

Cold-Climate Packaged Heat Pumps - Resistance is Futile

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Abstract

The United States currently has a large market for room/zonal space conditioning equipment focused primarily on cooling, namely packaged terminal air conditioners, packaged terminal heat pumps, and room air conditioners. This equipment largely relies on electric resistance for heating, particularly when outdoor temperatures fall to 40F or below, presenting a compelling opportunity for energy savings and carbon reductions from reverse-cycle heating. This paper provides an overview of cold-climate packaged heat pumps capable of high heating output down to outdoor temperatures of 5F and identifies technological and market barriers to adoption. For cold-climate packaged heat pumps sold in the retrofit market, defrost meltwater management is the principal barrier to implementation. An energy-use analysis is conducted for space heating by building vintage and IECC climate zone. An aggregate impact assessment estimates the total energy savings and carbon reductions if cold-climate packaged heat pumps replaced existing electric-resistance packaged terminal air conditioners and conventional packaged terminal heat pumps in the US hospitality building stock. A national two-track approach is proposed for increasing market adoption in the replacement and new construction markets.

Introduction

To meet long-term goals for reducing carbon emissions and lessen the impacts of climate change, federal and state governments in the United States plan to decarbonize, or reduce burning fossil fuels, to electrify the residential housing and commercial building stock. As part of this strategy, governments are developing policies to transition fossil-fuel end uses to electricity, and electric generation to non-fossil fuel sources. For this strategy to be effective, fossil fuel and electric-resistance space heating equipment across most building types in the US will need a viable and efficient electric substitute.

The US has a large market for packaged room or zonal space conditioning equipment, historically focused on cooling, specifically Packaged Terminal Air Conditioners (PTACs), Packaged Terminal Heat Pumps (PTHPs), and Room Air Conditioners (RACs). This equipment is typically installed in hotels, motels, offices, and multifamily apartments because the first cost is modest, installation is easy, and maintenance is low. When this equipment provides heating, it's typically inefficient. PTACs use electric resistance for heating, or are paired with fossil-fuel-based heating. PTHPs use reverse-cycle heating whenever the Outdoor Air Temperature (OAT) is above a compressor cutoff temperature (typically around 40F), and electric-resistance heating when the OAT is below the compressor cutoff temperature (Hallas and Shapiro, 2018). Most RACs only provide cooling, but some models provide heating through reverse cycle and can have a similar 40F OAT cutoff temperature. In many cases, RACs are paired with either electric-resistance baseboard heat or fossil-fuel-fired hydronic or steam heat.

Heat pump technologies capable of reverse-cycle heating offer significant energy savings and carbon emission reductions in US buildings. A primary challenge is designing and providing heat pumps to heat effectively below 40F OAT across all US climates and for all applications. Packaged heat pumps (PHPs) are a key primary technology for fulfilling room and zonal space conditioning applications, and this equipment category includes PTHPs and single packaged vertical heat pumps (SPVHPs). Cold-climate PHPs (ccPHPs) operate at a high coefficient of performance (COP) and provide high output down to 5F OAT or lower (NEEP, 2021). In particular, ccPHPs are important for decarbonizing heating loads for hotels, motels, offices, multifamily apartments, and other building types with significant room and zonal space conditioning applications.

This paper provides an overview of ccPHP technologies in the market and identifies key technological and market barriers to adoption. An energy-use analysis is described for a state-of-the-art ccPHP product for space heating by building vintage and IECC climate zone (CZ) in a zonal application akin to a hotel/motel room. Using the results of the analysis, an impact assessment was prepared for the hotel/motel sector if ccPHP technologies were widely adopted in place of PTACs and PTHPs. Lastly, potential market strategies are discussed for increasing adoption of ccPHP technology.

Technology Overview and Assessment

Most heat pumps use a refrigeration cycle to transfer heat between outdoor and indoor environments or by heating a fluid. Heat pumps have significantly higher heating efficiencies than electric-resistance heating. When properly designed and installed, heat pumps can efficiently, reliably, and quietly meet the full heating and cooling demand of spaces. Several key features in driving energy savings and market penetration of ccPHPs include:

- Provide at least 50% of its rated heating capacity at 5F OAT
- Achieve a $COP \geq 1.5$ at 5F OAT
- Arrive pre-charged with refrigerant, with no refrigerant technician required for installation
- Use a variable-speed compressor to achieve high part load efficiencies
- Have no remote-mounted outdoor unit
- Able to meet heating and cooling loads of individual rooms, between 3,000–12,000 BTU/hr
- Have a strategy in place for dealing with defrost meltwater (see Technological and Market Barrier section for more discussion).

The zonal heat pump market is primarily composed of PTACs, PTHPs, Vertical Terminal Air Conditioners (VTACs), and RACs. These technologies have been adopted largely due to certain key benefits including ease of installation and service, low cost, and room-by-room temperature control. Since these zonal heat pump products often have poor efficiency and capacity in colder weather, there is an interest to replace the zonal heat pump market with higher efficiency air source heat pumps such as mini-splits or large variable refrigerant flow (VRF) systems. However, limitations and challenges with mini-splits and VRF systems include: electrical service requirements, high installed costs (equipment, labor, distribution systems, and design), occupant disruption during installation, space constraints (outdoor units, refrigerant lines), and greater potential for refrigerant leaks (Montpellier et al., 2020).

Historically, PTHPs have posed a variety of challenges that a ccPHP can address. PTHPs often have limited low OAT performance, switching from heat pump to electric resistance at colder outdoor temperatures, typically around 40F. By using a ccPHP that operates down to 5F OAT or lower in heat pump mode, greater annual heating efficiencies can be achieved. PTHPs, which are installed in a 16 x 42-inch wall sleeve, are plagued by poor installation and high rates of air leakage. One study estimated that, on average, each PTAC/PTHP has 6.7 square inches of hole (air leakage) per unit (Urban Green Council 2011). Additionally, significant bridging and breaches in the thermal boundary are caused by metal wall sleeves. Other disadvantages of typical PTHPs on the market include single-speed compressors and compressor noise. While similar issues could be found in a ccPHP, manufacturers of ccPHPs are looking to overcome these challenges.

While ccPHPs are promising for buildings with existing PTAC/PTHP sleeves, ccPHPs also represent a significant opportunity to replace window ACs, through-the-wall ACs, and can even replace or supplement centralized heating systems. As an alternative to mini-split and VRF systems, a ccPHP offers many benefits. They can be installed in occupied apartments with limited disruption to the building occupants, they do not require in-the-field refrigerant piping and connections, and typically do not require major electrical upgrades since the electricity demand of the ccPHP would be similar to the existing AC it is replacing.

There are two Air Conditioning, Heating, and Refrigeration Institute (AHRI) test standards focused on zonal heat pump products. AHRI 310/380 is the test standard for PTACs and PTHPs. AHRI 390 is the test standard for SPVHP. Because the two AHRI test standards only require heating efficiency and capacity ratings be reported at 47F OAT (AHRI 2017, 2021), most manufacturers do not report heating efficiency at lower OAT points and therefore are not incentivized to focus on low-temperature heating (Hallas and Shapiro 2018).

In 2021, the Northeast Energy Efficiency Partnerships (NEEP) developed a specification for ccPTHPs and SPVHP to add to its Cold-Climate Air Source Heat Pump (ccASHP) listing to promote growth in ccPHP products. The purpose of this list is to help building professionals, energy efficiency program administrators, and owners identify products that are well-suited to replace PTACs and non cold-climate PTHPs (NEEP 2022). The two main technical aspects of the specification are that units must be pre-charged with refrigerant and not require a refrigeration technician to install, and they must operate with a COP ≥ 1.5 at 5F OAT.

Currently, there are a limited number of ccPHPs on the market. A few of the available products are summarized below; however, this list is not meant to be exhaustive. In addition, many of these products are new to the market, and we did not independently verify all manufacturer claims. As such, whether they meet the key attributes of a ccPHP is still under consideration.

Two of these ccPHP products fit the form factor of more traditional zonal space conditioning products. Ice Air's RSCX is a ccPTHP that uses a 16 x 42-inch wall sleeve and variable-speed compressor reported to operate in heat pump mode to -5F OAT. Friedrich Air's VRP unit is also connected to outside but with a vertical wall sleeve and uses a variable-speed compressor to operate in heat pump mode to 0F OAT. The VRP can be installed to serve one room or be ducted to serve multiple spaces.

There are at least three new products available that take different form factors and approaches than the traditional zonal space conditioning equipment available in the US. Ephoca offers the Wall Mount Pro unit that uses two 8-inch vents to bring outdoor air across the outdoor coil, which is located within the heat pump unit mounted indoors. This unit is reported to operate

in heat pump mode to below 5F OAT. There is a similar product, the Olimpia Splendid Maestro, that also uses two 8-inch vents to connect to the outdoors. The Maestro unit currently available has a variable-speed compressor and operates to temperatures below 20F OAT. Olimpia Splendid has reported that they are continuing development to improve low-temperature performance of the Maestro unit. Another interesting development is from Gradient Comfort, who has a new upside-down, U-shaped heat pump product designed to be installed over the sill of a window with the indoor coil served by a glycol loop from the outdoor portion of the unit. While Gradient Comfort's first-generation product is unlikely to be a cold-climate model, there are development plans to bring a cold-climate product to market.

Other products, which would not be classified as ccPHPs but provide similar advantages, are mini-splits where the outdoor unit is installed in an existing PTAC sleeve and connected to indoor units via field-installed refrigerant piping. While these products would require in-field refrigerant piping, pipe lengths would be limited and installation would not require major disturbance to the building occupants. The GREE GMV MTAC and Fujitsu EZ Fit are both examples of this type of product. There are also at least two manufacturers using heat pumps as part of energy-recovery ventilation equipment that can provide both ventilation and active heating, cooling, and dehumidification. These products are the Building Equinox CERV and Minotair Pentacare V-12.

Technological and Market Barriers

Despite the promise of these products to deliver efficient heating and cooling, there are technological and market barriers that center around low-temperature capacity issues and condensate/meltwater management. Due to their relatively small form factor, ccPHPs have limited heat exchange areas compared with larger split system heat pumps. This limitation on heat exchange area makes it more difficult to provide adequate heating capacity at lower temperatures. The challenge has been highlighted by the fact that manufacturers bringing ccPHP to the market have continued to update their offerings with larger compressors and heat exchangers. The low-temperature capacity challenges, while certainly an issue for new construction, are more pronounced for retrofit applications due to larger heating loads stemming from poorly performing building envelopes.

Condensate and defrost meltwater management also presents a major challenge for retrofit applications since the infrastructure to properly drain water is unlikely to exist. Condensate is created on a coil when its surface temperature is below the dew point of the environment around it. This condition is common in cooling applications and can occur on the interior coil of a ccPHP unit as it cools and dehumidifies indoor room air. Cooling condensate water is commonly managed by draining the condensate to the outdoor coil and evaporating it and is not a major barrier to adoption. Defrost water, on the other hand, is collected off the outdoor coil during heating at outdoor temperatures below approximately 40F OAT. Defrost water is formed by a similar process as cooling condensation water, but on the outdoor coil. Because of colder OAT conditions, condensed water can then in turn freeze on the outdoor coil. Typically, the frosted exterior coil is periodically warmed by reversing the refrigeration cycle which sends warm refrigerant to the outdoor coil. This melts the ice, and the water that is close to the freezing point is collected in a drain pan below the exterior coil.

There are several ways to remove the water that collects in the exterior coil drain pan. The most straight-forward approach to deal with defrost water is to drain it to an indirect sanitary sewer connection. The Uniform Plumbing Code restricts connections from "waste from air-

conditioning units” to locations in residential housing units below the unit being served (IAPMO 2018). The International Plumbing Code does not include a similar restriction (ICC 2018), but many jurisdictions adopt similar requirements by amendment. Since drains are not typically located near the exterior wall where a ccPHP would be mounted, one method to route the water to an approved location would be to use a pump to lift the water up to the ceiling joists, then gravity drain to an approved location within the same residential unit. While this is possible with a retrofit, it increases the cost of the project by adding work to the interior of the residential unit and could pose aesthetic and maintenance concerns. A more appropriate solution for new construction is the inclusion of a condensate waste riser that would collect meltwater from a vertical stack of ccPHP units and terminate in an approved location.

A novel approach for dealing with this meltwater is to add an electric-resistance element to the collection pan and evaporate it. The options discussed above were not sensitive to the amount of meltwater present other than details around pipe or pump sizing. Evaporation of this water is only feasible if the energy penalty is acceptable and if the evaporated water can be moved out of the unit and not deposited back upon the coil. The latter concern is a design parameter for manufacturers. Preliminary operational data can help estimate the quantity of meltwater produced and therefore the energy penalty associated with evaporating it. Estimates from an Olympia Splendid Maestro unit operating in CZ 4C in the Pacific Northwest produced roughly a gallon of meltwater per day (Odum et al., 2022). An Ephoca unit operating in CZ 5 in Ithaca, New York, produced a maximum of 3 gallons per day, which requires 30,000 BTU to evaporate. Assuming a worst-case scenario of full speed operation during an entire day, outside of defrost cycles, this evaporation energy would decrease the efficiency of the unit by roughly 40%. This performance hit would apply only to time periods where outdoor air conditions allow for high deposition rates of frost on the exterior coil. If this method of meltwater management is to be utilized, further research is needed to understand the amount of time per climate zone where this energy penalty would apply, and to more thoroughly characterize the magnitude of the energy penalty.

Another way to manage defrost meltwater is to drain water at the exterior of the building. Condensate/meltwater risers can be installed on the building exterior, but may cause aesthetic or code issues and incur an energy penalty if heat trace is required. Another option is to add an exterior facade to the building and run condensate risers in between the primary building shell and the facade. This option would require increased project scope and cost but would also provide the benefit of a higher performing envelope. This solution would allow for retrofit applications to drain meltwater in a similar manner as new construction without work in the interior of the building.

Several manufacturers have considered the use of a nebulizer or aspirator to directly discharge this water to the exterior as a mist. This strategy may face code-related resistance depending on jurisdictions and their interpretation of “nuisance” as it pertains to discharge location. Additionally, these devices have been noted to have high maintenance requirements due to clogging at regular intervals. Due to these challenges, this method to deal with defrost meltwater is not currently being used by manufacturers.

Methodology

A temperature bin analysis was used to estimate energy use, operational costs, and carbon emissions associated with using a ccPHP for heating in a 350 square foot guest room of a small hotel. Space heating load in each temperature bin was estimated from building load lines and

balance point temperatures that were developed using linear regressions on thermal zone loads from small hotel prototype models. These building loads were created for three building vintages – pre-1980, post-1980, and new construction (ASHRAE Standard 90.1-2010 compliant buildings) – in four cities representing different Climate Zones (CZs) – Atlanta, GA (CZ 3A); New York, NY (CZ 4A); Buffalo, NY (CZ 5A); and Rochester, MN (CZ 6A). TMY3 weather data for each location was used to determine the number of hours in each temperature bin.

Publicly available manufacturer data for the Ephoca HPAC 2.0 DP91XDXO unit, which included COP, heating capacity, and power use, was used to model the performance of a ccPHP. The model was created such that the ccPHP would operate in electric-resistance mode within a temperature bin if the lowest temperature in the bin was below a defined compressor cutoff temperature, or if the modeled heating capacity of the ccPHP in a temperature bin was insufficient for the estimated space heating load. To understand the effect of compressor cutoff temperature on heating energy use, operational costs, and carbon emissions, nine different compressor cutoff temperatures were modeled, ranging from 5–45F OAT.

All combinations of building vintage, representative cities/CZs, and compressor cutoff temperatures were modeled. Results for the analysis included energy use, electricity costs, and carbon emissions. Electricity costs were estimated using 2019 Energy Information Administration (EIA) state average commercial electricity prices, and carbon emissions were modeled using 2020 Environmental Protection Agency eGRID total output emission rates. In addition, heating energy savings, utility bill savings, and carbon emissions savings were estimated using weighted results from a standard PTAC with electric-resistance heating as baseline and a PTHP with a compressor cutoff temperature of 40F OAT as baseline. The weighting factors for ccPHPs replacing PTACs versus PTHPs were determined using 2012 EIA Commercial Buildings Energy Consumption Survey (CBECS) microdata – the method for determining these weighting factors are described in more detail in the Impact Assessment section. Energy required for defrost was not calculated in this model.

Results

Heating energy savings were modeled in each representative location for each building vintage. Figure 1 shows the annual heating energy savings for each guest room for a ccPHP with a compressor cutoff temperature of 5F OAT. As expected, ccPHPs that operate in colder climates and older building vintages yield more energy savings compared to milder climates with one exception. Rochester, MN (CZ 6A) is located in a colder climate relative to Buffalo, NY (CZ 5A), and thus is expected to yield more energy savings. However, this is not the case for both post-1980 and new construction because of the amount of time where the OAT is below the compressor cutoff temperature in Rochester versus Buffalo. As a result, the modeled ccPHP runs in electric-resistance mode much longer in Rochester than in Buffalo (e.g., 576 hours versus 32 hours respectively). Larger heating energy savings are observed in older construction because there is a higher total heating load.

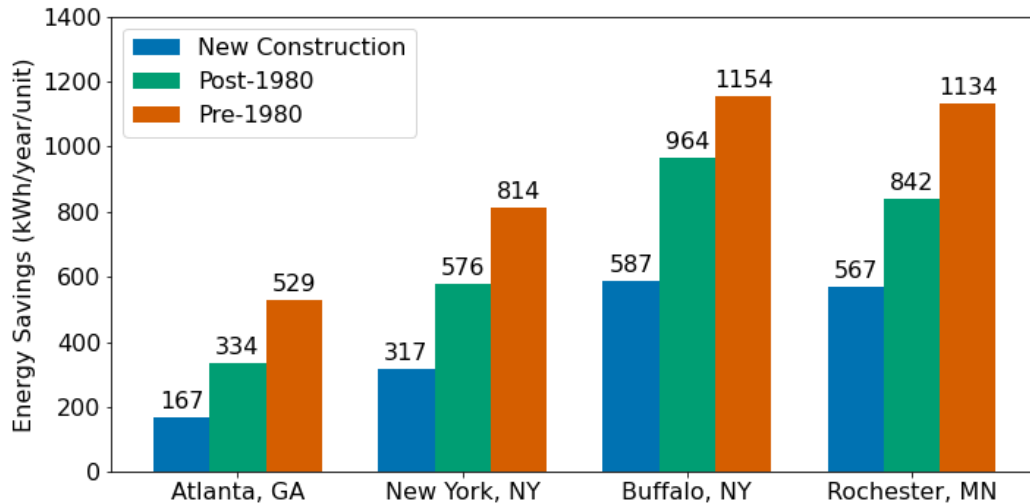


Figure 1. Modeled annual heating energy savings (kWh/year) for a ccPHP with a compressor shutoff temperature of 5F for each location and building vintage.

Cooling energy savings were not modeled, but additional energy savings from cooling could increase these savings estimates. A ccPHP product that has an inverter-driven compressor would likely operate more efficiently than traditional single-speed PTAC/PTHP.

Figure 2 shows the annual heating operation cost savings in dollars for each guest room for a ccPHP with a compressor cutoff temperature of 5F OAT. Heating operation savings follows a similar pattern to heating energy savings. Although energy savings are like Rochester, Buffalo heating operation cost savings are much higher due to higher commercial electricity rates.

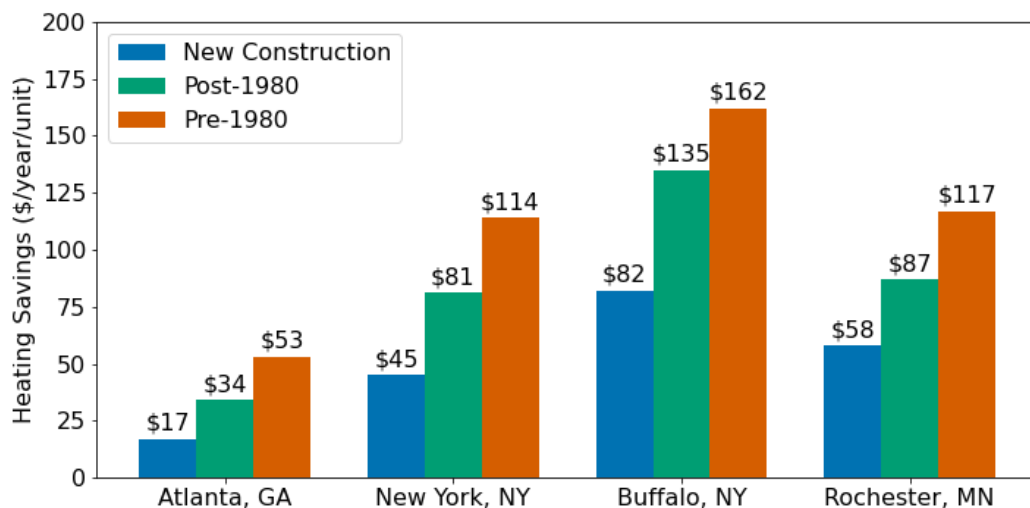


Figure 2. Modeled annual heating operation savings (\$/year) for a ccPHP with a compressor shutoff temperature of 5F for each location and building vintage.

Figure 3 shows the percentage of annual heating load supplied by the ccPHP while in heat pump mode as a function of compressor cutoff temperature for each building vintage and location. One observation is that with a 40F OAT cutoff temperature typical of a traditional PTHP, the unit meets most of the load with lower efficiency electric-resistance heating. In all of

the locations excluding Rochester, a compressor cutoff temperature of 5F enables the ccPHP to meet the heat load requirements with minimal to no use of supplementary electric-resistance heating.

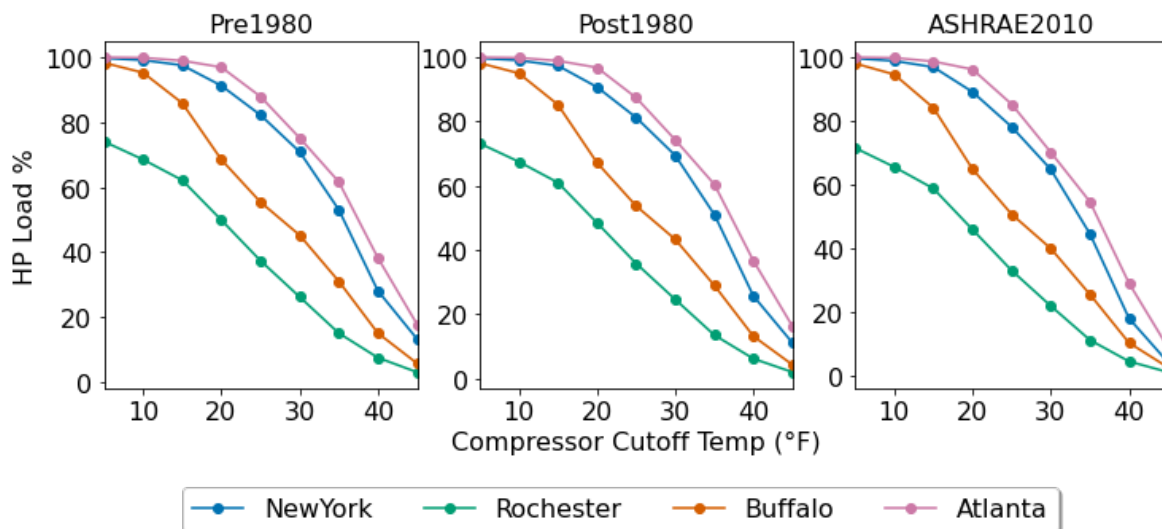


Figure 3. Percent of total annual heating load supplied while in heat pump mode as a function of compressor cutoff temperature for each location and building vintage.

Impact Assessment

Using the results of the energy-use analysis, an impact assessment was prepared estimating the energy savings and carbon emissions reduction of replacing all PTACs and PTHPs installed in the hotel/motel sector with ccPHPs. To determine the impact, the installed base was estimated using analysis from the Department of Energy (DOE) PTAC and PTHP standards rulemaking (DOE 2015). DOE forecasted the installed base as 4.4 million units in 2021 with approximately 80% of PTAC and PTHP equipment (~3.5 million units) installed in hotel/motel chains and independent hotels/motels.

The next step was to allocate the PTAC and PTHP installed base in hotels/motels by CZ and building vintage. The hotel and motel stock was divided into building vintage using three bins – pre-1980 (1980 and before), post-1980 (1981 through 2013), and new construction (2014 through 2021). Equipment installed in new construction was the sum of DOE forecasted shipments in the new construction market from 2014 through 2021, multiplied by the 80% installed base share for hotel/motel buildings, amounting to ~420,000 units. This total was further divided into CZs 3–6 using new construction weighting factors for hotels and motels: CZ 3 (27%), CZ 4 (23%), CZ 5 (21%), and CZ 6 (5%) (Lei et al. 2020).

The difference between the total PTAC and PTHP installed base (~3.5 million) and the equipment installed in new construction (~420,000) resulted in approximately 3.1 million units in the pre-1980 and post-1980 hotel/motel vintages. The EIA 2012 CBECS microdata were used to allocate these units by the two building vintages by CZ (EIA 2015). Hotel and motel records were identified by whether any space heating was provided by PTACs and PTHPs in the building. The percentage of heated floor space covered by PTACs and PTHPs was multiplied by the total building floor space to determine hotel/motel floor space heated by PTACs and PTHPs.

This floor space was summed by CZ and vintage for PTACs and PTHPs, and then divided into the total to generate weights, which were applied to the 3.1 million units. The breakdown of the installed base of PTACs and PTHPs in hotels and motels is provided in Table 1.

Table 1. Number of PTACs and PTHPs (rounded to the nearest thousand) by CZ and building vintage for the hotel/motel sector

CZ	Pre-1980	Post-1980	New Construction	Total
3	450,000	1,046,000	115,000	1,610,000
4	83,000	87,000	96,000	266,000
5	296,000	183,000	87,000	566,000
6	50,000	138,000	21,000	208,000
Total	878,000	1,454,000	319,000	2,651,000

Using the installed base breakdown and modeled annual weighted ccPHP energy savings per unit, aggregate annual ccPHP energy savings were estimated by CZ and building vintage for hotels and motels, assuming all PTHPs in the installed base have a compressor cutoff temperature of 40F and all PTACs in the installed base provide electric resistance heating below the balance point. The annual aggregate energy savings are shown in Table 2.

Table 2. Annual aggregate ccPHP energy savings (GWh) by CZ and building vintage for the hotel/motel sector

CZ	Pre-1980	Post-1980	New Construction	Total
3	238	349	19	606
4	67	50	30	148
5	342	177	51	569
6	56	116	12	184
Total	703	692	112	1,507

If all PTAC/PTHPs in hotels and motels were converted to ccPHPs, the energy savings would amount to 1.5 TWh/year (~5.1 trillion BTU) in CZs 3–6. This would translate to a carbon emissions reduction of nearly 1.1 million metric tons/year, equivalent to the carbon emissions produced by more than 230,000 passenger vehicles annually (EPA 2021). The estimated annual aggregate ccPHP energy savings and carbon emission reductions would increase further when taking the cooling efficiency of inverter-driven compressors into account.

Discussion

The ccPHP is a relatively new technology that has yet to gain mass adoption within the US market for the applicable stock. With momentum growing for energy efficiency and beneficial electrification, heat pump technologies such as ccPHPs can supplant existing less-efficient technologies such as PTACs and conventional PTHPs. Technical and market barriers remain. As with all newer or emerging technologies, continued demonstrations of ccPHPs and collaboration with manufacturers on areas for product improvement are vital to gaining broader market adoption.

Broader adoption of ccPHPs may be achieved by developing a two-pronged market strategy: one for new construction and another for replacements. The strategies for both markets need to address the barrier of defrost meltwater drainage. Because new construction has design flexibility to accommodate drainage and can provide condensate waste risers within the building's envelope on the exterior wall, deploying ccPHPs in new construction is simpler than in retrofits. However as demonstrated in the energy analysis, poor thermal performance of the building envelope in older buildings enable higher-efficiency ccPHPs to save more energy over the baseline technology compared to new construction. The replacement market is also much larger than the new construction market. For that reason, a strategy to broadly deploy ccPHPs in the replacement market is needed to achieve the full energy savings potential estimated in the impact assessment.

Building owners and installers are looking for innovative solutions to decarbonize heating and are asking manufacturers to bring ccPHP solutions to the market. There are many organizations interested in the replacement market, including NEEP, the New York State Energy Research and Development Authority (NYSERDA), New York City Housing Authority (NYCHA), New York Power Authority (NYPA), Bonneville Power Administration, among many others. In 2021 NYCHA, NYPA, and NYSERDA launched the Clean Heat for All Challenge, which challenges manufacturers to develop a low-cost, retrofit-ready ccPHP that eliminates cost barriers inherent in existing heat pump technologies and provide minimal disruption to residents (NYSERDA 2021). Nationally, one strategy that may work for resolving the technical and market barriers and deploying ccPHPs is to coordinate a bulk purchase for ccPHPs with a defrost meltwater solution that does not require a costly building retrofit for drainage with a specification for ccPHP performance. This offers a guarantee of demand to manufacturers who develop technology meeting that specification.

Conclusion

This paper presents an overview of cold climate package heat pumps and discusses technological and market barriers to broader adoption of currently available products. Energy-use and carbon emissions analyses were conducted across several building vintages and IECC climate zones. Replacing all PTACs and PTHPs in the lodging industry with ccPHPs would result in an estimated 1.5 TWh/year in CZs 3-6 and would reduce carbon emissions by nearly 1.1 million metric tons per year. The energy and carbon analyses and impact assessment in this study focused on market adoption in hotels and motels, but ccPHPs can have a more expansive impact in other building types such as multifamily buildings, dormitories, nursing facilities, and manufactured housing. Future work may include exploring additional barriers to implementing ccPHPs in these other types of buildings, as well as quantifying energy savings, carbon emissions reductions, and national impact for these other types of buildings. Additionally, further improvements can be made on the energy-use analysis by including cooling energy savings and a defrost energy penalty.

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