Field Demonstration and Adoption Impacts of an Affordable Thermoelectric Heat Pump

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ABSTRACT

This study presents the design, field validation, and utility impacts of an air source heat pump that uses thermoelectric (TE) technology to provide supplemental heating at outside air temperatures below 17°F. Conventional heat pumps experience reduced heating capacity and COP at low outdoor temperatures due to the temperature difference between the source and demand sides of the vapor compression cycle. Consequently, during colder months, supplemental heating such as electric resistance or natural gas furnace is often needed to provide additional warmth, which increases the overall equipment and energy costs.

To address this challenge, a TE subcooler (an array of solid-state, thermoelectric modules that provides heat pumping using non-vapor compression technique) is fabricated and integrated with the vapor compression cycle of a conventional air-source heat pump. In colder ambient conditions, TE subcooler exchanges heat with the refrigerant to provide additional subcooling, thereby enhancing the capacity of the heat pump.

The operation of thermoelectric-integrated heat pump was demonstrated in an occupied single-family home in Nashville, TN. The TE subcooler increased the system's heating capacity at 15°F outdoor temperature by 25–30% and reduced electricity demand by 10%. It also met the heating load in the house without supplemental electric resistance down to 5°F outdoors, delivering the additional heat at nearly 80% greater efficiency compared to electric resistance heating. With a modest first cost increment of 10–15% over conventional single-speed heat pumps, this approach offers a promising, energy-efficient solution to accelerate residential heat pump adoption in the U.S.

Introduction

Space heating is the largest energy end-use in U.S. buildings, accounting for roughly 42% of total household energy consumption in residential buildings (EIA 2023) and one-third of energy use in commercial buildings (EIA 2022). Of the 123.5 million residential homes in the United States, approximately 95% use some form of space heating equipment, consuming about 3,500 trillion Btu of fossil fuel annually and around 127 TWh of electricity (RECS 2020). In the small commercial sector, space heating demand is also largely met by fossil fuels, with these buildings consuming approximately 280 TBtu annually (CBECS 2018). Because a large share of this demand is supplied through fossil fuel combustion, the residential and small commercial sectors represent a significant opportunity for both electrification and decarbonization.

Heat pumps are a cleaner alternative to natural gas due to the absence of on-site emissions. They have experienced significant growth in recent times, with global sales increasing by 11 % in 2022 (IEA 2023) and accounting for about 10% of global space heating needs (IEA 2022). In the U.S., Air Source Heat Pumps (ASHPs) are the most common type of heat pumps installed in residences. But despite the increase in sales, heat pump adoption remains limited across the national housing stock. Heat pumps currently represent only about 15% of total installed space heating equipment in U.S. homes (RECS 2020). Penetration varies strongly by climate: in colder regions, heat pumps account for only about 4% of installed space heating systems and approximately 23% of electric heating systems, reflecting historical concerns regarding cold-climate performance and reliability. In milder climates, heat pump adoption is higher, representing roughly 23% of installed space heating equipment and nearly 50% of electric heating systems. This geographic disparity highlights both technical challenges and market opportunities for advanced heat pump technologies capable of maintaining efficiency in low-temperature conditions. A similar challenge exists in the small commercial building sector (<10,000 sq. ft.), which includes offices, retail spaces, restaurants, and small institutional buildings.

The technical challenge in deploying ASHPs in cold climate regions is their reduced efficiency as ambient temperatures drop. Often, ASHPs are supplemented by less efficient electric resistance for auxiliary heating, which places additional strain on the electrical grid. As a result, extensive research has been conducted to accelerate the adoption of ASHPs in colder regions, aiming to improve their performance and reduce the need for supplementary heating. For example, Roth, Dieckmann and Brodrick (2009) suggested various strategies to enhance heat pump acceptance in cold regions. These include using multiple or modulating compressors, increasing outdoor coil capacity, optimizing both indoor and outdoor coil systems, and incorporating mechanical liquid subcooling to improve performance. Variable-speed heat pumps and cold-climate certified heat pumps are commercially available products in the market today as a result of these and other industry research. However, many of these strategies are often expensive and require sophisticated design.

One emerging research area identified in our previous study (Krishnamoorthy et al. 2024) is to integrate thermoelectric (TE) technology into vapor compression refrigeration cycles. When in use, electrically powered TEs can increase capacity using a non-vapor compression based Peltier Effect (Britannica 2021), and has multiple advantages over traditional cooling devices (Zhao and Tan 2014), such as compact and lightweight design, high reliability, absence of mechanical moving parts, independence from a working fluid, operation on direct current power, and easy transition between cooling and heating. Using TEs with heat pumps has been researched in a few prior studies. Sanchez et al. (2020) and Aranguren et al. (2021) have focused on investigating the use of a thermoelectric subcooler in transcritical CO_2 ASHP systems, while a few others (Okuma, Radermacher, and Hwang 2012, Zu and Yu 2015, Wantha 2020) have examined the use of different refrigerants such as R-410A, R-134a, and R-290. A simulation study by Shen, Gluesenkamp, and Wan (2022) showed that thermoelectric-integrated heat pump could produce system coefficient of performance (COP) of 2.4 - 2.65 when averaged over the whole heating season in Climate zone 5, the cool regions of the U.S. (IECC 2021). Laboratory studies by Krishnamoorthy et al. (2024) and Hu et al. (2024) cascaded a conventional heat pump with TEs to assist the heat pump operation during times of low outdoor air temperature, and have measured the system COP of the thermoelectric-integrated heat pump to be 2.2 at 5˚F while producing 13% greater heating capacity at that temperature. These studies concluded that thermoelectric subcooler could improve both system capacity and COP. A logical next step is to translate the research on thermoelectric-integrated heat pumps into field tests. Field tests are especially important to validate the performance of thermoelectric heating in real-world operational conditions, especially at cold conditions, specifically at 5˚F ambient temperature, as defined by AHRI 210/240 (AHRI 2024) which only a few studies have explored even at laboratory scale.

The current research aims to address these gaps by conducting field demonstration of a residential scale thermoelectric-integrated heat pump in cold conditions at an occupied dwelling. The detailed design of the field prototype is explained in the following section. The prototype seeks to confirm whether heating performance (COP, capacity, and efficiency) observed in lab testing translates to actual installation as well as uncover any installation and commissioning challenges. The field study also benefits electric utilities as it clearly outlines the potential of thermoelectric-integrated heat pump to minimize the need for auxiliary heating in cold and moderately cold regions.

To comprehensively describe this research, the design and fabrication of the cascaded thermoelectric-integrated heat pump is outlined first. Following this, the approach used for field demonstration is described including the home characteristics, installation steps and the instrumentation incorporated within the system. Finally, the key findings are summarized from field data analysis. An analysis of the cost of the heat pump in a commercialized state is also provided as well as the resultant market potential for adoption.

Cascaded TE Heat Pump Design

The heat pump unit selected was a 3-ton (10.5 kW) single-speed heat pump employing R410A refrigerant, with a seasonal energy efficiency ratio (SEER2) of 14.3 Btu/W.hr. and a heating seasonal performance factor (HSPF2) of 8.2 Btu/W.hr. It is used for residential whole-house ducted applications, comprising both indoor and outdoor units. The capacity of the heat pump was determined based on heating needs of the specific home where the heat pump would be field demonstrated, which is described in the next section.

The thermoelectric-integrated heat pump prototype was developed by modifying the air-handler unit of this heat pump. The specific modifications include the addition of a thermoelectric subcooler, a supplemental coil to augment the heat exchange surface area, and an 8kW electric heat kit for heat pump defrosting, all installed inside the air handler. Its design is shown in Figure 1. A thermoelectric subcooler was first prepared by building an array of 80 TE modules arranged in series, where each module could consume a maximum DC power of 65W. This array was then sandwiched between a fin base and a bundle of capillary tubes. The hot side of the TE array is attached to a fin base and supported by small fans to aid airflow. This side of the TE subcooler is exposed to the supply-air side of the heat pump and further heats the air supply before entering the conditioned space. The capillary tube bundles located on the cold side of the TE assisted subcooled refrigerant that exits the liquid line of the 3-ton heat pump, and in the process, extracts heat and provides additional subcooling. The thermoelectric subcooler and fans were inserted into a plenum and attached to the air handler. This configuration was constructed with the idea that the enhanced heat pump is modular and retrofittable. Basically, they can be used as an add-on to any existing HP by installing a TE subcooler to the liquid line.

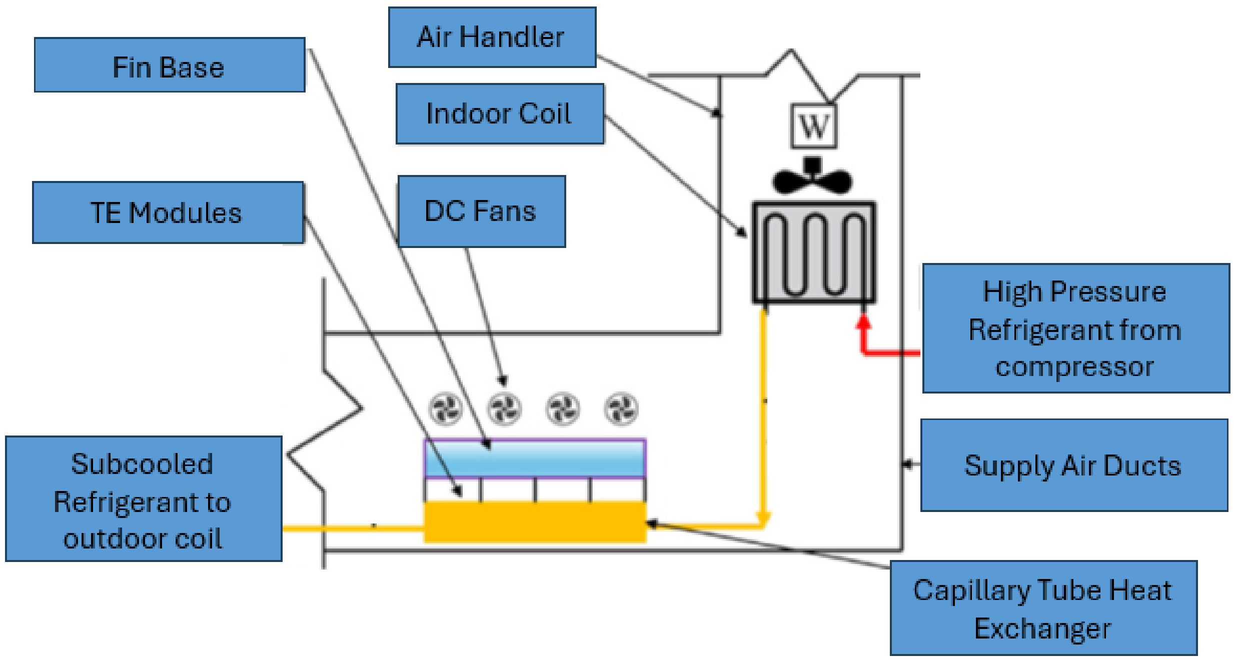

Figure 1. Schematic diagram of an air-source heat pump cascaded with a modular thermoelectric subcooler.

Figure 2 shows detailed views of the fabricated thermoelectric subcooler, thermoelectric assembly, capillary tube bundles, fin base, and fans. Figure 3 shows the finished heat pump equipment that consists of the air handler plus the plenum that houses the cascaded TE system. The height of the plenum increased the total height of the air handler by 13", for a total assembled size of 71" L x 24" W x 20" H. Additionally, a 16" diameter metal collar was installed at the back of the plenum to attach a flex duct for return air.

The control algorithm designed for this heat pump is shown in Figure 4. There are 3 stages of heating. The first stage uses only the heat pump's vapor compression cycle to provide heating, while the TE subcooler turns on when the second stage is called. If the heat pump and TE subcooler are unable to provide adequate heating capacity, then the electric resistance strip is called for as the third stage of heating. Note that the TE subcooler utilized in this design operates in an ON/OFF configuration, however due to the high controllability of the TEs, additional modifications can easily be performed if needed to control the TE operation in multiple stages.

Figure 2. Fabrication process for the modular thermoelectric subcooler. Left: TE subcooler containing TE modules sandwiched between capillary tube bundles and fin base. Right: 24V direct current fans placed above the fin base.

Figure 3. Thermoelectric-integrated heat pump assembly.

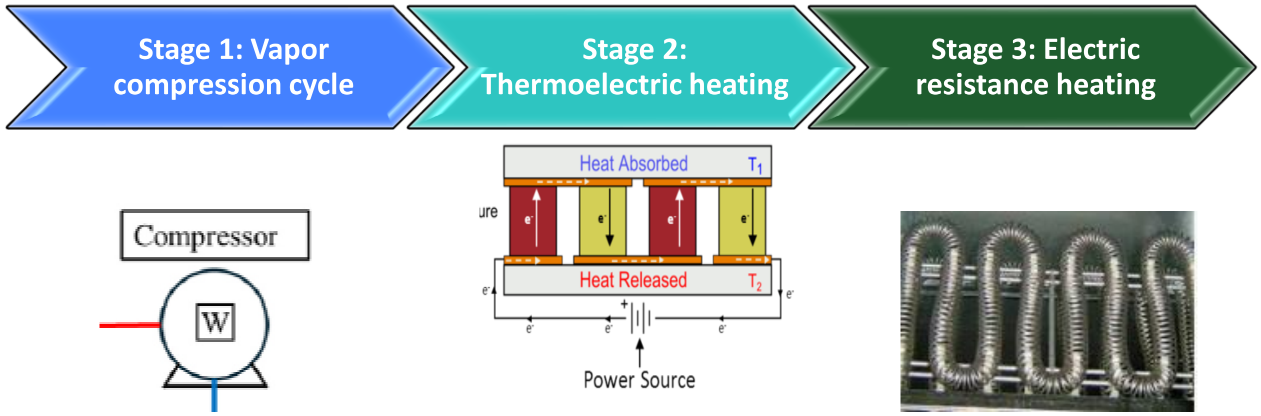

Figure 4. Control algorithm for the heat pump operation.

Approach for Field Demonstration

The objective of field demonstration was to validate the heating performance of the cascaded thermoelectric-integrated heat pump at an occupied residential dwelling. The local electric utility in Nashville, TN helped identify the appropriate home. The heat pump size needed for the home was determined based on Manual J calculations (ACCA 2016). The thermoelectric-integrated heat pump was then designed and tested at Oak Ridge National Laboratory, following which the installation took place. Table 1 shows the steps followed to complete the field installation.

Table 1. Steps followed for field installation

Step	Details
1	Review potential candidate homes and identify the site
2	Execute a customer agreement with homeowner
3	Construct prototype thermoelectric-integrated heat pump of the correct size
4	Perform laboratory testing of the field prototype for operational and functional validation
5	With the help of an HVAC contractor, install thermoelectric-integrated heat pump
6	Install M&V instrumentation (power metering and thermocouples), for automatic data upload to remote server
7	Obtain "Field UL" approval for the prototype

Home Characteristics

The home used for this demonstration was located in Nashville, TN which falls under climate zone 3A – warm humid (IECC 2021) and was a two-story, single-family residence with a basement. The home features three bedrooms and three and a half bathrooms and encompasses a total conditioned area of 1,800 ft^2. Three separate heating systems were utilized in the home prior to this installation, one of which was a small mini-split heat pump (for a newly added "sun room", added extension of downstairs floor), and the other two were 50,000 Btu/h natural gas furnaces. The first gas furnace was located in the attic along with a central AC to heat and cool the second floor, while the other furnace was located in the basement for heating the main level. The AC and gas furnace in the attic was removed for this demonstration study and replaced with thermoelectric-integrated heat pump.

Installation

The field prototype thermoelectric-integrated heat pump was installed and instrumented to be remotely monitored with the help of a prominent HVAC contractor in the local region. The details of the installation are mentioned herein, as they are helpful to understand several practical challenges for electrification projects on residential space heating using heat pumps. This installation was performed according to code and manufacturer specifications. The existing split gas HVAC system had to be removed and the gas line in the attic was capped, while also abandoning and capping existing flue in attic beneath the roof deck. Following this, the old R-22 refrigerant was evacuated and collected. The outdoor unit of thermoelectric-integrated heat pump was installed outside the building while the TE integrated air handler had to be moved up into the attic and placed in a horizontal configuration to accommodate the increased height.

Figure 5. Details of field installation of the cascaded thermoelectric-integrated heat pump. (a) Top left: horizontal installation of indoor unit in the tight attic space. (b) Top right: undersized ductwork due to which return duct was replaced with a larger size. (c) Bottom left: Original AC for 1st floor, New heat pump outdoor unit for 2nd floor, and M&V Box installation. (d) Bottom right: Capped gas line and capped combustion vents in the attic.

Figure 5 shows the attic installation of the air handler. The new R-410A refrigerant was provisioned to the heat pump and charged to design specifications before its startup. The HVAC contractor also ran dedicated code compliant electrical circuit from the main panel to the attic, in a route approved by the homeowner. One key performance limitation of the existing system was ductwork undersized to meet the required airflow for the home, which is common in many heat pump installations. New return ducts were therefore installed with its diameter increased from 12” to 16”. Finally, the installation of all wires, junctions, and disconnects, as well as data loggers for monitoring the indoor and outdoor unit was performed. The integration of the TE subcooler into the air-handler rendered the installed heat pump to be not an “off-the-shelf” equipment. A certified agency was therefore hired to inspect and approve that the installation was deemed to be compliant with the UL 60335-2-40:2022 Ed. 4 safety standard (UL Solutions 2022), or in other words it was certified that the modified heat pump is safe to operate in a residential setting for the duration of field testing.

Instrumentation

Temperature measurements for the indoor unit consisted of the return air entering the air handler, temperature of the air exiting the conventional heat pump supply plenum, and the air temperature downstream of the TE subcooler. Power measurements included the power consumed by the outdoor unit, indoor blower unit, TE subcooler, and electric resistance strip. The supply air flow rate was also measured during the installation as 590cfm (0.28m^3/s). All temperature measurements were obtained using thermocouples, attached to the piping inside the unit using thermal paste and insulation while current transducers were added to monitor power. In addition, temperature and relative humidity sensors were placed next to the thermostat, in the living area, in the upstairs bedroom, and outdoors to aid monitoring for research purposes. Using data loggers, measurements were uploaded to a remote server in one-minute intervals.

Results and Discussion

Figure 6 shows the field performance data for the thermoelectric-integrated heat pump for an eight-hour period on a typical winter morning. The measurements were recorded on 6th December, 2024 between 2:10AM and 10:10AM. The outside air temperature (represented by a dark blue line) was approximately 15˚F between 2:10AM and 8:30AM after which it steadily increases and reaches 25˚F by the end of the monitoring period. Power consumption of the TE subcooler is shown as a grey line, while the orange line represents the power consumed by electric resistance. The TEs turn on around 3:20AM and are ON until roughly 9:00AM with only one brief 10 minute OFF period in between. The air temperature downstream of the TE array is shown as a red line, the return-air temperature entering the indoor air handler as a pink line, and the corresponding air-side temperature rise attributable to the TE operation is shown in lime-green line(red line minus pink line).

It was observed during this monitoring period that the temperature in the occupied space at the thermostats (orange line in Figure 6) was relatively uniform, meeting the homeowner’s 72˚F setpoint with an average delta T of 1.3°F. The electric resistance heat strip operated almost exclusively during the heat pump's defrost cycle, with the exception of only three minutes where it supplemented the compressor heating when the outdoor temperature dropped to around 14˚F.

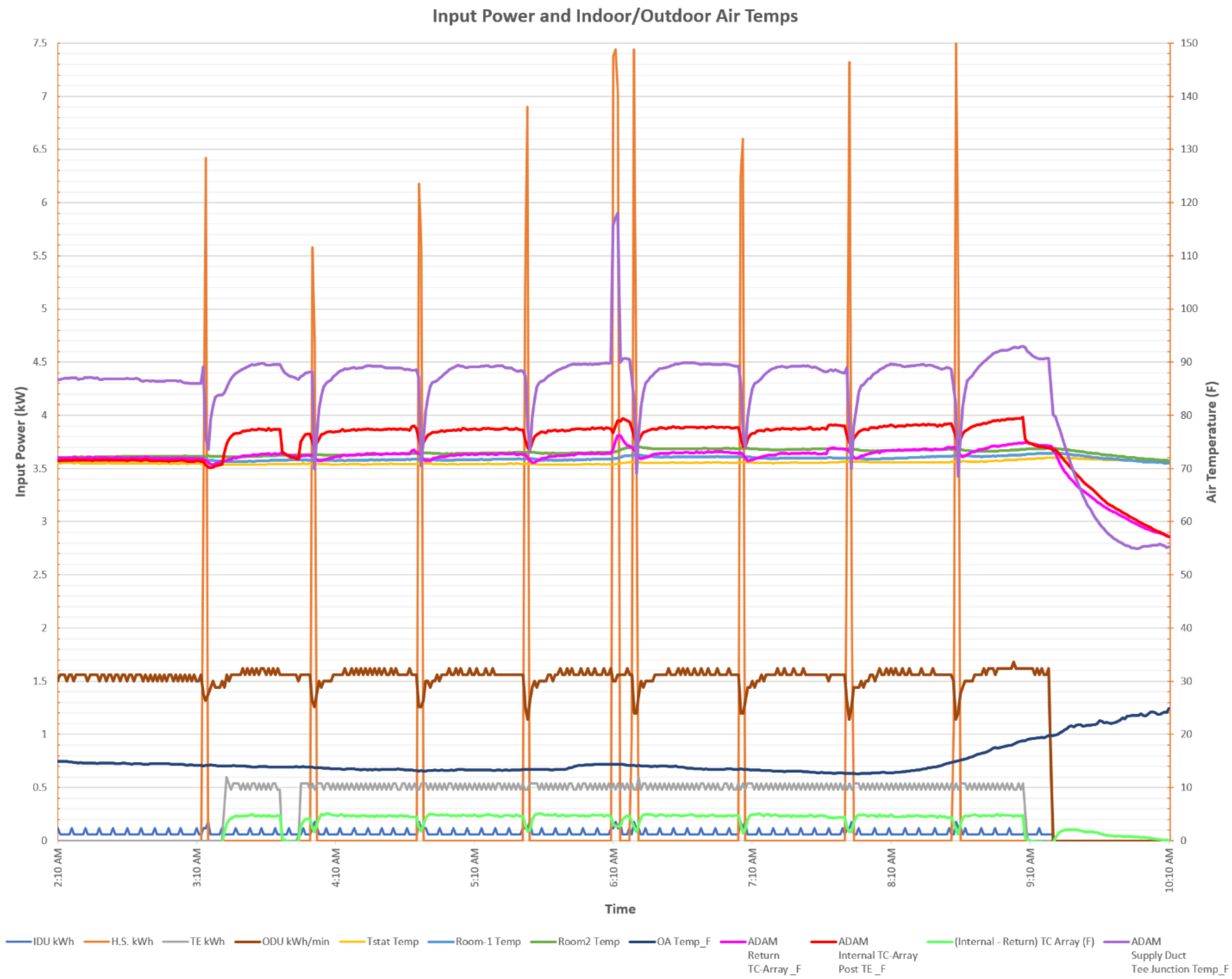

Figure 6. Field measured data for the cascaded TE heat pump acquired on 6th December, 2024.

Performance Of The Heat Pump With And Without Thermoelectric Subcooler

For a narrower 2-hour window on the same day, between 5:00AM and 7:00AM, the performance of thermoelectric-integrated heat pump is calculated in Table 2. The heating capacity output with and without the TE subcooler during this period when the outdoor air temperature is roughly 15˚F are 11,470 Btu/h and 8,920 Btu/h respectively. Thus, the additional heating provided by the TE subcooler is

$\dot{Q}_{TE\ Subcooler} = 11{,}470 - 8{,}920 = 2{,}550\ Btu/h$, or 29% additional heating capacity.

The corresponding TE subcooler COP is $\frac{Q_{TE\ Subcooler}}{P_{TESubcooler}} = \frac{2{,}550\frac{Btu}{h}}{510\ W\ x\ 3.412\frac{Btu}{h.W}} = 1.47$.

In other words, the TE subcooler portion of the heat pump operated during the cold hours (~<15˚F) and provided approximately 0.25 tons of additional heating capacity at an efficiency of

49% higher than a strip heat with COP = 0.98. Note in Table 2 that the COP of the entire system was 1.55, or in other words the TE subcooler had a very similar COP to the vapor compression cycle.
Table 2 also shows that the electric power consumption of the thermoelectric-integrated heat pump at ~15˚F is 2,170 W. If a resistance strip heat was used to meet the same heating needs in place of the TE heat pump, the demand of the heat pump would have been

Electricity Demand = P + $P_{TESubcooler}\ (COP_{TESubcooler} - 1) = 2{,}170\ + 510\ (1.47 - 1) = 2{,}410$ W.

Hence, the reduction in electricity demand at 15˚F caused by thermoelectric-integrated heat pump = 2,410-2,170 = 240 W, or ~10%.

Table 2. Key measured data and performance parameters for 2-hour steady operation on a typical winter day

Parameter	Equation or Symbol	Value when TE subcooler is OFF	Value when TE subcooler is ON
Return air temperature	$T_{return\ air}$	72˚F	72˚F
Supply air temperature	$T_{supply\ air}$	86˚F	90˚F
Air flow rate	m_{air}	590 cfm	590 cfm
Power consumed by indoor fan	$P_{indoor\ fan}$	60 W	60 W
Power consumed by outdoor unit	$P_{outdoor\ unit}$	1,550 W	1,600 W
Power consumed by TE subcooler	$P_{TESubcooler}$	-	510 W
Heating capacity	$\dot{Q} = m_{air} C_p (T_{supply\ air} - T_{return\ air})$	8,920 Btu/h	11,470 Btu/h (29% higher)
Total Power	$P = P_{indoor\ fan} + P_{outdoor\ unit} + P_{TESubcooler}$	1,610 W	2,170 W
COP	$COP = \frac{\dot{Q}}{P}$	1.63	1.55 (4.5% lower)

Figure 7 shows the measured data for the TE subcooler and the heat pump equipment recorded on January 20th, 2025 when the outside air was much colder. The outside air temperature for the analyzed period (12:00AM to 8:00AM) dropped below 10˚F, reached 5˚F at around 7:00AM, after which it increased again. The thermoelectric subcooler is ON for nearly all of this period (shown as the green line in the bottom portion of Figure 7). The spikes for electric resistance heat are shown as a red line in the bottom power portion of Figure 7 but most of these are during heat pump defrost cycles. Heating is provided by the electric strip only during three short duration spikes each lasting no more than two to three minutes which is evident from the supply air temperature spikes (green line in the top portion of Figure 7) that occur once around 4:00AM and twice shortly after 6:00AM. During the entire period, the heat pump is otherwise able to operate without electric resistance heat.

Applying the same calculation methodology as in Table 2 for this cold January morning, the additional heating capacity provided by the TE subcooler is calculated to be 902 W. For TE power consumption of 510 W, this translates to a TE COP of 1.77. This implies that thermoelectric-integrated heat pump operation was nearly 80% more efficient than an electric resistance (COP = 0.98) that would have provided the same equivalent capacity.

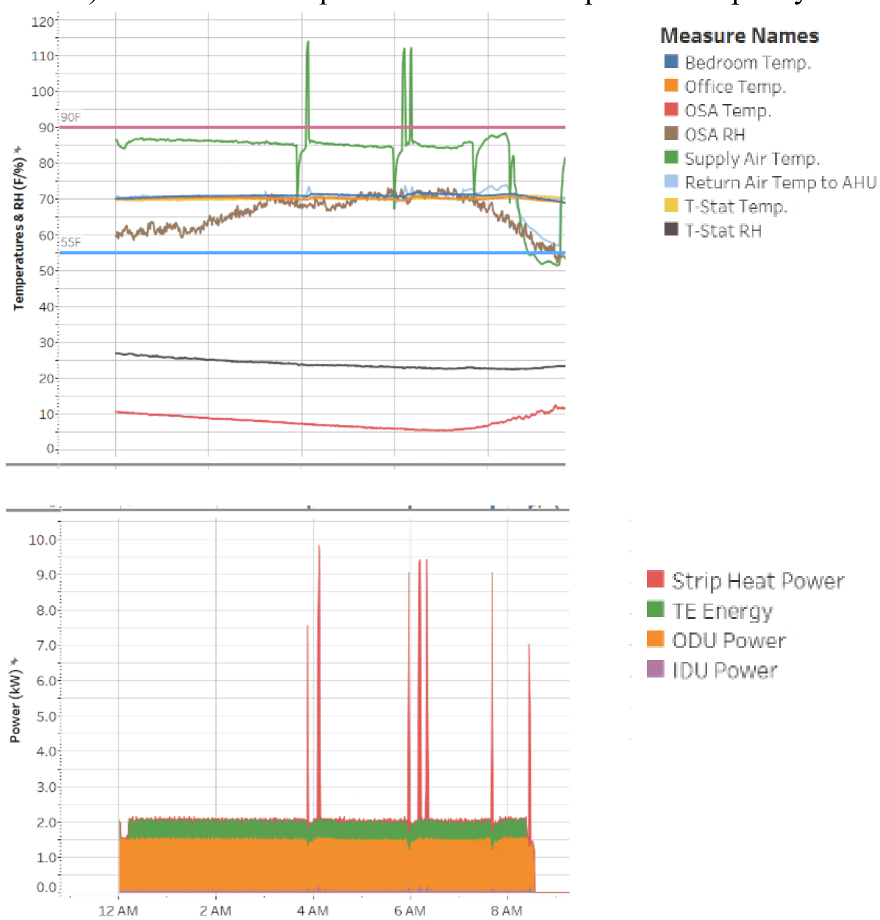

Figure 7. Field measured data for the cascaded thermoelectric-integrated heat pump acquired on 20th January, 2025.

Both above instances of field data analyzed show that cascaded thermoelectric-integrated heat pump can significantly reduce energy consumption and peak demand. For the end-customer, the cascaded thermoelectric-integrated heat pump creates annual heating energy savings vs. a conventional single-speed heat pump. For the electric utility provider, the cascaded thermoelectric-integrated heat pump eliminates or drastically reduces the use of supplemental heat and ensures managed adoption of electric heating on the grid. For the specific case of 5˚F operation outlined above, the peak demand was shaved only by 0.42 kW (calculated as 902 W/0.98 – 510 W). However, it is important to consider that the field prototype used for this study ran solely on vapor compression cycle down to about 15˚F outdoors because the heat pump was sized for heating needs. Most heat pump installations in the U.S. are sized for cooling needs, necessitating supplemental electric resistance starting at a much higher outdoor temperature.

Therefore, thermoelectric-integrated heat pumps have scope for significantly larger peak demand savings in the scope of current heat pump sizing practices followed by contractors.

Affordability Analysis of Cascaded Thermoelectric-Integrated Heat Pump

The proposed thermoelectric-integrated heat pump can be built using additional components that are easily available to augment a conventional air-source heat pump. These include the TE modules with the TE assembly, the heat exchanger capillary tube bundles with the fin base, small fans and control box to power the TEs. Note that no extra compressors or other sophisticated moving parts are necessary for fabrication, hence the additional components will only minimally increase the capital cost of the system.

Table 3 shows the key additional components needed to build the TE subcooler and their expected costs. For the field-demonstrated heat pump discussed in this study, the cost of TE modules was approximately $150-$300 ($2-$3 per module x 80 modules). The cost of the TE modules will scale with the required heating capacity from the TE subcooler and the number of modules required. The second set of components is the TE assembly, consisting of power supply to the TE subcooler, wiring and the fans to dissipate the heat from the TEs. Power supply can be accomplished by building a control box consisting of a relay and electric bridge which is estimated to cost between $30-$75. Along with the electrical wiring and the fans, the total cost can be around $200-$300. The third component, namely the heat exchangers consisting of the capillary tube bundles and the aluminum fin base would cost a similar amount ($200-$300). Considering also any additional supplies and the labor required to build the TE assembly, there is a 10-15% upfront cost increment over the conventional single-speed ASHP (i.e. $100-$150 per kW of heat pump's rated capacity).

Table 3. Key additional components that add to the system cost of cascaded thermoelectric-integrated heat pump

Item	Cost Estimate
TE Modules	$150-$300, scales with capacity and number of modules
Control Box, Fans, Electrical Wiring	$200-$300
Exchanger: Capillary Tube Bundles & Fins	$200-$300
Additional Labor Cost	Varies, estimate of $100-$200 per heat pump
Total Cost Increment	**Estimated at $100-$150 per kW of heat pump's rated capacity**

As mentioned earlier, commercially available cold climate heat pumps require expensive components such as vapor injection variable-speed compressors which significantly elevates the capital cost (additional incremental cost of $400-$650 per kW compared to a conventional single-speed ASHP); therefore, thermoelectric-integrated heat pumps have the potential to be highly affordable in addition to being more efficient than single-speed heat pumps. Combining the benefit of only minimally higher upfront costs with the energy and peak demand savings obtained compared to a conventional single-speed heat pump using electric resistance backup heating, it is practical for the proposed thermoelectric-integrated heat pump to yield attractive payback. Successful commercialization could render payback periods within 3-10 years for most of the U.S. regions depending on the prevailing fuel rates in the region of installation.

Energy Impacts of At-Scale Adoption for Electric Utilities

The cascaded thermoelectric-integrated heat pump configuration improves cold-climate heating performance without relying on electric resistance strip heat. Field testing results showed that the thermoelectric stage provides an incremental heating contribution with an effective COP of 1.4–1.8 for ambient temperatures below 15˚F (compared to 1.0 for resistance heating), while prior research (Shen, Gluesenkamp, and Wan 2022) has that the COP for the overall system can cross 2.5 when averaged over the entire heating season. These results support improved performance in cold-weather conditions compared to conventional heat pumps. As a result, thermoelectric-integrated heat pumps may expand electrification potential for utilities by influencing their electrification and energy efficiency programs.

Two complementary pathways define the at-scale market impacts of this technology. The first involves replacing fossil fuel heating systems, primarily natural gas furnaces and propane systems, with thermoelectric-integrated heat pumps in both existing buildings and new construction. This pathway increases electricity demand but eliminates direct combustion emissions and enables emissions reductions as the electric grid decarbonizes. The second pathway is energy efficiency potential, which replaces electric resistance furnace equipment, or lower-efficiency heat pumps with higher-performance thermoelectric-integrated heat pumps. This pathway reduces electricity consumption while maintaining or improving occupant comfort. These two impacts are reported herein as the technical electrification potential of thermoelectric-integrated heat pumps by 2050 for residential and small-commercial buildings, which represents the theoretical maximum deployment if all suitable applications adopted the technology.

For the electrification pathway, baseline fossil fuel heating consumption totals approximately 3,477 TBtu annually in U.S. residential buildings and 276 TBtu in U.S. small commercial buildings (RECS 2020, CBECS 2018). Converting this heating demand to electricity yields a technical electrification potential of about 453 billion kWh of additional electricity demand annually by 2050, including 413 billion kWh in residential buildings and 40 billion kWh in small commercial buildings. Under current grid emissions factors, this transition results in an estimated 74 million metric tons of CO_2 emissions reduction annually by 2050. These calculations assume an average seasonal COP of 2.5 for the thermoelectric-integrated heat pump and approximately 0.85 AFUE for conventional fossil fuel systems. A building stock projection of approximately 19% residential growth and 38% small commercial growth by 2050 (AEO 2024) is also assumed.

The energy efficiency pathway evaluates the replacement of electric resistance heating systems such as electric furnaces, which typically operate at approximately 1.0 COP. Current U.S. residential resistance heating systems consume about 127 billion kWh annually. Replacing these systems with thermoelectric-integrated heat pumps operating at 2.5 COP reduces electricity consumption by roughly 76 billion kWh annually, representing approximately 30 million metric tons of CO_2 emissions reduction by 2050 due to lower electricity use.

Combining both pathways yields an aggregate technical potential of 377 billion kWh (453 billion kWh for electrification and 76 billion kWh reduction for energy efficiency) net additional electricity demand. Electrification eliminates direct combustion emissions but shifts emissions to the electric grid while energy efficiency reduces emissions due to decrease in electricity consumption. Electrification and energy efficiency of U.S. space heating with thermoelectric-integrated heat pumps leads to reduction of approximately 104 million metric tons of annual CO_2 emissions by 2050. This estimate establishes the upper bound of potential thermoelectric-integrated heat pump deployment.

Realizing this potential will require coordinated market development efforts. Key enablers include continued technology improvements to enhance performance using more efficient TE modules, scaled manufacturing to lower capital costs by approximately 15–25%, utility incentive programs to address upfront cost barriers, and contractor training to support installation and market awareness. Apart from energy benefits, the other key utility impact is the peak demand savings, as discussed in the Results section. These benefits are key drivers for further evaluation of the technology.

Conclusion

This study demonstrated the design and field validation of a residential air-source heat pump enhanced with a modular thermoelectric (TE) subcooler. The results demonstrated that thermoelectric-integrated heat pumps are a viable approach to improving the performance of conventional air-source heat pumps, particularly under low ambient temperature conditions. Field testing in an occupied single-family home showed that the TE stage increased the system's heating capacity by 29% at 15˚F and reduced electricity demand by 10% compared to a conventional heat pump, while maintaining stable indoor temperatures and comfort.

At outdoor air temperatures below 15˚F, TE subcooler augmented heating capacity of the heat pump at a COP between 1.4 and 1.8, significantly outperforming electric resistance heating and eliminating the need for backup strip heating down to 5°F. The TE enhancement relies only on low-cost, widely available components and requires no additional compressor hardware; hence it introduces only a modest cost premium of approximately 10-15% above a conventional single-speed heat pump. This translates into a favorable payback period of 3-10 years depending on local energy prices.

At scale, thermoelectric-integrated heat pumps offer significant electrification and energy-efficiency potential for electric utilities. Nationwide adoption across suitable residential and small commercial buildings could produce roughly 375 TWh of net additional electricity demand while reducing more than 100 million metric tons of CO_2 annually by 2050. Overall, the field demonstration shows that this technology is a practical and scalable enhancement that can support low-carbon, affordable, and grid-friendly heating in cold and moderate U.S. climates, especially with proper support through utility programs, workforce training, and market incentives.

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