energy use. The cost and emissions rates were the same as those used in previous sections for consistency. This resulted in an estimate of the energy use characteristics of single-family homes in cold climate (zones 5–7) regions of the United States. These scaled values are dominated by climate zones 5A, 5B, and 6A, which comprise approximately 95% of the single-family homes in this cold climate region (zone 5A comprises 66%). These scaled energy characteristics are shown in Table 4, which illustrates the importance of improved building envelopes. An average of just under 300,000 tons of CO_2 and about $85 billion were saved by upgrading from a pre-1990 to a 2021 envelope. The results indicate 13%–15% scaled heating energy savings by switching from a typical HP to a CCHP. The results also indicate an estimated scaled demand savings of 24%–28% by adding TES to the CCHP. The optimal savings case of upgrading from a pre-1990 gas furnace to a 2021 CCHP with TES could result in heating energy savings of up to 2,266 TWh, emissions savings of 322 million tons of CO_2, and $70 billion per year in cold climate regions.

Table 4. Potential heating energy estimates for 31 million single-family homes in US cold climate zones 5–7

		Gas furnace (natural gas)	HP (electricity)	CCHP (electricity)	CCHP+TES (electricity)
Pre-1990	Energy use (TWh/year)	2,765	1,302	1,111	1,105
	Annual demand (TW)	-	5.12	4.67	3.56
	Emissions (tons CO_2/year)	551,584,212	598,650,862	510,792,811	507,723,699
	Cost ($ billion/year)	137.9	178.7	152.4	151.5
IECC 2021	Energy use (TWh/year)	1,265	584	503	499
	Annual demand (TW)	-	2.43	2.22	1.59
	Emissions (tons CO_2/year)	252,436,396	268,590,849	231,390,106	229,169,273
	Cost ($ billion/year)	63.1	80.2	69.1	68.4

At current natural gas and electricity rates, gas furnaces cost less in the cold climate regions based on energy consumption cost alone. However, as electrification continues, demand-based rate structures may become more prominent for residential homes. Figure 8 shows the breakeven point for which the CCHP+TES will become more cost effective than gas furnaces by varying the percent of the utility bill that is accounted for with a demand charge. To estimate these values, the natural gas cost is held constant, the electricity consumption cost is scaled by the percent shown in the figure, and the electricity demand cost is set as the value that keeps the HP cost constant to prevent the utility from taking a financial loss at this new rate structure.

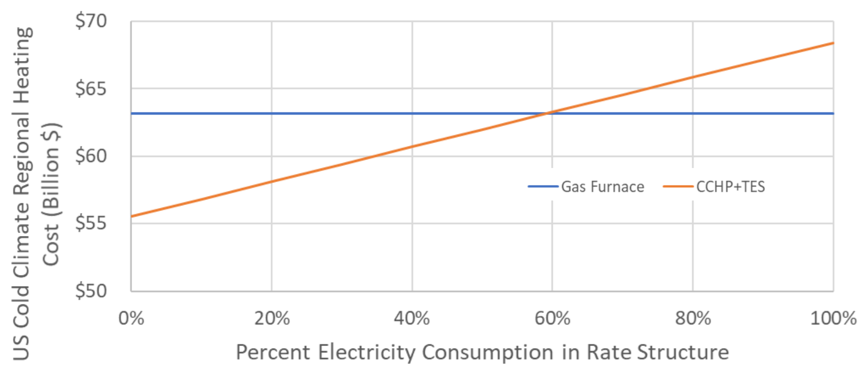


Figure 8. The breakeven point for gas furnaces and CCHP+TES. Varying percent of demand and electricity consumption in a new rate structure is about 60% of electricity consumption cost and 40% of demand cost. The electricity consumption cost at this level is 8.2 cents/kWh, and the electricity demand cost is $13.9/kW.

Limitations

The main limitation of this study is regarding the analysis of single-family detached homes as they relate to low-income households. A larger percentage of low-income individuals reside in apartments in buildings with five or more units. Additionally, housing type is a factor that strongly correlates to energy burden. Analyzing different housing types will provide a clearer explanation of how these energy-efficient measures will reduce electricity consumption, peak demand, and carbon emissions.

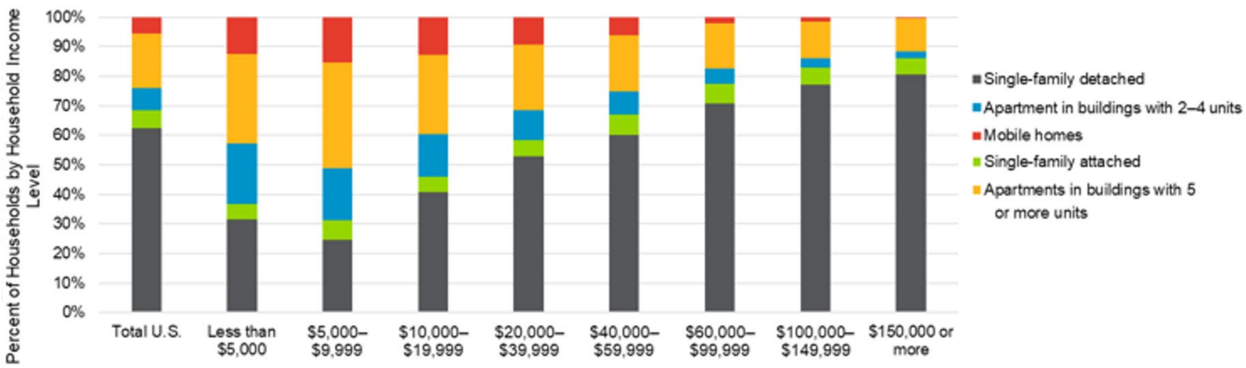


Figure 9. Housing type by household income. (Data from EIA 2022b, figure from Young et al. 2022.)

Conclusions

Determining the efficiency of incentivizing TES, a high-efficiency envelope, or both simultaneously will help policy makers decide how to best stimulate the adoption of this technology. Policy makers must design and implement policies that help the residential building sector become more energy efficient and that remove the additional energy burden of increased utility costs for low-income households when adopting CCHPs.

A CCHP can reduce electricity consumption and peak demand by 20% when compared against a typical HP. Spread across an estimated 31 million single-family residences in climate zones 5–7, a CCHP could conservatively save approximately 1.5 TWh when compared with a traditional natural gas system. However, completely switching from all natural gas systems to regular HPs could increase peak electric demand by 1.8 GW across climate zones 5–7. CCHP+TES can reduce this peak demand penalty for HPs.

This study showed that less than 10% of total heating energy is stored within PCM for a CCHP, and that small percentage is typically dissipated within 2 h, limiting both the amount of energy and temporal flexibility for peak demand. Improving the building envelope (e.g., insulation R-value, windows, airtightness) in pre-1990 constructions to become IECC 2021–compliant can significantly decrease energy use, resulting in up to 50% load reductions in climate zones 5–7.

Peak demand for electricity is expected to grow because of electrification efforts that support decarbonization, and the electrification of heating in residential buildings will exacerbate the problem. Current policies and programs of utility providers seek to reduce winter peak electricity use through utility time-varying pricing and load control strategies. Reduction is incentivized by encouraging household behavioral changes regarding energy consumption. These efforts benefit the utilities, but there are no paybacks or benefits to households. Very few policies and programs exist that allow households to be more active in reducing peak power and lowering utility costs. Existing government-sponsored programs, such as the Weatherization Assistance Program (WAP) and Low Income Home Energy Assistance Program (LIHEAP), help low-income individuals reduce energy burden by subsidizing energy-efficient retrofits (e.g., installing and replacing heating systems). This research shows that a concerted effort to support the pairing of energy-efficient retrofits, such as insulation and TES, can enhance the benefit of reduced energy and demand use and utility cost. Incentives for TES exist at a commercial level, and similar policies must be created to provide those same incentives at the residential level.

Acknowledgments

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